Risk-based Regulatory Design for the Safe Use of Hydrogen

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Foreword

Hydrogen technologies have the potential to contribute to the decarbonisation of economies and help tackle the climate crisis, by producing hydrogen from clean energy sources. Low-emission hydrogen can provide solutions to several "hard-to-abate" sectors that still rely heavily on fossil fuels, balance energy supply variabilities, and provide a green transport alternative, especially for heavy-duty and long-distance transport. As climate change becomes increasingly visible and the world faces shocks to energy markets, this potential becomes even more important. However, to promote hydrogen solutions and accelerate their safe and widespread use, a robust and agile regulatory framework is needed.

Based on current practices, future trends, and the regulation of hydrogen across countries, this report provides recommendations on the regulation of hydrogen in the Netherlands to support more widespread use of low-emission hydrogen. The recommendations address the governance of hydrogen along the regulatory cycle from risk assessment to policy development and regulatory delivery and include a range of safety considerations. These recommendations can help the Netherlands, as well as other countries, build regulatory frameworks that encourage rather than hamper new hydrogen technologies to decarbonise economies. As hydrogen is expected to play an important role in achieving ambitious climate objectives, progress in this direction could bring broad societal benefits.

Technological and scientific advances have reduced uncertainty around hydrogen risks, allowing countries to better manage them. Well-informed public deliberation and decision making can yield more accurate and up-to-date risk perceptions, avoid biases and achieve a well-managed balance of risks. Targeted approaches to licensing, inspections and enforcement can ensure regulatory requirements remain proportionate to actual risks and remove unnecessary burdens. Through effective communication and guidance, governments can improve public trust, drive consistency and foster a positive investment climate.

While the recommendations in this report are tailored specifically to the context of hydrogen regulation in the Netherlands, they might also provide inspiration for other countries and the regulation of other low-carbon energy applications. However, the research on safety risks and measures in the report is focused only on hydrogen and did not cover other related fuels such as ammonia.

The report builds upon international best practice in regulatory governance and complements other findings, in particular the report Understanding and Applying the Precautionary Principle in the Energy Transition (OECD, 2023). A set of additional background documents on hydrogen risk and regulation are added as separate parts to the current report. It includes the following parts:

- Part I – Report on literature review;
- Part II – Regulatory review;
- Part III – Review of international experience with hydrogen pilot projects;
- Part IV – Review on incident database and lessons learnt;
- Part V – Hazard and consequences analysis;
- Part VI – Lessons learned and preliminary findings regarding hydrogen safety elements; and
- Part VII – Quantitative risk assessments.

Disclaimer: The abovementioned parts contain background material that was used as input for the current report *on Risk-based regulatory design for the safe use of hydrogen*. They have been drafted by external experts following OECD guidance for the purpose of the project and do not necessarily reflect the views of the OECD.

This report is part of a project requested by the Netherlands on *Precaution in the energy transition and improved knowledge for hydrogen risk regulation*. The action was funded by the European Union via the Technical Support Instrument, and implemented by the OECD, in co-operation with the Directorate-General for Structural Reform Support of the European Commission. This document was produced with the financial assistance of the European Union. The views expressed herein can in no way be taken to reflect the official opinion of the European Union.

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The first part of this report, presenting the overall summary of findings and recommendations, was prepared by Vincent van Langen, with significant inputs from Carola Bertone, Florentin Blanc, Céliane Breuyre, Francesco Calisi, Costanza Caputi, Stella Giannisi, Blerta Guzina, Luca Megale, Hamsini Shankar and Giuseppa Ottimofiore. The report was edited by Nick Yannoulopoulos and Eleni Leontidou and prepared for publication by Jennifer Stein.

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Abbreviations and acronyms

ACM	Authority for Consumers and Markets (*Autoriteit Consument en Markt*)
ADR	European Agreement concerning the International Carriage of Dangerous Goods by Road (*Accord européen relatif au transport international des marchandises Dangereuses par Route*)
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
ASME	American Society of Mechanical Engineers
AT	Telecom Agency (*Agentschap Telecom*)
ATEX	Equipment intended for use in explosive atmospheres (*Appareils destinés à être utilisés en Atmosphères Explosibles*)
Bevb	Decree External Safety Pipelines (*Besluit externe veiligheid buisleidingen*)
Bevi	Decree External Safety Establishments (*Besluit externe veiligheid inrichtingen*)
Bkl	Decree Quality Living environment (*Besluit Kwaliteit Leefomgeving*)
BOVEN	Administrative Forum for a Safe Energy Transition in the Netherlands (*Bestuurlijk Overleg voor een Veilige Energietransitie in Nederland*)
BP	BP p.l.c.
Brzo 2015	Decree risks major accidents 2015 (*Besluit risico's zware ongevallen 2015*)
CBS	Statistics Netherlands (*Centraal Bureau voor de Statistiek*)
CCS	carbon capture and storage
CCTV	closed-circuit television
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation and storage
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CNG	Compressed natural gas
COAG	Council of Australian Governments
COMAH	Control of Major Accident Hazards
COP	Hydrogen Community of Practice
DEI+	Demonstration Energy and Climate Innovation Scheme (*Demonstratie Energie- en Klimaatinnovatieregeling*)

DG REFORM	Directorate-General for Structural Reform Support
DN	Nominal Diameter
DNV	Det Norske Veritas group
DoE	Department of Energy
DoT	Department of Transportation
DSB	Norwegian Directorate for Civil Protection
EC	European Commission
ECOSOC	Economic and Social Council
ECV	Emergency control valve
EFV	Excess flow valve
EHD	European Hydrogen Backbone
EIA	environmental impact assessment
EIGA	European Industrial Gases Association
ENSAD	Energy-related Severe Accident Database
ERF	European Risk Forum
ESD	Emergency Showdown system
ESD	Emergency-shut-down
EZK	Ministry of Economic Affairs and Climate Policy (*Ministerie van Economische Zaken en Klimaat*)
FCEV	Fuel cell electric vehicle
FCH 2 JU	Fuel Cells and Hydrogen 2 Joint Undertaking
FCHO	Fuel Cell Hydrogen Observatory
FCV	Fuel Cell Vehicle
FFD	Flame failure device
GHPGSO	General High Pressure Gas Safety Ordinance
GHRS	Gaseous Hydrogen Refuelling Station
GRHYD	Grid Management by Hydrogen Injection to Decarbonise Energies (*Gestion des Réseaux par l'injection d'Hydrogène pour Décarboner les Énergies*)
GSMR	Gas Safety Management Regulations
GTR	Global Technical Regulation
GTS	Gasunie Transport Services B.V
GW	gigawatt
H2	hydrogen
HEPHSA	Hydrogen Economy Promotion and Hydrogen Safety Act
HFCV	Hydrogen Fuel Cell Vehicle
HIAD	Hydrogen Incident and Accident Database
HPGSA	High Pressure Gas Safety Act
HPGSCA	High Pressure Gas Safety Control Act
HRR	Heat Release Rate

HRS	Hydrogen Refueling Station
HSE	UK Health and Safety Executive
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
IED	integrated environmental obligation
IFV	Institute Physical Safety (*Instituut Fysieke Veiligheid*)
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Projects of Common European Interest
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IPLO	Information Desk Living Environment (*Informatiepunt Leefomgeving*)
IR	Individual Risk
IRENA	International Renewable Energy Agency
IRGC	International Risk Governance Council
ISO	International Organization for Standardization
JRC	Joint Research Centre
KGSC	Korea Gas Safety Corporation
KLIC	Cable and Pipelines Information Centre (*Kabels en Leidingen Informatie Centrum*)
ksi	kilo pounds per square inch
LFL	Lower Flammability Limit
LH2	Liquid Hydrogen
LHRS	Liquid Hydrogen Refuelling Station
LNG	liquefied natural gas
LOHC	liquid organic hydrogen carrier
LOPA	Layers of Protection Analysis
LPG	Liquid petroleum gas
METI	Minister of Economy, Trade, and Industry
MIE	Minimum Ignition Energy
MOTIE	Ministry of Trade, Industry and Energy
Mt	million tonnes
Mtoe	million tonnes of oil equivalent
MW	megawatt
NDT	Non-Destructive Testing
NEC	National Electrical Code
NEN	Dutch Foundation Royal Standards Institute (*Stichting Koninklijk Nederlands Normalisatie Instituut*)
NERL	National Energy Retail Law
NERR	National Energy Retail Rules
NFPA	National Fire Protection Association
NG	Natural gas

NGL	National Gas Law
NGR	National Gas Rules
NL	The Netherlands
NLA	Dutch Labour Inspection (*Nederlandse Arbeidsinspectie*)
NPMS	National Pipeline Mapping System
NWBA	Dutch Hydrogen and Fuel Cell Association (*Nederlandse Waterstof en Brandstofcel Associatie*)
NWO	Dutch Research Council (*Nederlandse Organisatie voor Wetenschappelijk Onderzoek*)
NWP	National Hydrogen Initiative (*Nationaal Waterstofprogramma*)
OD	environment service (*omgevingsdienst*)
OSHA	Occupational Safety and Health Administration
PEM	proton exchange membrane
PGS	Publication series Dangerous Substances (*Publicatiereeks Gevaarlijke Stoffen*)
PHMSA	Pipeline and Hazardous Materials Safety Administration
PPP	Pressure Peaking Phenomenon
PRD	pressure relief device
PRV	pressure relief valve
PSR	Pipeline Safety Regulations
QRA	Quantitative Risk Assessment
R&D	Research and Development
RCS	Regulation, Codes and Standards
RIA	regulatory impact assessment
RIVM	National Institute for Public Health and the Environment (*Rijksinstituut voor Volksgezondheid en Milieu*)
SAC	Standardization Administration of China
SDE++	Stimulating Sustainable Energy Production and Climate Transition grant (*Stimulering Duurzame Energieproductie en Klimaattransitie*)
SEA	strategic environmental assessment
SGN	Scotland Gas Networks and Southern Gas Networks
SOEC	solid oxide electrolyser cell
SSAC	Scottish Science Advisory Council
SZW	Ministry of Social Affairs and Employment (*Ministerie van Sociale Zaken en Werkgelegenheid*)
TC	Technical Committee
TEN-T	Trans-European Transport Network
THT	tetrahydrothiophene
tpd	tonnes per day
TPRD	thermal pressure relief device
TSI	Technical Support Instrument

TSO	Transmission system operator
TWh	Terawatt-hour
UFL	Upper Flammability Limit
UN	United Nations
UNECE	United Nations Economic Commission for Europe
VR	safety region (*veiligheidsregio*)
Wabo	Act on the general provisions environmental law (*Wet Algemene bepallingen omgevingsrecht*)
WVIP	Hydrogen Safety Innovation Programme (*Waterstof veiligheid Innovatie Programma*)

Executive summary

This report was prepared at the request of the Dutch government and funded by the European Commission's (EC) Directorate-General for Structural Reform Support (DG REFORM). The findings and recommendations in the report are tailored to the Dutch context but may be relevant for other countries, taking into account contextual specificities. It aims to support the transition towards wide-spread use of low-emission hydrogen, by developing a set of recommendations on its regulation and governance. To do so, the report analyses six distinct scenarios that cover different parts of the hydrogen lifecycle from production to usage. These scenarios have been selected at the request of the Dutch Ministry of Economic Affairs and Climate Policy.

Sound, risk-proportionate regulatory policy and governance are crucial to drive the energy transition and enable the development of low-carbon energy solutions like low-emission hydrogen. Hydrogen, if produced from low-emission sources, can decarbonate "hard-to-abate" sectors still relying on fossil fuels, including in transport, turn low-carbon electricity into a fuel that can be transported through pipelines and allows for longer-term energy storage. Hydrogen can thus allow for a net reduction in societal risks, if managed responsibly. However, while its potential is widely acknowledged, rollout is not yet meeting many countries' strong ambitions, and perceptions and regulatory frameworks may be part of the issue. Regulation is a key element to ensure the hydrogen strategies of governments can materialise in practice, by facilitating the rollout of hydrogen technologies and ensuring their safety. A smooth deployment will require an enabling regulatory framework that is innovation-friendly, consistent, and agile, based on up-to-date evidence on actual risks.

The main findings and recommendations from the report are discussed below.

Advances in knowledge and technologies allow for a better management of hydrogen risks

Technological advances and increased scientific knowledge have decreased the "unknown risks" surrounding hydrogen use, reducing the need for additional caution compared to hydrocarbon fuel technologies. The behaviour and risks of hydrogen are currently better known and, if managed properly, hydrogen is overall not riskier than hydrocarbon fuels for many applications considered in this report, even when considering only safety risk in the narrowest sense.

Major hydrogen-linked accidents can, beyond their direct human harm, hinder further development of hydrogen through a loss of trust. Ensuring *effective* regulation is key – which requires adequate technical requirements, based on the latest research and technological advances, and supported through well-targeted, risk-based enforcement. Accidents and pilots can feed into improvements in technical designs and regulations to reduce future risks. Combining this with safe-by-design approaches, along with new knowledge as it arises, can help target the underlying causes of accidents and reduce risks.

Holistic risk assessments can ensure regulation effectively balances the multiple risks at stake

No technology is entirely risk-free. Safety is relative, and the risks of hydrogen technologies can be compared with other energy technologies. In some cases, behavioural biases such as the “risk regulation reflex”, a “rush to judgement” and “path dependency” may come into play; addressing them requires clear information, communication, and science-based decision making.

Holistic risk assessments can ensure that the regulation of hydrogen also consider hydrogen’s role in decarbonising and mitigating climate change risks. Safety risks and measures should be risk-proportionate and weighed against climate change-related risks of “stalled innovation”, among others. Risk mitigation strategies should not discriminate against new technologies and demand higher levels of safety than is required of high-carbon, existing technologies. This can achieve a well-managed balance of safety, health, environmental, social, political, and economic risks.

Additional caution should be applied where necessary and when risks are still largely unknown

Safety knowledge varies across hydrogen technologies, and thus they can be regulated differently. When scientific knowledge is more limited and risks are less known, additional pilots can improve scientific knowledge, while using more adaptive, iterative approaches to improve regulation as technology advances.

Risk-focused regulatory delivery can reduce unnecessary regulatory burdens

Focusing on outcomes rather than prescribing detailed procedures can support efficient licensing, inspection and enforcement practices. This could involve limiting permitting requirements to the minimum necessary and making procedures more proportionate and streamlined. It could also involve ensuring zoning policies allow for the use of hydrogen in a risk-proportional way.

Effective communication and guidance can support public trust and an enabling investment climate

While there are real risks associated with hydrogen, there are often large gaps between risk *perceptions* and science-based risk assessments. Clear engagement and messaging on risks and safety measures can promote correct perceptions and build public support and trust for a transition to hydrogen. Clear guidance for zoning officials, permitting and inspection bodies, and one-stop shops can be used to facilitate hydrogen roll-out.

Role clarity, effective co-ordination and sufficient resources can empower public institutions to keep pace with changes

Legislation should establish clear mandate, powers and objectives for all authorities involved with hydrogen. A formalised co-ordination platform across levels of government should further strengthen regulatory co-operation and consistency. Furthermore, resourcing frameworks should be sufficiently agile to allow bodies to act on new mandates and recruit or develop necessary skills.

1

Recommendations for the smooth development and rollout of hydrogen applications

This chapter discusses a number of key findings and recommendations that can support regulators and policymakers in developing effective risk-based regulation to increase the role of hydrogen in their societies. These recommendations concern various aspects of the governance of hydrogen, from risk assessment to policy development and from regulatory frameworks to regulatory delivery.

Effective regulation[1] is essential for the success of the hydrogen transition. Their design matters because, while keeping safety a priority they need to support and facilitate the hydrogen transition rather than impede and complicate it. Commitments by countries to tackle global warming depend on innovation to develop and use new energy sources. Hydrogen is expected to play an important role in the future net zero world, but this potential depends on an enabling regulatory framework that allows for the smooth development and rollout of hydrogen applications. This requires regulation and regulatory delivery that are innovation-friendly, consistent and based on up-to-date evidence and knowledge of actual risks. Figure 1.1 identifies a number of elements in the cycle from risk-based regulatory design to delivery that should all be carefully designed to support the Dutch hydrogen transition while ensuring appropriate risk management. These elements will be discussed in detail in this chapter, by making assessments and recommendations.

Figure 1.1. Elements of risk-based regulatory design and delivery

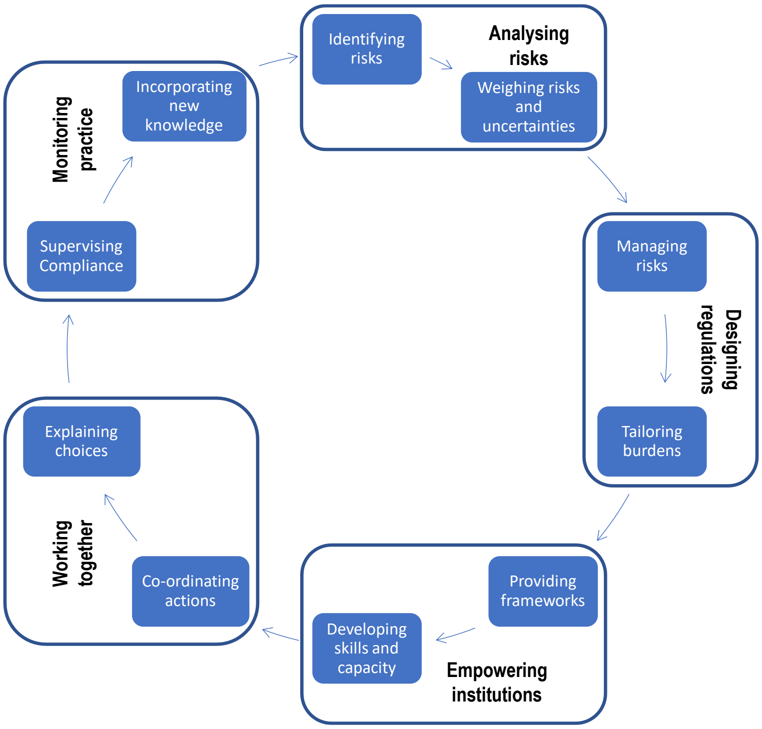


Figure 1.1 provides a simplified framework that highlights several considerations during the stages of design and delivery. In practice, certain steps may overlap in time, or take place at several stages along the cycle. For example, while "explaining choices" identifies a moment for stakeholder engagement, engagement will take place at several other stages as well, such as when weighing risks and uncertainties and when developing frameworks. This is discussed in more detail throughout the chapter.

This chapter discusses a number of key findings and recommendations that can support regulators and policymakers in developing effective risk-based regulation to increase the role of hydrogen in their societies. These recommendations build on findings regarding (comparative) risks, regulation and trends in deployment for six distinct scenarios, as discussed in Chapter 5. Recommendations are tailored to some extent to the Dutch context, but could provide inspiration to the regulation in other countries as well, provided country-specific conditions are taken into account.

How safe, and how strictly regulated, is hydrogen? – Challenges in comparing different technologies and fuels

The impossibility of a reliable comparison of accident rates

Ideally, one would compare accident rates of hydrogen-fuelled (H_2) vehicles against hydrocarbon-fuelled ones, or of refuelling stations against stations for different types of fuels, or of electrolysis facilities against oil refineries. However, the very small volume of hydrogen-powered vehicles and associated distribution and production, and the massive spread of hydrocarbon fuels worldwide, mean that such numbers cannot currently be reliably compared in terms of "damage per distance travelled" or "damage per energy unit". Available databases of industrial accidents (eMars, HIAD, ENSAD, H2tools, etc.) include all types of hydrogen-involved accidents, including many where hydrogen is only a by-product of the accidental reaction, or even hydrogen compounds (e,g, "hydrogen sulfide", "hydrogen chloride", "hydrogen cyanide", etc.), and not the cause or even one of the contributing drivers.

For instance, eMars (European Commission, 2023[1]) contains 142 accidents matching "hydrogen", of which only 22 pertain to hydrogen rather than a compound, and of these, in at least 9 hydrogen was produced accidentally in an industrial process unrelated to the use of hydrogen. A typical example is the 2001 Corus UK accident (Curry and Hodges, 2001[2]), where hydrogen was produced accidentally after water penetrated a blast furnace. The remaining accidents might involve hydrogen produced as such, but usually in the presence of oxidising agents, and are not representative of hydrogen as a power source for vehicles, which is the main focus of this report.

Is hydrogen "reasonably safe" in its key applications for the energy transition?

There are several ways to consider this question, and it is essential to remember that safety should always be assessed here in comparison with whatever energy source would be the alternative to hydrogen (hydrocarbon fuels in most cases, electric batteries in some cases), and not with a "zero risk" hypothesis. In summary:

- As part of preparing this report, a thorough literature review considered 99 publications spanning over 40 years, which led to the conclusion that hydrogen was overall often in the same range of safety as hydrocarbon fuels in the applications considered, while of course requiring safety measures and regulations adapted to its different physical behaviour compared to hydrocarbons (see Part I – "Literature review").
- The most serious and noteworthy hydrogen-involving accidents, or near-accidents, involve the simultaneous presence of hydrogen and of large quantities of oxidizing substances. For example, for rocket launches, liquid hydrogen *and* liquid oxygen are both present. These cases are totally different from the energy transition applications considered in this report, where hydrogen is not accompanied by any substantial amount of oxidising agents that could lead to explosion.

Accounting for risk reduction due to hydrogen use

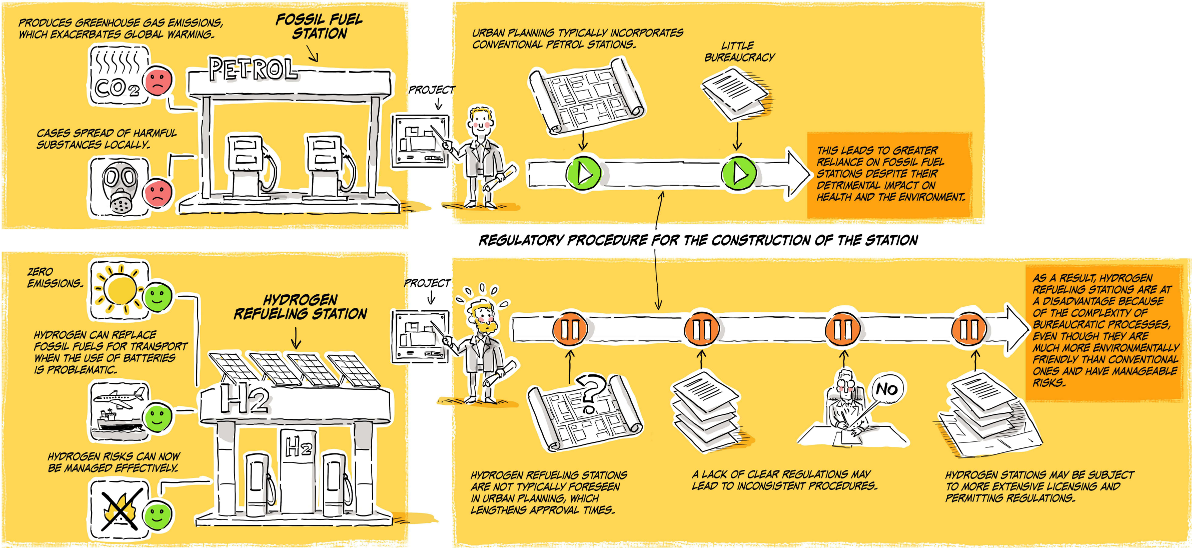
Because of hydrogen's specific physical and chemical behaviour, and of the considerable research efforts put into developing safer equipment, there are situations where hydrogen is safer than hydrocarbon fuels in a direct, immediate way (see Chapter 6 of Part I – Literature review). The main way in which hydrogen can overall reduce risks in a very important way is through its positive impact on climate change (assuming of course low-emission hydrogen is used, which this report focuses on). Reducing climate emissions means a considerable impact in terms of reduction of risks from catastrophic climate events. Finally, hydrocarbon fuels also present other major environmental and health risks, which hydrogen use would decrease. This is crucial particularly considering applications where other low-carbon alternatives such as electric batteries are inadequate for reasons of weight and range, e.g. transport of goods, particularly maritime transports but also road freight transport (see Box 2.1). To focus just on the climate angle, in the EU alone, transport is responsible for 800 Megatons of CO_2 equivalent, of which close to 40% due to trucks (EEA, 2022[3]). Achieving carbon neutrality for Europe will entail a 90% reduction in transport emissions by 2050, and hydrogen is explicitly mentioned as a tool for that purpose in the EU Commission's "Sustainable and Smart Mobility Strategy" (European Commission, n.d.[4]).

What levels of regulation does hydrogen face?

Defining levels of regulation (and possibly identifying "over-" or "under-" regulation) can only be done in comparison both to the risks specific to the application of hydrogen being considered, and with the regulation applied to hydrocarbon fuels for similar applications. This report only discusses a set of specific processes and applications (electrolysis, transport, refuelling, hydrogen-powered vehicles). Details of existing regulations are discussed in Part II – Regulatory review. The problem is often that these new applications of hydrogen have not been foreseen in existing legislation, and that they are thus "by default" either unaccounted for, subject to requirements that do not match its specific risks or facing regulatory uncertainty, particularly in terms of site approval and permitting. This does not in any way mean that hydrogen is generally over-regulated, and this report in any case does not cover the industrial processes involving hydrogen, which often benefit from long-established, specific regulations. Providing case-by-case comparison for every case and country would go beyond the scope of the report, we thus provided a comparison for one simple example: opening a hydrogen refuelling station (HRS), looking at three jurisdictions (California, England, and the Netherlands) (see Box 3.2). Even in the most favourable regime (California), opening a HRS remained longer and more difficult (restricted siting because of higher fire safety distances) (Harris et al., 2014[5]). While regulations are being eased to reduce safety distances, overall permitting procedures still take time. In England, it was much longer because of falling under gas licensing requirements and safety plus environmental permitting. In the Netherlands, it was both longer and more difficult because of no zoning provision for HRS and the need to obtain both zoning exemptions and environmental permits.

In summary: "Most [EU] countries currently lack specific regulation that target the dispensing of hydrogen in refuelling stations, as this is still new equipment that has not been targeted in regulations. For the HRS currently deployed, the permitting procedure follows existent guidelines on conventional fuelling stations combined with industrial hydrogen requirements or CNG specific regulation. Most countries agree that the lack of specific regulations increases the level of subjectivity in the permit decision" (MultHyFuel Project, 2021[6]).

Figure 1.2. Regulating hydrogen in practice: Opening a hydrogen refuelling station



Source: Stefano Tartarotti, 2023.

Identifying and enabling hydrogen innovations and their regulatory needs

Hydrogen as part of industrial processes is both long-known and long-regulated, through safety and environmental legislation covering industrial risks and emissions. **The energy transition requires the large-scale roll-out of a number of hydrogen innovations, which generally do not currently have a specific regulatory framework** – they include: production through low carbon electrolysis (long-known, but hitherto used on a very limited scale only), transport through pipelines and land transport, distribution through refuelling stations, use in private and commercial vehicles, and possibly in some cases use for domestic heating purposes. Because these uses are new, there are in many cases no specific rules for them, they are often not foreseen in zoning, and they can end up being covered by industrial permitting requirements, or require complex and lengthy *ad hoc* authorizations or derogations.

It is essential that these new uses of hydrogen be properly foreseen, enabled, and effectively regulated at the same time. As described in more details further on, technical rules need to be adopted that ensure best practices are used in a systematic way, including through "safe by design" installations whenever they are available. At the same time, planning authorities and regulators need to ensure that new hydrogen technologies and uses are effectively enabled, with requirements that are proportionate to the risks and benefits of these innovations, and regulatory processes that minimize unnecessary burden and delays, but rather focus on the essential risk factors (OECD, 2021[7]).

Recommendations

- Identify hydrogen innovations that are a priority for scaling up, and present difficulties in the existing zoning and permitting frameworks. Governments have often already developed important plans for scaling up hydrogen production and/or use, but have not necessarily conducted a review of potential regulatory and planning bottlenecks. This is essential in order to enable this scaling up at the desired speed. It can largely be done through conversations with stakeholders, in particular permitting authorities and the industry.

- Revise zoning and permitting for new hydrogen applications. Incorporating lessons from practice and research, define zoning rules that enable the development of hydrogen in a safe way, and define permitting processes that are risk-proportionate, particularly for lower-risk facilities and uses – for which high-risk industrial permitting requirements are likely to be disproportionately burdensome.
- Ensure adequate safety through fit-for-purpose technical requirements informed by science and practice. Enabling zoning and simplified permitting do not mean lower safety – on the contrary, developing specific requirements covering the higher risk aspects of these new hydrogen applications (as discussed further) can help ensure that best practices and techniques are more systematically applied.

Analysing risks

Identifying risks

The design and delivery of risk-based hydrogen regulation will depend on how actual hydrogen risks compare to the risks of existing fuels and should factor in the growing understanding of hydrogen risks. Energy applications are never entirely risk-free. While the properties of hydrogen pose certain hazards (see Chapter 2, Understanding and managing hydrogen risk), hydrogen is overall not riskier than hydrocarbon fuels for many of the applications considered in this report if managed properly, even when considering only safety risk in the narrowest sense. Sometimes, with the right technology, it can already be safer. Improvements in technologies and scientific knowledge have significantly decreased the number of "unknown risks" for many hydrogen applications and contributed to building safer technologies. This therefore reduces the need for more cautionary approaches.

A siloed assessment of individual risks could result in suboptimal decisions from a social welfare perspective. Risks do not exist in isolation, but often the reduction of one risk may come at the expense of another. If one takes into account the climate impact and other adverse health and environmental impacts of hydrocarbon fuels, there is little doubt that hydrogen is not a *riskier* fuel, but quite the contrary. However, a sole focus on one specific risk can lead to excessively risk-averse approaches, the ignoring of countervailing risks and risk-risk trade-offs. This may be further complicated in cases where responsibilities for different risks may be spread across different authorities and levels of government, as is the case in the Netherlands, resulting in differing appetites for risk across authorities and an incomplete assessment of all risks. Specifically in the context of hydrogen, this could mean that measures to reduce safety risks – for example, by restricting the deployment of low-emission hydrogen[2] applications – may ignore the very climate change risk that these technologies aim to tackle.

Recommendations

- **Use holistic approaches to consider all relevant risks, and risk-risk trade-offs, related to the deployment of hydrogen applications.** Identifying the interaction that may exist between different risks – including health, safety, environmental and economic risks – can allow for a more comprehensive assessment of the implications of decisions and build a common understanding of the definition of risk. This would help to take into account risk-risk trade-offs, as well as systemic and cumulative risks, and would reduce suboptimal "siloed" decision making that could lead to a disproportional focus on safety risks at the expense of potential environmental benefits. Where different risks are assessed by different authorities, this holistic risk assessment will likely require additional information sharing and co-ordination between bodies (see Co-ordinating actions).

- **Quantify risks based on robust empirical data.** The relative novelty of many hydrogen applications means that there is less knowledge and information available on risks. However, the increasing momentum for hydrogen, driven by hydrogen strategies across the globe, has led to a significant increase in scientific knowledge and robust data on risks for new applications. This will enable decision makers to objectively quantify the risks related to new hydrogen applications with more precision. By quantifying risks based on empirical data, governments can ensure that regulations and measures are focused on actual rather than hypothetical risks.
- **Put risks into context by comparing hydrogen's risks to those of other energy sources such as natural gas.** This comparison may highlight where hydrogen poses "familiar risks" that are similar to conventional energy sources, and those attributes that may result in risk profile differences. This analysis can then feed into decision making on the appropriate measures. By putting risks into context, where possible using quantitative risk assessments, decision makers can better assess the net effect on risks that changing to hydrogen applications would entail, including the effects on existing risks that might reduce or disappear. Moreover, by comparing hydrogen risks with those that are more familiar, the risk assessment can be prevented from becoming a theoretical exercise and made more understandable (see Chapter 5 – Hydrogen applications in practice; Part IV – Review on incident database and lessons learnt and Part VII – Quantitative risk assessment).

Weighing risks and uncertainty

Incomplete understandings of risks, public perceptions and behavioural biases may potentially result in a higher degree of risk aversion for new hydrogen applications. While there is no doubt that real risks are associated with hydrogen, there are often large gaps between risk *perceptions* and actual, science-based risk assessments. The rollout of hydrogen applications introduces new risks, some of which may be more uncertain than others due to a lower availability of scientific research and historical data. The level of risk aversion that policymakers will apply in response to these uncertainties depends on the context in which decisions are made. It is essential, however, that regulation of low-emission hydrogen not be more unfavourable, at comparable risk level, than regulation of fuels that are high CO_2-emitters (hydrocarbons, mostly). This involves, in particular, looking at zoning plans and permitting procedures to ensure they are proportionate and adequately enabling.

An in-depth consideration on the public perception of hydrogen can be an important element for managing the energy transition, to increase the degree of awareness and the level of acceptance for the energy transition. Socio-political and psychological elements as well as public perception can play a decisive role, because risks of fire and explosion are often at the centre of the debate. In some cases, policymakers may "rush to judgement", by excessively regulating certain risks without acknowledging the trade-offs with other risks. In particular, a lack of familiarity with hydrogen applications could result in a lower risk tolerance than for existing fuels, for which a certain degree of risk has already been accepted. Moreover, the "availability heuristic" may lead to an increasing focus on low-probability accidents and worst-case scenarios (see Chapter 3 – Behavioural biases and public perceptions). The "present bias" can lead people to give more importance to current needs and less importance to future needs. Finally, "path dependency" can result in difficulties when institutions try to change or reform existing processes.

The level of risk aversion may differ according to the type of hydrogen application, depending on the countervailing risk that "stalled innovation" could bring. This means that where certain types of hydrogen applications have a more prominent role in a country's net zero strategy, safety risks have to be weighed against a higher risk of inaction (i.e. innovation is slowed down or prohibited). This could lead to countries accepting a higher level of risk (or implementing a lower level of risk aversion) for those technologies that will play a bigger role in combatting the climate crisis, especially where other "green alternatives" are limited.

As the level of knowledge on safety varies for different hydrogen technologies, it makes sense to regulate them differently. When scientific knowledge is more limited and risks are not obvious or simply unknown, additional pilots could be carried out to improve scientific knowledge. Hydrogen technologies can be divided into three broad categories, based on the level of existing knowledge and scientific research:

- Category 1 – **Mature technologies on which there is extensive scientific knowledge and data**. These technologies often do not require additional caution compared with conventional fuels, but can be facilitated and managed using existing risk management approaches and findings from recent research and good practices;
- Category 2 – **Technologies for which a significant level of scientific knowledge exists but additional data may be needed**. These technologies can be handled through risk management approaches using available scientific knowledge and experience with comparable technologies. However, they will require additional regulatory development, using iterative approaches, as scientific knowledge and technology advance;
- Category 3 – **Technologies for which risks are not yet completely understood**. These technologies require further investigation and research through pilot projects to more reliably assess risks, identify suitable policy approaches, define regulatory requirements, and build public awareness.

Recommendations

- **Provide clear information to the public on risks, including any countervailing risks that hydrogen applications try to address.** The provision at an early stage of understandable and objective information on all relevant risks across the full energy cycle of an application, including low-probability extreme events, can support the growth of trust and build wider awareness. As hydrogen currently only makes up a relatively small portion of the overall energy mix, there is a need to engage the wider society through a phased, transparent and inclusive communication strategy which enables informed decision making. Using clear communication to support knowledge, critical reasoning and elicit social assessments based on data can be an effective way to overcome social prejudices and fears. This will require on-going public engagement and behaviourally-informed information campaigns, in order to create a counterweight against potential mis- and disinformation or fear-mongering regarding risks and uncertainties. Emphasising and discussing not just risks to health and safety, but also the role of hydrogen projects within the Dutch climate ambitions to address climate risks, will enable society to better understand the importance of new hydrogen initiatives.
- **Proactively involve the public in decision making on hydrogen risks, safety measures and strategies.** Governments could use open and transparent decision making on risks, uncertainties and risk management to invite wider input into cost-benefit analyses of prospective hydrogen policies and initiatives. This could contribute to better informed decision making, build ownership and trust, and increase the willingness of societal actors to accept risk-risk trade-offs. As part of this effort, public perception studies can be used to understand the values and interests at stake and allow governments to better respond to existing concerns.
- **Develop and make public the risk tolerance criteria against which existing and new technologies are compared.** A common approach to risk management can support more harmonised actions between different authorities. To ensure policies and regulations are consistent, governments could define clear and consistent methodologies for risk assessment and the way in which different risks should be weighed and prioritised. In particular, such criteria should be used to frame the risks of new technologies in the context of existing risks, to avoid higher levels of risk aversion for newer (less familiar) technologies.

Designing regulation

Managing risks

The risks of hydrogen are decreasing as technologies and safety approaches mature, thereby reducing the need for additional caution around hydrogen as compared with other flammable gases. Research into the use of hydrogen has led to significant improvements in safety, making today's technologies safer than older historical incident data may suggest (although new data already highlights this trend, see Scenario 1 – Production through water electrolysis in Chapter 5). Research suggests that current hydrogen production – making use of modern designs and safety regulations – could present a lower normalised fatality risk per Terawatt-hour (TWh) as compared to conventional fuels (see Part IV: Review on incident database and lessons learnt). For other hydrogen applications, incidents are often typical of those for other flammable gases, although exact risks differ across scenarios. It is thus essential to develop an effective regulatory framework, that ensures best safety practices are followed, and allows the development of hydrogen.

By updating regulatory approaches, governments aim to combine appropriate levels of caution with the necessity to innovate for cleaner energy sources. Responsible Research and Innovation and Safety-by-Design approaches place a stronger emphasis on anticipation and inclusion to foresee risks during product development. This limits the need for additional measures once technologies are being applied. Both approaches rely heavily on the regulatory capacity and resources to build open relationships, albeit within the constraints of available scientific knowledge and commercial sensitivities.

Recommendations

- **Apply responsible research and safety-by-design approaches to the prevent risks of hydrogen applications where this is reasonably possible.** Approaches should prioritise safe designs that account for human error. This could favour applications with automatic shutdown mechanisms and safer materials, complemented by mitigation measures such as ventilation. For example, modern valve design has already contributed to a reduction in hydrogen accidents (see Part VI: Lessons learnt and preliminary findings regarding hydrogen safety elements). Regulators could certify safe components and equipment through "type approvals" that do not require individual assessment and use quantitative risk assessments to prioritise measures. This will require regulatory preparedness and earlier engagement with stakeholders through:
    - Informal exchange and outreach by regulators, for example through "innovation hubs" where innovators can discuss upcoming projects with authorities.
    - Improved guidance to innovators, including guidance material on engagement between innovators and authorities at early stages of innovation.
    - Prior assessments to better understand applications and risks early on.
- **Learn from international experience and standards to avoid having to "reinvent the wheel".** Regulations developed in other countries that are further ahead in achieving their hydrogen ambitions, as well as international standards such as those by the ISO (see Part II – Regulatory review), can provide a strong starting point for the Netherlands to design appropriate safety standards that are internationally aligned. This approach should favour more precise safety measures over outright bans of activities, thereby incentivising innovation.
- **Do not mitigate safety risks excessively beyond the desired risk targets or apply precaution to risks that are largely well-understood.** Risk mitigation measures should be based on widely agreed levels of desired risk tolerance and clear, top-down guidance for implementing authorities. This is to avoid "risk regulation reflexes" and inconsistencies between inspectors. Moreover, precaution should be limited to those cases where it is absolutely necessary because risks are still

largely unknown (scenarios such as this are declining rapidly due to advances in scientific knowledge and technology). Risk mitigation strategies should not aim to reduce risks beyond agreed levels of risk tolerance and should favour measures that are most effective at risk reduction, with the goal of achieving a well-managed balance of safety, health, environmental, social, political, financial and economic risks. As part of this approach, safety incidents should not lead to excessive restrictions or bans but should be used as learning opportunities to improve regulatory frameworks.

Chapter 5 discusses general safety measures and regulations in other countries for each scenario.

Tailoring burdens

Complex licensing procedures can slow down or impede the hydrogen transition. Licences often require significant effort, making the scaling up and development of new technologies such as hydrogen time and resource consuming. In practice, permit designs may be based on approaches that focus on a specific risk, without balancing risk-risk trade-offs against the risk of climate change. Other factors that may lead to less efficient licensing procedures include resource constraints and the overlapping mandates of authorities. Mandate overlaps can lead to duplication of efforts, additional burdens or inconsistencies in decisions. In certain cases, it can also result in conflicting policies, where licensing procedures slow down transitions that other policy instruments such as subsidies aim to accelerate. Moreover, the time at which hydrogen initiatives first get into contact with the Dutch authorities may differ by project and there are different parallel channels to establish these contacts.

Existing procedures may not match the exact risk reduction needs for new low-emission hydrogen applications. Hydrogen applications are often subject to more general licensing procedures designed for applications with dangerous substances or they may be asked to meet extensive safety requirements due to a lack of scientific understanding. Moreover, licensing requirements in the Netherlands are universal regardless of the type of hydrogen.

Recommendations

- **Use simplified procedures, fast-tracking and minimise the use of licensing to what is absolutely necessary.** The burden of instruments should match the risks they try to manage, where targeted safety measures should be preferred over outright bans of activities. Licensing should not be the default, but should be used only to manage significant safety risks. For hydrogen applications that are lower risk or for which risks can be managed more easily, governments should consider fast-tracking, notification requirements or so-called *silence is consent* provisions that limit the duration of procedures. For higher-risk applications, prior assessments of safety risks at earlier stages may be used to decrease the length of procedures after the finalisation of projects. Reducing document requirements and standardising requirements and forms can reduce costs and time for applicants. Competent authorities should consider ways to minimise the number of interactions between governments and hydrogen developers.
- **Make use of one-stop shops and guidance for innovators to clarify and streamline procedures.** A one-stop shop allows innovators to find all the requirements related to their project in a single location, saving them time and effort and reducing the number of authorities they need to engage with. This may be built from the online Environment Desk (*Omgevingsloket*), which already performs a number of one-stop shop functions and could include a dedicated platform with information for hydrogen projects (for example, information on the relevant authorities for different types of hydrogen applications and their contact information). A one-stop shop could be complemented by straight-forward guidance materials on relevant steps, to help innovators navigate the regulatory landscape and reduce uncertainty. Such guidance can support a reduction in the number of incorrect licence applications, thereby reducing the burden on both innovators and authorities.

- **Use outcome-based and risk-based regulatory models to target actual risks and outcomes.** Safety does not depend on the existence of an extensive set of requirements, but rather on the presence of efficient measures to reduce risks. Efficient licensing regimes will require agility to focus on the most pressing concerns, while reducing those requirements that have a low impact on actual risks. Processes should avoid a focus on specific measures that may become outdated as technology advances, and instead specify the risk levels that innovators need to show they conform with. Such outcome-based models can harness the opportunities offered by digital technologies and data to improve efficiency.

Empowering institutions

Providing frameworks

The Dutch hydrogen ambitions create new sector segments, which could give rise to an initial lack of role clarity and regulatory uncertainty. The introduction of low-emission hydrogen applications raises the question of how new responsibilities fall within existing institutional mandates, which are often linked to specific energy sources. This could result in a duplication of efforts or situations where regulatory agencies do not have the appropriate powers to respond to regulatory issues, thereby affecting the pace of the hydrogen transition. Moreover, in the absence of a dedicated regulatory framework for hydrogen, applications are mostly regulated under more general regulatory requirements, such as Seveso requirements or other frameworks for dangerous substances. These regulations can provide a suitable solution to manage risks until assessments of regulatory requirements have been concluded. However, they may not necessarily be the most efficient option to address the actual risks of hydrogen in all scenarios.

The hydrogen transition creates a need for additional guidance and direction, to avoid inconsistencies in decision making between national and local levels that could harm climate goals. Many licensing and supervision functions in the Netherlands are executed at the provincial or local level. On the one hand, this will allow authorities to better factor in the local context in their decision making. However, in combination with the lower levels of scientific knowledge that exist for many hydrogen applications, it could also give rise to inconsistent approaches across regions or an excessive focus on (local) safety risks over more global risks such as climate change. There is therefore a need to safeguard the harmony between policy direction at the national level and local implementation.

Recommendations

- **Provide clarity on roles and responsibilities and identify areas with potential gaps or overlaps.** Legislation should clearly set out the mandates, powers and objectives for authorities. Governments may wish to reconsider existing mandates where there are overlaps or gaps, and make sure responsibilities are clearly assigned. As it may not be possible to remove all "grey areas", effective co-ordination mechanisms can be used to align actions and resolve any conflicts (see Co-ordinating actions). Where the responsibility for one specific risk is shared among different authorities, consolidation of responsibilities or "lead agencies" could be used to ensure accountability. These efforts could support a harmonised execution of regulatory tasks to achieve envisaged outcomes. Furthermore, assigning clear mandates to authorities, if matched with the necessary resources, could enable authorities to invest in their capacities.
- **Conduct a "stock assessment" of existing frameworks that apply to hydrogen to assess their impact, with the goal to build a simple and effective regulatory framework.** This could for example include a public stocktake of existing frameworks for hydrogen to identify problem areas and solicit public views, or a principle-based review to focus on a specific performance area

such as administrative burdens (OECD, 2020[8]). More general regulatory provisions and thresholds may need modification, in cases where they do not target actual risks of hydrogen, or they create regulatory gaps or unnecessary regulatory burdens that excessively restrict activities. Regulatory options should be decided upon through regulatory impact assessments and stakeholder engagement. In addition, where existing requirements allow for significant regulatory discretion, the Netherlands should consider providing additional guidance to implementing authorities at the local level through decrees, codes, guidelines and standards (for example guidelines on QRAs for hydrogen refuelling stations).

- **Provide temporary solutions only on a time-limited basis.** Regulatory exemptions can facilitate the controlled trialling of new technologies and approaches in situations where regulatory frameworks are missing, for example through regulatory sandboxes. To provide predictability and ensure a level playing field, such exemptions should be time-limited and target a specific regulatory gap. Once scientific knowledge improves and legislation catches up, exemptions need to be phased out. Similarly, guidelines and other “soft law” may provide direction during early stages of developments while frameworks are absent, but should not replace legislative provisions that involve a higher level of scrutiny and engagement, and enhance predictability and legal protection.

Developing skills and capacity

The hydrogen transition is increasing the overall responsibilities of governments and regulatory authorities in the short term. As the application of hydrogen technologies throughout the Netherlands expands, policymakers and regulators will be asked to take on new responsibilities in fields they have relatively little familiarity with. These duties come on top of their existing responsibilities in other energy sectors, such as electricity, gas and (somewhat more recently) district heating. This will result in an increase in workload in the short term, though they may decrease in the longer term due to higher levels of experience and a reduction of activities towards energy systems that are phased out.

The effective delivery of new hydrogen responsibilities will depend on the ability to stay agile, build knowledge and skills, and keep abreast of new developments. Regulating hydrogen effectively will require an investment from public bodies to (1) understand hydrogen technologies, (2) incorporate the new economic, legal and safety realities of the hydrogen transition into their decision making, and (3) foresee upcoming developments through horizon scanning. This investment will put pressure on the overall resources of public bodies, where demands related to hydrogen compete with existing demands. Ultimately, their success in delivering on new hydrogen expectations will depend on the agility they have within their resource constraints to build new capacities and skills.

Recommendations

- **Conduct capacity assessments for public bodies at the organisation level and government-wide to understand skills needs.** Such capacity assessments should factor in the nature of existing and upcoming hydrogen responsibilities, the expected trajectory of hydrogen deployment in the country and the necessity of knowledge retention within the organisation. To stay relevant, the assessment should identify required skills, experience and competencies on a continuous basis, using periodical review to factor in new experiences, developments and demands.
- **Develop training programmes for existing staff and hire new skills as necessary.** Public bodies require new skills and knowledge to assess the impact of innovations on their work and to deliver upon new responsibilities with agility. This could be achieved through a mix of training existing staff and additional recruitment. Needs for new skills could be tied into the career development of existing staff by providing training and development opportunities and staff incentives. Where possible, training could be provided in collaboration with other public bodies and countries through online platforms to achieve economies of scale. This could be complemented by

the hiring of new staff to meet skills needs, especially where these have changed significantly or where overall responsibilities increase. The contracting of external expertise should be considered mainly for more temporary skills needs or to fill urgent skills gaps in the short term.

- **Assign the appropriate resources for authorities to be able to respond with agility.** Coherent and robust workforce planning can help build a forward-looking public service, a crucial element to incorporate the new responsibilities that the hydrogen transition will bring (OECD, 2021[9]). Conducting workforce plans at the level of organisations and government-wide can allow governments to translate skills assessments into human, financial and digital resource needs – in both the short and longer term – and assess and monitor the status quo. Moreover, more predictable resources will support public bodies in delivering effectively upon new demands, acknowledging the fact that it takes time to build new skills and capacities. Wherever reasonably possible, new responsibilities of a permanent nature should not be met with temporary resourcing mechanisms, as this could make it more difficult for bodies to develop and retain in-house skills.

Working together

Co-ordinating actions

The regulation of hydrogen in the Netherlands involves a range of actors at the local, national and EU level. Together, these actors will determine the success of the hydrogen transition. While hydrogen ambitions and policies are developed by EZK at the national level, they are implemented by a range of authorities at the national level (ACM, SodM, AT and NLA) and local level (provinces, municipalities, Ods and VRs). Moreover, regulations in the Netherlands depend on wider EU initiatives, with efforts to align policies at EU level through EU Directives and agreements such as the ADR.

Co-ordination of actions could bring efficiencies and burden reduction. Given the many actors involved, there is a need to ensure actions are co-ordinated and harmonised. In practice, there is not always sufficient clarity around the point in time when co-ordination between different bodies, such as between the OD and VR, is required. More co-ordinated action could decrease the burdens on regulated entities by reducing duplicated effort or inconsistencies in approach. As hydrogen ecosystems tend to cut across national and jurisdictional boundaries, there is an increasing need to co-ordinate regulatory action with authorities in neighbouring countries. Coherence of rules and approaches at the EU-level (and beyond) can support system integration, prevent regulatory arbitrage, improve the investment climate and allow for an international level playing field.

Recommendations

- **Identify areas for joined-up approaches and coherence in action between public bodies at different levels of government.** The Netherlands could strengthen regulatory co-operation across policy-making departments and regulatory agencies by identifying gaps or overlaps in existing co-ordination mechanisms. A formalised co-ordination platform for public bodies involved with hydrogen at different levels of government – such as a network or a periodic meeting – could support consistency and enable shared planning or execution of regulatory activities (while respecting each body's mandate, resources and level of autonomy). Frameworks should enable seamless co-ordination of approaches, where appropriate, through whole-of-government visions and approaches. This can prevent potential regulatory failures or suboptimal outcomes due to siloed approaches, support the proactive resolution of issues as they appear, and realise synergies. Joined-up approaches could also include an "emergency response plan", to co-ordinate actions after accidents and bolster public trust in decision making.

- **Enable wide knowledge sharing across public authorities to harmonise approaches.** The sharing of data, information and research findings across public authorities – through networks and joint research initiatives such as the EU Joint Research Centre (JRC) (see Chapter 4 – "Institutional context for hydrogen") – can support a shared understanding of developments and risks assessments. Knowledge sharing will be especially relevant in a context where the sector is subject to significant development, as is the case with hydrogen. Furthermore, it could reduce the risk of differential treatment or excessive risk aversion beyond agreed levels of risk tolerance that can stem from isolated risk assessments. To enable knowledge sharing, authorities could consider collective knowledge databases, periodic workshops and conferences, including interdisciplinary challenge events.
- **Exchange experiences and practices internationally to establish international best practice.** The Netherlands could use existing co-ordination platforms at the EU and international level to promote a continuous dialogue and engage in information and data exchange. This would enable mutual learning across countries and bring in the most relevant evidence and approaches to support its hydrogen ambition. Where necessary, additional co-ordination mechanisms could be considered, such as an EU network of hydrogen regulators or co-operation agreements. Moreover, ex ante impact assessments of policy options could include options that involve joint approaches with other jurisdictions, thereby addressing transboundary policy implications.

Explaining choices

Mechanisms of public accountability can support trust and public buy-in for the hydrogen transition. The Dutch hydrogen sector brings together many different public bodies. All are expected to contribute to the functioning of a healthy hydrogen sector, but through different roles and mandates. Accountability mechanisms can support the effectiveness of the respective actions of such public bodies, holding decision makers to account for their actions and supporting the integrity of their decision making. If done well, this can enable the public to scrutinise regulatory actions, identify cases in which authorities may have overstepped their mandate, and assess if public institutions do indeed contribute to the improvement of sector outcomes through their actions.

Increased transparency will benefit the predictability of regulatory frameworks, thereby giving companies the confidence to invest in hydrogen technologies. Regulatory frameworks are a key aspect for investors to consider when deciding whether to invest in a specific technology because they determine the constraints within which activities may be undertaken. The more transparent and predictable regulatory frameworks are, the lower the "regulatory uncertainty" to factor into decision making. Therefore, transparency in regulatory decision making can support a more positive investment climate. Transparency may be especially crucial in a context where there are higher levels of discretion in decision making by regulatory authorities, as it can explain to stakeholders how regulatory principles are applied in practice.

Recommendations

- **Provide clear and non-technical explanations of regulatory decisions.** Such explanations should describe the different risks assessed and weighed by the authority. This should be in a clear and non-technical format and communicated proactively through a range of communication channels to support awareness. This enables the authorities to explain how decisions have been made and to put hydrogen risks in perspective by comparing them with the existing risks of conventional energy sources. Furthermore, as no application will be entirely risk-free, explanations can be used to acknowledge risk-risk trade-offs and any remaining risks. In particular, care should be taken to avoid technical discussion of a specific risk in isolation, without the appropriate context or comparisons, which could harm public perceptions.

- **Establish mechanisms for stakeholders to provide input into decision making and appeal decisions.** These mechanisms create a challenge function to decision making and could for example include public consultation on draft decisions, or engagement with stakeholders at earlier stages of the regulatory process. The scope and impact of the regulatory decision will determine the design of any mechanisms to provide input into regulatory decisions. For more significant decisions, the authority could publish draft decisions to collect broader input and provide a response to comments to show how they have been taken on board. Appeal mechanisms should provide for an independent review of appeals on decisions, to support trust and the quality and integrity of decision making.
- **Report on the achievement of stated goals through a comprehensive set of indicators and targets.** Through periodic reporting, public entities can report back to the public on how their actions have contributed towards the achievement of envisaged objectives (such as safety, health, environmental, social or economic objectives). This could allow society to assess if intended outcomes have indeed materialised, and support any learning by authorities in cases where approaches did not lead to the desired outcomes.

Monitoring practice

Supervising compliance

Inspections are one of the most important ways to enforce regulatory compliance and ensure conditions for risk reduction are met in practice. A smooth deployment of hydrogen applications will not only rely on the design of regulations, but also on how these regulations are implemented and enforced. Without appropriate inspections and enforcement, regulations risk being a “paper reality”, which could harm the effective achievement of their envisaged goals. Rigid processes and uniform control will be less effective in improving compliance than responsive[3] and outcome-based regulation. Moreover, inspections can act as a sanity check on implemented measures, to see how well they address actual risks in practice and to assess if additional actions are needed. The main objective is to design inspection and enforcement mechanisms that deliver the highest level of compliance, while keeping the regulatory costs and administrative burdens on businesses as low as possible.

Regulators are increasingly expected to do “more with less” without compromising on protection of public interests. This is forcing them to reconsider how they can make their approaches to inspections and enforcement more efficient. Societies expect higher levels of safety, health and environmental protection, while regulators often face more significant budget constraints than in the past. Regulators therefore need to make their actions more targeted, addressing those areas that pose the biggest risks, while reducing efforts with relatively small impacts. This will require consistent risk methodologies and well-defined criteria and thresholds to identify low, medium and high-risk activities. This task has become even more challenging as innovations disrupt the sectors that regulators oversee. At the same time, pressures from political leadership, industry or concerned citizens can increase risk aversion or result in slower decision making.

Recommendations

- **Prioritise enforcement and inspections actions to ensure they are risk-based, proportional and outcome-focused.** Regulators should plan inspections proactively based on evidence, where the frequency of inspections and resources employed are in proportion to the actual risk of the regulated activities. Rigid processes and detailed prescriptive rules should be avoided where possible, as they may not necessarily be most efficient at achieving the desired outcomes. This may be the case especially in a context where innovations rapidly transform regulated activities.

Outcome-based approaches can allow regulators to promote compliance and target risk reduction more directly, while providing space for innovators to find the most efficient means to achieve those outcomes.

- **Modulate inspection and enforcement actions based on "responsive regulation" principles to incentivise compliance.** Responsive regulation, which differentiates regulatory enforcement based on the behaviour of regulated entities and on the level of risk created by violations,[4] can deliver better outcomes than a system of heavy sanctions for each and every violation – an approach that may not necessarily be most effective at increasing overall compliance. To respond effectively to different types of infractions, regulators should be armed with a set of sanction instruments, ranging from information provision and warnings to fines and closure. This gradation of sanctions can provide a credible deterrence: it gives regulators the flexibility to find the instrument that is most likely to improve overall compliance and potentially facilitates the creation of a more "forgiving environment" while regulation is still developing. Furthermore, approaches should correspond to the regulated entity's track record to reward compliance, which could factor into the frequency of inspections or the type of instrument used.
- **Use new technologies and data-driven solutions to monitor compliance.** Regulators can make use of digital technologies and big data to improve the monitoring of compliance, allowing for more remote and real-time monitoring, bringing down regulatory costs for authorities and regulated entities (see Chapter 3 – The agility of regulation). These technologies and solutions could provide more data and knowledge on compliance and risks, which in turn could support the build-up of scientific knowledge on hydrogen applications.

Incorporating new knowledge

The speed of innovation can lead to outdated procedures and requirements if regulation does not catch up in time. Regulations often respond with a delay to innovations and the availability of novel scientific research. This issue is referred to as the so-called "pacing problem". Regulations that are tailored to yesterday's hydrogen technology and scientific understanding of risks may not always be most efficient at targeting the actual risks of today's hydrogen applications. In particular, as innovation and scientific research can support the development of safer technologies and a decrease in scientific uncertainty over time, this delay could lead to excessive risk reduction and disproportionally risk-averse approaches. This outcome increases the regulatory burden on regulated entities and could result in a slowing of the hydrogen transition.

There is a need for agility in regulation to enable and harness innovation, rather than hinder it. The regulation of hydrogen may require a different approach from that taken with other more mature energy technologies, due to the speed of innovation and scientific research. As hydrogen technologies and our understanding of risks improve, the application of caution and the risks related to hydrogen will also need to develop over time. Hydrogen regulations will be asked to respond and adapt to new developments, to ensure regulations do not become the bottleneck for the hydrogen transition.

Recommendations

- **Develop adaptive, iterative and flexible regulatory cycles to enable continuous learning and improvement.** The periodic and frequent updating of regulations and procedures may be especially relevant for innovations, to reflect new knowledge and improvements in technologies and to improve the robustness and reliability of data on risks. It will require that policymakers and regulators move from "set and forget" to "adapt and learn" approaches to regulation. This more dynamic and continuous approach could for example include changes in requirements or guidance for impact assessments to consider the impacts on innovation, legislative requirements for systematic and period review or the use of sunset clauses and the shortening of timeframes throughout the policy cycle with more frequent analysis (which may at times be less thorough). As part of this approach, regulatory impact assessment, stakeholder engagement and ex post evaluations should not be seen as consecutive steps, but as complementary tools to inform the design of regulations.

- **Monitor international experience and the arrival of novel scientific research, to feed into the revision of existing approaches.** The Netherlands can make use of the experiences of other countries that are at more advanced stages of their hydrogen transition, as well as findings from international research by platforms and bodies such as the EU JRC (see Chapter 4 – "Institutional context for hydrogen"). This can help to set adequate scientific standards, avoid making mistakes that have been made before, and improve the design of risk-based regulations over time.
- **Use horizon scanning and expectations on trends to make regulations more anticipatory, robust and future-proof.** To foster innovation-robust and forward-looking regulations, knowledge on future developments can be taken on board in the design of regulations even before trends materialise. This will require institutional capacity to foresee changes, international exchange between regulators to share insights, a more open sharing of information between regulators and innovators and clarity on mandates to act upon developments. For example, the Regulatory Horizons Council in the United Kingdom acts as an independent expert committee to provide advice to the government on the implications of technological innovation and the need for regulatory reform.

Annex 1.A. Safety measures and regulations

This annex includes potential safety measures and highlights of regulations and standards for each of the six scenarios. It draws on the information as presented in Part II – "Regulatory review" and Part VI – "Lessons learnt and preliminary findings regarding hydrogen safety elements". The values mentioned in this annex including those on safety distances, time and pressure are directly based on scientific studies which are available in the various Parts that follow this report. All references to the studies analysed can be found therein. Risk mitigation strategies should take into account the specific context and characteristics of a project, as well as desired risk targets and countervailing risks, to determine the most effective measures (see Managing risks). Box 3.5 discusses a number of methodologies for prioritisation and review of risk measures that can be considered.

Annex Box 1.A.1. General safety measures and regulations – Scenario 1 – Production through electrolysis

Safety recommendations

The following measures can be considered to reduce safety risks under this scenario:

Site layout

- The inventory of the on-site hydrogen storage should be limited to the smallest practical amount required to meet operational demands.
- The electrolyser should be located outdoors. If this is not possible, then any building or room in which an electrolyser is situated should be adequately ventilated to quickly disperse any hydrogen concentrations.
- Hydrogen storage tubes should be situated outdoors.
- Compressors should be located outdoors, or where this is not possible, indoors within a well-ventilated room. Compressors should be protected from impact by being located behind barriers or within a cage.
- Safety distances between the different components of the production site should be implemented. In siting and layout design a safety distance of 6 m between all components and the compressors, which are considered the major risk contributors along with storage system, whereas a minimum of a 2-metre distance between electrolysers should be considered. Electrolyser size and capacity, local conditions, and pressure are additional factors and should be considered while adjusting minimum distance. This is because the size of the electrolyser determines the hydrogen production rate.
- Protective walls can reduce the safety distances, because they can act as a physical barrier protecting from the expansion of a potential explosion, provided that their endurable pressure is higher than the explosion pressure. The location of the protective walls relative to the facility should be carefully designed as in case of ignition protective walls can lead to increased overpressures in the area that they enclose. Furthermore, the reflected shock waves may cause secondary damage in front of the wall.

Standards / materials

- The installation of hydrogen generation systems should meet the requirements of relevant standards, like ISO 22734:2019 (construction, safety, and performance requirements for hydrogen gas generation appliances). Moreover, standards like the OSHA Standard 1910.103 can be considered as safety reference for separation distances between the storage system and certain types of exposures. In the United States NFPA 2 is the primary source for separation distances and is required by states or through direct reference in the International Fire Code.
- Protective walls, if installed, should be constructed of non-combustible materials.
- All equipment which is located within a potential flammable zone should comply with the ATEX Directive (European Commission, 2014[10]). The US on the other hand relies on NEC (NFPA 500)
- Non-combustible materials should be used in compartments or locations containing hydrogen storage vessels or hydrogen pipelines.

Safety devices

- Pressure relief valves (PRV) should be fitted to all components that operate at high pressure. Relief valves should direct any vented hydrogen upward.
- Flammable gas detectors and alarm systems should be provided. Alarms should be activated before a flammable gas concentration reaches 2 vol% (half LFL of 4 vol%), while automatic safety shutdown devices are recommended to shut of the hydrogen supply at 3 vol% concentration levels. The International Electrotechnical Commission standard, IEC 60079-29-1, specifies general requirements for construction, testing and performance, and describes the test methods that apply to portable, transportable and fixed equipment for the detection and measurement of flammable gas or vapour concentrations with air. ISO 26142:2010 – Hydrogen detection apparatus — Stationary applications[1] provides the performance requirements of hydrogen detection apparatus in stationary installations (ISO, 2010[11]). The provision in this International Standard covers the hydrogen detection apparatus used to achieve the single and/or multifaceted safety operations, such as nitrogen purging or ventilation combined with supply system shut-off according to a hydrogen leak concentration. Hydrogen detection apparatus certified under this Standard ensure functional performance requirements, such as reliability, response time, stability, measuring range, selectivity and contamination.
- Automated shutdown systems and local emergency stop buttons should be fitted in the electrolyser, compressor and storage areas.

Practices

- The production site should be kept clean, free of combustible materials and potential ignition sources and without obstructions.
- Proper and clear marking of the area with visible warning signs in the electrolyser room, the compressor site and in the storage facility to minimise the risk of ignition.
- The number of flanged joints to pipework should be minimised, as flanged joints pose a greater risk of hydrogen leakage. Welded connections for joining pipework are preferred as they can reduce the generation of flammable atmospheres from small scale leakages.
- Emergency arrangements should include specification of site evacuation arrangements and the provision of cooling to compressors and storage tanks in the event of a fire. During an incident an exclusion zone of at least 50 m to keep the public away from an accident scene should be provided.

Controls

- Regular visual inspections (at least weekly) and risk-based maintenance of the electrolyser, the compressor and the equipment components, including the pipework, is crucial. Incorrect operation of a water electrolyser can lead to oxygen ingression in the hydrogen stream, which may exceed the explosion threshold limit. Using two staff (two pairs of eyes) for maintenance activities can reduce the risk of human error.

Part VI – "Lessons learnt and preliminary findings regarding hydrogen safety elements" discusses safety measures for this scenario in more detail.

Regulations and standards across countries – highlights

- In China, Korea and the United States, standards or codes are drawn up for the safe design and use of hydrogen production facilities, such as the OSHA standard and NFPA-2 in the United States.
- In Japan, requirements for hydrogen production facilities are set under the regulation of high-pressure gas facilities.
- In the EU, regulations are based on the maximum stored hydrogen inventory rather than the production capacity, and include requirements for safety policies and reports, emergency plans and licensing procedures (notification or authorisation) depending on this maximum inventory.

Part II – "Regulatory review" discusses regulations across countries for this scenario in more detail.

1. https://www.iso.org/standard/52319.html.

Annex Box 1.A.2. General safety measures and regulations – Scenario 2 – Pipeline transport

Safety recommendations

The following measures can be considered to reduce safety risks under this scenario:

Plan and design of pipeline system

- For a new pipeline construction, perform route survey and planning to identify geological challenges and to select a stable route free from ground movement and erosion.
- Use of buried pipelines. There is no "golden rule" for pipeline burial. Pipe diameter and length could be important factors to consider. Japanese regulation requires the pipelines to be buried at least 0.6 m below ground surface and in crossings of public roads, where vehicle traffic is particularly heavy, the depth shall be at least 1.2 m. However, larger depth might be necessary to avoid normal agricultural activities, surface water drainage works and imposed road loads. For the construction of new pipelines avoid populated and agricultural regions to reduce the likelihood of pipe damage due to external activities, like building construction, excavation, etc.
- Appropriate separation distances between pipelines and nearby vulnerable populations. The methodologies used to determine separation distances vary across all the studies. To determine separation distances risk-based approaches should be used.
- Pipe casings or load shields should be installed at railroad or road crossings or where unusual aboveground loading can occur.

- Establish the quality of an existing pipe before it is used for hydrogen gas (or hydrogen blends) transport by conducting a quantitative risk analysis and deterministic analysis such as through Computational Fluid Dynamic Model (CFD) (Ministry of Transport and Water Management and Bilfinger Tebodin Consultancy, 2019[12]).

Standards/materials

- Ensure that pipeline design and construction meet the requirements of relevant standards (e.g. NEN 3650 Requirements for pipeline systems – Part 1: General requirements, NEN 3651 Additional requirements for pipelines in or nearby important public works, ASME B31.12 Standard on Hydrogen Piping and Pipelines).
- Limit joint flanges. Welded connections are preferred.

Safety devices

- When possible and practical, use a sudden loss of pressure automated shut down systems to isolate any damaged section of the pipeline and limit any loss of containment.
- Implement an automatic leak warning that notifies nearby residents.

Practices

- Provide signs at regular space intervals (every 1 km) for underground hydrogen pipelines to advise against activities that can damage the pipes, like excavation and provide a contact number to report damage.
- Land use planning policy and control development near the pipelines and to control development encroachment (e.g. in terms of safety distances from vulnerable populations and objects).
- Give notification before starting any excavation activities to obtain information about pipelines (in the Netherlands this is called KLIC-notification) (Cable and Pipelines Information Centre, *Kabels en Leidingen Informatie Centrum*, KLIC).

Controls

- Inspection and maintenance interventions for both underground and aboveground pipelines. Routine, 5 yearly, Non-Destructive Testing (NDT) examination of the internal surface and thickness testing.

Part VI – “Lessons learnt and preliminary findings regarding hydrogen safety elements” discusses safety measures for this scenario in more detail.

Regulations and standards across countries – highlights

- Many countries, such as China, Japan and the United Kingdom, do not have specific regulations on hydrogen pipelines, but apply more general regulations for pipelines or sometimes more specifically pipelines with high-pressure or flammable gasses.
- In the United States, a specific industry standard was developed for hydrogen pipelines safety (ASME B31.12).
- The mixing of hydrogen as a blend into existing gas infrastructure is usually capped at a certain percentage share of total volume, as is the case in Australia, China and the United Kingdom, or is prohibited, as is currently the case in the Netherlands.

Part II – “Regulatory review” discusses regulations across countries for this scenario in more detail.

Annex Box 1.A.3. General safety measures and regulations – Scenario 3 – Road transport

Safety recommendations

The following measures can be considered to reduce safety risks under this scenario:

Design

- Limit the maximum size of individual tube containers.
- Limit the maximum pressure in tube trailers to not more than 25 MPa. Alternatively, size-based limits can also be considered for setting the maximum pressure i.e. tubes with pressure greater than 25 MPa could be smaller in size. An exemption can be made taking into consideration the travelling distances and the routes to avoid transporting high pressure vessels close to populated areas and vulnerable areas, like hospitals and schools.
- The package securing system in tube trailers should be designed with adequate safety margins to assure that hydrogen cylinder packing remains secured to the transport trailer under adverse conditions.
- In hydrogen FCEVs consider the use of new technologies, like TPRD-less (leak-no-burst) tank that would not release hydrogen through TPRD in extreme conditions, like engulfing fire in hydrogen tank. However, since studies in the TPRD-less technology is yet to be conclusive, such a technology should be considered along with the fire resistance of the tank.
- Hydrogen transport and hydrogen-powered vehicles should be fitted with warning signs to alert emergency services approaching defective / crashed vehicle.

Safety devices

- Pressure relief valves should be effectively connected to vent tubing to route hydrogen to the top of the truck to safely disperse in the atmosphere.
- Systems involving more than one PRD should be designed to avoid simultaneous opening of all PRDs to limit the size of a flammable cloud in the event of an incident.

Safety measures in confined spaces

- Mechanical ventilation in confined spaces where hydrogen transport and/or hydrogen-powered vehicles are allowed. Ventilation in garages should achieve at least 10 ACH (air change per hour) (Lach and Gaathaug, 2021[13]).

Practices

- Train and educate drivers on the explosive characteristics of hydrogen. Haulage company's policies should require safe driving practices under all conditions (Hydrogen Tools, 2017[14]).
- Train first responders to deal with all safety aspects for a range of hydrogen applications and design emergency plans based on hydrogen safety science and engineering.
  - In case of an accident involving hydrogen FCEVs, first responders would be able to approach the vehicle, conservatively, approximately two minutes after pressure relief valve activation (hearing the hissing sound). For the safety of the general public, a perimeter of 100 metres is suggested to be set in the accident scene if no hissing sound is heard. However, the perimeter can be reduced to 10 metres once the hissing sound of hydrogen release is observed. The first responders should remain 6 m from the vehicle if there are no signs of hydrogen leakage.

Controls

- Regular maintenance of the trailer, fastenings, manifolds and safety devices.

Part VI – "Lessons learnt and preliminary findings regarding hydrogen safety elements" discusses safety measures for this scenario in more detail.

Regulations and standards across countries – highlights

- Most countries apply regulations developed for the road transport of flammable gasses to hydrogen road transport.
- The ADR agreement that regulates road transport of flammable gasses in Europe does not require adjustment for hydrogen transport, as it is already fully incorporated.
- Hydrogen-powered vehicles (FCEVs) are not covered by the same regulations as hydrogen road transport, and often face similar requirements as vehicles powered by conventional fuels.

Part II – "Regulatory review" discusses regulations across countries for this scenario in more detail.

Annex Box 1.A.4. General safety measures and regulations – Scenario 4 – Tunnels

Safety recommendations

The following measures can be considered to reduce safety risks under this scenario:

Design of vehicles

- Design hydrogen vehicles based on United Nations Global Technical Regulation No. 13 (GTR #13).
- Consider the use of new technologies, like TPRD-less (leak-no-burst) tank that would not release hydrogen through TPRD in extreme conditions, like engulfing fire in hydrogen tank. However, the TPRD-less technology should be considered along with the fire resistance of the tank.
- Using multiple TPRDs to prevent the leak of the total mass of the tank in localised fires can be considered.
- Hydrogen powered vehicles should be fitted with warning signs to alert emergency services.

Design of tunnels

- Provide mechanical ventilation inside tunnels (1-2 m/s) to reduce the hydrogen vapour concentration in the event of a leakage.
- Ensure sufficient distance of main tunnel and fittings and equipment, like dust collectors and exhaust fans that can trap hydrogen in flammable concentrations.
- Avoid roof obstructions inside the tunnel, because they pose a potential risk in respect to possible fast deflagration or transition to detonation.
- The design of future tunnels should include appropriate cross section design to avoid flammable mixture accumulating in the tunnel ceiling.
- Set larger safety distances between vehicles when driving inside tunnels.

Safety devices

- The TPRD size should be reduced to avoid a flammable mixture at the tunnel ceiling in the event of a leak. However, the size consideration should be made in a way that an extended-release time does not prolong the high-pressure state of hydrogen. The TPRD orientation in buses should be at the top of the vehicle.
- Systems involving more than one PRDs should be designed to avoid simultaneous opening of all PRDs.
- Additional protection could be provided by:
  - a battery fire suppression system within the battery pack;
  - a fire barrier between the battery pack area and the hydrogen tank;
  - increasing the tank integrity/fire resistance to thermal threats, and
  - a fire resisting deck to protect the upper deck area.

Practices

- Risk-based categorisation of tunnels to define which ones allow or not H2 powered vehicles to enter. Similarly, vehicle class based considerations can be made to differentiate between Light Duty Vehicles (5 kgs onboard) and Class 8 fuel cell trucks (100+ kgs onboard)
- Emergency responders should receive training for reaction to incidents that involve hydrogen vehicles. Some key elements are presented below:
  - Emergency responders should remain at least 2 min before approaching damaged vehicles following activation of TPRD.
  - If there’s no sign of hydrogen release, first responders should stand at least 6 m away from the vehicle.

Controls

- Perform frequent safety checks on vehicle integrity by an independent, competent engineer.

Part VI – “Lessons learnt and preliminary findings regarding hydrogen safety elements” discusses safety measures for this scenario in more detail.

Regulations and standards across countries – highlights

- In Europe, vehicles transporting hydrogen are forbidden to enter most tunnels based on the ADR agreement.
- In Japan, vehicles transporting hydrogen are prohibited or restricted in long tunnels or those underwater.
- There are currently no specific regulations that restrict FCEVs from entering tunnels.

Part II – “Regulatory review” discusses regulations across countries for this scenario in more detail.

Annex Box 1.A.5. General safety measures and regulations – Scenario 5 – Hydrogen refuelling stations

Safety recommendations

The following measures can be considered to reduce safety risks under this scenario:

Design

- For on-site hydrogen production, water electrolysis is the recommended production process as it presents lower risk than steam methane reforming.
- Limit the inventory in the storage facility as low as practical based on the average daily number of fillings of the HRS.
- Transportation of hydrogen through high-pressure pipelines allows station to dispense fuel without onsite compression and storage and reduce the risk. However, this system should additionally consider the risk of operating high-pressure pipelines in residential areas.
- A QRA study indicated that liquid hydrogen refuelling stations entail less risk than compressed hydrogen refuelling stations, but the differences were small. Based on that the use of liquid hydrogen instead of compressed hydrogen could be recommended, but further research on that topic is highly advised.

Site layout

- Hydrogen processing systems, high pressure storage containers and generators should be sited outdoors in well ventilated areas.
- Implementation of safety and separation distances:
    - Separation distances from exposures in GHRS can follow the NFPA-2 code.
    - Hydrogen storage tank (up to 40 MPa) should be configured 5 m from the location of the hydrogen onsite production facility.
    - Safety distances can be reduced when installed safety systems are effective and can be quickly activated, by employing for instance a dispenser which operates in parallel with an emergency shutdown valve.
    - To determine safety distances for facility layout and under specific operating conditions it is recommended to perform quantified risk assessment targeted to the facility’s specific parameters.
        - This requires a checklist of the HRS sub-systems and components and an extensive description of sub-systems, components, preventive and mitigation measures, configurations (including piping and instrumentation diagrams) and input parameters.
        - The estimated failure rate should be a function of number of fillings rather than based on survival time, as it is more reliable and realistic approach.
        - Establishing a national, independent review function for Quantitative Risk Assessments (QRAs) of HRSs is advisable (Khalil, 2017[15]). Such an entity would have the potential to become a centre of expertise that could collect existing and future QRAs of HRSs to monitor the latest developments and progress towards the consistent application of the approach as well as provide guidance to permitting authorities on how to apply the approach for HRSs.
- Protective walls around the HRS can lead to reduced safety distance requirements if they are designed so that flammable concentrations will not reach outside these barriers. However, in

case of ignition protective walls can act as obstacles and generate higher overpressures inside the facility. Therefore, their installation should be carefully examined and evaluated under the specific conditions of the facility.

- Installation of a fire protection wall along station boundaries. This will also reduce the required safety distances.
- A protective wall surrounding the production site and the storage tank can protect them from the impact from an explosion. Careful design of the protective wall is essential as its resistance to over pressure is another factor. A concrete wall without steel reinforcing bars can withstand a pressure of up to 0.2 bar. This limit may be exceeded under certain conditions if an explosion occurred, for example, in the dispenser. Thus, an additional distance of 2 m away from the dispenser is also recommended for the protective wall and the control room.[1]

Standards / materials

- Use of equipment in compliance with ATEX to eliminate ignition sources.

Safety devices

- Fit pressure relief valves to components that operate at high-pressure.
- Provide hydrogen leak sensors and automatic shutdown systems as well as manual ESD buttons.
- Use infra-red temperature sensors for compressor linked to a high temperature alarm.

Safety measures

- Use proper ventilation if hydrogen equipment is located indoors (see Annex Box 1.A.6 for recommendations on ventilation).

Practices

- Install warning signs to prohibiting ignition sources at the HRS.
- For physical security, install of CCTV surveillance system to act proactively in case of malicious actions.
- Avoid self-refilling. Refuelling should be undertaken by trained staff. Alternatively, similar to Japanese regulations, self-filling could be allowed if the driver receives safety education and training on how to mount and demount of the nozzle.

Controls

- If the leak rate based on historical data is estimated to be high, inspections activities shall be more frequent to limit the unrevealed leak time (evaluated from the estimated leak frequency) and increase the process of safety.
- In densely populated areas, where large safety distances may be impossible to achieve, stricter requirements for quality, inspection and protection of refuelling stations against impact should be implemented.

Part VI – "Lessons learnt and preliminary findings regarding hydrogen safety elements" discusses safety measures for this scenario in more detail.

Regulations and standards across countries – highlights

- Japan, China and the state of California in the United States have regulations in place for hydrogen refuelling stations.
- Korea developed codes with technical standards for hydrogen refuelling stations.

- In the EU and Australia, national and international standards or codes are used as a reference in absence of regulations on regulatory frameworks for hydrogen refuelling stations.

Part II – "Regulatory review" discusses regulations across countries for this scenario in more detail.

1. Based on scientific work by (Kim et al., 2013[16]).

Annex Box 1.A.6. General safety measures and regulations – Scenario 6 – Domestic use

Safety recommendations

The following measures can be considered to reduce safety risks under this scenario:

For hydrogen injection into the existing natural gas grid

Materials

- Use existing carbon steel transmission pipelines in medium to high pressure systems, as they can tolerate pressures between 55 to 210 bar and can withstand hydrogen concentrations up to 15% v/v without any significant impact.
- Use plastic pipelines, which are commonly used in low-pressure systems, as they are generally unaffected by hydrogen injection up to 20 v/v and pose no danger in embrittlement. Generally speaking, up to 20% v/v blend of hydrogen with natural gas is still compatible with the existing infrastructure and heating appliances.
- A phased transition to 100% polyethylene network is recommended, since most observed flammable gas leaks are caused by metallic network components. However, even with 100 % polyethylene pipelines for a 100 % hydrogen network additional mitigation measures should be implemented downstream of the gas meter to achieve fatality risk lower than the current network and as safe as the natural gas network.

Devices

- The existing domestic pressure regulators can be safely used with hydrogen, and it is therefore unnecessary to replace the regulators as part of the conversion to hydrogen.

Practices

- The seal tightness specifications in current pipelines should be stricter, ensuring that the maximum permissible leakage rate for hydrogen as 74% of that of natural gas.
- Mechanical crimp fittings should be used in pipework instead of soldered joints, which are more prone to leakages. It can be considered safe to use the same materials and fittings for internal pipework for hydrogen as is currently used for methane, at least in the short term, in the context of a community trial.

For the domestic use of hydrogen:

Design

- The gas metre should be installed outside of the property, where possible, and comply with current best practice and BS6400-1:2016.
- Provide sufficient ventilation and venting in any cavity should be mandatory, as specified by Building Regulations (i.e. an exemption should not be granted for hydrogen appliances). Such mitigation measures can reduce the maximum concentration of hydrogen and the risk of explosion.

- Fit wall vents (non-closable) at the upper part of the room (no more than 50 cm from the ceiling) in all rooms with gas appliances or installed hydrogen-carrying pipes.
- Fit vents to all the cupboards and other compartments (e.g. boilers) where hydrogen appliances are present should have vents.
    - Simple vent geometry, like rectangular vent area, should be promoted.
    - High aspect ratio (height/length) of the vent is also recommended as it provides more efficient ventilation.
    - Open ventilation grids can reduce to half the maximum concentration and up to 2 vol% (half of the LFL of 4 vol% hydrogen in air) for rates typical of leak through the piping connected to the gas meter. At such low concentration, ignition is unlikely to take place.
    - The use of airbricks in basements can be helpful, but current research studies have not reached conclusive results.

Safety devices

- Fit leak detection and alarm systems in the upper part of the rooms and inside cavities inside buildings, as hydrogen tends to accumulate in the ceiling and might be trapped inside cavities. The alarm should be activated as soon as hydrogen is detected at concentration above some fraction of the LFL.
- Fit excess flow valves (EFV) to stop the flow of hydrogen in the service pipes when it reaches a certain level and emergency control valves (ECV) should be deployed to safely isolate a customer's pipe from the network. The first EFV should be placed in the service pipe or immediately after the emergency control valve and the second one should be integrated in the hydrogen gas metre or added upstream of the metre.
- Install flame failure devices (FFDs) to all hydrogen appliances.

Practices

- Odorise hydrogen supply gas for the early detection of hydrogen gas leaks. Odorant NB, which is a blend of 78% t-butyl mercaptan and 22% dimethyl sulphide and THT have also been tested and are found to be effective and compatible with network components and hydrogen appliances.
- Provide a stronger flexible pipe at the rear of cookers to limit the likelihood of damage when the cooker is moved. Additionally, the cooker should be fixed to the wall using a chain and Rawl bolts to limit the loading on the flexible cooker connection.

Controls

- Inspection and maintenance in all equipment should be performed at a regular base by specialised personnel.

A more general recommendation for domestic hydrogen use is to aim at a smooth system conversion. In the short term, a 20 vol% blend of hydrogen with natural gas for heating can be preferred, which would still be compatible with existing infrastructure and household heating appliances and will not increase the risk (Khalil, 2019[17]).

Part VI – "Lessons learnt and preliminary findings regarding hydrogen safety elements" discusses safety measures for this scenario in more detail.

Regulations and standards across countries – highlights

- Other countries often do not have specific regulations on the domestic use of hydrogen, with only China and the United Kingdom showing effort to regulate this scenario.
- The mixing of hydrogen as a blend into existing natural gas infrastructure is usually capped at a certain percentage share of total volume, as is the case in Australia, China and the United Kingdom, or is prohibited, as is currently the case in the Netherlands.

Part II – "Regulatory review" discusses regulations across countries for this scenario in more detail.

Note: The safety measures discussed under this scenario are mainly based on the conditions that apply in the United Kingdom, because most of the pilot projects for domestic use of hydrogen reported in the Literature review report, which has been used as an input for this report, have been carried out in the UK. However, these findings and measures can provide guidelines for other countries as well.

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Notes

[1] For the purpose of this report, and in line with the 2012 OECD *Recommendation on Regulatory Policy and Governance*, regulation “is defined broadly, referring to the diverse set of instruments by which governments set requirements on enterprises and citizens. Regulations include laws, formal and informal orders and subordinate rules issued by all levels of government, and rules issued by nongovernmental or self-regulatory bodies to which governments have delegated regulatory powers” (OECD, 2012[20]).

[2] In line with the definition used in the IEA’s Global Hydrogen Review 2022, low-emission hydrogen as referred to in this report includes hydrogen produced via electrolysis where the electricity is generated from a low-emission source (renewables or nuclear), biomass or fossil fuels with CCUS (IEA, 2022[18]).

[3] Responsive regulation modulates inspection and enforcement actions depending on the profile and behaviour of specific businesses (OECD, 2014[19]).

[4] Responsive regulation is based on the principle that regulators should take into account the culture, behaviour and context of those they are aiming to regulate. The behaviour of businesses or citizens, culture and context therefore elicit the type of enforcement response, which must be proportionate to the seriousness of the harm and the resulting impact (see Chapter 3 – Regulatory delivery in the energy transition).

2

Hydrogen in context

This chapter provides the context for hydrogen risk regulation and governance. It first discusses the role of hydrogen within the energy transition and hydrogen strategies in the Netherlands and Europe. The chapter also highlights trends in the production and use of hydrogen and projections for the future. The chapter concludes with a discussion on the properties of hydrogen by putting these in comparison with other conventional fuels.

Hydrogen in the energy transition

Hydrogen (H_2) is expected to play an important role in the transition to a net zero emissions world. Countries around the world are establishing ambitious goals for the application of hydrogen within their economies, in an effort to reach environmental targets from the 2015 Paris Agreement to reduce emissions and limit the global temperature increase (IEA, 2021[1]).[1] As the impacts of climate change and the interlinked biodiversity crisis become more tangible, climate action becomes all the more pressing; 2022 saw episodes of extreme wildfires such as those in France and Spain – incidents that are expected to grow more common as global temperatures rise. As oceans warm, ecosystems are affected and tropical cyclones occur more frequently. More broadly, weather and climate adverse events, such as floods and droughts, will affect food and water security (IPCC, 2022[2]).

Recent disruptions affecting global energy markets, such as the one following Russia's large-scale aggression against Ukraine, may put ambitions regarding the deployment of clean energy (including hydrogen) in a new light and create greater urgency for ongoing transitions. Higher natural gas prices and restricted supply affect the reputation of natural gas as a reliable and affordable energy source – a factor which could lead to (accelerated) fuel switching. Accelerating clean energy transition policies and increasing the scale of low-carbon gas – including hydrogen – could, over time, help ease supply pressures and build resilient energy systems, while reducing emissions (IEA, 2022[3]).

Hydrogen is seen as a promising option to tackling emission from a number of sources. In particular, its potential is grounded in three main benefits:

- **Provide solutions for "hard-to-abate" sectors:** hydrogen and hydrogen-based fuels such as ammonia can provide a cleaner source of energy or feedstock in a number of sectors that still rely heavily on fossil fuels – such as trucking, sea and air transport, and industrial processes such as iron, steel and chemical production. In many of these sectors, electricity is not the current energy form and electricity-based solutions may be too costly or technically unfeasible to replace existing high-temperature processes that use fuels such as diesel or natural gas (IEA, 2019[4]).
- **Turn low-carbon electricity into fuel and balance supply variabilities:** hydrogen holds the potential as a medium for energy storage, by turning low-carbon electricity via water electrolysis into hydrogen. Combined with the benefit that it can be transported through existing gas infrastructure, it can strengthen system resilience by absorbing seasonal variations and intermittent production from solar and wind energy sources (European Commission, 2020[5]).
- **Provide a green transport alternative:** hydrogen-powered vehicles can complement other types of green transport, in particular for heavy-duty and long-distance transport. Hydrogen-powered vehicles require fewer rare materials (for example, in their batteries) and can be refuelled relatively quickly. Hydrogen has a high energy density per mass, and the large volumes required to store large amounts of hydrogen are typically not a problem in goods transport (be it in trucks or, even more so, in maritime transport).

While hydrogen's potential is widely acknowledged, there is still some way to go. At present, hydrogen only represents a marginal share of the total energy mix and almost 80% of hydrogen is currently produced from fossil fuels such as coal, natural gas or lignite (European Commission, 2020[5]). Much of the remainder results as a by-product from other production processes such as the reformation of naphtha into gasoline (IEA, 2021[6]). Low-emission hydrogen production comes in two main forms, both of which are yet to be applied on a large scale. The first, hydrogen production with carbon capture builds on existing production processes with fossil fuels but refers to applications where carbon emissions are reduced by using carbon capture and storage (CCS) or carbon capture and utilisation (CCU) technologies. While this option can significantly reduce greenhouse gasses, this option still requires fossil fuels and its carbon impact depends on the variable effectiveness of greenhouse gas capture (European Commission, 2020[5]).

For the hydrogen transition to succeed in contributing to climate action, it must be generated from clean energy sources (LucidCatalyst, 2020[7]). In this effort, many countries therefore have an ambition to shift further towards the second main form of low-carbon hydrogen production. This second form of hydrogen is produced with renewable energy sources or other cleaner energy sources, usually using water electrolysis to split water into oxygen and hydrogen gas (IEA, 2021[1]).

To achieve hydrogen's potential, countries are looking to stimulate hydrogen demand and promote investment and research. Boosting hydrogen demand could support a more widespread adoption of hydrogen technologies along the full hydrogen value chain[2] and scaling up of applications. This, in turn, could lower the costs of hydrogen and make it more competitive.[3] Investment incentives could help mitigate investment risks and push pioneer companies to develop new applications and start new low-emission hydrogen projects. In combination with research and development, this could support innovation, bring in new technologies and increase efficiency. Eventually, this could allow low-emission hydrogen to become more competitive when compared with other existing energy sources (IEA, 2021[1]).

Crucially, for hydrogen to fulfil its promise, regulations, standards and oversight mechanisms need to be developed, tailored and reviewed to support its deployment. Hydrogen technologies continue to advance and safer systems are being built. But, given the novelty of many of these applications and their increasing role in future energy systems, regulatory and oversight frameworks need to keep pace. Some countries have already developed guidelines on the safe use of hydrogen and there exist international codes and standards for some types of hydrogen application. However, in many cases, countries have not developed regulatory frameworks specifically for hydrogen and generic rules are applied to the sector instead. It should be assessed whether the use of more general rules is the most efficient option to address the actual risks of hydrogen in all scenarios, and whether there are any regulatory gaps. Safety strategies during the hydrogen life cycle will be required to ensure safe production, transport, usage and the building of public confidence and awareness. On the other hand, unnecessarily complex or outdated legal barriers and excessively precautionary rules, procedures and requirements need adjustment to ensure a smooth development of the hydrogen sector.

These regulations can provide a suitable solution to manage risks until assessments of regulatory requirements have been concluded, but may not necessarily be the most efficient option to address the actual risks of hydrogen in all scenarios.

Hydrogen strategies: ambitious and urgent goals for the Netherlands and the EU

In 2020, the Dutch government published its hydrogen strategy, part of a wider wave of strategies being developed and deployed around the world (Rijksoverheid, 2020[8]). This trend exemplifies the current momentum for the deployment of hydrogen throughout energy systems. While, at the time of the 2019 *Future of Hydrogen* report by the International Energy Agency (IEA), only three governments[4] had strategies in place for hydrogen, this had increased to 17 governments by 2021[5] And to 26 governments by 2022.[6] Moreover, more are expected to join this list, with many having announced, preparing or currently consulting their strategies (IEA, 2022[9]).

The Netherlands identifies low-emission hydrogen as an essential element to ensuring a sustainable energy system that is reliable, clean, affordable, safe and spatially compatible (Rijksoverheid, 2020[8]). To reach 2030 climate targets[7] and support a net zero 2050 target, the 2019 Climate Agreement ("the Agreement") for the Netherlands foresees that hydrogen could be used in a number of areas. These include the chemical industry and other energy-intensive sectors, for the storage of wind and solar energy, for transport and the heating of buildings. The Agreement also envisages the creation of a global hydrogen market in which the Netherlands could take a leading role, building on the current energy hub function of the Rotterdam harbour and the development of a hydrogen pipeline infrastructure (Klimaatakkoord, 2019[10]).

The Dutch government foresees a wide application of hydrogen technologies across different sectors. This will contribute to its actions to accelerate climate change measures as required by the "Urgenda court ruling".[8] To meet future hydrogen demand, production in the Netherlands is expected to include large electrolysers and production installations, with CCS close to existing industrial clusters, as well as smaller production locations. The Netherlands aims to have an electrolyser production capacity of 600MW by 2025 and 80 petajoule (PJ) hydrogen production from renewable sources by 2030 (NWP, 2022[11]). This would also require facilities for hydrogen storage and the development of a basic national hydrogen infrastructure to connect clusters. For the transport sector, the Netherlands also foresees an important role for hydrogen in the achievement of a 100% emission-free mobility sector by 2050 (NWP, 2022[11]). To support these ambitions, the Netherlands will make available a number of financial mechanisms to provide financial support to investors (Rijksoverheid, 2020[8]).[9]

The Netherlands' hydrogen ambitions complement broader EU ambitions as defined in the European Commission's hydrogen strategy and the ambitions put forward in the Commission's RePowerEU Plan (European Commission, 2020[5]) (European Commission, 2022[12]). These two plans together "put forward a comprehensive framework to support the uptake of renewable and low-carbon hydrogen to help decarbonise the EU in a cost-effective way and reduce its dependence on imported fossil fuels". Since the adoption of the strategy, the Fit-for-55 package put forward legislative proposals to translate the strategy into legislation (European Commission, 2023[13]).The EU hydrogen strategy defines ambitions across three different time horizons:

- **2020-2024**: installation of 6 GW of renewable hydrogen electrolyser capacity to decarbonise existing hydrogen production such as that found in the chemical sector, and to facilitate the uptake of hydrogen consumption in new applications such as industrial processes and heavy-duty transport. The RePowerEU Plan aims for ten million tonnes of domestic renewable hydrogen production and 10 million tonnes of renewable hydrogen imports by 2030.
- **2025-2030**: installation of 40 GW of renewable hydrogen electrolyser capacity, gradually allowing hydrogen produced through electrolysis with renewable electricity to become more cost-effective by comparison with other forms of hydrogen and with applied uses in steel making, road haulage, rail and maritime transport, and for daily or seasonable storage of renewable electricity. This could be complemented by increased use of CCS technologies in existing hydrogen production, planning towards a pan-European hydrogen grid, a refuelling station network, and local hydrogen clusters that could extend the use of hydrogen towards the heating of buildings.
- **2030-2050**: renewable hydrogen technologies reach maturity and could be deployed at a larger scale to reach all hard-to-decarbonise sectors, including aviation, shipping and to decarbonise certain industrial and commercial buildings. A strong increase in renewable electricity will be required to fulfil demand for low-emission hydrogen production through electrolysis, while biogas may have a role to play in replacing natural gas in hydrogen production.

Given these significant ambitions for the development of hydrogen applications in the EU and the Netherlands, there will be a need for a regulatory framework for hydrogen that can support a smooth hydrogen transition, while removing any unnecessary obstacles for innovation and development.

Box 2.1. An overview of some key benefits of hydrogen as an energy vector

Because of hydrogen's specific physical and chemical behaviour, and of the considerable research efforts put into developing safer equipment, there are situations where hydrogen is safer than hydrocarbon fuels in a direct, immediate way (see Chapter 6 in Part 1- Literature Review). The main way in which hydrogen can overall reduce risks in a very important way is through its positive impact on climate change (assuming of course low-emission hydrogen is used, which this report focuses on).

Reducing climate emissions means a considerable impact in terms of reduction of risks from catastrophic climate events. Finally, hydrocarbon fuels also present other major environmental and health risks, which hydrogen use would decrease. This is crucial particularly considering applications where other low-carbon alternatives such as electric batteries are inadequate for reasons of weight and range, e.g. transport of goods, particularly maritime transports but also road freight transport.

Looking more specifically at detailed benefits of the switch from hydrocarbon fuels to low-emission hydrogen:

Climate

In the EU alone, transport is responsible for 800 Megatons of CO2 equivalent, of which close to 40% due to trucks (EEA, 2022[14]). Achieving carbon neutrality for Europe will entail a 90% reduction in transport emissions by 2050, and hydrogen is explicitly mentioned as a tool for that purpose in the EU Commission's "Sustainable and Smart Mobility Strategy" (European Commission, n.d.[15]).

Globally, 15% of greenhouse gas emissions stem from transportation, and with a high energy density and low refuelling time, low-emission hydrogen is well suited for transport decarbonation. Apart from its strong advantages for transportation of goods (trucking and shipping), it is also (if technical obstacles can be solved) an interesting alternative for aviation. Being a highly energy-dense fuel on a mass basis (120 MJ/kg, against 43.1 MJ/kg for kerosene), hydrogen has particular strengths to replace petrol-based fuels in aviation (https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen).

Shipping pollution

Large ships typically burn bunker fuel on the high sea (or indeed in the national water and harbours of those countries that do not or cannot regulate effectively). In addition to greenhouse gas emissions, bunker fuel causes large harmful emissions of sulphur dioxide and nitrogen dioxide. Shipping thus accounts for about 10% of all anthropogenic sulphur emissions (Eyring, 2005[16]) (ITF, 2016[17]). A switch to hydrogen will especially benefit developing countries, which have until now lacked the ability to effectively regulate shipping emissions (Saiful, 2010[18]).

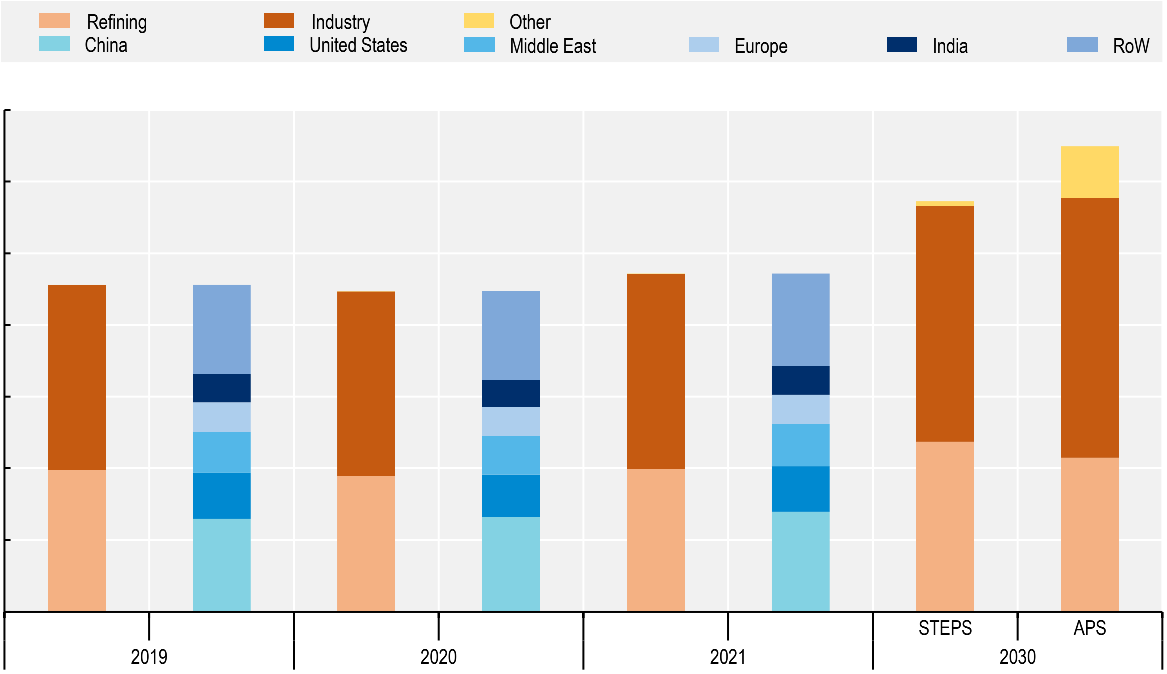
Status quo and future trends in hydrogen use worldwide

Current usage of hydrogen can be seen as modest compared with its future aspirations as an energy source. Global hydrogen demand was 94 million tonnes (Mt) in 2021, almost entirely for refining and industrial purposes. Oil refineries consumed nearly 40 Mt, with industrial processes consuming the remaining 54 Mt (Figure 2.1). Natural gas was used as the primary source for hydrogen production, accounting for roughly three-quarters of total hydrogen production (6% of global natural gas use). Twenty-three percent of hydrogen production used coal as an energy source (2% of global coal use). The remaining (small) share of production used oil and electricity.

In oil refining, hydrogen is used mainly to remove impurities (in particular sulphur) and to upgrade heavy oil into lighter oil products. Most of the supply of hydrogen for oil refining is created as a by-product from other processes in the refinery, using naphtha, natural gas and to a lesser extent coal. China, and North America together account for nearly half of global hydrogen demand in refining (IEA, 2022[9]).

Ammonia (NH_3) and methanol (CH_3OH) production consume the vast majority of hydrogen used in industrial processes. Ammonia is mainly used in the production of nitrogen fertilisers, but also for industrial applications in explosives, synthetic fibres and other materials (IEA, 2021[1]). Methanol is used mainly in the manufacturing of a number of solvents and industrial chemicals – used for the production of plastics and other materials – and in the process to produce gasoline from natural gas and coal (IEA, 2019[4]). Most of the remaining hydrogen in industrial processes is used in iron and steel manufacturing.

Figure 2.1. Hydrogen demand by sector and by region based on stated policies and announced pledges, 2019-2030



Note: Mt H2 = million tonnes of hydrogen; STEPS = Stated Policies Scenario, which reflects the scenario based on the policies currently in place as well as those that have been announced by governments; APS = Announced Pledges Scenario, which reflects the scenario in which all climate commitments by governments will be met in full and on time. Other includes transport, buildings, power generation sectors and production of hydrogen-derived fuels and hydrogen blending.
Source: (IEA, 2022[9]), Global Hydrogen Review 2022, https://www.iea.org/reports/global-hydrogen-review-2022.

In Europe, hydrogen has been applied in industrial processes in the chemical sector and oil refineries for a long time, including in the Netherlands where hydrogen production for industrial purposes is mature and well-developed. However, Europe's rollout of hydrogen-powered vehicles (in particular fuel cell electric vehicles, or FCEVs) stations is trailing developments in other countries, where China, Japan, Korea and the United States together held over 90% of the global total of FCEVs (see Chapter 5 – "Scenario 3 – Road transport"). Europe held the largest share in water electrolysis production capacity as of 2020, but China has more recently pioneered the development of larger-scale electrolysers (see Chapter 5 – "Scenario 1 – Production through water electrolysis"). In their efforts to keep pace with these global developments, the Netherlands and the EU can make use of the experiences in other countries, to design regulatory frameworks that address actual hydrogen risks while supporting the hydrogen transition.

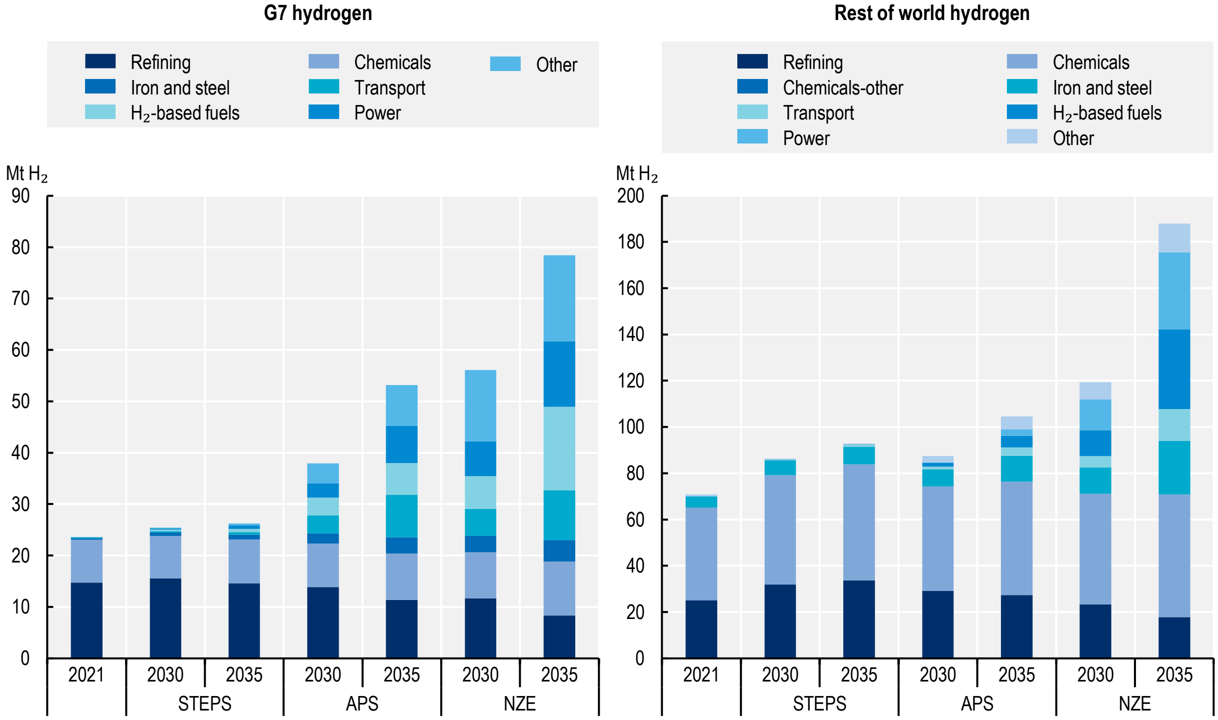
Future trends

The IEA identifies a significant gap between the announced pledges by governments regarding the use of hydrogen and the Net Zero Emissions by 2050 Scenario it developed (IEA, 2021[1]). To meet the Net Zero Emissions scenario, the IEA estimates that hydrogen usage would have to increase to 175 Mt in 2030 and 266 Mt in 2035 (Figure 2.2). To reach these net zero objectives, the IEA foresees an initial focus on converting existing hydrogen uses to low-emission hydrogen, with a subsequent expansion of hydrogen across all end-uses. Before 2030, a rapid scaling up of electrolyser manufacturing and development of transport infrastructure could bring down production costs and facilitate the use of hydrogen storage to balance demand and supply fluctuations. The scenario also requires a large increase in the number of FCEV, which the report estimated to reach 15 million vehicles by 2030. After 2030, hydrogen could expand its role across sectors and provide flexibility to electricity systems through storage and hydrogen-based electricity generation. By 2050, a significant share of total hydrogen and hydrogen-based fuels (such as ammonia, synthetic kerosene and synthetic methane) would be used in transport, requiring a strong increase in its applications across road, sea and air transport (IEA, 2021[19]).

The significant role for hydrogen envisaged in the IEA's future scenarios is also underlined in EU and Dutch energy strategies. The European Commission expects hydrogen's share in Europe's energy mix to increase from less than 2% to 13-14% by 2050 (European Commission, 2020[5]). In the Netherlands, the Cabinet's vision expects gaseous energy carriers, including hydrogen and biogas, to supply at least 30% of total energy use by 2050 (Rijksoverheid, 2020[8]).

Regulation is a key element to enable this projected growth to actually happen – both in terms of facilitation (enabling zoning, simplified licensing and permitting) and of safety (ensuring best safety practices are effectively followed). Indeed, as has often been underlined, major hydrogen-linked accidents would, beyond their direct human harm, hinder further development of hydrogen through a loss of trust. Ensuring *effective* regulation is key – which requires adequate technical requirements, taking into account the latest research and technological advances, and supported through well-targeted, risk-based inspections and enforcement. Hydrogen development requires zoning and permitting streamlining, but this does not mean "less regulation" – on the contrary, it means developing *specific regulation for new hydrogen applications* (MultHyFuel Project, 2021[20]).

Figure 2.2. Hydrogen demand in the G7 and the rest of world by sector and by scenario



Note: STEPS = Stated Policies Scenario, which reflects the scenario based on the policies currently in place as well as those that have been announced by governments; APS = Announced Pledges Scenario, which reflects the scenario in which all climate commitments by governments will be met in full and on time; NZE reflects the IEA's Net Zero Emissions by 2050 Scenario. "Other" includes generation of high temperature heat in industry, small demands in industrial applications such as electronics or glassmaking, other industries and use in buildings. "H2-based fuels" includes ammonia used as a fuel and synthetic hydrocarbons.

Source: (IEA, 2023[21]), *Towards hydrogen definitions based on their emissions intensity*, https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity.

Understanding and managing hydrogen risk

There is a disconnect between the large hydrogen ambitions discussed above and the relatively limited progress in its deployment in practice. Consequently, the deployment of low-emission hydrogen solutions needs to speed up if it is to achieve its potential as a low or zero-carbon solution in the future energy mix. However, the properties of hydrogen, as well as the technologies through which hydrogen is being deployed, differ from other conventional fuels and their technologies. This could make decision makers more precautionary or risk averse in its deployment and will require public bodies to develop new expertise to manage hydrogen risks effectively. A careful assessment of its actual risks and potential risk mitigation measures will therefore be crucial for a smooth hydrogen transition.

While there is no doubt that real risks are associated with hydrogen, there are often large gaps between risk *perceptions* and actual, science-based risk assessments (Høyland, Kjestveit and Østgaard Skotnes, 2023[22]). This is in line with risk perception problems that have been well studied over the last decades (Slovic, 1987[23]) (Slovic and Peters, 2006[24]), which only underlines the need to address this perception issue through adequate engagement and communication. There is also an insufficient differentiation between high risk applications in some industrial processes (or in rocketry) and far lower risk applications e.g. in fuel-cell-powered vehicles. Indeed, records of industrial accidents involving hydrogen are typically in situations where it is combined with large amounts of oxidising substances, or where hydrogen is a by-product (but not a cause or driver) of a chemical reaction gone awry.[10]

Hydrogen is a colourless, odourless, tasteless and flammable gas. It has a high energy content by mass (per kilogram), but, due to its low density, it has a low energy content by volume (per cubic metre). Hydrogen is the lightest element. Thus, a common practice for the efficient storage, transportation and handling of hydrogen is its compression or liquefaction.

To put its properties in context, hydrogen can be compared with other conventional fuels, in particular natural gas (which consists of 87-98% methane). In comparison with methane, hydrogen has a lower density, lower energy content by volume and a lower auto-ignition temperature.[11] On the other hand, it has a higher heat capacity,[12] energy content by mass,[13] flame temperature, laminar burning velocity[14] and molecular diffusivity.[15] Moreover, hydrogen has wider flammability limits – meaning that it can ignite or explode at a wider range of concentrations of hydrogen in air – and a lower minimum ignition energy (MIE) for hydrogen volume fractions in air between 8 and 58%.[16] These are factors why – without appropriate safety measures – hydrogen may sometimes be considered more hazardous than methane under similar circumstances. In addition, the application of available safety measures have the potential to reduce these risks substantially.

Moreover, as with all flammable gases and vapours, the consequences associated with hydrogen releases are dependent on the situation and the presence of ignition sources. When hydrogen is released outside, its low density combined with moderate wind will usually cause hydrogen to rise and disperse. Indoors, hydrogen releases tend to accumulate near the ceiling, where ignition sources are less likely to be present. The exact consequences will, among other things, depend on the presence of appropriate safety measures, the total volume of hydrogen released, the total volume of the space into which hydrogen is released, the speed and direction with which it is released, and the ventilation systems that are present.

While certain properties of hydrogen differ from conventional fuels that are currently used, this does not necessarily mean that the use of hydrogen applications increases overall risk levels. Already, research and development have resulted in increased knowledge and made available a range of technical solutions that counter the more hazardous properties of hydrogen (see Chapter 5 for a discussion of safety measures for specific scenarios of hydrogen production and usage). Given this, governments should make use of smart and agile regulatory frameworks that incentivise innovation to lower climate change risks and provide the necessary protections to health and safety (see Chapter 1 – Designing regulation).

Managed properly, hydrogen is overall not riskier than hydrocarbon fuels for many applications considered in this report, even when considering only safety risk in the narrowest sense – and can sometimes, with the right technology, already be safer (Institute for Safety, 2021[25]). If one takes into account the climate impact and other adverse health and environmental impacts of hydrocarbon fuels, there is little doubt that hydrogen is not a *riskier* fuel, but quite the contrary. It is thus essential to develop an effective regulatory framework, that ensures best safety practices are followed, and allows the development of hydrogen as a fuel through in particular revisions to zoning requirements and licensing processes.

A more extensive discussion of hydrogen properties and associated risks can be found in the Part 1 – Literature review. A discussion of the risks of specific hydrogen applications can be found in Chapter 5 – Hydrogen applications in practice.

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Notes

[1] The Paris Agreement is a legally binding international treaty on climate change, adopted on 12 December 2015 at the twenty-first session of the Conference of the Parties to the United Nations Framework Convention on Climate Change signed by 194 parties (UN, 2022[27]).

[2] For a simplified overview of the hydrogen value chain, see (Cordonnier and Saygin, 2022[26]).

[3] At present, the price of hydrogen is still significantly higher than other conventional fuels (LucidCatalyst, 2020[7]).

[4] France, Korea and Japan already had a strategy in place for the use of hydrogen at the time of the IEA Future of Hydrogen report (IEA, 2019[4]).

[5] Australia adopted its hydrogen strategy in 2019; Canada, Chile, Germany, the Netherlands, Portugal, Russia, Spain and the European Union adopted hydrogen strategies in 2020, whereas France updated its strategy in 2020. The Czech Republic, Colombia, Hungary and the United Kingdom adopted their strategies in 2021 and Norway updated its strategy that same year (IEA, 2021[6]).

[6] The total of 26 governments includes 25 countries and the European Commission.

[7] The Dutch Climate Agreement is based on the objective to decrease greenhouse gasses by 49% in 2030 compared with 1990 levels.

[8] At the end of 2019, in a court case between the Urgenda Foundation and the State of the Netherlands, the Dutch Supreme Court ruled that the Dutch government must reduce emissions immediately in line with its human rights obligations. This was the first time a country was required by a court to take action on climate change (OECD, 2021[28]).

[9] These include the Demonstration Energy and Climate Innovation Scheme (Demonstratie Energie- en Klimaatinnovatieregeling, DEI+), and the Stimulating Sustainable Energy Production and Climate Transition grant (Stimulering Duurzame Energieproductie en Klimaattransitie, SDE++).

[10] The eMARS database describes 1186 accidents, of which 142 involve the phrase “hydrogen"; however, filtering out chemical compounds (such as hydrogen fluoride, chloride, sulfide, etc.) and accidents in the petrochemical industry reduces that number to 22. At least 8 of these are clearly not relevant to hydrogen as an energy vector (e.g. the Corus UK 2001 accident, involving formation of hydrogen from water having infiltrated a blast furnace).

[11] The auto-ignition temperature is the lowest temperature at which a substance spontaneously ignites.

[12] The heat capacity indicates how much heat one kilogram of substance needs to absorb to increase its temperature by one degree. The heat capacity can be expressed as units of Kilo Joules per kilogram per degree Celsius.

[13] The energy content by mass is the amount energy that can be released when one kilogram of the substance is combusted. It is also called the calorific value and can be expressed in units of kJ/kg or kJ/unit volume (m^3).

[14] The speed at which a flame spreads through a substance.

[15] The molecular diffusivity shows how fast a substance is diffused in air. This is important as quicker dispersion could reduce risk levels.

[16] The minimum ignition energy is the lowest amount of energy that is required for the substance to be ignited.

3 Regulatory governance and delivery in the energy transition

This chapter highlights existing work on the regulatory governance and delivery of hydrogen, with a specific focus on the energy transition. It first discusses key considerations for the regulation of innovations, focusing on the risks and agility, and the use of licensing for new energy applications. The chapter continues by discussing the application of precaution, highlighting the interaction with innovation as well as Responsible Research and Innovation and safety-by-design approaches.

Regulating innovation in the energy transition

Innovations drive the creation of renewable or low-carbon energy sources such as low-emission hydrogen. The deployment of low-emission hydrogen solutions can fundamentally change how societies and economies function, bringing potential benefits that increase overall welfare. However, to realise the full potential of any innovation, appropriate attention should be paid to its risks. This requires safeguards that ensure novel technologies are developed in a way that upholds fundamental rights, democratic values and the rule of law, while preserving the appropriate protections for citizens and the environment (OECD, 2021[1]).

Innovations often emerge more quickly than the regulations that govern them, giving rise to a "pacing problem" (OECD, 2021[2]). On the one hand, this can create regulatory gaps, where existing regulations do not sufficiently cover the new activities driven by the innovation. This may bring undesirable consequences from a societal point of view – for example when safety or environmental risks are not appropriately managed. On the other hand, the pacing problem may result in regulations that are inadequately tailored to the context of the hazard and associated risks, with unnecessarily high or inappropriate regulatory burdens for innovations and slow the speed of their rollout.

Technological innovations may require policymakers and regulators to change the way they work, including through the creation of new roles and tools. The energy landscape is changing, with new sources of energy such as solar and wind power, and the development of new hydrogen applications. Meanwhile, there is an increasing reliance on digital technologies and online platforms for many regulatory activities (OECD, 2019[3]). Such changes can affect the structures and operations of sectors overseen by regulators and may require them to oversee new activities that did not exist before. At the same time, innovations can support the effectiveness of regulators, in particular through the development of data-driven regulatory tools (OECD, 2020[4]).

Technological innovations may necessitate new or updated mandates, functions and powers for regulators. They may also require regulators to develop new knowledge and skills to supervise and guide new activities and make full use of data-driven approaches. These new demands could put pressure on the overall resources of the regulator (OECD, 2020[4]). Responding to new roles or activities could require regulators to adjust the resources in use: bringing in new staff with the appropriate competences, providing different training and guidance, as well as ensuring that appropriate support and tools are available. As such, appropriate governance can support the continued ability of regulators to both design objective and evidence-based regulatory decisions, and to stay abreast of market developments (OECD, 2022[5]).

Policymakers and regulators may have to consider if existing institutional frameworks and governance arrangements are still effective and efficient in supervising new technologies. This may be especially relevant where new technologies disrupt and cut across the traditional boundaries of markets (OECD, 2020[4]). In light of the foreseen or anticipated change, there may also be a need to develop new institutional co-ordination mechanisms to connect and align the work of different bodies.

Regulatory policy and governance

Sound regulatory policy and governance are crucial to driving the energy transition and enabling the development of renewable or low-carbon energy solutions such as low-emission hydrogen. In 2012, the OECD developed a recommendation to provide guidance to countries on the design, enforcement and review of their regulatory frameworks. The recommendation recognises regulation as one of the crucial factors for governments to promote prosperity, welfare and the public interest (OECD, 2012[6]). To achieve this potential, regulations need to be well designed, implemented and enforced. The recommendation provides governments with twelve key considerations to make sure this is the case (Box 3.1).

Box 3.1. OECD 2012 Recommendation on Regulatory Policy and Governance

To improve the quality of regulation as well as the tools and institutions for evidence-based decision making, the OECD Council adopted the *2012 Recommendation on Regulatory Policy and Governance*. This recommendation advises countries to:

1. commit at the highest political level to an explicit **whole-of-government policy** for regulatory quality.
2. adhere to principles of open government, including **transparency and participation** in the regulatory process.
3. establish mechanisms and institutions to actively provide **oversight of regulatory policy procedures and goals** to foster regulatory quality.
4. integrate **Regulatory Impact Assessment** (RIA) into the early stages of the policy process for the formulation of new regulatory proposals.
5. conduct systematic programme **reviews of the stock of significant regulation** against clearly defined policy goals, including consideration of costs and benefits.
6. regularly publish **reports on the performance** of regulatory policy and reform programmes and the public authorities applying the regulations.
7. develop a consistent policy covering the **role and functions of regulatory agencies** to provide greater confidence that regulatory decisions are objective, impartial and consistent.
8. ensure the effectiveness of **systems for the review of the legality and procedural fairness** of regulations and of decisions made by bodies empowered to issue regulatory sanctions.
9. as appropriate, apply **risk assessment, risk management and risk communication strategies** to the design and implementation of regulations.
10. where appropriate, promote **regulatory coherence** through co-ordination mechanisms between the supranational, national and sub-national levels of government.
11. foster the development of regulatory management **capacity and performance at sub-national levels** of government.
12. give consideration to all relevant **international standards and frameworks** for co-operation in the same field and, where appropriate, their likely effects.

Source: (OECD, 2012[6]), Recommendation of the Council on Regulatory Policy and Governance, https://doi.org/10.1787/9789264209022-en.

When innovations transform sectors or create new activities, as is the case with the development of low-emission hydrogen applications, governments should ensure sufficient role clarity among public actors. When an innovation emerges, it may not always be clear which regulatory agency should supervise or enforce activities, or which ministry may be in charge of policymaking. The 2012 recommendation advises governments to ensure that roles, functions, powers and objectives are therefore defined in legislation (OECD, 2012[6]). Clarifying roles and mandates in law can support an effective execution of regulatory tasks, and prevent overlaps or gaps in mandates.

While hydrogen has been around for a long time as a feedstock in industrial processes, its production process is changing and, most importantly, is expected to become less polluting. Moreover, the scale and scope at which its application is envisaged – beyond the industrial sectors in which it is currently applied – means that policymakers and regulators need to reconsider its regulatory governance. To support a smooth hydrogen transition while acknowledging and addressing its actual risks, more agile regulatory approaches will be required.

Risks in regulation

Innovations can introduce new risks and may reduce existing risks, giving rise to so-called "risk-risk" trade-offs. This context will require governments to define strategies on risk assessment, risk management and risk communication (OECD, 2012[6]). This is also relevant in the case of hydrogen, the properties of which differ from conventional fuels. To ensure regulation is targeted and effective, governments need to provide clear and consistent guidance on methodologies for risk assessment and an objective communication of those risks to the public. As the mitigation of one risk could come at the expense of another, strategies on risk management should communicate how the government expects to approach such "risk-risk" trade-offs (Graham, J. and Wiener, J., 1995[7]).

A risk-based and proportionate approach is not only necessary to the formulation of regulations, but also to their implementation and enforcement. This means that inspections and enforcement activities by regulatory bodies should be proportional and prioritised according to the actual risk level of activities (OECD, 2014[8]). In this context, it is important to emphasise that risks result from the combination of the likelihood of a hazard occurring with the magnitude of damage of such an event. An evidence-based approach to this assessment of risks can ensure an objective risk ranking and avoid a disproportionate focus on hypothetical (rather than actual) risks.

The formulation and communication of comprehensive and clear risk-based approaches to innovations can ensure consistent and predictable decision making. However, the mere existence of risk-based approaches may not be sufficient to achieve this (OECD, 2018[9]). A common understanding of the definition of risk and a common approach to risk management will allow for more harmonised and co-ordinated actions between different regulatory authorities at different levels of government, as well as between teams or units within a regulatory authority. Of course, this need would have to be balanced against any need for regulatory discretion in order to customise decisions based on circumstantial factors.

An important consideration in developing strategies for risk assessment, risk management and risk communication for new hydrogen technologies will be to ensure these are in proportion to the actual risks. This may require a comparative risk assessment with existing fuels, where differential regulatory treatments or stricter risk measures for hydrogen applications should be based on significant and defined additional risks as compared with these fuels. As there is a real momentum driving improvements in technologies and approaches, safety measures based on older data or outdated technologies may result in excessive risk reductions that could obstruct the hydrogen transition. Moreover, without appropriate risk communication, actual risks and public perceptions might deviate, creating a need for decision makers to explain their approaches and provide clear information on risks and measures.

In dealing with the risks and accidents with hazardous installations, the OECD developed the *Guiding Principles for Chemical Accident Prevention, Preparedness and Response*, with a third edition forthcoming (OECD, 2003[10]). These principles address issues related to preventing accidents, preparing for accidents, responding to accidents and follow-up after accidents. The OECD also developed among other things a *Recommendation concerning Chemical Accident Prevention, Preparedness and Response*, and is currently developing a new *Decision-Recommendation concerning Chemical Accident Prevention, Preparedness and Response* that brings together existing OECD legal instruments on the topic (OECD, 2004[11]) (OECD, forthcoming[12]).

The agility of regulation

To acknowledge and account for innovations, enhancing their benefits while managing risks, governments will need to adjust their traditional approach to regulatory governance. To advise governments how they can make their regulatory governance "innovation-proof", the OECD developed the *2021 Recommendation on Agile Regulatory Governance to Harness Innovation* (OECD, 2021[2]). It supports countries in defining more agile and forward-looking approaches that are able to absorb changes in highly uncertain and dynamic contexts. The recommendation is structured along four pillars:

- First, to ensure regulations remain fit-for-purpose, governments should adjust regulatory processes to make them more adaptive, iterative and flexible (OECD, 2021[2]). Existing “regulate and forget” approaches, in which regulations are not regularly assessed after their implementation, may not be robust for dynamic contexts. New technologies, emerging scientific knowledge and changing social and political contexts can create a mismatch between yesterday’s policies and today’s world (Bennear and Wiener, 2019[13]). Governments therefore require an “adapt and learn” approach in regulating innovations, to incorporate new developments and findings into the development of regulation (OECD, 2021[1]).[1] Stakeholder engagement throughout the different regulatory stages (design, implementation and evaluation), with a wide range of stakeholders, enables governments to bring in expertise from various sources and build trust. Wider international engagement and knowledge sharing can support countries in making use of the most up-to-date knowledge on technologies and approaches.
- Second, given how many emerging technologies crosscut and interlink traditional sectors and borders, governments will need to create the institutional foundations for strengthened co-operation and joined-up approaches (OECD, 2021[2]). Whole-of-government approaches can promote effective policy responses. Moreover, institutional co-ordination can be used to identify and resolve institutional or regulatory gaps and overlaps (OECD, 2021[1]). International regulatory co-operation can ensure policy responses and regulatory decisions are harmonised across countries where possible. This could prevent regulatory arbitrage by companies (giving rise to a “race to the bottom” among governments), and remove unnecessary discrepancies between regulatory frameworks.
- Third, governance arrangements should allow for the development of agile and future-proof regulation through forward-looking and outcome-based regulation and experimentation. Horizon scanning can help governments to anticipate developments and so build out institutional capacity and assign mandates in a timely manner. Outcome-based regulatory approaches can support a move away from prescriptive regulation, creating more scope for entities to introduce innovations that improve outcomes while also reducing the “pacing problem” (OECD, 2021[1]). Finally, experimentation, through regulatory sandboxes, testbeds and innovation spaces, can allow for policy learning at a stage where evidence and knowledge still need further development. The testing of regulatory frameworks through dedicated test projects can provide a platform for stakeholders to come together, discuss and assess regulatory improvements and to identify areas for further development (Vannan and Gemmell, 2012[14]).
- Fourth, governments and regulators should consider adapting regulatory enforcement activities to make them more risk-based and focused on outcomes and compliance promotion. Rigid processes and detailed, prescriptive rules can make regulatory compliance unnecessarily burdensome and stifle innovation. Instead, proactive support and guidance for innovators can support a sector-wide understanding of the regulatory framework, drive compliance and could, in turn, feed information to regulators about how to reduce regulatory burdens. At the same time, innovations and data-driven solutions can support the monitoring of compliance through real-time monitoring and continuous data collection (OECD, 2021[1]).

The above considerations to ensure regulations are effective apply broadly across sectors but may be especially relevant in the context of hydrogen. This is due to the characteristics of the hydrogen transition, namely the strong ambitions of countries in this domain, the rapid development of new hydrogen technologies at a larger scale and the emergence of new scientific knowledge. As new hydrogen technologies and applications fundamentally redefine the use of hydrogen across economies, policymakers and regulators will require more agile regulatory models to absorb changes and avoid “regulating the past”.

Box 3.2. Regulating hydrogen in practice: opening a hydrogen refuelling station (HRS)

A key problem is often that new applications of hydrogen have not been foreseen in existing legislation, and that they are thus “by default” either unaccounted for, subject to requirements that do not match its specific risks or facing regulatory uncertainty, particularly in terms of site approval and permitting. This does not in any way mean that hydrogen is generally over-regulated, and this report in any case does not cover the industrial processes involving hydrogen, which often benefit from long-established, specific regulations. Providing case-by-case comparison for every case and country would go beyond the scope of the report, we thus focused here on one simple example: opening a hydrogen refuelling station (HRS), looking at three jurisdictions (California, England, and the Netherlands).

- In California, the state seeks to develop HRSs and to phase out the opening of any new hydrocarbon refuelling stations (petrol stations). A regulatory framework has thus been developed to facilitate HRS openings. Still, the HRS opening process tends to be longer than for petrol stations, and mandatory safety distances for HRS mean that larger lot sizes are required to accommodate them. If there is insufficient space, then additional mitigation measures must be put in place (GO-Biz, 2022[15]). This, however, complicates the licensing process resulting in delays. Furthermore, lots that are large enough to comply with the distancing requirements might be hard to find in more densely populated areas, resulting in the HRS being in more distant locations that might be less convenient to drivers (Harris et al., 2014[16]).
- In England, while the overall opening process features much the same approvals and licenses, HRS require a “gas license” (as if the HRS belonged to a natural gas operator), which typically takes around nine months to obtain, and has very little to do in its specifics with the actual safety issues pertaining to hydrogen (Ofgem, 2022[17]). Larger installations will also require a specific safety approval, and an environmental approval, because all hydrogen installations are regulated as hazardous industrial installations, and there are no specific provisions for HRS.
- In the Netherlands, likewise, based on the current regulations, HRS require environmental permits which are also required for LPG and LNG stations, but are not usually required for petrol stations, unless they are unsupervised and located less than 20 meters away from houses or other vulnerable objects (WVIP, 2020[18]) (RVO, n.d.[19]). New regulation, which is expected to enter into force in 2024, limits the scope of the environmental permit to just the hydrogen fueling process, however, this is still a stricter requirement than for petrol stations, for which environmental permits will no longer be a requirement in any scenario (IPLO, n.d.[20]). In addition, other parts of the HRS licensing process take significantly longer than for hydrocarbons, because the existing development (zoning) plans do not foresee this land use, and “ample time” is required to obtain a special exemption from the plan (WVIP, 2020[18]).

Thus, even in the most favourable regime (California), opening an HRS remained longer and more difficult (restricted siting because of higher fire safety distances). In England, the process was much longer because of the current gas licensing requirements, which are not specific to hydrogen, as well as the safety and environmental permitting needed. In the Netherlands, it was both longer and more difficult because of no zoning provision for HRS and the need to obtain both zoning exemptions and environmental permits.

In summary: "Most countries currently lack specific regulation that target the dispensing of hydrogen in refuelling stations, as this is still new equipment that has not been targeted in regulations. For the HRS (Hydrogen Refuelling Stations) currently deployed, the permitting procedure follows existent guidelines on conventional fuelling stations combined with industrial hydrogen requirements or CNG specific regulation. Most countries agree that the lack of specific regulations increases the level of subjectivity in the permit decision" (MultHyFuel Project, 2021[21]).

Figure 3.1. Regulating hydrogen in practice: Opening a hydrogen refuelling station

Source: https://www.shutterstock.com/image-vector/green-sustainable-hydrogen-energy-gas-fueling-2061029765; https://www.shutterstock.com/image-vector/petrol-pump-fuel-car-auto-1408643744.

Regulatory delivery in the energy transition

Regulatory delivery looks at the activities and actions, measures and processes used to secure the implementation of regulations in practice (OECD, 2021[22]). It looks at regulatory delivery mechanisms such as licensing regimes, inspections and enforcement by regulatory authorities.

Licensing

Licensing is a tool used by governments and regulators to control the conduct of specific activities. Licensing is an overarching term for the use of permits, licences, certifications or other forms of authorisation before the start of an activity. It is understood to be any administrative procedure whereby official approval by at least one competent authority is required to perform, use or own something [BPP licensing]. Reasons for licensing requirements can be the achievement of public policy goals, the control and reduction of potential harms or a restriction to the use of certain goods or resources.

Licensing is a form of regulation in which activities usually cannot take place until permission in the form of a licence or other authorisation has been granted. For this reason, it can be perceived as a rather restrictive form of regulation, where it poses a burden on industry by slowing down the deployment of new technologies and reducing the agility of innovators. Licensing also gives rise to a potential risk of regulatory capture, whereby the regulator, having granted a licence or given permission for an activity, may feel a degree of responsibility for any adverse safety outcomes that arise.

Delays and bottlenecks due to licensing procedures can significantly delay the time it takes to build clean energy infrastructure such as hydrogen. The IEA finds that while construction is a relatively efficient process, taking two to four years depending on average, planning and permitting procedures may end up taking two to seven years, depending on the jurisdiction and type of infrastructure (IEA, 2023[23]).[2] Such lead times could pose an obstacle to the timely expansion of the hydrogen infrastructure.

A number of constraints in licensing requirements can affect the speed of rollout of innovations such as renewable or low-carbon energy applications. Complex licensing procedures with excessive safety requirements can make it more time-consuming to scale up and develop new energy technologies. Moreover, different regulatory requirements, sometimes enforced by different regulatory bodies with low levels of co-ordination, can lead to risk assessment in silos, without consideration of risk-risk trade-offs. This could therefore result in an unbalanced weighing of local safety risks against the more global risks of the climate crisis. Given the novelty of many green energy technologies, licensing requirements may sometimes still be based on older forms of technology or apply disproportionately high levels of precaution for relatively low levels of risk [licensing renewables paper].

A lack of scientific understanding of the actual risks of new energy solutions, combined with poor public perception, can lead to an overly cautious approach to their licensing. Even in contexts where overall risks of new technologies may be relatively low, the occurrence of accidents can negatively affect public perception and regulators or regulatory systems may be blamed for not preventing them (Van der Heijden, 2022[24]). The lack of absolute certainty on risks, given the novelty of technologies, can result in overly restrictive safety requirements in licensing procedures. Safety risks related to existing fossil fuel technologies often meet a higher risk tolerance, which may be explained by a higher degree of familiarity by the public with these applications and more publicly available data [licensing renewables paper].

To ensure licensing regimes are effective, governments should take a risk-based approach to licensing. The proportionality and burden of the instrument should match its purpose and the risks it aims to manage. The level of risk that a specific activity poses, based on reliable data and evidence, should be the key criterion for determining the severity of licensing requirements. Specifically, for the case of new green solutions, governments will also need to balance the harms from new technologies against the risk of climate change that these try to counter [licensing renewables paper].

Consequently, licensing should be the exception, not the default, when managing significant risk in contexts where there are no other regulatory instruments with a lower burden on regulated entities. A good practice is to minimise the use of licensing to the level absolutely necessary. However, in practice across countries, licensing is often applied more systematically for a variety of situations, regardless of its adequacy in protecting the defined public goals [BPP licensing]. A system with “silent consent” or notifications could be used for green technologies with a low risk profile, and prior assessments for larger-scale projects with higher risk profiles. This could reduce the need for assessment only at the end of projects, thereby reducing potential delays [licensing renewables paper].

Where licensing is required, governments and regulators should assess ways to lower burdens on entities. This will require simplification of requirements and procedures whenever possible, for example through the streamlining of processes or “one-stop shops”, removing overlapping requirements, reducing document requirements to the absolute necessary, and digitalisation. Licensing authorities could furthermore provide straight-forward guidance material to innovators, informing them of the different steps and requirements. This could reduce the burden on both applicants and authorities by limiting the number of incorrect submissions and the delays and extra work they cause [BPP licensing].

Inspections and enforcement

Governments and regulatory bodies establish laws, regulations, and principles to guide the energy transition. These frameworks outline the specific requirements and standards that companies must meet. As the energy sector shifts towards cleaner and more sustainable energy sources, it is essential to monitor and enforce adherence to established standards.

Ensuring effective compliance with these rules and regulations is an important factor in creating a well-functioning society and trust in government. It can help to safeguard health and safety, environmental protection, and delivery upon other policy goals (OECD, 2014[8]). By designing effective inspection and enforcement frameworks for the energy transition, regulatory authorities can promote sustainable development, foster innovation in clean energy technologies, and ensure compliance with environmental and safety standards throughout the energy sector.

Inspections help verify compliance with regulations and ensure that companies are contributing to the established goals. They can evaluate safety protocols and risk management practices, which includes assessing worker safety, emergency response plans, maintenance procedures, and adherence to industry standards. Inspections are crucial for renewable energy projects such as hydrogen fuel stations, wind farms, solar installations, and hydroelectric plants. They help verify the proper implementation of these projects, including site selection, construction practices, equipment quality and grid integration.

Non-compliance with regulatory requirements can result in enforcement actions. These can include warnings, improvement notices, fines, license revocation, project shutdowns, or prosecutions. Regulatory actions complement other enforcement of regulation through information, guidance and prevention, data collection and analysis and inspections (OECD, 2014[8]).

Box 3.3 includes the OECD *Best Practice Principles on Regulatory Enforcement and Inspections*, which are crucial to design an effective framework for regulatory delivery to support the energy transition.

Box 3.3. OECD Best Practice Principles on Regulatory Enforcement and Inspections

The OECD defined eleven key principles on which effective and efficient regulatory enforcement and inspections should be based:

1. **Evidence-based enforcement.** Regulatory enforcement and inspections should be evidence-based and measurement-based: deciding what to inspect and how should be grounded on data and evidence, and results should be evaluated regularly.
2. **Selectivity.** Promoting compliance and enforcing rules should be left to market forces, private sector and civil society actions wherever possible: inspections and enforcement cannot be everywhere and address everything, and there are many other ways to achieve regulatory objectives.
3. **Risk focus and proportionality.** Enforcement needs to be risk-based and proportionate: the frequency of inspections and the resources employed should be proportional to the level of risk and enforcement actions should be aiming at reducing the actual risk posed by infractions.
4. **Responsive regulation.** Enforcement should be based on “responsive regulation” principles: inspection enforcement actions should be modulated depending on the profile and behaviour of specific businesses.
5. **Long term vision.** Governments should adopt policies and institutional mechanisms on regulatory enforcement and inspections with clear objectives and a long-term road-map.
6. **Co-ordination and consolidation.** Inspection functions should be co-ordinated and, where needed, consolidated: less duplication and overlaps will ensure better use of public resources, minimise burden on regulated subjects, and maximise effectiveness.
7. **Transparent governance.** Governance structures and human resources policies for regulatory enforcement should support transparency, professionalism, and resultsoriented management. Execution of regulatory enforcement should be independent from political influence, and compliance promotion efforts should be rewarded.

8. **Information integration.** Information and communication technologies should be used to maximise risk-focus, co-ordination and information-sharing – as well as optimal use of resources.
9. **Clear and fair process.** Governments should ensure clarity of rules and process for enforcement and inspections: coherent legislation to organise inspections and enforcement needs to be adopted and published, and clearly articulate rights and obligations of officials and of businesses.
10. **Compliance promotion.** Transparency and compliance should be promoted through the use of appropriate instruments such as guidance, toolkits and checklists.
11. **Professionalism.** Inspectors should be trained and managed to ensure professionalism, integrity, consistency and transparency: this requires substantial training focusing not only on technical but also on generic inspection skills, and official guidelines for inspectors to help ensure consistency and fairness.

Source: (OECD, 2014[8]), Best Practice Principles on Regulatory Enforcement and Inspections, Paris, http://dx.doi.org/10.1787/9789264208117-en.

Exercising precaution

While evidence-based decision making is essential to regulatory governance, innovations such as new hydrogen technologies and applications could force governments and regulators to make decisions based on smaller scientific evidence bases regarding risks than they are used to (or comfortable with). Governments may apply the precaution principle in such situations, to account for existing gaps in knowledge on risks. A complete discussion of this principle and its implications can be found in the OECD publication *Understanding and Applying the Precautionary Principle in the Energy Transition* (OECD, forthcoming).

The precaution principle (or precaution approach) can be applied in various contexts, including legislation, regulation, standards and licensing procedures. While there is no single definition, the principle is usually applied in situations characterised by a need for (environmental) protection, considerable scientific uncertainty, and a threat or risk of serious damage (Pinto-Bazurco, 2020[25]) (Sands, P. & Peel, J. (Eds), 2012[26]). It is based on the philosophy that a lack of scientific certainty should not be a reason to not take preventative action (HSE, 2001[27]). The precaution principle should not be confused with the concept of prevention, which deals with risks that are better understood.

The literature identifies both pros and cons to the application of the precaution principle. Proponents argue that it allows for the consideration of risks or effects that are not accurately covered under alternative methods. Importantly, the precautionary principle can help to address the risks of latent impacts or the delayed effect of risks – i.e. where it takes time before risks materialise, such as with the climate crisis. It can also help avoid a bias that disregards poorly understood risks that may not be covered under traditional cost-benefit analyses (Wiener, 2018[28]) (European Commission, 2017[29]). Criticism of the principle focuses on the multiple possible interpretations that may result in practice and the impact overly prescriptive approaches can have on innovation (Gemmell, J. Campbell; Scott, E. Marian, 2013[30]). Some argue that the absence of a clear definition could undermine legal certainty and that the principle appears not to be applied in a consistent manner (Wiener, J. and Rogers, M., 2002[31]).

Precaution principle as regulatory approach

The application of precaution matters for the exercise of risk governance by decision makers. It should not be applied where there is sufficient certainty regarding risks, as these situations can be dealt with by using "normal" risk management approaches (Von Schomberg, R., 2012[32]). However, where scientific evidence is lacking or there is no consensus on the likely adverse effects, precaution may be applied by policymakers (European Commission, 2000[33]). The exact application of the precaution principle may depend on which risks policymakers care about most, as well as the regulatory context and legal system, with differences in application across and within countries (Wiener, J. and Rogers, M., 2002[31]).

Risk trade-offs

A potential shortcoming from the application of precaution could be that policymakers focus too narrowly on a single risk, where minimising a specific target risk may be at the expense of other countervailing risks (Wiener, 2016[34]). Applying precaution too narrowly on a single risk could lead to a suboptimal outcome in terms of overall risk reduction. For example, in the case of the application of precautionary approaches to hydrogen technologies, precautionary measures to safeguard health or safety may impede efforts to decrease climate change risks or vice versa. To account for all different risks, a wider impact analysis beyond the single risk could be used to identify any countervailing risks and benefits in order to determine the degree of precaution required (Graham, J. and Wiener, J., 1995[7]) (Wiener, 2020[35]).

Iterative approach

As the precaution principle allows governments to factor scientific uncertainty on risks into decision making, the degree of precaution required will reduce as scientific knowledge evolves. New hydrogen technologies will face lower levels of scientific certainty regarding their risks during the earlier stages of development. As applications become more mature and more research becomes available, the degree of scientific uncertainty tends to decrease.

To allow for improvements in the scientific knowledge base, the regulatory analysis and application of precaution should therefore be based on an iterative process that can incorporate learning into the resulting regulations. In this way, precautionary measures may need to be modified or abolished as stronger knowledge on risks becomes available. This would not be dependent on time, but rather on the rate at which new scientific research becomes available (European Commission, 2000[33]). This iterative approach to policymaking in light of scientific uncertainty requires knowledge sharing and encourages more dynamic modes of stakeholder engagement.

Socio-political context

While the level of available scientific evidence will factor into the desired level of precaution, the socio-political context and psychological elements can play an important role as well. The degree of risk aversion that regulators exercise in their decision making may depend on how benefits and risks are distributed across society, as well as the mobilisation and engagement of different stakeholder groups.

As risk aversion may differ on a case-by-case basis depending on the decision-making context, the precaution principle tends to be applied with a high degree of discretion. Some argue that this is also one of the precaution principle's main functions, to provide "a rationale and justification for administrative discretion" (Heyvaert, 2006[36]). However, it has also been pointed out that the application of precaution to regulatory decision making could, in a politicised context, be driven by interests and circumstantial factors, rather than maximising social well-being based on a careful weighing of pros and cons (A. Dembe, Raffensperger, C., & Tickner, J., 2004[37]).

Behavioural biases and public perceptions

Public perceptions about the magnitude of risk and the associated costs and benefits can constitute certain behavioural barriers and biases. These biases have a real effect on the market and on people's acceptance of risk. Analysing and understanding these perceptions – also in relation to the economic and environmental impact – is a fundamental step for the regulator. Knowing in advance biases, behaviours and how people will react to energy innovations can help policymakers to design strategies and regulations to support a "proactive" perception and acceptance towards energy technology innovations.

To investigate the fears and risk perceived by society, various initiatives have been launched to identify the level of social awareness and the costs and benefits associated with hydrogen (Huijts, Molin and van Wee, 2014[38]) (Iribarren et al., 2016[39]). Several studies analyse how fears and non-acceptance may be connected with the absence or presence of social awareness and information campaigns (Heinz and Erdmann, 2008[40]). The risk-acceptance model built by Huijts et al. describes the structure of social acceptance as a cognitive model directly related to the level and quality of information shared with society (Huijts and van Wee, 2015[41]).

Heuristics and biases play a vital role in people's ability to receive information and make decisions. Sometimes the regulator has to respond to social pressure due to lack of information or biases that alter the perception of the available data. Research has shown how social cognitive heuristics play a decisive role in political and regulatory decisions, especially when faced with complexity, sustainability, lack of time and uncertainty (Korteling, Brouwer and Toet, 2018[42]).

A number of behavioural biases may be particularly relevant to policymaking and the regulation of risks related to an emerging energy technology such as hydrogen:

- The notion of the “risk regulation reflex” refers to situations in which decisions may be adopted too fast and based on little analysis, resulting in disproportional safety or protection measures and potential “regulatory inflation” (Blanc, Macrae and Ottimofiore, 2015[43]).
- There may be certain psychological impulses and political pressures that could lead politicians to “rush to judgement” and neglect trade-offs that are inherent to the decision making (Coglianese C., and Carrigan, C., 2012[44]).
- Path dependency refers to the theory “that policies, once established, can be difficult to change or reform”, resulting in a situation where earlier actions will have an impact on the actions of institutions today (Kay, 2005[45]).
- The “availability heuristic” or “availability bias” is where people assign a higher probability to events that come to mind more quickly when evaluating situations. Factors such as media coverage could result in people placing an increased attention on worst-case scenarios, making such outcomes appear more frequent than they actually are.
- The “present bias” or hyperbolic discounting refers to the bias in which people give a high importance to current needs and a lower importance to future needs (O’Donoghue and Rabin, 2015[46]) (Samuelson and Zeckhauser, 1988[47]) (Kahneman and Tversky, 1979[48]). This bias prevents people from being open to innovation that will have an impact in the future. This may be especially the case when combined with the “loss aversion bias”, whereby people make decisions mainly driven by the fear of losing someone or something important (Wang, Rieger and Hens, 2016[49]).

Public information and deliberation will affect the public perception of risks, as was shown through case studies on the public perception of hydrogen (Box 3.4).

Box 3.4. Ambiguity, complexity and uncertainty surrounding hydrogen and public views

The fact that some of the risks associated with the use of hydrogen energy are not yet perfectly known or quantified does not, in itself, justify the use the precautionary principle. After all, no risks are ever perfectly known or quantified. As the hydrogen industry, research, and regulation develop, there will be opportunities for further refining the regulatory framework as more evidence becomes available. To be sure, a number of specific applications of hydrogen energy (e.g. in homes) do warrant more precaution due to higher uncertainty and potential harm. However, even in these cases, precaution should not revolve around a yes-or-no question but rather rely on stepwise, scalable experimental approaches.

The International Risk Governance Council's (IRGC) model on risk governance suggests the use of the precautionary principle in risk assessment and management. However, in terms of alternative scenarios on the possible development of the hydrogen economy, there is also uncertainty reflecting different stakeholders' interests and values, and about appropriate regulatory regimes. Hence, the IRGC model recommends deliberative methods and participatory discourse to address some of these issues. In line with the notion of concern assessment, the framework includes consultation, participation, and public engagement to build more transparent and inclusive systems of risk governance.

As part of a wider series of case-studies about hydrogen in England and Wales, the authors carried out two all-day meetings with citizens' panels in Teesside (Middlesbrough, in North-East England) and Wales (Llanelli, South Wales) during 2008–2009. These two areas were selected as they already had some hydrogen production plants, as well as demonstration projects for hydrogen energy technologies.

During the two meetings, members of the public were provided with basic information about hydrogen including alternative scenarios created by a hydrogen economy. The authors identified several "knowledge gaps" among citizens about the nature and properties of hydrogen as an energy carrier, and the regulatory codes and standards to deal with anticipated risks. The authors found that "though the final deliberations by this panel suggested some positive interest in hydrogen use as energy carrier, this was conditional upon people receiving more detailed information and reassurance about measures to regulate safety in the entire system of production, storage, and distribution". This experience illustrates that public perception of the risks associated with hydrogen can depend on the knowledge and information made available. Citizen involvement can help ensure more transparent and inclusive risk governance, which is recommended in situations where there is a high degree of uncertainty surrounding the risk problem.

Source: (OECD, 2023[50]), Understanding and Applying the Precautionary Principle in the Energy Transition*;* (Bellaby and Clark, 2016[51]) (Flynn, Ricci and Bellaby, 2012[52]).

Precaution applied to innovation

New hydrogen technologies or applications that are introduced to markets are often accompanied by questions regarding their risk. As innovations, by their very nature, have not previously been applied, there is little experience with their exact consequences in practice (beyond a theoretical understanding). This therefore raises the question of how well precaution and innovation go together.

There is some controversy about the potential effects of the precaution principle on innovation, and some would say that the two tend to conflict. They argue that the precaution principle leads to legal uncertainty and that precautionary measures could "paralyse" innovation (Sunstein, 2002[53]). In addition, application of the precaution principle may not factor in the risk or opportunity cost of forgone progress or welfare that innovation could achieve (Orset, 2014[54]) (Institut économique Molinari, 2013[55]). As scientific uncertainty is often inherent to the introduction of innovation, regulations focusing too narrowly on eliminating risk and removing scientific uncertainty could therefore impede innovation.

Rather than hindering innovation, it has also been argued that precaution can be used to stimulate or steer innovation. The UK Interdepartmental Liaison Group on Risk Assessment states that an appropriate application of the precaution principle could “encourage technological innovation and sustainable development by helping to engender stakeholder confidence that appropriate risk control measures are in place” (Interdepartmental Liaison Group on Risk Assessment, 2002[56]).

The European Risk Forum (ERF) suggests including the innovation principle, to allow for the consideration of the impact of regulations on innovation. The “innovation principle” intends to give weight in decision making to the potential benefits that innovations can bring (such as job creation, growth, environment, health and well-being) and acts as a counterweight to potential risks. The European Commission defines the innovation principle as a “tool to help achieve EU policy objectives by ensuring that legislation is designed in a way that creates the best possible conditions for innovation to flourish” (Vos E. and Smedt K., 2020[57]). The OECD Recommendation on Agile Regulatory Governance to Harness Innovation also highlights the role of regulatory policy to ensure innovation can drive more sustainable and inclusive growth and address global challenges (OECD, 2021[2]).

The Responsible Research and Innovation approach was developed as a response to the challenge of reconciling the precaution and innovation principles, to systematically weigh precautionary measures against the societal benefits of innovation. The approach essentially encompasses four elements (Stilgoe et al., 2013[58]):

- *Anticipation*: “Involves systematic thinking aimed at increasing resilience, while revealing new opportunities for innovation and the shaping of agendas for socially-robust risk research.”
- *Reflexivity*: “At the level of institutional practice, means holding a mirror up to one’s own activities, commitments and assumptions, being aware of the limits of knowledge and being mindful that a particular framing of an issue may not be universally held.”
- *Inclusion*: Means taking the time to involve different stakeholders in order to lay bare the different impacts of a new technology on different communities
- *Responsiveness*: “Responsible innovation requires a capacity to change shape or direction in response to stakeholder and public values and changing circumstances.”

Safety-by-design

A specific elaboration of Responsible Research and Innovation are so-called safety-by-design approaches (also referred to as “safe-by-design”, “safer-by-design” or “design for safety”). Safety-by-design approaches aim to combine the precaution and innovation principles by addressing safety issues during the design phase, thereby using innovation as a solution to safety concerns. By “frontloading safety”, safety-by-design approaches can be used to strike a balance between the need for innovation, to bring societal benefits such as well-being or sustainability, and a need to be cautious about potential safety risks that could emerge (van Gelder et al., 2021[59]).

Looking at the hierarchical approach to risk management – ranging from risk elimination and substitution to control and mitigation – safety-by design approaches put a strong emphasis on earlier stages of risk control (i.e. reducing risks wherever possible during the design phase until the “design freeze”). It aims to facilitate preventative design practices that minimise risks, through inclusive and responsive approaches that help innovators to think as early as possible about hazards during the product life cycle (van Gelder et al., 2021[59]).

The extent to which safety-by-design approaches will be able to control risks will depend on the existing knowledge and data on potential risks that is available during the early stages of design. Importantly, safety-by-design approaches do not remove the need for other stages of risk management, such as control and mitigation, but can reduce the level of risk that needs to be managed at these stages (see Box 3.5 for a discussion of methodologies for the prioritisation and review of risk measures).

Safety-by-design approaches will require regulatory preparedness, in order to ensure innovations undergo suitable safety assessment before rollout to identify risks and appropriate safety measures and designs. Regulators need to become aware of upcoming technologies and develop foresight, skills and know-how at a sufficiently early stage of innovation if they are to drive action and use the appropriate regulatory tools. This will require open engagement and knowledge exchange between regulators, innovators, industry members and other stakeholders in order to anticipate the regulatory challenges and risks posed by new technologies (OECD, 2020[60]). By building more awareness across stakeholders, regulators can ensure procedures and regulations for safety assessment are available at an early stage, and that innovators will understand the relevant regulatory requirements.

The application of safety-by-design will require a culture change for both innovators and regulators. At present, there may not be sufficient open communication or collaboration to facilitate a collective approach to safety reduction during the design phase. The application of safety-by-design approaches would need to be supported by the implementation of safety-by-design approaches in frameworks, guidance and tools.

Crucially, the use of safety-by-design approaches will require an investment in terms of resources by regulators at early design stages. These additional resources will be needed to allow for sufficient time and capacity to exchange knowledge and thoughts with innovators and to develop expertise on new technologies. Not all investments will pay off, as some innovations will prove more successful than others.

Box 3.5. Methodologies for prioritisation and review of risk measures

One methodology that can be instrumental for prioritisation and review in the context of safety and risk management during the energy transition is the **Layers of Protection Analysis (LOPA)**. LOPA is a widely used technique that helps identify and evaluate layers of protection to prevent or mitigate potential hazards and risks. It is a semi-quantitative risk assessment methodology that assesses the effectiveness of existing protection layers and identifies any gaps in risk reduction. LOPA focuses on identifying independent layers of protection and their associated likelihood of failure on demand (LOFOD). LOPA presents several benefits for the prioritisation of mitigating measures such as: improved understanding of risk scenarios and potential consequences; identification of critical protection layers and potential areas for improvement; rational allocation of resources for risk reduction measures; enhanced decision making for risk management strategies and compliance with regulatory requirements and industry standards.

Another methodology that can be instrumental for prioritisation and review in the context of the energy transition is the **Bowtie Analysis**. Bowtie Analysis is a risk assessment and management tool that visually depicts the relationships between hazards, potential causes, consequences, and control measures. Bowtie Analysis is a barrier-based methodology that utilises a bowtie-shaped diagram to illustrate the relationships between threats (top event), causes (left side), consequences (right side), and control measures (barriers) in the middle. It provides a clear and concise representation of the risks and the controls in place to manage them.

Bowtie Analysis presents several benefits such as an intuitive visual representation of risks and control measures; comprehensive understanding of the relationships between hazards, causes, consequences, and controls in a holistic manner; helps identify gaps or weaknesses in the control measures, highlighting areas where additional measures or improvements are needed; facilitates the prioritisation of actions based on their potential impact on risk reduction and can be used as communication tool to engage stakeholders and support discussions on risk management.

Other methodologies that can be considered for prioritisation and review include **Fault Tree Analysis** (FTA), **Event Tree Analysis** (ETA), **Failure Mode and Effects Analysis** (FMEA), and **Hazard and Operability Study** (HAZOP). Each methodology has its unique characteristics and suitability depending on the specific context and objectives of the analysis. It is important to select the most appropriate methodology based on the nature of the risks, available data, resources, and expertise within the organisation.

Source: CCPS (2001), *Layer of Protection Analysis: Simplified Process Risk Assessment,* John Wiley & Sons; HSE (2008), *Bowtie Methodology: A Technique for Risk Management and Incident Analysis*, Offshore Technology Report OTO 2008/030.

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Notes

[1] This would involve “more holistic, open, inclusive, adaptive and better-co-ordinated governance models to enhance systemic resilience by enabling the development of agile, technology neutral and adaptive regulation that upholds fundamental rights, democratic values and the rule of law” (OECD, 2021[1]).

[2] The IEA report uses the time to develop natural gas infrastructure as a proxy for the time it takes to deploy hydrogen infrastructure, due to similarities in project types and processes (IEA, 2023[23]).

4

Hydrogen governance in the Netherlands

This chapter discusses the institutional and regulatory context for hydrogen risk regulation in the Netherlands. It first discusses the relevant legislation and regulations and on-going regulatory initiatives. It then goes on to discuss the main actors involved and the existing co-ordination platforms at the national and international level. The chapter concludes by discussing the licensing and inspections for hydrogen projects in the Netherlands.

How is hydrogen currently regulated in the Netherlands?

Existing regulatory framework

The foundations of hydrogen policy in the Netherlands have been determined in the 2019 Climate Act and the 2019 Climate Agreement. The Climate Act establishes the target of a 49% reduction in greenhouse gas emissions by 2030, and a 95% reduction and entirely carbon neutral electricity production by 2050, in both cases compared with 1990 levels (Rijksoverheid, 2019[1]). The Dutch Climate Agreement is a package of measures focusing on achieving those 2030 targets. The measures resulted from roundtable discussions between the government and 150 parties including companies and civil society organisations (Klimaatakkoord, n.d.[2]). The Ministry of Economic Affairs and Climate Policy (EZK) has a co-ordinating responsibility and safeguards the overall coherence of actions envisaged in the Climate Agreement (Klimaatakkoord, 2019[3]). On 8 February 2023, The Netherlands improved on its ambitions, by amending the Climate Act to aim for a 55% reduction in greenhouse gas emissions by 2030 and climate neutrality by 2050 (Rijksoverheid, 2023[4]).

The Climate Agreement establishes the vision for future hydrogen applications in the Netherlands, and this has been further developed in the Dutch hydrogen strategy. The Climate Agreement determines the functions that hydrogen could perform across sectors and announces the start of a substantial "hydrogen initiative" (Klimaatakkoord, 2019[3]). As a lead-up to this hydrogen initiative, EZK shared a hydrogen vision and policy agenda with the House of Representatives in 2020 which details the government's hydrogen plans in further detail (Rijksoverheid, 2020[5]). The hydrogen initiative was formalised in the National Hydrogen Initiative (*Nationaal Waterstofprogramma*, NWP) which started in 2022 (NWP, 2022[6]).

At the time of writing this report, there is no single comprehensive piece of Dutch legislation that defines all regulatory requirements specifically for hydrogen. Existing rules that are specific to hydrogen mostly focus on industry and related activities such as production and transportation. This is because hydrogen in the Netherlands is, at present, mostly used in industrial processes such as in the chemical sector and oil refining (CBS, 2020[7]). For new hydrogen applications in the energy transition, most relevant legislation does not consider the specific case of hydrogen, but rather defines general requirements, such as those for dangerous or hazardous substances (as listed in Table 4.2). A few notable exceptions relate to hydrogen use as a fuel for vehicles (see Chapter 5 – "Scenario 5 – Mobility and partially confined spaces: refuelling stations").

Table 4.1 provides an overview of relevant legislation for the application of hydrogen in the Netherlands.

Table 4.1. Relevant legislation for the application of hydrogen in the Netherlands

Legislative document	Relevance	Scope
Acts		
Spatial planning act (*Wet ruimtelijke ordening*)	Defines requirements for spatial planning and the development of zoning plans	Production, pipeline transport and refuelling
Act on general provisions of environmental law (*Wet Algemene bepallingen omgevingsrecht*, Wabo)	Defines requirements for environment permits	Production, pipeline transport and refuelling
Environment and planning act (*Omgevingswet*)	Defines rules regarding the spatial planning of the living environment	Production, pipeline transport, road transport and refuelling
Transport on hazardous substances act (*Wet Vervoer gevaarlijke stoffen*)	Defines rules regarding the transport of dangerous substances	Road transport
Gas act (*Gaswet*)	Defines rules regarding the operation of gas infrastructure and the role of gas grid operators	Pipeline transport
Decrees		
Decree risks major accidents 2015 (*Besluit risico's zware ongevallen 2015*, Brzo 2015)	Defines requirements for the prevention of major accidents at installations with dangerous	Production

Legislative document	Relevance	Scope
	substances	
Construction decree 2012 (*Bouwbesluit 2012*)	Defines safety requirements for construction of buildings	Production and refuelling
Decree external safety establishments (*Besluit externe veiligheid inrichtingen*, Bevi)	Defines external safety conditions for establishments	Production and refuelling
Decree external safety pipelines (*Besluit externe veiligheid buisleidingen*, Bevb)	Defines external safety conditions specifically for pipelines	Pipeline transport
Decree alternative fuels infrastructure (*Besluit infrastructuur alternatieve brandstoffen*)	Contains rules relating to the implementation of the European Directive for the development of infrastructure for alternative fuels	Road transport and refuelling
Decree quality living environment (*Besluit Kwaliteit Leefomgeving*, Bkl)	Defines certain safety distances for hydrogen refuelling stations	Refuelling
Regulations		
Transportation of energy regulation (*Regeling energie vervoer*)	Defines rules regarding the transportation of energy	Road transport
Norms and guidelines		
The Netherlands norm (*Nederlands Norm*, NEN-norm) 3650	Defines safety requirements for the design, installation, operation and abandonment of pipeline systems	Pipeline transport
The Netherlands norm (*Nederlands Norm*, NEN-norm) 17124	Defines quality characteristics of hydrogen fuel dispensed at hydrogen refuelling stations for FCEV	Refuelling
Publication series Dangerous Substances (*Publicatiereeks Gevaarlijke Stoffen*, PGS) 35	Defines guidelines for the safe us of hydrogen installations to supply hydrogen to vehicles	Refuelling

On-going initiatives

Legislation

The Dutch government is currently developing a new Energy Law. It is envisaged that it will replace the existing Gas act (*Gaswet*) and Electricity act 1998 (*Electriciteitswet 1998*), but it does not include a regulatory framework for hydrogen (Rijksoverheid, 2022[8]). In a letter to the House of Representatives in December 2020, the Minister of EZK highlighted several on-going initiatives with regard to the development of hydrogen regulation:

- On-going research into the possibility to use the existing gas infrastructure for hydrogen.
- Exploration regarding the market structure of the hydrogen sector.
- Exploration regarding the assignment of temporary tasks to grid operators to pilot hydrogen transport.
- A legislative proposal to implement the revised EU Directive on guarantees of origin.
- The establishment of a working group on a policy framework for hydrogen safety (Rijksoverheid, 2020[9]).

Since the Minister's letter, progress has been made on a number of topics. In early 2022, the government conducted a public consultation on the market structure for hydrogen (Rijksoverheid, 2022[10]). In mid-2022, it communicated its intentions to ask the state-owned entity responsible for natural gas transport and storage (*Gasunie*) to develop the hydrogen infrastructure – although the exact role of *Gasunie* still needs to be defined (EZK, 2022[11]).

Principles and guidelines

EZK is developing its draft principles on the responsible management of safety and health in the energy transition. These include seven principles that policymaking, licensing, communication and supervision should incorporate:

1. for risks that are quantifiable, authorities should define and monitor the safety and health requirements and additional risk mitigation measures, while regulated entities should justify how they comply;
2. precaution will be applied for risks that are uncertain, where the entities will get a degree of freedom in determining how they would like to meet the precaution requirements;
3. the national government will develop guidelines for cases where existing legislation does not cover all aspects of new applications, and will involve stakeholders in the development of the guidelines;
4. pilot projects should be monitored through the development of a monitoring plan, the sharing of findings and the translation of those findings into legislation and regulation;
5. the government communicates proactively and openly on the social benefits and risks of the energy transition and urges other stakeholders to do the same;
6. the response to incidents should allow the drawing of lessons for the future, through evidence-based research;
7. a clear and balanced division of responsibilities will increase the effectiveness of safety policy; this should involve co-operation around, and solutions to, unexpected policy issues.

EZK developed a first version of two hydrogen safety guidelines (*richtsnoeren*), with more guidelines expected to follow (Netherlands Enterprise Agency, 2022[12]). So far, there is one guideline on general hydrogen safety and a second one on its application to heating in buildings (specifically in relation to four pilot projects). The documents are a response to EZK's commitments to develop a policy framework for hydrogen safety and to develop a temporary policy framework for the safety of hydrogen pilots. While the guidelines are policy documents, they are not official regulations or legislation.

These documents define a number of guiding principles that hydrogen applications should adhere to, including that:

- The application should be at least as safe and healthy as current fossil fuel applications (for hydrogen, these are often natural gas applications), and where there are uncertain risks, precaution should be applied. It is up to the entity to justify how the safety measures result in a sufficient risk reduction.
- Where possible, new applications should be safer and healthier than current fossil fuel applications, but risk reduction above the target should be proportional.
- A comparison with existing reference norms should be made where possible, and where this is not possible, the risk measures should support a sufficient degree of risk management.
- Risk management policy should be based on the best available insights, with new insights swiftly applied.

The safety guidelines refer to the use of hydrogen as a gas, whether or not pressurised. It further provides guidance on different scales of hydrogen application (which can affect the regulations they are subject to), communication on safety risks and monitoring and research of incidents.

Framework for pilots

In 2022, the Authority for Consumers and Markets (*Autoriteit Consument en Markt*, ACM) developed a framework to facilitate pilots for the domestic use of hydrogen. This was done by the regulator to avoid a situation where grid operators and energy retailers need to wait for new legislation before they can pilot domestic hydrogen applications. EZK has indicated that it will develop a policy framework for the safety of hydrogen pilots, and this is expected before the start of the first pilot (ACM, 2022[13]). In addition, the ministry has appointed the State Supervision of Mines (*Staatstoezicht op de* Mijnen, SodM) as the supervisory body to supervise the safety of the pilots (SodM, 2022[14]).

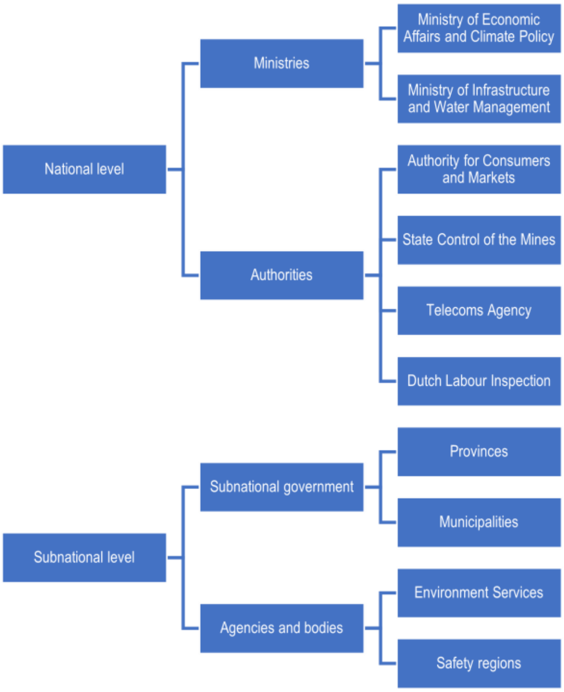
Institutional context

The Netherlands is a unitary state with several layers of government. The national government (*Rijksoverheid*) consists of twelve ministries, each with one or two ministers and one or more secretaries of state that are politically responsible (Rijksoverheid, n.d.[15]). Regional and local governments function in a hierarchy where the regional and local government are subsidiary to the national government. There are twelve provinces (*provincies*) with responsibility for the spatial layout of the province, including aspects such as the location of business parks and the implementation of regional economic policy. There are 344 municipalities,[1] responsible for matters such as the registration of citizens, the provision of social benefits, local subsidies, schools, certain health care provision, the development of zoning plans, local infrastructure and building supervision (Rijksoverheid, 2022[16]) (Ministerie van Binnenlandse Zaken en Koninkrijkrelatiies, n.d.[17]). Provincial and municipal authorities have important functions in physical and environmental planning and licensing, based on regulations laid down by central government (OECD, 2010[18]). The Water Boards (*Waterschappen*) constitute an additional level of government, with responsibilities related to water safety, quality and management (Waterschappen, n.d.[19]).

Institutional context for hydrogen

The application of hydrogen technologies in the Netherlands involves a wide range of stakeholders, resulting in a complex framework of different bodies (Figure 4.1). Responsibilities to direct, supervise and enforce the use of hydrogen are shared among policymakers and authorities across the three tiers of government (national, regional and local level) (Table 4.2).

Figure 4.1. Institutional framework for hydrogen in the Netherlands



EZK is the ministry responsible for the development of economic, energy and climate policy. There is a Minister of Economic Affairs and Climate Policy (in charge of the ministry) as well as a Minister for Climate and Energy (Rijksoverheid, 2022[20]). EZK is responsible for the development of the government's vision and policy on hydrogen, as part of its intended transition to a climate neutral society with environmentally sustainable energy sources. The Ministry of Infrastructure and Water Management (*Ministerie van Infrastructuur en Waterstaat*, I&W) is responsible for policy on the use of hydrogen in transport and hydrogen infrastructure.

Table 4.2. Main actors involved in the Dutch hydrogen sector

Institution	Overall function	Role towards hydrogen
Ministries		
Ministry of Economic Affairs and Climate Policy (*Ministerie van Economische Zaken en* Klimaat, EZK)	Ministry – responsible for economic, energy and climate policy.	Develops the government's vision and policy on hydrogen. Co-ordinates and safeguards the overall coherence of actions within the Climate Agreement, including those related to hydrogen.
Ministry of Infrastructure and Water Management (*Ministerie van Infrastructuur en Waterstaat*, I&W)	Ministry – responsible for infrastructure and management of waterways.	Develops policy on the use of hydrogen in transport and hydrogen infrastructure.
National authorities		
Authority for Consumers and Markets (*Autoriteit Consument en Markt*, ACM)	Independent body – responsible for competition oversight, sector regulation and consumer protection.	Regulates and supervises the energy sector. In absence of legislation on the supply of hydrogen to end users, it developed a framework to facilitate hydrogen pilots by energy system operators and energy retailers (ACM, 2022[13]).
State Supervision of Mines (*Staatstoezicht op de Mijnen*, SodM)	Independent body – responsible for the regulation and supervision of mineral and energy extraction, safety oversight and environmental protection in the energy sector.	Supervises the safety of natural gas network and the quality of the natural gas in networks. SodM is also responsible for the safety supervision for the hydrogen pilots in buildings, which has been granted to the authority as a temporary task (SodM, 2022[21]).
Dutch Labour Inspection (*Nederlandse Arbeidsinspectie*, NLA)	National agency – responsible for inspections of labour conditions.	Conducts occupational safety inspections (SZW, 2021[22]).
Telecom Agency (*Agentschap Telecom*, AT)	National agency – responsible for supervision of the digital resilience of essential services such as energy, the use of metering services and the exchange of information on overground and underground networks to prevent excavation damage.	Supervises the law on information exchange overground and underground networks (*Wet informative-uitwisseling bovengrondse en ondergrondse netten en netwerken*, Wibon) to prevent excavation damage, which will be relevant for the deployment of hydrogen pipelines.
Subnational government		
Provinces (*provincies*)	Regional government – responsible for spatial layout, implementation of regional economic policy, planning, licensing and supervision.	Competent body for the permitting of larger production sites. Holds limited responsibilities for the licensing of hydrogen applications (above five tonnes of storage capacity) (IFV, 2021[23]).
Municipalities (*gemeenten*)	Local government – responsible among other things for the implementation of local policy, government services, subsidies, benefits, planning, licensing and supervision.	Competent bodiy for the permitting of small production sites. Holds broad responsibility for the licensing of hydrogen applications within their authority remit and for the supervision of construction and housing (*Bouw- en woningtoezicht*) (IFV, 2021[23]).
Regional agencies and bodies		

Institution	Overall function	Role towards hydrogen
Environment services (*omgevingsdiensten*, ODs)	Regional agencies – responsible for the environmental licensing, supervision and enforcement in the fields of safety, air, noise, energy, waste and soil, as tasked by municipalities and provinces (Omgevingsdienst NL, n.d.[24]).	Assesses licensing requests and issues licences, as assigned by municipalities or provinces.
Safety regions (*Veiligheidsregio's*, VRs)	Public bodies – responsible for fire prevention and control, disaster and crisis preparedness and management within an area and advice on safety aspects in licensing procedures (Rijksoverheid, n.d.[25]).	Provides advice to subnational governments on safety and emergency aspects in hydrogen licensing procedures.
State-owned entities		
Gasunie	State-owned entity – responsible for the operation of the national gas transmission network in the Netherlands through its subsidiary Gasunie Transport Services B.V (GTS), the transmission system operator (TSO) (Gasunie, 2023[26]).	Involved in the development of a future hydrogen transport network, although its precise role has not yet been determined (EZK, 2022[11]). Gasunie repurposed for the first time a natural gas pipeline to transport hydrogen in 2018 and is planning future pipelines (Gasunie, 2018[27]) (Port of Rotterdam, 2022[28]) and a terminal for the import of green ammonia with a connection to the so-called "hydrogen backbone" (Gasunie, 2022[29]).
Gas distribution system operators (DSOs)	State-owned entities – responsible for the operation of regional and local gas distribution systems.	Conducts pilots on the use of hydrogen by residential users (Netbeheer Nederland, n.d.[30])

Source: (ACM, 2022[13]) (SodM, 2022[21]) (SZW, 2021[22]) (IFV, 2021[23]) (Omgevingsdienst NL, n.d.[24]) (Rijksoverheid, n.d.[25]) (Gasunie, 2023[26]) (EZK, 2022[11]) (Gasunie, 2018[27]) (Port of Rotterdam, 2022[28]) (Netbeheer Nederland, n.d.[30]).

There is a variety of national co-ordination and collaboration platforms on hydrogen in the Netherlands:

- The **roundtable 'Hydrogen and Green Chemistry'** is chaired by EZK and twice a year brings together executives from companies in the energy, chemical and hi-tech sectors, think tanks and universities (NWO, 2020[31]).
- The **H2Platform** functions as a discussion platform between EZK, the Ministry of Infrastructure and Water Management (*Ministerie van Infrastructuur en Waterstaat*, I&W), and companies with hydrogen activities (H2Platform, n.d.[32]).
- **HyDelta**, a national research programme (**HyDelta**) on the implementation of hydrogen (in particular its integration into existing gas infrastructure), brings together grid operators, research institutions and technical experts (HyDelta, n.d.[33]).
- The **Dutch Hydrogen and Fuel Cell Association** (*Nederlandse Waterstof en Brandstofcel Associatie*, NWBA) is an industry association of companies in the hydrogen sector (NWBA, n.d.[34]).
- The **Administrative Forum for a Safe Energy Transition in the Netherlands** (*Bestuurlijk Overleg voor een Veilige Energietransitie in Nederland*, BOVEN) is a working group bringing together local government representatives on the topic of the energy transition (Crisislab, 2021[35]).
- **The Hydrogen Safety Innovation Programme** (*Waterstof veiligheid Innovatie Programma*, WVIP), led by the Dutch Foundation Royal Standards Institute (*Stichting Koninklijk Nederlands Normalisatie Instituut*, NEN) under the H2Platform initiative, brings together industrial parties, ministries, the Institute Physical Safety (*Instituut Fysieke Veiligheid*, IFV), knowledge institutes and local government to develop safety norms (NEN, 2022[36]).
- The **Environment Services NL** platform brings together the 29 regional environment services (*omgevingsdiensten*, Ods) to co-ordinate and share knowledge (Omgevingsdienst NL, n.d.[24]).

- The **Safety Council** (Veiligheidsberaad) enables co-ordination between the 25 regional safety regions in the Netherlands (Rijksoverheid, n.d.[25]).

There is substantial co-ordination and collaboration between the Dutch government and international partners, especially across European Union countries:

- Through the **Pentelateral Energy Forum**, the Netherlands co-ordinates on hydrogen issues with the governments of Austria, Belgium, France, Germany, Luxemburg and Switzerland, developing joint political declarations on hydrogen (Rijksoverheid, 2020[37]).
- The Dutch government co-ordinates with the **European Commission** to communicate the Dutch hydrogen position and contribute towards shared standards on sustainability, quality, safety, blending of hydrogen in gas networks, market regulation and innovation stimulation.
- **Important Projects of Common European Interest** (IPCEI) is a European instrument that supports the rollout of projects with an important social value, including hydrogen projects in the Netherlands.
- The **Clean Hydrogen Partnership**[2] is a public-private partnership that contributes to the development of hydrogen technologies by funding research and innovation activities (European Union, 2021[38]).
- The **Joint Research Centre** is the science and knowledge service of the European Commission, carrying out research to provide independent scientific advice and support to EU policy, including in the area of hydrogen research.
- The **Clean Hydrogen Alliance** is a platform that brings together industry, public authorities, civil society and other stakeholders in six working groups or roundtables to discuss the deployment of hydrogen applications (European Commission, 2022[39])
- The **Hydrogen Valley Platform** is a joint initiative by the Clean Hydrogen Joint Undertaking and Mission Innovation, to collaborate and share information on large-scale, flagship hydrogen projects (Hydrogen Valleys, 2022[40]).
- Beyond the EU, the Netherlands also discusses hydrogen developments through international collaborations such as the **International Partnership for Hydrogen and Fuel Cells in the Economy** (IPHE), the **International Energy Agency** (IEA), the **Clean Energy Ministerial**, the **Clean Energy Ministerial Hydrogen Initiative**, the IEA, the **Hydrogen Technology Collaboration Programme** and **Mission Innovation** (Rijksoverheid, 2020[5]) (Clean Energy Ministerial, n.d.[41]) (IEA, n.d.[42]).

Licensing and inspections for hydrogen activities

Licensing

The Dutch government is planning an overhaul of the relevant legislation related to the spatial planning of the living environment through the enactment of an updated Environment and Planning Act (*Omgevingswet*). It is envisaged that this updated act will bundle, modernise and simplify existing procedures and requirements into one overarching act, thereby replacing a range of existing acts. It also creates a digital one-stop shop that should make it easier to apply for permits and start projects. The Law was accepted by Dutch parliament in 2015 and the Senate in 2016, but its implementation has been repeatedly delayed. On 14 October 2022 it was announced that the implementation date had been postponed to 1 July 2023, to allow for further testing of the new digital system (Rijksoverheid, 2022[43]). On 26 January 2023, the Dutch government announced the implementation date was further postponed to 1 January 2024 (Rijksoverheid, 2023[44]). The new Environment and Planning Act will affect the permitting procedures for hydrogen.

Companies that intend to develop any hydrogen activities at a site usually require one or multiple licences that are brought together in the 'environment permit' (*omgevingsvergunning*). These relate to aspects that require licences, such as spatial planning, construction and environmental impact. Hydrogen activities are also earmarked as activities that require a separate licence. For most applications, requirements as part of the licensing application include risk assessments, health and safety requirements, integrated environmental obligations and environmental impact assessments (HyLAW, 2018[45]). Procedures also include an advice by the VR and the enforcement unit within the permit-granting authority. Specific requirements for the different applications of hydrogen are discussed in more detail in Chapter 5.

There are several channels through which hydrogen-based initiatives can get into contact with the authorities, determining the point in time at which authorities first get involved on a project. Hydrogen initiatives can make use of the Environment Desk, which allows them to get into contact with the relevant authorities concerning questions on licensing and to get information on licensing procedures. The Environment Desk is an overarching online portal for all licensing procedures but does not include specific information or checklists for hydrogen initiatives. In other cases, companies may be referred by the municipality.

The authority in charge of issuing permits differs by both regulation and activity. Environment permits are often issued by the local government, based on the "decentralised, unless" (*"decentraal tenzij"*) principle.[3] However, facilities that operate with a large quantity of hazardous substances require a permit from the province (IPLO, n.d.[46]). In certain more exceptional cases, a permit may be needed from the Water Boards (*Waterschappen*) or the national infrastructure agency (*Rijkswaterstaat*), particularly when projects involve surface or ground water or infrastructure (Rijkswaterstaat, n.d.[47]) (Waterschap Rivierenland, n.d.[48]). In the case of a production installation or production site, the licensing authority depends on the amount of hydrogen that is stored:

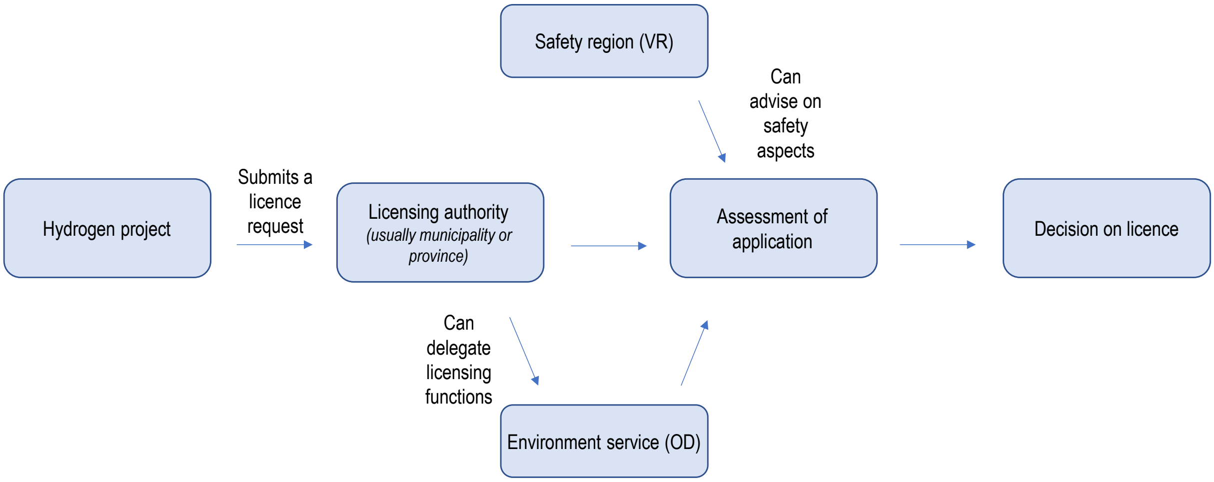
- For installations with quantities of hydrogen storage below five tonnes, the municipality is the relevant authority.
- Installations with quantities of hydrogen storage above five tonnes qualify as Seveso installations, based on EU Directive 2012/18/EU. For such installations, the province is the relevant authority (H2Platform, 2021[49]).

While municipalities and provinces are the relevant authorities, they often assign licensing, inspection and enforcement functions to the Ods (Figure 4.2). However, the exact roles that are delegated to the OD tend to differ across regions and authorities (Omgevingsdienst NL, n.d.[24]). As municipalities and provinces are often not obliged to assign licensing and supervision roles to the ODs, they reserve the right to give guidelines regarding the licensing process (Crisislab, 2021[35]).

Given the absence of an overarching regulatory framework for hydrogen, there is some ambiguity regarding the methods used to assess licensing requests. Ods usually require quantitative risk assessments (QRAs) as part of their licensing procedures, although this may not be necessary in certain cases where the legislation already determines the safety distances for specific activities. Where hydrogen refuelling stations have been granted a licence, this has been done using risk analysis based on a number of sources, including:

- Ministerial memos on calculating risks.
- General requirements from existing legislation such as the Act on general provisions of environmental law (*Wet Algemene bepallingen omgevingsrecht*, Wabo) and the Transport of hazardous substances act (*Wet Vervoer gevaarlijke tiffen*).
- Local and regional expertise and priorities regarding the living environment – taking into account different public interests, such as safety, sustainability, reliability and affordability.

Figure 4.2. Current licensing procedure



Note: While the licensing authority tends to be a municipality or province, in certain cases this may also be another authority, such as the water board or national infrastructure agency. In some cases, a licence request may also be issued directly to the Environment Service (OD), depending on the communication channel used.
Source: Developed by OECD based on available information.

VRs are usually involved in the evaluation of these risk assessments, although this may depend on the agreements on procedures between Ods and VRs. In some cases, VRs are only involved at the later stages of procedures when QRAs are already drawn up. This illustrates that the point in time at which the VR should be consulted may not always be clear or consistent.

The Construction Decree 2012 determines that for buildings not defined as a standard type by the decree – as is the case for hydrogen applications – authorities need to apply a risk-based approach to assess if the application is sufficiently safe. As a guideline to assess the safety, it is sufficient to examine if the safety situation meets the applicable NEN-norms, if these are available. Risks should, in general, not exceed a threshold for the fatality risk of 1 in 100 000 per year for industrial and non-vulnerable objects, and 1 in one million per year for vulnerable objects such as residential buildings and buildings with vulnerable people (EZK, 2022[50]).

Inspection

The organisation that carries out inspections can differ between regulations. There are environment inspections as well as occupational safety inspections by the Dutch Labour Inspectorate (*Nederlandse Arbeidsinspectie*, NLA). For environment inspections, the rule of thumb is that the licence issuing authority is also responsible for inspection and enforcement (InfoMil, n.d.[51]). The VRs are responsible for conducting a stocktake of fire, disaster and crisis risks in their region, as well as the preparations for their management.

Regarding domestic use of hydrogen, there appear to be a number of gaps in terms of appropriate supervision. There is no regional structured overview of hydrogen applications for domestic use, which could make it more difficult for fire fighters to assess domestic hydrogen risks within their area.

Conduciveness of regulatory framework

Overall, the development of new hydrogen applications highlights a number of areas within the Dutch regulatory framework for hydrogen that require further attention. With new modes of hydrogen application appearing, existing arrangements and frameworks may not yet provide for sufficient role clarity.

Furthermore, existing regulatory frameworks may not necessarily be effective at addressing and balancing the specific risks of hydrogen. Safety risks from new applications demonstrate themselves at the local level, whereas climate change risks have a more global impact. As safety risks are usually managed at the local level, there could potentially be a stronger focus on safety risks over climate risks. This may not necessarily lead to optimal overall outcomes, as (by making it more expensive, slower, more difficult to site) it could slow down or reduce the deployment of low-emission hydrogen solutions that can counteract climate change risks.

It is essential that new uses of hydrogen be properly foreseen, enabled, and effectively regulated at the same time. As described in more details elsewhere in the report, technical rules need to be adopted that ensure best practices are used in a systematic way, including through "safe by design" installations whenever they are available. At the same time, planning authorities and regulators need to ensure that new hydrogen technologies and uses are effectively enabled, with requirements that are proportionate to the risks and benefits of these innovations, and regulatory processes that minimize unnecessary burden and delays, but rather focus on the essential risk factors. This involves revising zoning and permitting for new hydrogen applications. Incorporating lessons from practice and research, define zoning rules that enable the development of hydrogen in a safe way, and define permitting processes that are risk-proportionate, particularly for lower-risk facilities and uses – for which high-risk industrial permitting requirements are likely to be disproportionately burdensome. It also involves ensuring adequate safety through fit-for-purpose technical requirements informed by science and practice. Enabling zoning and simplified permitting do not mean lower safety – on the contrary, developing specific requirements covering the higher risk aspects of these new hydrogen applications (as discussed further) can help ensure that best practices and techniques are more systematically applied.

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Notes

[1] Number of municipalities as of 24 March 2022.

[2] The Clean Hydrogen Partnership is the successor to the Fuel Cells and Hydrogen Joint Undertaking (European Union, 2021[38]).

[3] The "decentralised, unless" principle states that in principle, tasks and competences are carried out by municipalities and water boards, unless i) a provincial or national interest cannot effectively be managed by a municipal government or ii) this is required for an effective execution of tasks and competences on the basis of the law or the execution of an international commitment (IPLO, n.d.[46]).

5

Hydrogen applications in practice

This chapter provides information on six main scenarios along the hydrogen value chain from production to usage. For each scenario, the chapter discusses i) the current state of play, ii) safety risks and measures and iii) regulation and regulatory delivery.

The energy transition is transforming the hydrogen landscape by spurring new ways of producing, transporting and using hydrogen. While countries currently mainly use hydrogen from fossil fuels in industrial processes, wider and "greener" hydrogen applications with larger-scale electrolyser production using renewable energy sources are foreseen in the future (IEA, 2021[1]).

While there are many ways in which hydrogen can be applied, this chapter focuses on six main scenarios covering the entire hydrogen value chain. These scenarios are based on hydrogen applications that could support the Dutch climate targets. For each scenario, the report discusses current practice and regulation and zooms in on specific situations with a higher level of risk.

Findings on safety risks, measures and regulation are based on other outputs from the project on Precaution in the Energy Transition and Improved Knowledge for Hydrogen Risk Regulation. These outputs have been included as separate Parts to the current report.

The scenarios included in the report cover different parts of the hydrogen lifecycle from production to usage and have been selected at the request of the Dutch Ministry of Economic Affairs and Climate Policy. They are of particular interest as they cover use of hydrogen technology in densely populated areas requiring safety and risk management techniques. The six scenarios are:

1. Production through water electrolysis
2. Pipeline transport
3. Road transport
4. Mobility and partially confined spaces: tunnels
5. Mobility and partially confined spaces: hydrogen refuelling stations
6. Domestic use

Not all these cases have the same degree of technological maturity, and domestic use is really at a pilot stage only right now. Several cases, however, are well known and understood, present risks that are readily manageable with good practices, and are generally not higher (or lower) than their closest comparable "hydrocarbon fuel" competitors. Nonetheless, they often are subject to more constraining regulations than the said "hydrocarbon competitors", because of not having a specific regulatory framework (ending up regulated as high-risk industrial processes) and in some cases no provision in zoning.

In this context, governments and regulators should identify hydrogen innovations that are a priority for scaling up, and present difficulties in the existing zoning and permitting frameworks. This should lead, where needed, to revisions of zoning and permitting for selected hydrogen applications. Incorporating lessons from practice and research should allow to define zoning rules that enable the development of hydrogen in a safe way, and define permitting processes that are risk-proportionate, particularly for lower-risk facilities and uses – for which high-risk industrial permitting requirements are likely to be disproportionately burdensome.

As the level of knowledge on safety varies for different hydrogen technologies, it makes sense to regulate them differently. When scientific knowledge is more limited and risks are not obvious or simply unknown, additional pilots could be carried out to improve scientific knowledge. Hydrogen technologies can be divided into three broad categories, based on the level of existing knowledge and scientific research:

- **Category 1 – Mature technologies on which there is extensive scientific knowledge and data on safety**, such as hydrogen production through electrolysis (in particular alkaline and PEM) and hydrogen refuelling stations. These technologies often do not require additional caution compared with conventional fuels because of the accumulation of operational experience relating to risk management within the technology, and can be facilitated and managed using existing risk management approaches and findings from recent research and good practices;

- **Category 2 – Technologies for which a significant level of scientific knowledge exists but additional practical risk data may be needed**, such as driving hydrogen-powered vehicles through tunnels and blending of hydrogen in gas networks. These technologies can be handled through risk management approaches using available scientific knowledge and experience with comparable technologies. However, they will require additional regulatory scrutiny and oversight, using iterative approaches, as scientific knowledge and technology advance;
- **Category 3 – Technologies for which risks are not yet completely understood**, such as the domestic use of hydrogen, because the technology is in its infancy or not currently widely deployed and as such there is a lack of standardisation of design and operation. These technologies require further investigation and research through pilot projects, to more reliably assess risks, identify suitable policy approaches, define regulatory requirements, and build public awareness.

Scenario 1 – Production through water electrolysis

This scenario focuses on low-emission hydrogen derived from water electrolysis. This production method is given a prominent role in the hydrogen ambitions of many countries, as — when produced with low-carbon electricity — it allows them to produce hydrogen in a way that supports net zero targets. In particular, the scenario looks at the safety considerations of a hydrogen leakage from pipes connected to electrolysers.

Hydrogen production can be onsite or offsite, depending on the distance to external hydrogen sources and the available transport infrastructure, among other factors. Onsite production can be more suitable for hydrogen consumption without nearby hydrogen sources, whereas offsite production generally involves larger scale production delivered through tube trailers, liquid hydrogen trucks or hydrogen pipelines (Tian et al., 2021[2]).

Hydrogen produced by water electrolysis using low-carbon electricity features prominently in many hydrogen strategies, as it is the main method of producing hydrogen in a way that aligns with green ambitions. However, it currently represents only a small part of hydrogen production; the majority is produced from natural gas and coal (see section on Status quo and future trends in hydrogen use worldwide in Chapter 2).

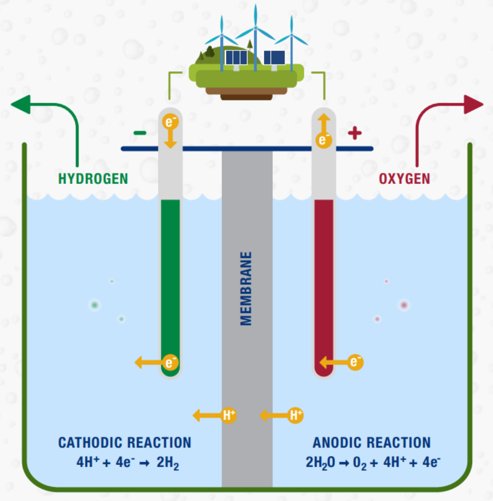
Because hydrogen can be cheaply produced with steam methane reforming, electrolysis has been mostly applied on a smaller scale (around 1 MW), although in recent years production capacities have increased in response to a drive towards green hydrogen. Most large-scale electrolysis plants were built for the chemical industry (e.g., ammonia production) between the 1920s and 1980s, using alkaline electrolyser technology. (Krishnan et al., 2020[3]). Other electrolyser technologies, including proton exchange membrane (PEM) and solid oxide electrolyser cell (SOEC), are gaining market traction due to their increased flexibility (IRENA, 2018[4]) (Hu et al., 2022[5]) (Sebbahi et al., 2022[6]). PEM technology have more recently shown significant cost reductions, with costs now approaching the costs of alkaline technologies, and are increasing its share in overall installed electrolyser capacity (IEA, 2022[7]). Self-pressurising electrolysers (i.e., operating at pressure) can produce hydrogen at a higher pressure, which can avoid the cost of an additional stage of mechanical compression (Hancke, Holm and Ulleberg, 2022[8]). Hydrogen is typically delivered at 30 bar, although pressure in storage systems and compressors is higher (350 to 700 bar).

In general, an electrolyser production unit consists of the following elements:

- An electrical power source, along with power electronics
- An electrolyser stack, that uses electricity to split water (H_2O) into oxygen (O_2) and hydrogen gas (H_2) (Figure 5.1).

- An external compressor that increases the hydrogen pressure to reduce its volume (for electrolysers other than self-pressuring electrolysers).
- Pipelines to transport the hydrogen gas for onsite use and/or temporarily stored within pressure cylinders with subsequent use onsite or at another location (Zarei, Khan and Yazdi, 2021[9]).

Figure 5.1. How a water electrolyser works



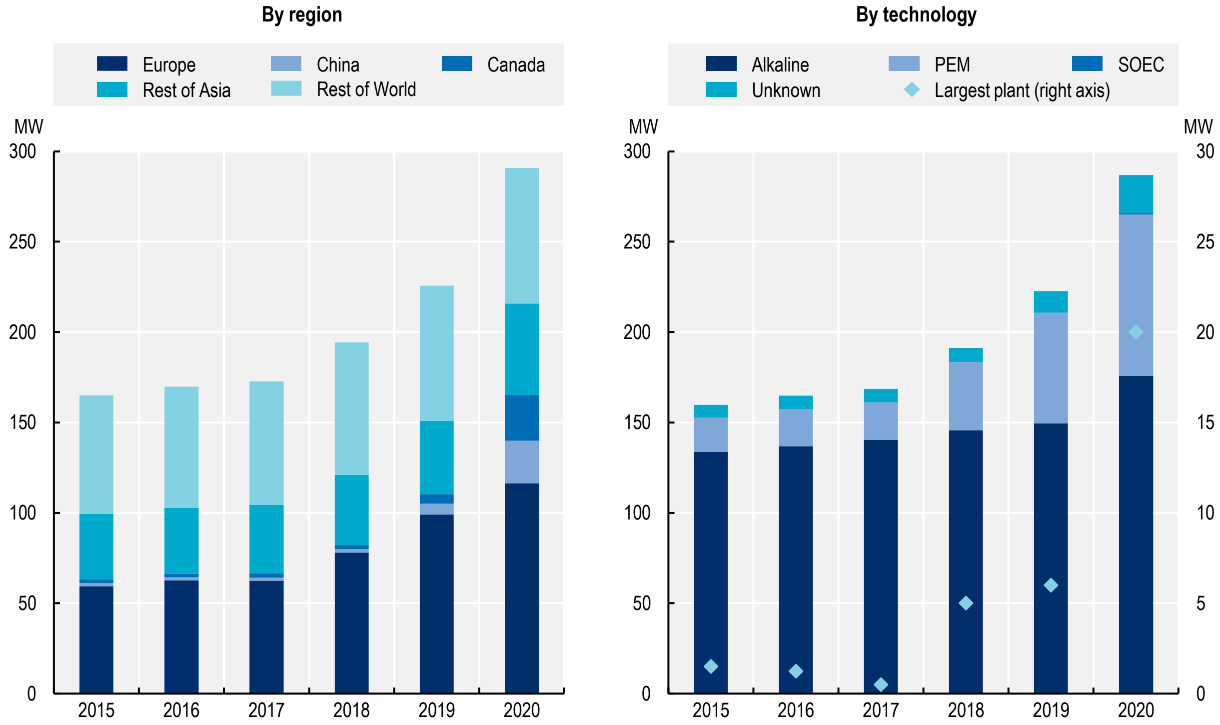
Note: The application of water electrolysers within the energy transition relies of their ability produce low-emission hydrogen using renewable electricity or other low-carbon sources such as nuclear electricity.
Source: Iberdrola (n.d.), Green hydrogen: an alternative that reduces emissions and cares for our planet, https://www.iberdrola.com/sustainability/green-hydrogen.

State of play

Water electrolysis accounted for roughly 0.03% of hydrogen production for energy and chemical feedstocks in 2021, but this share is expected to increase significantly. The total global electrolyser capacity in 2020 was 290 Megawatt (MW), with roughly 40% located in the EU[1] (Figure 5.2). The total installed capacity increased to over 500 MW in 2021 and was expected to increase to over 1 300 MW by 2022 (IEA, 2022[10]). Alkaline electrolysers accounted for almost 70% of global electrolyser capacity, followed by one quarter for PEM. Production by SOEC and anion exchange membrane (AEM) electrolysis only accounts for a marginal share of overall production. The company Sunfire has recently finished the construction of a 2.6 MW SOEC electrolyser in the Netherlands – the largest SOEC electrolyser in the world (IEA, 2022[7]) (Sunfire, 2023[11]).

Production by electrolysis needs to rapidly increase its share of overall hydrogen production to realise hydrogen's potential in the fight against the climate crisis and get on track with IEA's Net Zero by 2050 scenario. Hydrogen production through electrolysis is taking place at an increasingly large scale, with the largest production site reaching a 150 MW capacity and starting operation in 2021 (IEA, 2022[10]). By 2030, total electrolysis capacity could increase to 134-240 GW based on capacity under construction or planned (although this includes a significant share of projects at earlier stages of planning without a final decision).[2] Alkaline electrolysis continues to feature more predominantly in new hydrogen production projects due to its lower costs, although new research is driving significant cost reductions especially for PEM (IEA, 2022[7]).

Figure 5.2. Global installed electrolysis capacity by region and technology, 2015-2020



Source: (IEA, 2021[1]), Global Hydrogen Review 2021, https://www.iea.org/reports/global-hydrogen-review-2021.

To support the scaling up of hydrogen production, many countries are developing new projects with larger-scale production sites, which may reduce unit costs for low-emission hydrogen. Although these larger-scale production sites can use various raw material sources to produce hydrogen, many put a strong focus on the development of low-emission hydrogen with larger electrolysers. For example, the United Kingdom is expecting to develop a 60 MW hydrogen production capacity through electrolysis by 2025 (BP, 2021[12]). China holds a significant share of hydrogen production through electrolysis, with a 150 MW electrolyser that became operational in 2021 and a new 260 MW electrolyser expected in 2023 (Upstream, 2022[13]). In the Netherlands, a number of larger-scale electrolyser projects are also envisaged, such as the H2.50 project developing a 250 MW capacity electrolyser (expected to become operational by 2025) (IEA, 2021[1]).

Within Europe, Germany is the largest producer of hydrogen by electrolysis, with 33 installations out of the total 114 installations in Europe. France has the second-largest number of installations (23), although most of these have a relatively low production capacity. The Netherlands had four electrolysis production installations in 2020. With a significant planned deployment of new electrolyser capacity in 2021, total European electrolysis capacity was expected to increase to 136 MW in 2021 (FCHO, 2022[14]). The Clean Hydrogen Monitor 2022 estimated the operational electrolysis production capacity in Europe in August 2022 at 162 MW (Revolve, 2022[15]).

In 2021, (blue) hydrogen production with carbon capture, utilisation and storage (CCUS) accounted for 0.7% of total hydrogen production (IEA, 2022[10]). This type of hydrogen often features less prominently in the ambitions for a net zero 2050 because it still relies on fossil fuels to produce hydrogen. However, it is considered by countries in certain cases to reduce carbon emissions especially in the medium term, such as through the retrofitting of existing fossil-based hydrogen production plants (European Commission, 2020[16]). In 2021, the IEA reported 40 projects for producing hydrogen with CCUS that were under development at that time. Of these, 19 were in Europe, predominantly in the Netherlands and the United Kingdom.

The Netherlands is taking significant steps to increase its production of blue hydrogen. It recently committed EUR 2 billion to fund the Portus project in the Port of Rotterdam, which will store 2.5 megatons of CO_2 annually, with a significant share coming from hydrogen production (Porthos, 2022[17]). Moreover, two projects with blue hydrogen production are already operational in the EU, one of which is at the Pernis refinery in Rotterdam (with CCUS expected from 2024). In December 2022, the Netherlands also announced the funding of seven projects for the production of hydrogen through electrolysis, for a total additional capacity of 1 150 MW (Rijksoverheid, 2022[18]).

Given the large ambitions for hydrogen production through water electrolysis, there will be a need for a robust and conducive regulatory framework that can facilitate them. A particular challenge will be to ensure risks are managed effectively – but not excessively – through clear direction and guidelines. An up-to-date overview of scientific knowledge on the risks and measures and experience from other countries facing similar challenges will be crucial.

Safety risks and measures

Not all components at a hydrogen electrolysis production site are equally prone to the risk of failures. The typical events that could result in a hydrogen leak during production are mechanical failure of components such as compressors or pipework, overpressure in one of the components, corrosion or damage due to impact, and human error such as an accidental opening of valves.

Research suggests that current hydrogen production presents a lower normalised[3] fatality risk as compared to the production of oil, coal and natural gas (see Part 4 – Review on incident database and lessons learnt) (Brook et al., 2014[19]). Risk analyses on hydrogen production show that most causes of accidents (and therefore the likelihood of harmful consequences) can be either eliminated or reduced by following recommended safety measures, such as safety valves, leakage detectors, fire walls, “spark-free” components and the siting of facilities at a safe distance from vulnerable populations (Zarei, Khan and Yazdi, 2021[9]) (Kasai et al., 2016[20]) (Schefer et al., 2009[21]).

Key factors in the likely occurrence of an explosion or other hydrogen accident such as a fire are the gas concentration in air, as well as the degree of confinement of the released flammable gas. The flammable mixture that is created by a high pressure leak (at 350 bar)extends to three times the distance than that of a low pressure (at 30 bar) release. Flammable mixtures around stoichiometric composition (~30% vol. hydrogen-air mixture) are more hazardous due to their higher burning velocities. However, they are limited to a smaller area around the leak, even with high pressure releases. Higher degrees of congestion can also lead to increased risks of explosion.

The main causes of hydrogen accidents at installations are typical of the type and range seen in conventional hydrocarbon-based industry sectors (see Part 4 – Review on incident database and lessons learnt).[4] The component most prone to failure in the past is the hydrogen pipework, often related to a valve failure. However, the frequency of pipeline failures decreased with the introduction of modern valve design and safety regulation, and pipework accidents are less likely to have fatal consequences than in the past. The hydrogen compressor has the highest ratio of number of deaths to number of accidents, followed by accidents in storage. Looking at the root causes of accidents, the most frequent cause was equipment failure, followed by deficiencies in procedures leading to human error. This emphasises the importance of guidance on the expected lifespan of critical components such as safety valves.

The databases, as well as findings in scientific literature, confirm that the compressors and high-pressure storage vessels are the major risk contributors, whereas the risks associated with the electrolyser itself are relatively small in comparison (Pan et al., 2016[22]) (FCH 2 JU, 2020[23]). Flash fires caused by a rupture to a stationary high-pressure storage vessel can lead to harm over a wider distance of tens of metres, placing the compressor and storage systems at higher risk than other components.

Calculations by Sandia National Laboratories (based on historical hydrogen data for compressors, cylinders, hoses, joints, pipes and valves) showed that the leaking frequency of connecting pipes (between 2.99×10^{-9} m^{-1} $year^{-1}$ for very small leakage and 3.13×10^{-10} m^{-1} $year^{-1}$ for rupture at 95% confidence level) falls within the acceptable range set by Purple book – a guideline for quantitative risk assessment (QRA) in the Netherlands (Glover, Baird and Brooks, 2020[24]).

Annex Box 1.A.1 presents the safety measures that can be considered to decrease the risks related to hydrogen production through electrolysis. Risk measures should be decided upon based on desired risk targets and taking into account countervailing risks (see Chapter 1 – "Managing risks").

Regulation and regulatory delivery

In the Netherlands

There is no hydrogen-specific safety regulation for hydrogen production in the Netherlands. A hydrogen production site in the Netherlands is considered as a standard chemical manufacturing facility for licensing and safety regulation purposes. This treatment does not differ depending on whether the hydrogen is produced through electrolysis with alkaline, PEM, or SOEC, or through natural gas reforming (HyLAW, 2018[25]). Hydrogen production and storage is also governed by European Commission directives on chemical processes involving emissions,[5] including the Seveso Directive.

There is no distinction in licensing procedures between fossil fuels and greener forms of hydrogen production, or between onsite or offsite production. Furthermore, there is no simplified process whereby the procedures laid down in the Act on the general provisions environmental law (the so-called "Wabo-procedure" — *Wet Algemene bepallingen omgevingsrecht*, Wabo) are further defined according to the scale or type of production or scale (HyLAW, 2018[25]). This could slow down the rollout of smaller-scale, onsite low-emission hydrogen production, such as that linked to hydrogen refuelling stations, as they will face the same procedures as larger producers (see Part II – "Regulatory review").

The authority in charge of licensing, safety inspections and enforcement may differ depending on the scale of production (or more specifically, the storage capacity). The province is the responsible authority for installations with quantities of hydrogen storage above five tonnes. In other cases, the municipality is the responsible authority. In general, the authority in charge of licensing will also be responsible for inspections and enforcement. Moreover, the respective authority can assign to the ODs the tasks to issue licences, inspect and enforce (see Chapter 4 – "Licensing and inspections for hydrogen activities").

In general, as part of the process to apply for land use and environment permits, hydrogen production plants need to adhere to the following requirements:

- Conducting risk assessments in line with the Brzo 2015 decree (the implementation of the Seveso-III Directive in Dutch legislation)[6] and the Bevi decree.
- Meeting health and safety requirements (in line with the EU Equipment Directive intended for use in explosive atmospheres (Appareils destinés à être utilisés en Atmosphères Explosibles, ATEX) and other relevant legal codes).
- Aligning with integrated environmental obligations (following from the EU IED Directive).
- Conducting environmental impact assessments and strategic environmental assessments (based on the EU EIA and SEA Directives) (HyLAW, 2018[25]).

Other countries

There are differences across countries in the way in which hydrogen is regulated, and in particular, whether rules are specifically tailored to hydrogen. As a somewhat more mature and well-developed technology, hydrogen production via electrolysis is often subject to a more advanced regulatory framework than some of the other scenarios. In China and Korea, codes and standards on hydrogen are in force, whereas in many other countries the requirements for hydrogen production follow general regulations for flammable gasses. Moreover, for jurisdictions such as the EU and Japan, hydrogen requirements differ according to the storage capacity rather than the production capacity. A few highlights:

- China has legally binding standards for the safe design and maintenance of hydrogen production stations. The relate to restrictions on maximum allowable storage capacity, operational conditions, safety equipment, technical specifications of pipework and safety requirements, such as the minimum ventilation rate, separation and safety distances, etc..
- In the EU, notification of the regulatory authority is required for production or storage of more than five tonnes based on the Seveso Directive (Lexparency, 2008[26]). There is a requirement to draw up a written safety policy for the prevention of hazardous accidents. Storage greater than 50 tonnes requires a safety report and emergency plan to be prepared, submitted to and assessed by the competent authority.
- In Japan, the requirements for hydrogen production facilities are set under the regulation of high-pressure gas facilities.
- Korea has developed codes that cover most of the requirements for hydrogen production and storage facilities.
- In the United States, hydrogen production facilities are governed by Occupational Safety and Health Administration’s (OSHA) standards and the National Fire Protection Association’s NFPA-2 standard which, among other issues, define safety and separation distances as well as requirements for safety systems.

Hydrogen production through water electrolysis is, in many cases, regulated under the more general regulatory requirements for flammable gases. Going forward, the increasing scale at which this technology is expected to be applied may prompt countries to review existing requirements, to assess if they will facilitate the expected rapid increase in electrolysis production. This could create a need for more specific guidelines, standardisation, and risk management good practices to support its smooth deployment.

A further discussion of regulatory practices of hydrogen production across countries is presented in Part 2 – “Regulatory review”.

International standards

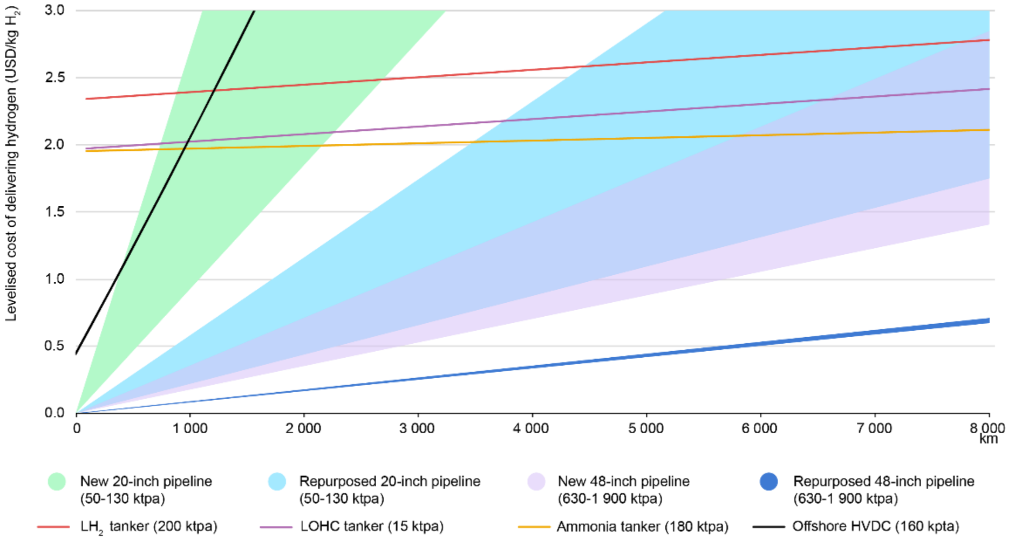
The international standard ISO 22734:2019 has been developed to cover construction, safety and performance requirements for hydrogen gas generation appliances, i.e. electrolysing water to produce hydrogen. The standard applies to electrolysers for industrial and commercial use, and indoor and outdoor residential use in sheltered areas (such as garages, utility rooms and similar residential locations).

Scenario 2 – Pipeline transport

The current scenario focuses on the transport of compressed gaseous hydrogen through high-pressure pipelines.

Hydrogen can be transported in gaseous form by pipelines in cases where there is a sufficiently large, sustainable and localised demand (IEA, 2019[27]). Analysis by the IEA shows that transporting gaseous hydrogen by pipeline can often be a cost-efficient option for a wide range of distances, depending on pipeline capacity and whether it is a new or repurposed pipeline (Figure 5.3) (IEA, 2022[10]). Recent research in the area suggests pipeline transport may even be, under certain conditions, the most cost-efficient option for distances up to 10 000 kilometres (Perey and Mulder, 2023[28]). For longer distances, transport of hydrogen as a liquid or converted into ammonia may be more attractive due to the higher energy densities per volume for these substances (IEA, 2021[1]).

Figure 5.3. Estimated transport cost per unit for different options, 2030



Note: ktpa = kilotonnes per year; LH_2 = liquefied hydrogen; LOHC = liquid organic hydrogen carrier. Includes conversion, export terminal, shipping, import terminal, storage costs at the port and reconversion costs for each carrier system (LH2, LOHC and ammonia); HVDC = high-voltage direct current electricity transmission.
Source: (IEA, 2022[10]), Global Hydrogen Review 2022, https://www.iea.org/reports/global-hydrogen-review-2022.

Historically, carbon steel or stainless-steel pipelines have been used for high-pressure hydrogen transmission. This is because higher grades of steel (above 100 ksi[7]) can more easily lead to hydrogen embrittlement of pipelines (IEA, 2021[1]). Hydrogen embrittlement is due to the technical properties of hydrogen gas (see Chapter 2 – "Understanding and managing hydrogen risk").

Transport of hydrogen by pipeline is a mature technology, which was first employed in the Rhine-Ruhr area in Germany in 1938. Pipelines can be newly-built or repurposed or retrofitted[8] natural gas pipelines (IEA, 2022[10]). Similar to the construction of natural gas pipelines, constructing hydrogen pipelines is capital-intensive and requires long-term investments with high upfront costs.

Investment costs of newly-built hydrogen infrastructure tend to be higher than for natural gas. At similar pipeline diameters, the IEA estimates that capital expenditure for hydrogen-specific steel pipelines can be 10 to 50% higher (IEA, 2021[1]). Additionally, the same amount of energy transported requires a higher volume of hydrogen gas as compared with natural gas (by a factor three). This is due to the low energy density by volume of hydrogen (see Chapter 2 – "Understanding and managing hydrogen risk") (IEA, 2019[27]).

However, costs can be reduced by repurposing existing natural gas infrastructure. The HyWay27 project estimates that reusing natural gas pipelines is four times more cost-effective than constructing new hydrogen pipelines (HyWay27, 2021[29]).[9] The suitability of gas infrastructure to be repurposed as hydrogen pipelines will depend on the type of steel used in the pipeline and the purity of hydrogen being transported (where higher concentrations of hydrogen may lead to embrittlement of pipelines) (see Scenario 6 – Domestic use) (IEA, 2019[27]).

State of play

In 2021, roughly 5 000 kilometres of hydrogen pipeline were in operation worldwide, compared with roughly 3 million kilometres of natural gas pipeline (IEA, 2019[27]). More than 90% of total hydrogen infrastructure is in Europe and the United States.[10] The current infrastructure is mostly made up of closed systems owned by large hydrogen producers within or near industrial sites with chemical plants or oil refineries (IEA, 2021[30]).

Repurposing of natural gas pipelines is a relatively new trend, where earlier hydrogen pipelines are mostly newly built or converted pipelines originally for other fuels. In the 1970s and 1990s, pipelines for crude oil and related products were repurposed to transport hydrogen. Gasunie in the Netherlands was the first to repurpose a natural gas pipeline for hydrogen transport with a total length of 8 kilometres, put into commercial service in 2018 (IEA, 2021[30]). Similar repurposing projects with longer hydrogen pipelines are envisaged in other countries such as Germany and Australia (IEA, 2021[1])

A consortium of 31 European infrastructure operators, the European Hydrogen Backbone (EHB) initiative, aims to roll out a trans-European hydrogen grid (EHB, 2022[31]). Its 2020 proposal envisages 39 700 kilometres of hydrogen pipeline across 21 countries by 2040. The initiative foresees a significant role for the repurposing of natural gas infrastructure to reduce cost and make new use of existing infrastructure, with 69% of the envisaged network consisting of repurposed gas pipelines compared with 31% newly built (IEA, 2021[30]).

Two studies from 2017 and 2018 indicate that the existing Dutch natural gas infrastructure could be used to transmit hydrogen with certain modifications (DNV, 2017[32]) (Netbeheer Nederland, 2018[33]). The studies argue that the pipeline grades used in the Netherlands are suitable for hydrogen transport. As the utilisation of the Dutch natural gas transmission network decreases as natural gas is substituted by other energy forms, otherwise “stranded assets” may be converted to hydrogen pipelines. Many countries report on-going pilots to determine the impact of hydrogen on different gas pipeline materials, including in subsea transmission.

Hydrogen may also be injected into existing natural gas infrastructure as a blend with natural gas. Research on the impact of blending hydrogen into natural gas pipelines is still at an early stage, with further evidence needed on the performance and durability of pipelines for different levels of blends and required maintenance activities. There is an increasing scientific interest to understand the impact of different blends of hydrogen on different pipeline materials, including so-called “killed” steels that improve the toughness of steel pipelines (EIGA, 2004[34]).

Safety risks and measures

The main risk related to hydrogen transport by pipeline is the possibility of hydrogen leakage and subsequent ignition. Leakage can occur either through failure of flanged pipe joints or due to damage to pipelines such as corrosion or due to impact. An incident with hydrogen leakage can have several consequences including fire, explosions or unignited releases. The exact risk level and consequence depends on factors including the type of failure, hole size, pipeline pressure, ignition probability, time to ignition, meteorological conditions, pipeline condition and soil type (for buried pipelines. The successful operation of safety systems will also be a factor.[11]

New hydrogen transmission pipelines are usually buried underground. This can support the safety and reliability of hydrogen transport and protect against accidental damage and frost. However, their underground location means there is also a requirement for pipeline protection against excavation accidents, the impact of shifting soil and heavy loads imposed on the soil due to heavy-duty vehicles or equipment.

The properties of hydrogen gas in comparison with natural gas affect its risk profile, where its relative risk depends on the context in which it is released. Hydrogen is lighter than air or natural gas and its volume leakage from pipelines is generally approximately 1.3 to 2.8 times larger than methane leakage (Rigas and Amyotte, 2013[35]). For underground hydrogen releases, the pipe depth, release orientation and soil properties will determine whether a crater is formed due to the release pressure and how quickly the hydrogen disperses. Due to its properties, in the case of leakage, hydrogen diffuses more quickly in air compared with natural gas. Moreover, for the same mass flow, hydrogen leaks are greater in volume flow than those of natural gas. The subsequent risk depends on the level of hydrogen concentration built up following an incident. For hydrogen concentrations in air below 10% vol., hydrogen has a minimum ignition energy similar to that of natural gas and its combustion results in hardly any overpressure. For concentrations above 10% vol., hydrogen presents a greater risk as it is more likely to deflagrate with the pressure building up faster.

An analysis of incident data shows a slightly lower normalised[12] incident rate for hydrogen compared with natural gas, although this value could change once hydrogen pipelines become more widespread (see Incident database report). Reported incidents in incident databases equate to 0.09 incidents per 1 000 km of pipeline per year, compared with 0.13 (Europe) to 0.16 (United States) incidents for natural gas. However, this value is based on relatively few reported incidents for hydrogen, as its transport through pipelines is still limited. As hydrogen pipeline networks will grow, this will provide for additional data to assess the exact incident rate more accurately.

A comparative (theoretical) risk study of hydrogen and methane in pipelines found that, in the case of immediate ignition of a hydrogen leak, the increase in expected risks for hydrogen is negligible when compared to methane (see Part 7 – Quantitative risk assessment: Hydrogen versus conventional fuel). However, the modelling did not consider cases of delayed ignition and showed that assumptions on the ignition probability have an important impact on results, both of which should be explored further.

The types of hydrogen incident are typical of those hazards observed with other major pipelines such as natural gas or liquid hydrocarbons. The reported root causes of hydrogen incidents include design errors, human error, inadequate maintenance and deficiencies in procedures. Most incidents resulted in hydrogen fires, with others resulting in explosions or the unignited release of hydrogen.

Annex Box 1.A.2. presents the safety measures that can be considered to decrease the risks related to hydrogen transport by pipeline. Risk measures should be decided upon based on desired risk targets while taking into account countervailing risks (see Chapter 1 – Managing risks).

Regulation and regulatory delivery

In the Netherlands

The Dutch government has not yet developed an overarching regulatory framework for high-pressure hydrogen transport through pipelines in the Netherlands, as it awaits a broader EU directive first (EZK, 2021[36]). However, the Decree external safety pipelines (Bevb) applies also for hydrogen. Within this framework the National Institute for Public Health and the Environment (*Rijksinstituut voor Volksgezondheid en Milieu*, RIVM) did provide advice on the failure frequency of hydrogen pipelines and the preferred calculation method to assess the risk of hydrogen pipelines (RIVM, 2021[37]).

On 15 December 2021, the European Commission adopted a legislative proposal to update the 2009 EU Gas Regulation that includes a legislative framework for hydrogen networks (European Commission, 2021[38]). The proposal aims to support "the development of a cost-effective, cross-border hydrogen infrastructure and competitive hydrogen market".

To achieve this, it proposes a number of rules for hydrogen networks and markets. These span:

- Tariffs for the transmission and distribution of hydrogen by system operators will be approved by a regulatory authority.
- Ownership unbundling for hydrogen network operators.
- Regulated third party access to hydrogen networks.
- A transition period until 31 December 2030, until which existing private hydrogen networks may be exempt from certain access requirements.[13]

The existing legal framework in the Netherlands already offers certain opportunities for infrastructure companies to develop hydrogen infrastructure, as was done by Gasunie in 2018 (see State of play) (EZK, 2021[36]). The envisaged new Energy Act specifies that infrastructure companies can be involved in activities including the development and maintenance of hydrogen networks, the transport of hydrogen and metering activities. However, it does not allow system operators, or the holding companies to which they belong, to produce, trade or supply hydrogen (as is also the case for their involvement with electricity and gas) (EZK, 2021[39]).

Hydrogen pipelines do not require a specific licence. However, developers and operators of larger hydrogen pipelines[14] need to comply with the Decree on the external safety pipelines (*Besluit externe veiligheid buisleidingen*, Bevb). Among other things, this decree requires operators of hydrogen pipelines to implement a safety management system. The construction or replacement of pipelines is only allowed when it is aligned with the zoning plan or an environment permit has been issued, so as to prevent major accidents or disproportional risks to vulnerable people or buildings. The local risk[15] (*plaatsgebonden risico*) for vulnerable objects in the proximity a of pipeline shall not exceed a set threshold of 10^{-6} (or one in a million) per year. Moreover, the pipeline operator is required to construct or replace the pipeline in such a way that the local risk does not exceed the 10^{-6} per year threshold at a distance of five meters from the heart of the pipeline.[16] Additionally, the Bevb also defines the criteria and thresholds for the group risk.[17] Acceptance criteria for hydrogen pipelines are similar to those for natural gas pipelines.

Other countries

There is no common approach across countries as to how hydrogen pipelines are regulated:

- In some countries, such as Australia and Germany, regulations have been amended to allow hydrogen to be transmitted though existing pipelines. In Australia, injection of up to 10% hydrogen into natural gas pipelines has been allowed, whereas in Germany an ordinance was passed to allow operators to use existing natural gas infrastructure for hydrogen.
- In the UK, hydrogen transport through pipelines requires permission and must adhere to pipeline requirements for design, safety systems, construction, installation, operation, maintenance, and decommissioning as well as to industry codes such as the Pipeline Safety Regulations Act of 1996.
- In Japan, even though the transport of hydrogen is limited to short-distance uses, there are safety regulations for the pipe layout and pipe materials. However, many of them are still being verified.
- In the United States, regulations for flammable gases in hydrogen pipelines are applied. The American Society of Mechanical Engineers (ASME) provides standards for piping and transportation pipelines. Requirements for piping in gaseous and liquid hydrogen service, and for pipelines in gaseous hydrogen service can be found in the ASME B31.12 Standard on Hydrogen Piping and Pipelines. This standard covers the requirements for materials, brazing, welding, heat treating, forming, testing, inspection, examination, operating and maintenance.
- China has developed a national code that sets general requirements for pipelines.

A further discussion of regulatory practice across different countries for hydrogen transport by pipeline is presented in Part II – “Regulatory review”.

Scenario 3 – Road transport

This scenario involves the transport of hydrogen by road. This includes both hydrogen-powered vehicles (such as FCEVs) and vehicles transporting a hydrogen cargo that is not intended as fuel for the vehicle itself.[18] For ease of reference, the latter will be referred to as ‘vehicles transporting hydrogen’, although technically hydrogen-powered vehicles also transport hydrogen but with the distinction that this serves only for the consumption by the vehicle itself. The scenario looks in particular at the presence of hydrogen in road transport within built-up areas – including the potential for incidents such as hydrogen leakage in parking garages and road accidents.

Vehicles transporting hydrogen

In the absence of pipelines or onsite production, hydrogen can be transported by road, supplying hydrogen from production sites to consumption sites such as industrial users and hydrogen refuelling stations. Transport by road includes the transport of hydrogen in gas tanks, metallic cylinders, tubes or composite vessels. Hydrogen may be transported as a compressed gas or as liquid[19] (IEA, 2019[27]).

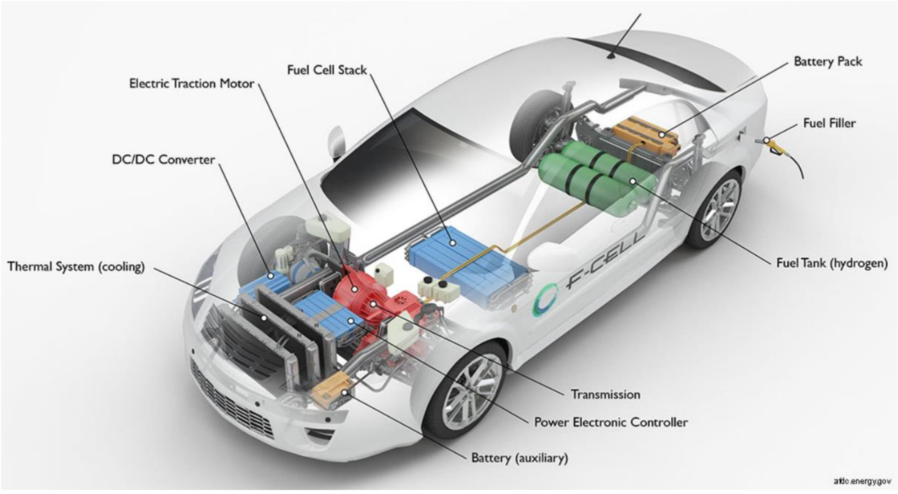
Transporting hydrogen as a liquid has certain advantages over gaseous hydrogen especially for longer-distance transport, as a liquid tanker truck is able to hold larger quantities of hydrogen than gaseous tube trailers can. The liquefaction involves cooling hydrogen to temperatures as low as minus 253 degrees Celsius. However, hydrogen liquefaction is a process that is energy intensive, consuming as much as 30% of the hydrogen’s energy content when using current technologies (US Department of Energy, n.d.[40]).

Hydrogen-powered vehicles

Hydrogen-powered vehicles can be passenger cars, as well as medium to heavy-duty vehicles such as buses, commercial vehicles and trucks.

FCEVs use a fuel cell (or “fuel cell stack”) to produce electricity (Figure 5.4). Hydrogen is stored in a fuel tank – usually as a compressed gas for more efficient storage[20] – and is converted in the fuel cell into electricity and water.[21] The electricity is then used to power the motor. This can be used in combination with a battery pack, which smooths out the power delivered from the fuel cell, recaptures braking energy and provides extra power for acceleration. (US Department of Energy, n.d.[41]). The most common type of fuel cell for FCEVs is the PEM fuel cell (US Department of Energy, n.d.[42]).

Figure 5.4. Example of an FCEV passenger car and its components



Source: (US Department of Energy, n.d.[41]).

State of play

Vehicles transporting hydrogen

Most local distribution of hydrogen currently takes places by trucks carrying hydrogen gas (IEA, 2019[27]). However, there is no information available on the exact volume of hydrogen transported by road in the Netherlands, Europe or worldwide.

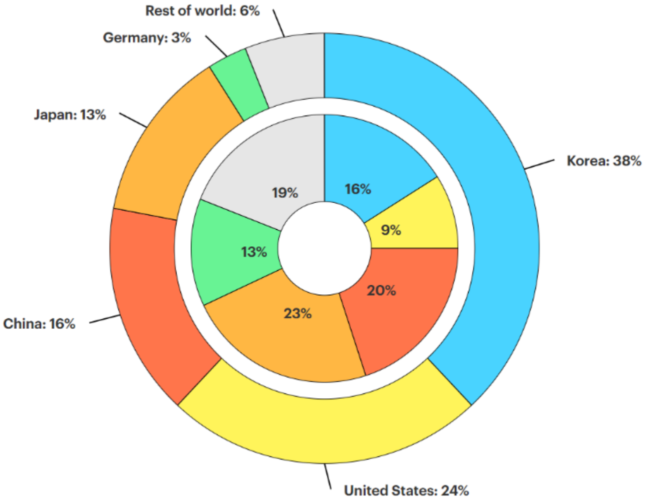
Hydrogen-powered vehicles

Hydrogen-fuelled vehicles still makes up only a small share of the transport sector, but the number of hydrogen-powered vehicles has experienced significant growth levels recently. In 2020, FCEVs made up less than 0.01% of total road vehicles worldwide and 0.3% of total electric vehicles. However, the number of FCEVs grew at an average annual rate of 70% over the period from 2017 to 2020 and there were 51 600 FCEVs on the road in 2021, as well as 730 hydrogen refuelling stations (Figure 5.5). Due to substantial subsidies to increase the adoption of FCEVs, Korea is the largest stockholder globally when it comes to the number of vehicles, although Japan has the largest network of public refuelling stations.

Regional priorities in FCEV deployment differ. Efforts to increase the use of FCEVs focus mostly on passenger cars in Korea, Japan and the United States, whereas China and Europe focus more medium- and heavy-duty commercial vehicles such as buses and trucks. China has the largest fleet of both fuel cell buses and trucks, with a total of more than 8 400 vehicles (or 90% of fuel cell buses and 95% of fuel cell trucks worldwide) (IEA, 2022[43]). Countries are also increasingly showing an interest in using hydrogen in other non-road transport, with plans and pilots for the use of hydrogen in trains, trams, ferries, ships and aviation (IEA, 2021[30]).

Figure 5.5. Number of FCEVs and hydrogen refuelling stations worldwide, 2021

Outer circle represents 51 600 FCEVs, inner circle represents 730 hydrogen refuelling stations



Source: (IEA, 2022[44]), *Fuel cell electric vehicle stock and hydrogen refuelling stations by region, 2021*, https://www.iea.org/data-and-statistics/charts/fuel-cell-electric-vehicle-stock-and-hydrogen-refuelling-stations-by-region-2021.

The total FCEV fleet in Europe in March 2022 consists of 4 050 vehicles, of which roughly a third was deployed in Germany. The Netherlands held the third largest fleet with around 550 vehicles (FCHO, 2022[45]).

Current numbers of FCEVs across the world are still far from ambitions for the future. The IEA Net Zero by 2050 Scenario will require a large increase in the number of vehicles, from the current number of 51 600 in 2021 to 15 million vehicles by 2030 (see Chapter 2 – “Future trends”).

Safety risks and measures

Incidents with hydrogen-powered vehicles and vehicles transporting hydrogen can be caused by the leakage of hydrogen from tanks or cylinders. Such leaks can be due to equipment failure, inadequate maintenance of components, tank ruptures, corrosion or the release of hydrogen through a pressure relief device. In many cases, incidents are caused by external factors such as traffic accidents.

The risks related to hydrogen leakage in transport depend on the level of confinement in which accidents occur. Hydrogen is less likely to cause a fire or explosion in open or well-ventilated spaces, where it can disperse more easily. Within covered and poorly ventilated spaces, hydrogen concentrations can — due to the gas’ buoyant nature — build up close to the ceiling. Natural or mechanical ventilation can reduce the level of hydrogen concentration and thereby reduce the risk of fires or explosions. Therefore, the safety of hydrogen vehicles in confined spaces, such as parking garages, maintenance workshops and covered refuelling stations, may be especially relevant, making an urgent case for efficient ventilation.

In total, 71 incidents were reported in the HIAD 2.0 and H2tools incident databases (see Part 4 – Review on incident database and lessons learnt). Fifty-three incidents (or 75%) involved vehicles transporting hydrogen, whereas 18 involved hydrogen-powered vehicles. The causes of such accidents are relatively comparable to those for liquefied petroleum gas (LPG) vehicles. Forty-two per cent of incidents were caused by traffic accidents, whereas equipment failure was the cause in 15% of cases. Other less frequent causes include design error, human error, inadequate maintenance, deficiencies in procedures and external factors.[22]

Consequences of incidents differ between hydrogen-powered vehicles and vehicles transporting hydrogen. For vehicles transporting hydrogen, 53 incidents were reported, of which 58% resulted in no or only an unignited release, whereas 28% resulted in a fire and 13% in an explosion. For hydrogen-powered vehicles, 18 incidents were reported, of which 17 resulted in no or only an unignited release and only one resulted in a fire. (It should be noted, however, that most of these hydrogen-powered vehicles were busses in use as part of a pilot project. As a result, minor incidents were reported that may not have been reported otherwise). Looking forward, the deployment of hydrogen in road transport is projected to increase, providing additional data as to the causes and consequences of accidents.

In Japan, a comparison between LPG and hydrogen-powered vehicles shows a somewhat higher risk for hydrogen-powered vehicles (see Part 4 – Review on incident database and lessons learnt). Evidence on traffic incidents for both vehicle types shows an incident probability for hydrogen-powered vehicles of 0.0026% per vehicle per year (i.e. 1 in every 38 461 vehicles being involved in an accident each year). At the same time, it found an incident probability of 0.0003% (i.e. 1 in every 333 333 LPG vehicles being involved in an accident). However, these probabilities may not yet be very precise, given the low overall number of FCEVs currently in operation. Nonetheless, causes of accidents for both vehicles were comparable, and a further rollout of FCEV will likely provide further insights into the exact probability of accidents and allow more meaningful comparisons.

Annex Box 1.A.3 presents the safety measures that can be considered to decrease the risks related to hydrogen transport by road. Risk measures should be decided upon based on desired risk targets while taking into account countervailing risks (see Chapter 1 – Managing risks).

Regulation and regulatory delivery

In the Netherlands

Vehicles transporting hydrogen

The regulation of vehicles transporting hydrogen in the Netherlands is in accordance with the Carriage of Dangerous Goods by Road Regulation (ADR) from 1957 under the auspices of the United Nations Economic Commission for Europe (UNECE). The ADR is an international regulation that regulates the transportation of hydrogen in cylinders, tubes, trailers and tank vehicles. It specifies packaging types, load security, the classification and labelling of dangerous goods, and the training of drivers. The Economic and Social Council Committee of Experts on the Transport of Dangerous Goods, organised by the UNECE, develops and updates safety provisions for the transport of hydrogen by all modes of transport. These provisions are included in the UN Model Regulations on the Transport of Dangerous Goods. The ADR is frequently revised, with a new edition that came into force on 1 January 2023 (UNECE, 2022[46]).

The municipality is charged with a number of licensing functions regarding vehicles transporting hydrogen. Vehicles transporting hydrogen require an exemption to transport hydrogen across roads other than those designated by authorities for the transport of dangerous substances, as well as for loading and unloading purposes. This exemption can be requested from the municipality (Rijksoverheid, 2015[47]). Additionally, staging areas for tube trailers require an environment permit from the municipality.

Hydrogen-powered vehicles

Hydrogen-powered vehicles are not subject to the ADR Regulation, which exempts the carriages of "gases contained in the fuel tanks or cylinders of a vehicle performing a transport operation and destined for its propulsion or for the operation of any of its equipment used or intended for use during carriage" (UNECE, 2022[46]). There are no specific regulations, codes and standards for hydrogen-powered mobility. The parking of hydrogen-powered vehicles in parking garages is currently not subject to the Publication Series Dangerous Substances Guideline PGS26 (H2Platform, 2020[48]).

Other countries

Most countries currently apply regulations that were developed for other flammable gases in their regulation of vehicles transporting hydrogen. Countries in Europe apply the ADR, ensuring consistency between the Dutch and European systems. Australia applies the Dangerous Goods Safety (Road and Rail Transport of Non-explosives) Regulations of 2007 and the Australian Dangerous Goods Code. Training of transport company employees on the associated risks of these goods is obligatory in France.

International standards

The Global Technical Regulation (GTR) No. 13 defines vehicle requirements for hydrogen FCEVs, including equivalent (or higher) levels of safety as those required for conventional, fuel-powered vehicles. It includes specifications on the allowable hydrogen levels within vehicle enclosures during in-use and post-crash conditions and on the allowable hydrogen emissions levels of vehicle exhaust during certain modes of normal operation. GTR can be applied globally; however, the regulatory bodies in each country decide its incorporation into national regulations.

The International standard ISO 11623 provides requirements for the periodic inspection of certain composite transportable gas cylinders (ISO, 2015[49]).

Scenario 4 – Mobility and partially confined spaces: tunnels

This scenario involves the transport of hydrogen by road through tunnels. In particular, it looks at situations where traffic accidents may lead to hydrogen releases in tunnels, and the corresponding risks. An example of this scenario would be a hydrogen bus driving through a tunnel and being involved in a collision.

The transport of hydrogen by road through tunnels includes two distinct categories: hydrogen-powered vehicles and vehicles transporting hydrogen (see Scenario 3 – Road transport). Both categories involve vehicles that carry an amount of hydrogen that might be released inside the tunnel in the case of a traffic accident or an involuntarily leak due to a mechanical malfunction or human error. For the current scenario, these, categories are referred to together as hydrogen vehicles.

State of play

At present, there are no available figures on the volume of hydrogen transported by road through tunnels, although volumes are expected to be relatively modest given the current level of hydrogen deployment in road transport (see Scenario 3 – Road transport). However, as ambitious targets for the hydrogen transition and its deployment in transport are set by many countries, the use of hydrogen vehicles is expected to increase (see Status quo and future trends in hydrogen use worldwide in Chapter 2). In turn, this will likely increase the number of hydrogen vehicles using tunnels in the future.

Safety risks and measures

Hydrogen vehicles can pose different levels of risk in enclosed environments such as tunnels, due to the properties of hydrogen and the high levels of confinement. In the open air, hydrogen releases will disperse quickly due to the low weight of hydrogen. However, in tunnels and other closed spaces, accidental leaks of hydrogen from vehicles can be trapped or accumulate below the ceiling or in cavities, leading to the build-up of higher hydrogen concentrations. Therefore, particular attention should be paid to the safe use of hydrogen vehicles in tunnels.

The risks associated with accidents involving hydrogen vehicles inside tunnels depend on several conditions, including whether hydrogen is leaked, the volume of hydrogen being released, the presence of any ignition source, the shape and length of the tunnel, the presence of effective tunnel ventilation and other prevention and mitigation systems, and the properties of the vehicle's thermal pressure relief device and tank. In a scenario with thermal pressure relief device (TPRD) activation, an immediate ignition poses fewer hazards compared to a delayed ignition. Where hydrogen releases are severe and unignited, the high level of confinement in tunnels may result in overpressures that can maintain their strength for long distances (Venetsanos et al., 2008[50]). Where concentration levels are sufficiently high, they could result in explosions in the presence of an ignition source.

While hydrogen may pose different risks in tunnel environments, a risk assessment by LaFleur et al. (2017) and Ehrhart et al. (2019) shows that the most likely outcome of a FCEV crash inside a tunnel is that there will be no additional hazard due to the hydrogen fuel – with a probability of 98.1-99.9% (see Literature review report) (LaFleur et al., 2017[51]) (Ehrhart et al., 2019[52]). In cases where the hydrogen does ignite, the most likely consequence, with a probability of 0.03-1.8%, is a jet flame from the pressure relief device.

Existing research identifies how exact tunnel conditions can impact the risks of accidents with FCEVs in tunnels, with on-going research expected to shed further light on these consequences. A number of existing studies indicate that the worst-case scenario for a hydrogen-powered bus accident would involve the release of the entire hydrogen volume, followed by ignition when the maximum flammable volume inside the tunnel is achieved, resulting in unacceptably high levels of overpressure (Venetsanos et al., 2008[50]) (Middha and Hansen, 2009[53]). However, more realistic scenarios woud involve lower levels of harm that correspond to the eardrum rupture threshold and moderate building damage (or less). Other research also highlights how the use of protective measures – in particular thermal pressure relief devices, ventilation, or leak detection with safety shutdown – can reduce risks related to hydrogen accidents in tunnels.

The preliminary results of a quantitative risk assessment provide some insights into the comparative risks associated with hydrogen and methane city bus accidents in tunnels, as categorised by different types of accident. In the case of an accident involving a jet fire from a thermal pressure relief device with immediate ignition, the study showed that the incident frequency (events per year) and hazard distances are higher for hydrogen, as compared with methane. Similarly, in the case of a catastrophic tank rupture, the study observed a similar profile for both hydrogen and methane but a higher individual risk and hazard distances for hydrogen.

Further research into hydrogen accidents in tunnels will support a deeper understanding of risks and the safe application of hydrogen vehicles in tunnels. One promising project that has improved the understanding of risks for hydrogen vehicles in tunnels is the HyTunnel-CS project. This project, funded by the Clean Hydrogen Partnership, conducted pre-normative research on the safe use of hydrogen-driven vehicles and transport through tunnels and confined spaces and provides a set of safety recommendations (HyTunnel, 2022[54]).

Annex Box 1.A.4 presents the safety measures that can be considered to decrease the risks related to hydrogen vehicles in tunnels. Risk measures should be decided upon based on desired risk targets while taking into account countervailing risks (see Chapter 1 – Managing risks).

Regulation and regulatory delivery

In the Netherlands

Access to tunnels for vehicles transporting hydrogen in cylinders, tubes, trailers and tank vehicles in the Netherlands is restricted by the ADR regulation (see Vehicles transporting hydrogen). Restrictions on tunnel access are based on the assumption that there are three main hazards that could lead to victims or serious damage in tunnels: explosions, releases of toxic gas or volatile toxic liquid, and fires. As a consequence, vehicles carrying dangerous goods that are expected to pose a higher risk in terms of these three hazards face stronger restrictions (UNECE, 2022[46]). The regulation uses a classification of road tunnels that includes five classes:

Table 5.1. Classification of tunnels according to the ADR regulation

Class	Restrictions on carrying dangerous goods
A	No restrictions for the carriage of dangerous goods
B	Restriction for the carriage of dangerous goods which may lead to a very large explosion
C	Restriction for the carriage of dangerous goods which may lead to a very large explosion, a large explosion or a large toxic release
D	Restriction for the carriage of dangerous goods which may lead to a very large explosion, to a large explosion, to a large toxic release or to a large fire
E	Restriction for the carriage of all dangerous goods, except those excluded in Chapter 3.2 of the ADR

Source: (UNECE, 2022[46]), ADR – Volume I, applicable as from 1 January 2023, https://unece.org/sites/default/files/2023-01/ADR2023_Vol1e.pdf.

Vehicles transporting hydrogen in tanks are allowed to enter tunnels with a class A classification, but cannot enter those tunnels classified as B, C, D or E. In practice, this means that hydrogen in tanks can only be delivered through five tunnels in the Netherlands.[23] Such transport is expected to follow the obligatory Hazmat routing in order to avoid water tunnels. Similar restrictions apply to the transport of LPG by road – but, of course, LPG does not present the climate benefits that low-emission hydrogen has (UNECE, 2022[46]).

There is no comprehensive framework regulating the access of hydrogen-powered vehicles to tunnels, as the ADR agreement does not apply to the transport of hydrogen in fuel tanks used to power the vehicle. For this reason, hydrogen-powered vehicles are currently allowed to enter all tunnels in the Netherlands.

Other countries

The regulation of access to tunnels for vehicles transporting hydrogen in the Netherlands is aligned with other European countries, which also regulate tunnel access based on the ADR regulation. The ADR regulation specifies the restrictions for hydrogen, in compressed and liquid form, and as a mixture with methane. It therefore does not require further amendments to incorporate new hydrogen applications in road transport.

Outside Europe, countries often apply more general national regulations developed for flammable gases to the transport of hydrogen through tunnels. For example, in Japan, vehicles carrying explosive or flammable dangerous goods are prohibited or restricted from entering long tunnels over five kilometres long, as well as underwater and waterfront tunnels.

Similar to the case in the Netherlands, there are, in general, no specific restrictions on hydrogen-powered vehicles entering tunnels in the other countries that were analysed.

International standards

There are currently no international standards on the access of vehicles transporting hydrogen and hydrogen-powered vehicles to tunnels. However, for FCEVs specifically, the Global Technical Regulation No. 13 includes specifications for the safe design of vehicles (see Scenario 3 – Road transport), which can reduce the risks involved with using FCEVs in tunnels.

Scenario 5 – Mobility and partially confined spaces: refuelling stations

The potential of hydrogen in road transport relies on the availability of an infrastructure to refuel FCEVs. Similar to the case for the rollout of battery-powered electric vehicles, this will require a network of hydrogen refuelling stations at the national and international level to allow sufficient mobility for users of FCEVs.

Hydrogen refuelling stations can operate with liquid hydrogen or compressed (gaseous) hydrogen. Unlike the case for battery-powered electric vehicles, hydrogen refuelling may take around as much time as refuelling with conventional fuels. However, supplying refuelling stations may require more time and labour than for conventional fuels (IEA, 2019[27]).

Although the exact configuration and design of a hydrogen refuelling station may differ depending on the regulations, capacity and type of hydrogen, it may consist of the following components (Haskel, n.d.[55]) (Iberdrola, n.d.[56]):

- An electrolyser, if hydrogen is produced onsite (see Scenario 1 – Production through water electrolysis).
- Storage tanks of intermediate pressure.
- A compressor, to increase the pressure of hydrogen for dispensing.
- High-pressure buffer storage tanks (in cascade) to store the available hydrogen before dispensing.
- A cooling system, to remove excess heat from the compression process and cool the hydrogen for dispensing.

- A hydrogen dispenser to supply the hydrogen to FCEVs.

Investment costs for hydrogen refuelling stations may depend on the pressure and capacity, and the country's safety and licensing requirements. The two largest cost components are the station's compressor (up to 60% of total costs) and the storage tanks (IEA, 2019[27]). Required station capacities will depend on the number of FCEVs as well as the types of vehicles being refuelled (passenger vehicle, buses or trucks).

There are strong economies of scale in terms of the capacity of hydrogen refuelling stations. Increasing the capacity of a station from 50 to 500 kilograms of hydrogen per day could cut costs per kilogram by three quarters. For stations with hydrogen at a pressure of 350 bar, investment costs are estimated in the range of 0.15 to 1.6 million USD, whereas at 700 bar investment costs are estimated within the range of USD 0.6 to 2 million. The lower end of these ranges applies for stations with a lower capacity (50 kg of hydrogen per day) and the higher end for stations with a higher capacity (1 300 kg per day) (IEA, 2019[27]).

State of play

In 2021, 730 hydrogen refuelling stations worldwide were in operation, to supply a total of 51 600 FCEVs (see Figure 5.5). Japan holds the largest share of the total number of stations (23%), followed by China (20%) and Korea (16%). Between 2020 and 2021, the global number of hydrogen refuelling stations increased by 35% (IEA, 2022[43]).

Within Europe, Germany has the largest network of public hydrogen refuelling stations and the largest number of FCEVs, while deployment in the Netherlands is rising. The total number of hydrogen refuelling stations in Europe by March 2022 was 170. At that date, Germany had 90 public hydrogen refuelling stations in operation, making up 53% of the total number of public stations in Europe. The Netherlands had ten stations in operation, which translates to a 100% increase since 2020 (FCHO, 2022[45]).

Deployment of hydrogen refuelling stations is still far from future goals (see Scenario 3 – Road transport). The potential of FCEVs as a road transport alternative relies on a robust refuelling infrastructure. This therefore creates a need for a rapid scaling up of available refuelling stations to support the envisaged increase in FCEVs worldwide.

Within Europe, the current number of 170 refuelling stations in Europe is still some way off from the international network of refuelling stations as envisaged by the European Commission (European Commission, 2020[16]). The European Commission therefore plans for a strong increase in the number of hydrogen refuelling stations in the EU. At present, hydrogen refuelling stations exist mainly in only a few European member states and are usually not suitable for heavy-duty vehicles such as trucks, thereby limiting the possibility for using hydrogen in heavy-duty transport. To improve this situation, the Commission drafted a proposal for a revised directive on an Alternative Fuels Infrastructure, which would require all publicly accessible stations to serve gaseous hydrogen at 700 bar, with a minimum number of stations also serving liquid hydrogen. The 2014 version of the directive already envisaged one hydrogen refuelling station every 400 kilometres along the Trans-European Transport Network (TEN-T) by 2025. The new proposal outlines plans for one hydrogen station serving compressed hydrogen every 150 kilometres along the network by the end of 2030 and one station that serves liquid hydrogen every 450 kilometres (European Commission, 2021[57]). Furthermore, In March 2023, the European Parliament and the Council reached a political agreement to increase the number of publicly accessible electric recharging and hydrogen refuelling stations. The agreement defines that hydrogen refuelling infrastructures, which can serve both cars and trucks, are to be installed from 2030 in all urban nodes and every 200 km along the core TEN-T network (European Commission, 2023[58]).

Safety risks measures

The risks of hydrogen refuelling stations depend on a number of factors, including whether production and compression is onsite, the amount of hydrogen stored onsite, the type of hydrogen (liquid or compressed gas), the facility layout, equipment and the population density in the area surrounding the station. Risks are therefore likely to differ between individual refuelling stations, which will affect the need for specific safety measures.

The literature identifies a number of elements that contribute to the particular risks of hydrogen refuelling stations. Pan et al. (2016) identified the compressor as the main risk contributor of all the elements that make up a refuelling station, whereas Khalil (2017) noted that a small leakage from a compressor is associated with unacceptable risks (Pan et al., 2016[59]) (Khalil, 2017[60]).

For hydrogen refuelling stations with onsite production, Tchouvelev et. al showed that production through water electrolysis presents a lower individual and societal risk than production through methane reforming (Dash, Chakraborty and Elangovan, 2023[61]). A comparative risk assessment conducted by (Yoo et al., 2021[62]) indicated that hydrogen refuelling stations that supply liquefied hydrogen have a lower risk than those that supply gaseous (compressed) hydrogen, but with only small differences (Yoo et al., 2021[62]).

Historical data on accidents related to hydrogen refuelling stations show that most accidents at stations have only minor consequences. Data from accident databases include a total number of 25 accidents. A majority (56%) resulted in no release of hydrogen, whereas in another 24% of cases the accident led to an unignited release. Five accidents (or 20% of all accidents) resulted in more serious consequences, where the hydrogen release resulted in a fire or explosion (see Incident database report).

Most incidents at hydrogen refuelling stations are due to equipment failure, especially the malfunction of the dispenser or compressor. The dispenser-related accidents are usually due to flexible hose failures. However, accidents caused by equipment failure often do not result in a hydrogen leak. Other accidents in accident databases have been caused by deficiencies in procedures, design errors, inadequate maintenance or human error by FCEV users. Most of the cases of hydrogen leakage occurred at joint sections in the installations and were due to inadequate torque or sealing. A Japanese study found that hydrogen leakage was often caused by screw joints, highlighting how the use of welded joints may reduce hydrogen leakage (Sakamoto et al., 2016[63]).

A first comparison of accident rates for hydrogen refuelling stations found that, in their current state, these stations may be considered slightly safer than LPG stations. This comparison, using historical incident data, found a normalised accident rate of 1.19×10^{-7} per time of refuelling a hydrogen-powered vehicle (or one in every 8 million times of refuelling) against an accident rate of 2.52×10^{-7} (or one in every 4 million times of refuelling) per time of refuelling an LPG-powered vehicle (see Incident database report). However, it should be noted that the number of hydrogen refuelling stations at the moment is still relatively low, which can affect the accuracy of these estimates based on historical accident data.

A first quantitative risk assessment comparing the risks between hydrogen and compressed natural gas (CNG) found a lower average individual risk for hydrogen refuelling stations than for CNG stations (see summary QRA 5). For hydrogen refuelling stations, risks are expected to be lower for stations with production via electrolyser onsite than those stations with a supply by pipeline or tube trailer. For both gases, the risk was lower for continuous supply via gas pipeline than for discontinuous supply via tube trailer.

Annex Box 1.A.5 presents the safety measures that can be considered to decrease the risks related to hydrogen refuelling stations. Risk measures should be decided upon based on desired risk targets while taking into account countervailing risks (see Chapter 1 – Managing risks).

Regulation and regulatory delivery

In the Netherlands

The regulation of hydrogen refuelling stations in the Netherlands is governed by a number of documents:

- The Decree Quality Living environment (*Besluit Kwaliteit Leefomgeving*, Bkl) defines certain safety distances for hydrogen refuelling stations, in particular the “fire attention zone” and “explosion attention zone” (Staatsblad, 2018[64]).
  - The Publication series Dangerous Substances (*Publicatiereeks Gevaarlijke Stoffen*, PGS) 35 defines the guidelines for the safe use of hydrogen installations supplying gaseous hydrogen at a maximum pressure of 700 bar to vehicles (PGS, 2021[65]). The guidelines can be used by licensing authorities, ODs and inspections as a reference framework (IFV, 2019[66]);
  - The Netherlands norm (*Nederlands Norm*, NEN-norm) 17124 defines the quality characteristics of gaseous hydrogen fuel dispensed at hydrogen refuelling stations for FCEVs (NEN, 2022[67]).
  - The Act on general provisions environmental law (*Wet Algemene bepallingen omgevingsrecht*, Wabo) and the Decree environment law (*Besluit omgevingsrecht*) define the rules regarding the environment permit (Rijksoverheid, 2023[68]).
  - The Spatial planning act defines rules regarding the spatial planning requirements for hydrogen refuelling stations (Rijksoverheid, 2021[69]).

The development of a hydrogen station in the Netherlands requires an environment permit, which brings together one or multiple licenses related to spatial planning, construction and environmental impact (see Chapter 4 – “Licensing”). Hydrogen refuelling stations often do not align with prevailing land use plans, as these plans do not consider the possibility of using hydrogen as a fuel. A quantitative risk assessment will need to be developed as part of this procedure, to inform the licensing process. For a hydrogen filling station, a “Wabo” environmental permit must be applied for in all cases and usually also a building permit.

Existing norms and guidelines can be used as a basis for the licensing process, although these mainly focus on the supply of gaseous hydrogen to FCEVs. The scope of the PGS 35 guideline is limited to those stations supplying gaseous hydrogen at a pressure not higher than 700 bar, although it considers the delivery of hydrogen to these stations in both gaseous and liquid condition. The guideline focuses on occupational, environmental and fire safety aspects for installations and related equipment, and defines potential risks, scenarios and safety measures (PGS, 2021[65]). A similar standard for hydrogen refuelling stations supplying liquid hydrogen is currently lacking. A second PGS guideline (PGS 38) on multifuel stations is currently in consultation. This includes stations supplying both gaseous hydrogen and other fuels, but excludes stations supplying liquid hydrogen (PGS, 2023[70]).

The Decree Quality Living environment defines safety distances for hydrogen refuelling stations, based on an analysis of risk and effect distances for hydrogen refuelling stations by the RIVM. In line with the PGS 35 guideline, this analysis identifies three types of hydrogen delivery to refuelling stations: (1) in gaseous condition via pipeline or local production; (2) in gaseous condition via tube or cylinder trailer and (3) in liquid condition via tank truck. In all the three cases, the hydrogen that is supplied to FCEVs is in gaseous condition. The analysis defines safety distances based a set of risk scenarios (RIVM, 2016[71]).

At the time the decree was written, only gaseous hydrogen was supplied by hydrogen refuelling stations in the Netherlands, and stations supplying liquid hydrogen were not expected in the coming years. Therefore, the decree does not include safety distances for the supply of liquid hydrogen. The decree notes the following safety distances (Staatsblad, 2018[64]):

- The distances for the local risk[24] are set at:
  - 30 metres from the storage unit, for stations where the hydrogen is delivered to the refuelling station via pipeline or is produced onsite.

  - 35 metres from the point of dispensing for stations where the hydrogen is delivered via tank trucks.
- The distances for the fire attention zone (*brandaandachtsgebied*)[25] are set at 55 metres from the storage unit.

Other countries

There are significant differences between the countries analysed in the extent to which hydrogen refuelling stations are subject to a comprehensive regulatory framework:

- In the EU and Australia, in the absence of solid regulatory frameworks for hydrogen refuelling stations, national and international standards or codes are often used as a reference. In other cases, hydrogen refuelling stations are sometimes considered a par with LPG and liquefied natural gas (LNG) stations.
- Japan, China and the United States have regulations in place for hydrogen stations and their equipment (dispensers, compressors and storage) used for the supply of both compressed and liquid hydrogen.
  - Japan and China have regulations that indicate the technical specifications for materials and equipment They also include prevention and mitigation measures, detailed safety distances from site boundaries and different components of the stations, vulnerable objects, as well as oxygen facilities.
  - The state of California, has developed a comprehensive set of rules for hydrogen refuelling stations, including requirements for dispensing systems and approved equipment (cylinder, containers, tanks, pressure relief devices, hoses, compressors, hydrogen generators, dispensers, detection systems, electrical equipment and others). The NFPA-2 standard defines among other things the separation distances for hydrogen refuelling stations, as well as other fundamental safeguards for the generation, installation, piping, use and handling of hydrogen.
- Korea developed codes with technical standards for hydrogen refuelling stations.

International standards

The international standard ISO 19880-1:2020 covers the technical specifications for public and non-public fuelling stations that supply gaseous hydrogen to light-duty vehicles (but does not apply to stations supplying liquid hydrogen or hydrogen to heavy-duty vehicles). The standard includes the minimum design, installation, commissioning operation, inspection and maintenance requirements for station safety and performance. The standard also applies to:

- fuelling stations for motorcycles, fork-lift trucks, trams, trains, fluvial and marine applications
- fuelling stations with indoor dispensing
- residential applications to fuel land vehicles
- mobile fuelling stations
- non-public demonstration fuelling stations (ISO, 2020[72])."

Scenario 6 – Domestic use

This scenario looks at the use of hydrogen in residential and other buildings, mainly for heating and cooking purposes. The discussion of this scenario will also consider the use of existing distribution networks to transport hydrogen blends or pure hydrogen to households. The safety and appropriateness of existing household appliances to run on hydrogen is outside the scope of this scenario.

The potential of hydrogen use in buildings depends on several factors, including the existence of a natural gas infrastructure, other energy needs within the building, energy efficiency and safety concerns (IEA, 2019[27]) (IEA, 2021[1]). As the use of natural gas for heating and cooking in buildings is expected to decrease, the use of hydrogen can be an alternative to electricity-based solutions such as heat pumps and electric stoves. This may be especially the case for those situations where heat has to be provided to existing (older) buildings where a gas infrastructure already exists and other green solutions are less feasible. In those cases, local low-emission hydrogen applications could support the decarbonisation of the domestic use of energy. In other cases, the co-existence of hydrogen and other heat technologies can add flexibility in colder climates to cover peak demand if heat pumps cannot meet the heating demand (IEA, 2021[1]).

While hydrogen provides a green alternative to existing heating solutions, its prospects in the heating of buildings at present remain limited to specific contexts. This is in part due to the green alternatives that are already available, in particular photovoltaic (PV) powered heat pumps. These heat pumps operate at a higher efficiency and do not face the same energy losses that result from converting hydrogen. As such, they require five to six times less electricity than a boiler running on hydrogen produced through electrolysis to deliver the same amount of heating (IEA, 2021[1]). Other challenges to the use of hydrogen in buildings relate to safety concerns and consumer acceptance (IEA, 2019[27]). For these reasons, it remains controversial whether low-emission hydrogen will be able to play a significant role in the future of building heating (Weidner and Guillén-Gosálbez, 2023[73]).

Technologies for the use of hydrogen in buildings include hydrogen boilers, fuel cells to co-generate heat and electricity, hybrid heat pumps[26] and gas-driven heat pumps[27] (IEA, 2021[1]).

State of play

At present, the share of hydrogen in the energy mix for residential and other use in buildings is still negligible. In 2020, it was estimated at below 0.005% of total heating energy demand, with many countries piloting its use through demonstration projects (IEA, 2021[1]). These projects look at the injection of hydrogen into gas infrastructure and the use of hydrogen appliances in households, with the ultimate goal of developing hydrogen networks for heating and cooking purposes.

Pilot projects have been reported in countries including China, France, Germany, the Netherlands and the United Kingdom, to assess and demonstrate the safe use of hydrogen in residential and commercial buildings (IEA, 2021[1]). Some notable pilot projects include:

- Blending hydrogen into gas networks was first piloted on the Dutch island Ameland, where from 2007 to 2011 hydrogen was blended into the existing natural gas network, with injection volumes of up to 20% for heating and cooking with standard appliances (Kiwa, 2012[74]). More recently, injection volumes up to 20% were also demonstrated in the Grid Management by Hydrogen Injection to Decarbonise Energies (*Gestion des Réseaux par l'injection d'Hydrogène pour Décarboner les* Énergies, GRHYD) project in France and the HyDeploy project in the United Kingdom (IEA, 2021[1]).
- Other projects to pilot the use of pure hydrogen in existing networks are under development. The delivery of pure hydrogen to 300 households in the United Kingdom through the H100 project, initially planned for 2022, is expected to commence in 2024 (SGN, 2022[75]) (The Guardian, 2022[76]). Projects in the Netherlands that will pilot the delivery of pure hydrogen to households include projects in Rozenburg, Hoogeveen, Stad aan 't Haringvliet and Wagenborgen (IEA, 2021[1]).

The overall injection of hydrogen into natural gas networks has grown sevenfold between 2013 and 2020, but overall volumes remain low. Almost all blending into natural gas network takes place in Europe, with Germany accounting for 60% of the hydrogen volume blended into natural gas grids (IEA, 2021[1]). The

EU JRC estimates that with a 5% blending threshold, 18.4 GW of electrolyser capacity could be integrated across the EU, or 40-70.8 GW with a 20% blending threshold. The maximum amount of annual hydrogen blended into the EU network is estimated at 49.5 TWh at a 5% blending threshold and 220 TWh at a 20% blending threshold (EU JRC, 2022[77]).

Safety risks and measures

Risks and safety measures regarding the use of hydrogen in residential or other buildings distinguish between aspects related to the transport of hydrogen through distribution networks *to* buildings and those related to the transport and use of hydrogen *inside* buildings.

A main point of attention when looking at the distribution of hydrogen blends or pure hydrogen through existing low-pressure distribution networks is the impact that hydrogen may have on pipelines. Hydrogen has different properties than the natural gas for which existing networks were initially designed. In particular, there is a risk that hydrogen can lead to embrittlement[28] of carbon steel pipelines. This may be valid in particular for the transport of pure hydrogen or blends with a high share of hydrogen through carbon steel pipelines, but less so for blends with a small share of hydrogen or for plastic pipelines (see Part 6 - Lessons learnt and preliminary findings regarding hydrogen safety elements).

The main risk factors that come with the distribution of gas through distribution networks are due to the possibility of hydrogen leakages from the network. The properties of hydrogen, in particular its lower weight as compared with natural gas, mean that leakage volumes may be larger under the same conditions. This information can feed into the design of networks and safety measures, to ensure comparable risk levels for hydrogen as is currently the case for natural gas.

Data on natural gas leak incidents can nevertheless still provide useful indications regarding risk factors as well as mitigating measures. Data on past gas leak incidents in the United Kingdom show that most leaks occur in the connecting pipe, at the gas meter or the indoor piping, especially where network components are made of materials such as grey and ductile iron, asbestos cement and steel (Van den Noort et al., 2020[78]). Findings from other research indicate that a switch from the current composition of the UK network of 74% polyethylene and 26% metal parts to a 100% polyethylene network could reduce flammable gas leakages by a factor 2.5, and “gas in building” incidents by a factor 3.5, for both natural gas and hydrogen (Mouli-Castillo, 2021[79]).

The risks related to hydrogen leakages from distribution networks differ in their impact depending on the level of hydrogen concentration and whether the leakage occurs in open air or underground (see also Scenario 2 –). Overall, the risks of natural gas and hydrogen releases from distribution networks are comparable in the case of free flow in open air (Van den Noort et al., 2020[78]). Risks associated with hydrogen releases underground depend on the soil type and its permeability.

Similar to the case of natural gas inside buildings, the risks related to the use of hydrogen inside buildings depend on the possibility of hydrogen concentrations building up inside the house, which could potentially ignite. Research in the United Kingdom found that hydrogen (meeting quality standard ISO 14687 Type A) was compatible with all the domestic gas fittings and pipes tested, where components that displayed no leakages with natural gas also showed no leakages with hydrogen (Ryan and Roberts, 2020[80]). Leakage volumes from damaged components were, however, larger for hydrogen than for natural gas. Hydrogen can more easily ignite, but at the same time it has a lower energy content per volume and dissipates more quickly due to its lower weight. The impact is therefore likely to differ depending on the presence of effective ventilation at the location of a leak.

Experiments with the use of hydrogen blends of up to 20% in natural gas showed that these are likely to result in only small increases in overpressure in the event of a leakage compared with natural gas (by a factor 1.2) (Lowesmith et al., 2011[81]). Other experiments in the HyHouse found that, for the scenarios considered, the associated potential to cause severe structural damage was comparable for hydrogen and natural gas. A study to assess the likelihood of household items causing the ignition of hydrogen found that only a few of the domestic appliances – that did not cause natural gas to ignite – caused hydrogen to ignite (Crewe, Johnson and Allason, 2020[82]). Nearly all these items require a human operator present, who would most likely smell a gas release provided an odorant is added to the gas.

Annex Box 1.A.6 presents the safety measures that can be considered to decrease the risks related to domestic use of hydrogen. Risk measures should be decided upon based on desired risk targets while taking into account countervailing risks (see Chapter 1 – Managing risks).

Regulation and regulatory delivery

In the Netherlands

The existing legal framework in the Netherlands related to the distribution of hydrogen to households is expected to change with the new Energy Act (see Scenario 2 –). The act specifies the activities related to hydrogen that network operators are allowed to engage in, which would include the operation and maintenance of hydrogen networks.

Transmission and distribution system operators are currently not allowed to blend any amount of hydrogen into the natural gas infrastructure, although this is expected to change with the proposed Energy Act (EZK, 2021[39]). Within the proposed new law, system operators are required to accept gases other than natural gas (including hydrogen) on their network. This is contingent on them being able to reasonably blend the additional gas into their system and maintain the quality of gas delivered (in line with quality criteria set out in a ministerial regulation). Moreover, hydrogen transportation through newly constructed hydrogen pipelines is regulated under the Decree External Safety Pipelines.

While there is currently no regulatory framework that determines the conditions for the supply of hydrogen to consumers or the safe use of appliances inside buildings, the ACM has developed a framework to facilitate pilot projects (ACM, 2022[83]). This framework will allow network operators and energy retailers that adopt adequate safety measurs to already test and gain experience with domestic hydrogen applications before new legislation is expected to come in place. The ministry has appointed the SodM as the body to supervise the safety of these pilots (SodM, 2022[84]).

Other countries

In other countries, there is usually no or only limited regulation regarding the distribution and domestic use of hydrogen:

- In **Australia**, the government is conducting a review of the volume of hydrogen that can be blended into gas networks. There is no regulation allowing pure hydrogen as gas appliances are only suitable for a blend of up to 10% or 20%.
- **China**'s policies and regulations support hydrogen blending in existing natural gas grids and the government has published a group of standards for natural gas and hydrogen mixing stations. It is currently completing a review on how to bring hydrogen into the gas network.
- In **Japan** and **South Korea**, the domestic use of hydrogen involves fuel cell systems, which are subject to regulations that apply to fuel cells in general.
- In the **United Kingdom**, in the absence of hydrogen related rules and regulations, the concentration of hydrogen that can be injected into the gas network and consequently be supplied to domestic homes should be no greater than 0.1% molar.[29]
- In the **United States**, there are no regulations specifically targeting the domestic use of hydrogen, although such use is not prohibited as can be seen from the existence of small-scale pilot projects.

International standards

As the application of hydrogen for domestic use is currently still at the stage of piloting, there is no international standard that applies to this scenario.

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Notes

[1] This share is significantly lower in 2021, when a new 150 MW electrolyser become operational in China.

[2] Currently, only 4% of projects (in terms of production output in 2030) are at advanced stages of development (under construction or with final investment decision), whereas one third is at the concept stage and the remaining projects are undergoing feasibility and engineering studies (IEA, 2023[85]).

[3] Normalisation allows for a comparison of fatality risk by adjusting for the total production volume of energy sources, resulting in a fatality risk per energy volume (such as TWh).

[4] Based on data from three incident databases (Energy-related Severe Accident Database (ENSAD), Hydrogen Incident and Accident Database (HIAD) 2.0 and H2tools).

[5] Directives 2011/92/EU on the environmental impact assessment (EIA), Directive 2001/42/EC on the strategic environmental assessment (SEA), Directive 2010/75/EU on industrial emissions (IED) and Directive 2012/18/EU on the control of major hazards involving dangerous substances (Seveso Directive).

[6] Requirements following from the Seveso Directive may differ between so-called "lower-tier" establishments (with quantities above 5 tonnes) and "upper-tier" establishments (with quantities above 50 tonnes) (Lexparency, 2008[26]).

[7] Ksi stands for kilo pounds per square inch and measures the amount of stress a material such as steel can undergo before failing.

[8] Retrofitting is the upgrade of existing gas infrastructure to allow the injection of certain amounts of hydrogen as a blend, whereas repurposing involves the conversion of existing infrastructure to a dedicated hydrogen infrastructure.

[9] Similarly, the European Hydrogen Backbone (EHB) study estimates that conversion costs are 21 to 33% of the cost of new hydrogen pipelines.

[10] Looking at hydrogen shares by country, in 2017 57% of worldwide hydrogen pipelines were in the United States (2 608 km), 13% in Belgium (613 km), 8% in Germany (376 km), 7% in France (303 km), 5% in the Netherlands (237 km), 3% in Canada (147 km) and 6% in other countries (258 km). In total, hydrogen pipelines amounted to 4542 kilometre in 2017 (Shell, 2017[86]).

[11] Where hydrogen leakages occur, the corresponding drop in pressure should usually activate installed protection systems such as the automatic closing of safety valves to limit the quantity of release. The magnitude of the consequences of a hydrogen incident will therefore depend on the successful operation of this safety system.

[12] The incident rate (number of leakage incidents per year) was normalised per 1 000 km pipeline.

[13] In other cases, a system of negotiated third-party access applies until the implementation of regulated third party access in 2030.

[14] The decree applies to pipelines for flammable substances with an external diameter of at least 70 millimetres or an internal diameter of at least 50 millimetres and a pressure of 1 600 kPA or higher.

[15] The local risk is the risk of a fatal accident due to a pipeline incident for a person who is continuously exposed and unprotected at a given location.

[16] The Minister of EZK can decide in a ministerial regulation to adjust this distance for certain category of pipelines or to accept a different risk level.

[17] The group risk is defined as the cumulative risk per year and per kilometre that at least 10, 100 or 1 000 persons die as a direct consequence of their proximity to a pipeline that is experiencing an incident.

[18] While the main focus of the scenario is on vehicles transporting hydrogen, a significant part of the literature on safety risks due to releases in transport concerns hydrogen-powered vehicles. For this reason, both will be considered under this scenario.

[19] Hydrogen in liquid state is a so-called cryogenic liquid, referring to liquids with a boiling point at extremely low temperatures. Therefore, to transport hydrogen as a liquid rather than a gas, it needs to be cooled to low temperatures.

[20] Due to its low weight and energy content by volume, unpressurised gaseous hydrogen would require a volume of 11 m^3 of hydrogen for 1 kg of hydrogen, roughly needed to drive 100 km by car. By compressing the gas, the energy value per volume increases, allowing hydrogen cars to drive further on a single tank (Air Liquide, n.d.[87]).

[21] This conversion into electricity and water requires the combination of hydrogen and oxygen from the air.

[22] For a significant share of incidents (28%), the cause was unknown.

[23] These tunnels include the Roertunnel, the Schipholtunnel, the Swalmentunnel, the Leidsche Rijntunnel and the Willem-Alexandertunnel.

[24] The local risk is the risk of a fatal accident due to a pipeline incident for a person who is continuously exposed and unprotected at a given location. The local risk distance is set at such a distance to ensure the local risk for vulnerable buildings and locations does not exceed a threshold of 10^{-6} (or one in a million) per year (Staatsblad, 2018[64]).

[25] A fire safety distance limits the zone beyond which the impact of an unusual incident that causes a puddle or flare fire does not lead to a heat radiation higher than 10 kilowatts per square metre (Staatsblad, 2018[64]).

[26] Hybrid heat pumps use a hydrogen boiler as a supplement to an electric heat pump to meet peak demand.

[27] Gas-driven heat pumps use a gas engine that produces electricity to run a heat pump.

[28] Embrittlement is a significant decrease of ductility of a metal, which makes the material brittle.

[29] 0.1% molar indicates the percentage of moles (or units) of hydrogen as a share of total number of moles in the mixture.

Part I Literature review

6

Examining scenarios involving hydrogen leakage

This chapter presents the approach to the literature review examining scenarios involving hydrogen leakage. Six scenarios relevant for hydrogen safety are briefly presented. Key takeaways and further areas of research are also discussed.

Hydrogen is a crucial element for the energy transition towards a low carbon economy. It can contribute significantly to the reduction of carbon emissions, which in turn could mitigate potentially catastrophic climate related disasters. A successful increase in hydrogen adoption would also play a key role in meeting the goals of the European Green Deal. Hydrogen can be used in several sectors, including transportation, industrial and domestic use. However, safety concerns and a lack of national-level safety regulations could potentially hinder its widespread use. The goal of this reform project and the report on literature review is to support the Dutch government to speed up its energy transition, and to develop country-specific recommendations for the safer and sustainable use of hydrogen.

This report consists of a study **into the likelihood of a number of ignition/effect scenarios as resulting from hydrogen leakage.** It consolidates existing knowledge, research, and data, on hydrogen leakage and ignition risks. It also aims at improving knowledge in relation to the risks associated with the use of hydrogen in small-scale applications. It provides main findings and guidance with regard to adequate risk-management of hydrogen applications in different scenarios, especially for the development of appropriate regulations and regulatory processes for the safe use of hydrogen technologies.

The report, which builds on both numerical and experimental research in the field of hydrogen safety and risk assessment, intends to help identify current gaps in hydrogen safety – to further help local authorities clarify risks related to hydrogen-based technologies in relation to the issuance of efficient, risk-based permits for their applications.

The literature review covers 99 scientific articles, divided into six distinct scenarios, covering potential sources of accidents in production, transportation, fuelling stations and residential use. The scenarios described in this report have been selected at the behest of the Dutch Ministry of Economic Affairs and Climate Policy. They are of particular interest as they cover use of hydrogen technology in densely populated areas requiring safety and risk management techniques.

The study of the six scenarios describes the evolution of hydrogen safety requirements over the years and the acceptable risk standards. For instance, it studies the risk associated with hydrogen production by electrolysis, focusing on pipes connected to electrolysers. Given that alkaline electrolysers are a very mature technology,[1] the risk is considered acceptable should current risk measures be followed. When dealing with the domestic use of hydrogen for heating, preliminary results from on-going large-scale pilot projects indicate that such use could be as safe as using natural gas for heating, if the necessary mitigation measures are put in place.

This chapter presents lessons learnt and recommendations on key safety elements for hydrogen technologies that new/revised regulations could consider in order to achieve better outcomes. The findings are presented in separate sections for each scenario with a synthesis of the review of findings from research data and relevant safety recommendations for that scenario. These recommendations are based on the OECD research findings and should be considered as a list of options to reduce the risks related to hydrogen technologies. The recommendations are focused on six scenarios/applications that cover a wide spectrum of the hydrogen supply chain.

Improvements in technological standards and better risk-management studies show that hydrogen is not as risky as previously perceived to be. This finding runs parallel to the fact that no fuel is 100% risk free. With more understanding of the manner in which hydrogen functions and improvement in certain technologies such as those related to sensors, ventilation, and storage materials have improved, regulators should strive to improve the public perception of hydrogen against the greater risks of climate change. As the evaluation of safety codes and regulations on a rolling basis and pilot projects already shows, it can be stated that with adequate safety protocols in place hydrogen fuel can be used safely for commercial and small-scale private purposes.

Structure

Chapter 7 *Hydrogen Safety Aspects* presents a brief summary of scientific articles on existing knowledge by theoretical, experimental and numerical research on hydrogen safety in general.

Chapter 8 *Mapping Exercise* summarises and discusses existing knowledge from scientific research on previously defined scenarios. It focuses on data regarding safety of hydrogen as a fuel in **six scenarios**, covering the hydrogen lifecycle in its various phases. The literature review covers 99 scientific articles, divided into six distinct scenarios, covering potential sources of accidents in production, transportation, fuelling stations and residential use. A brief description of these scenarios is provided below:

Scenario 1 – Production: Leakage from pipes connected to electrolysers

This section presents a discussion on safety aspects of hydrogen production from water electrolysis, with a focus on leakage from pipes connected to electrolysers. It starts with a brief introduction on up-to-date electrolysis technology, which is followed by a holistic picture of risks associated with hydrogen production sites. With the major risk contributor (compressor) identified, a discussion on hydrogen pipeworks[2] Within a production site focusing on those connected to electrolysers is presented: Incident database records together with experimental and computational work by independent authors conclude that the risk associated with pipework leakage is acceptable should current safety measures be followed.

Scenario 2 – Transport pipelines: Leakage from high-pressure pipeline

The studies in this section analyse the transport of compressed gaseous hydrogen through pipelines and the safety measures that should be taken into account. The research focuses on ignition, leakage and explosion likelihood, potential damage to buildings, people and the necessary safety (viz., separation) distances to mitigate these hazards. Quantitative and experimental research alongside models verify the impact of the pipe material, nature of ground soil, the internal flow and the position of the pipeline (viz., above or below ground level) on the aforementioned hazards. It concludes that more detailed verification of relevant — that can influence the hazard situations and the relative safety mitigation measures are needed.

Scenario 3 – Road transport: Hydrogen leakage in confined spaces/ built environments

This section presents a discussion of important safety aspects of hydrogen behaviour. This includes hydrogen-related risks arising from parking garages and accidents in urban areas, as well as comparisons between hydrogen fuel cells vehicles (FCVs) and compressed natural gas (CNG) cars from a safety perspective. One of the key considerations for policy makers regulating hydrogen use in confined spaces is the use and design of ventilation (natural and mechanical) systems. Experimentation and computational methods show that natural and/ or mechanical ventilation contribute to the reduction of risks associated with hydrogen leakage. Studies have shown that sensors and their placement in the HFCVs is an important consideration for regulators to reduce risks associated with hydrogen leakage. It can therefore be considered that if adequate precautions exist such as ventilation, sensors, and well-tested safety valves, the public perception for HFCVs could gradually be improved.

Scenario 4 – Mobility and partially confined spaces: Examples of this scenario include a hydrogen city bus driving in a tunnel is involved in a collision traffic accident

An important issue concerning the safe use of hydrogen-powered FCVs is the possibility of accidents inside tunnels resulting in the release of hydrogen.[3] To understand the potential consequences, several experimental and theoretical studies as well as risk assessments have been conducted. The studies presented herein determine the severity of the predicted consequences. These studies analysed the behaviour of the flammable hydrogen cloud inside the tunnel, predicted the overpressures arising from accidental hydrogen releases in areas with no or limited ventilation and determined the probability of ignition and the possible delay before the cloud ignites. The height, shape and architectural design of the tunnel as well as different ventilation regimes were studied as potentially important parameters in determining explosion risks and appropriate mitigation measures. The role of the TPRD's size and orientation were investigated: smaller sizes were recommended and vertically downwards releases were discouraged. The time delay prior to ignition, in case of a hydrogen leak, was found to be an important parameter, since: ignition delays of about 4 to 8 seconds can result in dangerously high overpressures, approaching or surpassing the fatality threshold level.

Scenario 5 – Mobility and partially confined spaces: Accidents at a hydrogen refuelling stations

Through several studies, safety measures were gauged via risk-based approaches to prevent leak and explosion of hydrogen. These included studies aimed at determining the safety distances on hydrogen stations planned to be installed and the ignition likelihood in the station's components. Additionally, aspects such as the nature of accidents and incidents at hydrogen fuelling stations over time were analysed to identify key safety issues. The catastrophic rupture of a tube trailer and a liquefied hydrogen tank were found to be the worst accidents of hydrogen refuelling stations.

Scenario 6 – Domestic use: safety of hydrogen in buildings with focus on hydrogen heating of houses

In this scenario, the studies that have been conducted on the safe use of hydrogen in residential buildings, mainly for heating, are being investigated. The findings of large-scale projects, such as the Hy4heat project, the H100 project and the HyDelta project, which aim to investigate the possibility of substituting natural gas with hydrogen for heating, are presented and summarised in this section. Based on findings from these projects it has been concluded that the use of hydrogen for heating could be as safe as using natural gas, as long as a fit for purpose s distribution network is used and additional mitigation measures are implemented downstream of the gas metre.

Results and main takeaways from the scientific literature review for the six above-mentioned scenarios are presented in separate subsections in this report. Each study is briefly summarised, together with its main conclusion, and supported by relevant supplementary material. The mapping exercise provides important parameters of hydrogen in case of an accident, (release rate, dispersion, overpressure, heat flux, etc.), as well as possible prevention and mitigation measures (such as ventilation, safety distances etc.). Recommended actions are proposed based on the gaps identified in the scientific papers.

Key takeaways

Hydrogen can contribute to the reduction of carbon emissions; however, its simple structure makes hydrogen more flammable, thereby raising more safety concerns. In order to evaluate the safety of hydrogen as a fuel, regulators must compare its safety risks, benefits, and disadvantages against other fossil fuels. It should be noted that no source of fuel is entirely safe. In fact, on some counts, hydrogen is found to fare better than other conventional fuels. For instance, while fossil fuels are carcinogenic and polluting, hydrogen is absolutely non-toxic and there is little evidence to suggest that hydrogen leakage will cause catastrophic environmental disasters like those arising from oil spills. On the other hand, hydrogen requires 18-59% oxygen for explosions as compared to just 1 to 3% in case of fossil fuels. Due to its low weight, hydrogen rises easily. This property reduces the probability of secondary fires.

General prevention measures for hydrogen applications include installation of pressure relief valves, flow restrictors and shut down emergency systems, regular maintenance of individual components, training of personnel, controlling ignition sources, limiting congestion in closed spaces and use safety distances. Possible mitigation measures are: proper installation of detection sensors at locations where hydrogen accumulation is expected, e.g. on ceiling, and limiting/stopping the hydrogen supply before concentration reaches 15 % v/v, natural ventilation with multiple vent configuration, large vent area and small aspect ratio (length/height) with no obstructions in front of them or mechanical ventilation with ATEX-compliant systems to prevent concentrations above LFL, when possible. The use of fire suppressing system, such as water mist, can also mitigate the consequences in case of fire and explosion and prevent the fire spreading.

Over the years, technological standards related to sensors, ventilations, and materials have improved. The same is the case with safety codes and regulations. Pilot projects have shown that with adequate safety protocols in place, hydrogen fuel can be used safely for commercial purposes. For instance, new research shows that hydrogen FCVs should be treated at par with CNG vehicles even in serious cases involving crashes. Given that CNG cars are now publicly accepted as safe, such kind of assurance could improve the regulatory case for hydrogen as well. Similarly, for parking garages especially those in confined spaces and basements, the use of ventilation has been found to be a good mitigation measure for accidents arising from hydrogen leakage. In addition to this, prominent signage informing the public about bans on smoking, mobile use or fire lighting are simple yet well-known steps for controlling ignition sources at refuelling stations. Incorporating a behaviour change using these measures is relatively less work due to similar global restrictions at fuel stations involving conventional fuels.

As far as hydrogen production via water electrolysis is concerned, alkaline electrolysers represent a mature technology with most large production plants built between 1920s-1980s. Risk analysis together with historical data from 3 databases (ENSAD, HIAD 2.0 and H2tools) show that most root events can be either reduced or eliminated following current risk measures. ENSAD reported no hydrogen release at production sites; HIAD2.0 data suggest the risk associated with electrolysers are small compared to compressors and pressurised storage; while H_2tools reported no such accidents after 1990 - when modern valve design became available. In addition, calculations performed by Sandia based on historical hydrogen data suggest that the risk associated with leakage from pipeworks connected to the electrolyser is within the boundary set by the purple book. Therefore, we can conclude that existing knowledge of Scenario 1 is sufficient and we expect the risk to be acceptable.

Research concerning hydrogen pipeline transport has highlighted the consequences and risks related to pipeline failures. The two main incidents of leakage and rupture of a high pressure pipeline lead to potential damages to people and buildings with both individual and societal risks. Different QRA have been to define the probability of accidents to occur and the risks connected to ignition and explosion. With the release of hydrogen due to rupture the potential ignition and explosion leads to a maximum value of $1.65 \cdot 10^{-3}$ death/year/1000 km. To mitigate this risk it is advisable to establish zoning in land use management to create a distance between the source of risk and nearby buildings and people. As well as the potential of external interferences with the pipeline site. A great influence to the scale of damage is linked with wind speed, ground roughness, tube pressure and leakage gap area on the diffusion distance and overpressure distance. Experiments on the surrounding feature can factor in other mitigation and safety measures.

The second major hazard is leakage of hydrogen which happens at a higher pace and is greater in volume flow in confined spaces compared to natural gas. It is highly influenced by contact with air. Conversely it has a lower ignition likelihood determining a lower probability of explosion damage. Being hydrogen gas odourless, colourless, and tasteless, leaks are not detected by human senses. Therefore, as a safety measure to counter major consequences from hazards, the use of hydrogen sensors is recommended to successfully detect hydrogen leaks. As well as a ventilation system that mitigates the potential damage by enabling hydrogen to escape to adjacent spaces.

Regarding hydrogen mobility inside tunnels, risk analysis studies showed that a hydrogen accident inside a tunnel will most likely not lead to ignition since there will be no release of hydrogen (probability of 94.1%). However, if hydrogen does ignite, fire can spread quickly inside the tunnel. An appropriate ventilation is key to help prevent ignition and reduce the chance of an explosion. Appropriate ceiling design and additional measures are also needed to reduce or mitigate potential damages. For example, attributes of the TPRD, such as diameter and orientation of gas release can make a difference when it comes to hazard mitigation. Storage systems involving more than one TPRDs should be designed to avoid simultaneous opening of all PRDs. The deliberate activation of TPRD can also mitigate the consequences from a tunnel accident. New technologies, like the leak-no-burst tank, that prevent tank rupture, can significantly reduce the risk and address the concerns of firefighters, especially in tunnels and other confined spaces. If hydrogen is ignited right after being injected in the tunnel it forms a jet fire with a heat release rate that gradually decays with the injection rate. In the case of delayed ignition however, a pressure wave propagates through the detonable hydrogen cloud resulting in a blast wave and overpressures that may approach the fatality threshold level. A potential failure of the TPRD failing is a hazard that should be taken very seriously as there can be severe consequences from the ensuing explosion.

Research within the area of accidents at hydrogen fuel stations highlighted the need to guarantee a high level of safety for hydrogen fuelling stations, in view of their increasing widespread construction across the world. Not only do correct and adequate sealing and torque need to be carefully considered, but also a set of safety recommendations. These include the installation of a protective wall surrounding the dispenser, limiting the inventory in storage facilities on-site, refuelling stations and setting appropriate safety distances not only between the station and residential area but also among different elements of the station, e.g. between dispenser and storage room. Moreover, the study, by looking into life parameters in QRA and fire spreading at both GHRS and LHRS could provide concrete information about risks and what can be done to reduce their likelihood.

Overall, recent research into the residential use of hydrogen for heating has shown that hydrogen can be as safe as natural gas, as long as the right mitigation measures are put in place such as appropriate pipeline components and leakproof design. The use of a 100% polyethylene network is proposed to minimise gas leaks and the installation of two emergency flow valves is recommended to cut off the flow of hydrogen before a hazardous scenario can occur (Mouli-Castillo et al., 2021[1]). By ensuring that all hydrogen appliances adhere to the proper specifications and are properly ventilated, the risks can be reduced even further.

In conclusion, there are gaps of existing knowledge relating to hydrogen safety. However, the success and learnings from existing projects is a positive sign that hydrogen could be a key pillar in the fight against climate change, and environmental disasters. The involvement and initiative of governments around the world, academic and scientific institutions as well as private firms shows that a scientific foundation for hydrogen-use already exists. However, more work is required to improve public perception on hydrogen safety.

Areas for further research

Through numerous experimental and theoretical studies, the behaviour of hydrogen and its intrinsic properties are fairly well established. However, there are still some knowledge gaps on how accidents could lead to harmful consequences. This is particularly challenging because of the prevalence of uncertainties in the application of QRA. Moreover, current data collection efforts in the hydrogen fuelling industry do not impose the obligation of the quality necessary to perform QRA. Therefore, data coherence continues to pose challenges.

To offset the scarcity of hydrogen-related field failure data, scientists use statistical methods such as bounding analysis and uncertainty propagation techniques such as Monte Carlo sampling and the Latin Hypercube sampling methods so that the predicted outcomes can be represented by probability distribution as compared to single-point values.

Scenario 1, shows that alkaline type electrolysers, as a mature technology for hydrogen production, were thoroughly assessed in the last century. Based on entries in accidents databases and estimation using hydrogen specific historical data, we concluded that there is sufficient knowledge regarding Scenario 1. Nonetheless, continuous monitoring of hydrogen accident databases is recommended to gain further insights on the risks associated with Scenario 1.

There has been a large number of experimental research on Transport pipelines: leakage from high-pressure pipeline (scenario 2) both in lab and in external environments. It is advisable to deepen the knowledge, through experiments, of pipeline ruptures and possible ignition likelihood due to adverse and different weather conditions that can vary the impact and damages of accidents. In terms of safety measures the HSE and EIGA experiments can streamline a series of guidelines useful to mitigate the possible adverse effects.

For HFCVs (scenario 3), QRAs can help identify important hazards. Some hazards identified under HySafe studies include internal (random component failure) and external (crashes, high winds, floods, earthquakes) incidents, accident sequences where hydrogen leakage and ignition lead to fires and explosions, as well as consequences of such incidents due to thermal and pressure effects on neighbouring property and people. Current research is simplistic. For instance, current ignition probability models tend to ignore several complicated ignition-induced scenarios such as vehicle crash scenarios. A second example relates to sensors. While sensors and gas and flame detection equipment are established as necessary, there still isn’t enough information on the accuracy of these equipment, or for instance their proper placement to reduce the consequences of a crash involving vehicle roll-over. In addition to equipment failure, studies should also factor human, software and organisations errors. In Germany and Norway, several non-fatal hydrogen accidents were a result of human-related errors. While a full-scale QRA is always desirable, as it could help evaluate all the types of potential accidents, their consequences, frequencies, and it can also help prioritise the risks, a full-scale QRA could be costly and labour intensive to collect the needed equipment failure data.

There has been a large number of experimental and numerical studies of the risks of hydrogen vehicles in tunnels (Scenario 4). Additional research can be performed to understand the effects of deflagration or detonation inside tunnels of different configurations and for accidents involving different types and classes of hydrogen vehicles. Determining the extent in which obstructions inside the tunnel can raise additional hazards in the case of a detonation or deflagration could also be an important step forward to improve the current state of knowledge in this area. The now concluded EU-funded project, HyTunnel-CS, has answered several knowledge gaps around the safe use of hydrogen inside tunnels and other confined spaces, notably showcasing a TPRD-less tank that releases hydrogen in a controlled manner by turning porous under extreme heat. However, given that the Hy-tunnel project findings were released when this report was near completion, the present report does not delve deep into the findings from Hy-Tunnel.

There is quite extensive literature on postulated accidents in refuelling stations (scenario 5). However, some further research as well as actions to facilitate further collaboration and research between hydrogen industry and research organisations with the aim of transferring knowledge should be promoted. In addition, developing a more thorough knowledge on accidents and incidents that took place at hydrogen refuelling stations involving small leakages of hydrogen is needed and suggested safety measures shall be taken. Further analysis on QRA guidelines for HRSs is needed to facilitate the implementation of such recommendations.

For scenario 6, knowledge gaps are actively being filled-in by on-going demonstration / pilot projects. It would be useful to get in contact with the consortium of these projects to obtain up-to-date information on their research and on their future plans.

The findings arrived at in Part 1 for the various scenarios have been through an analysis of scientific articles and reports published over the last couple of decades. In addition to this, several ongoing projects in the field of hydrogen safety have also been referenced. These international projects are either ongoing or have concluded and help shed light on hydrogen safety including its safety features in the selected scenarios. The international projects referred to in this report are in Table 6.1 below.

Table 6.1. List (non-exhaustive) of projects that focus on hydrogen safety

Project name	Dates	Objective	Website
HyTunnel	1 Mar 2019 – 28 Feb 2022	Perform pre-normative research for safety of hydrogen vehicles and transport through tunnels and other confined spaces with the aim to provide recommendations for inherently safer use of hydrogen vehicles in underground transportation systems and recommendations for RCS	https://hytunnel.net/
H_2tools		Through support from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), the portal brings together and enhances the utility of a variety of tools and web-based content on the safety aspects of hydrogen and fuel cell technologies to help inform those tasked with designing, approving or using systems and facilities, as well as those responding to incidents.	https://h2tools.org
HySafe	1 Mar 2004- 28 Feb. 2009	The project contributed to the safe transition to a more sustainable development in Europe by facilitating the safe introduction of hydrogen technologies and applications.	http://www.hysafe.org/home
HyIndoor	2 Jan 2012-1 Jan 2015	The project provided scientific and engineering knowledge for the specification of cost-effective means to control hazards specific to the use of hydrogen indoors or in confined space and developing state-of-the-art guidelines for European stakeholders. Specific knowledge gaps have been closed in the areas like indoor hydrogen accumulations, vented deflagrations, and under-ventilated jet fires in order to be able to optimally implement the most effective safety strategies. The generated knowledge has been translated into state-of-the-art safety guidelines including specific engineering tools supporting their implementation. Recommendations have been formulated with regards to evolutions needed in the Regulations Codes and Standards framework at European and International levels to support the safe introduction of fuel cells and hydrogen in early markets.	www.hyindoor.eu
Safe Hydrogen Fuel Handling and use for Efficient Implementation (SHIFT)2	2019-	SHIFT2 is a large experimental program to include release of hydrogen and ammonia in confined, ventilated spaces, ignition of non-homogenous mixtures of hydrogen-air as a result of high-pressure leaks, and realistic fire scenarios with and without passive fire protections. Results will be used to validate advanced models including commercial CFD code and phenomenological models. Materials testing will be conducted to study material compatibility and degradation. Barriers for operational safety will be designed for risk-based guidelines for inspection	https://www.sintef.no/projectweb/sh2ift/

Project name	Dates	Objective	Website
		planning Risk-based approach for operational safety to be explored, including assessment of existing risk systems for new energy.	
HyDeploy Project		The project focused on the blend of 20% of hydrogen with different mixes of gas and their impact on appliances on samples of boilers, burners and cookers in lab conditions and on connected gas networks. The findings of this research built the safety case and Quantitative Risk Assessment necessary for the HSE to give exemption from the GSMR.	https://hydeploy.co.uk/faqs/what-are-the-benefits-of-hydeploy/
HyHouse Project	2021	The study took place in a three-bedroom farmhouse in Scotland to verify the potential dispersion of flammable gases in a house. The study involved simulating realistic leaks using five test gases (100% hydrogen, 100% natural gas, and three different mixtures of the two). These gas leak tests were conducted at various rates, and distribution of those gases throughout the house was measured, at three levels of air tightness (to simulate different ages of construction). The outcome of the project proved that the likelihood of the build up to dangerous amounts due to a leak in a house is less than natural gas.	https://www.kiwa.com/gb/en/areas-of-expertise/hydrogen/kiwa-uk-hydrogen-case-studies/hyhouse-case-study-hydrogen/
Hy4Heat		The project analysed technically the feasibility and safety of replacing natural gas with hydrogen in residential and commercial buildings and gas appliances.The work focused on: • Hydrogen Gas Standards: defining a hydrogen quality standard, including purity, odorant and colourant levels, defining a hydrogen reference standard for installations and defining a training competence framework for hydrogen conversion training of qualified gas installers and network operators. • Appliance Certification: establishing guidance on certification of a new generation of hydrogen appliances. • Domestic Hydrogen Gas Appliances: development of hydrogen-fuelled boilers, cookers and fires and innovative hydrogen gas appliances. • Commercial and Industrial Appliances: research into the variety of commercial gas appliances and industrial gas systems and the issues to be addressed in their conversion or replacement with hydrogen appliances and systems, plus development of selected commercial hydrogen appliances. • Comparative Quantitative Risk Assessment (QRA) of the use of hydrogen vs. natural gas in properties: assessment of the relative risks of using hydrogen vs. natural gas in properties, including investigation of leak rates, dispersion patterns, ignition likelihood and consequences of ignition, plus identification of protection measures to reduce risk. • Demonstration: demonstration of hydrogen appliances in a purpose-built temporary facility	https://www.hy4heat.info/

Project name	Dates	Objective	Website
		for stakeholder engagement and feedback	
HYPER	1 Nov 2006 – 31 Jan 2009	The aim of the HYPER project was to develop fast-track approval for small stationary hydrogen and fuel cell systems, concerning safe procedures and to enable a comprehensive agreed installation process for developers, design engineers, manufacturers and installers across the European Union.	https://cordis.europa.eu/project/id/39028
H21	Sep 2014 -	H21 is a suite of gas industry projects, carrying out vital work to prove that the UK natural gas network can safely transport hydrogen in the future.	https://h21.green/
HyResponse	1 June 2013-30 Sep 2016	The HyResponse project established the World's first comprehensive training programme for first responders, i.e. a European Hydrogen Safety Training Platform (EHSTP), to facilitate safer deployment of FCH systems and infrastructure. EHSTP will train first responders to deal with all safety aspects for a range of hydrogen applications, including passenger vehicles, buses, forklifts, refuelling stations, backup power, stationary fuel cells for combined production of heat and power, etc.	https://cordis.europa.eu/project/id/325348

Reference

Mouli-Castillo, J. et al. (2021), "A quantitative risk assessment of a domestic property connected to a hydrogen distribution network", *International Journal of Hydrogen Energy*, Vol. 46/29, pp. 16217–16231, https://doi.org/10.1016/j.ijhydene.2021.02.114. [1]

Notes

[1] Nonetheless, there is still room for innovation and newer technologies such as PEM (proton exchange membrane) and SOECs (solid oxide electrolysis cells) can provide either better control or efficiency.

[2] Pipes within a site used for transfers internally and to the site boundary.

[3] This scenario examines the possible hazards from a hydrogen vehicle crash inside a partially confined space. The example most prominently used here will be that of a collision involving a hydrogen vehicle driving inside a tunnel. Other partially confined spaces, such as parking garages are discussed elsewhere in the report as they are more relevant to Scenario 3 ("H_2 leakage in a confined space/ built environment").

7 Hydrogen safety aspects

This section addresses some of the main hydrogen safety concerns. Possible scenarios, including vapour cloud dispersion, ignition and hydrogen tank rupture, are discussed, along with their possible consequences. The section also identifies significant safety hazards and proposes the most important prevention measures.

In 2020, IFV (*Instituut FysiekeVeiligheid*), Netherlands, performed a review on the safety aspects associated with the release of hydrogen in confined space. The research questions in the IFV report were drawn up in collaboration with participants in the Hydrogen Community of Practice (CoP) and followed the timeline of a scenario where hydrogen is released into a confined space. Approaches to estimate the likelihood of hydrogen ignition and measures that can be taken, in order to prevent and mitigate the consequences were also provided.

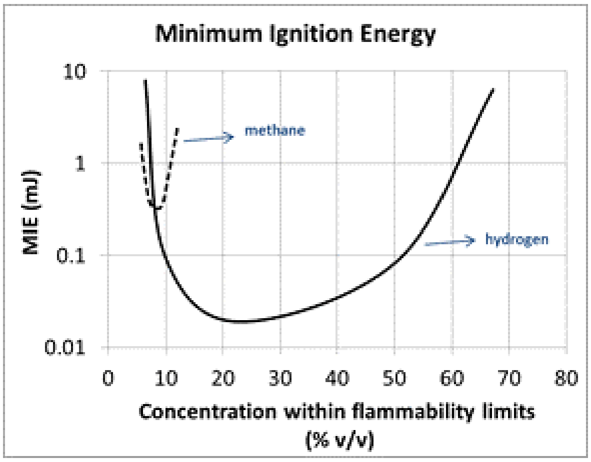
In this Section, complementary to the IFV review, the main hydrogen safety aspects are discussed based on existing knowledge by theoretical, experimental and numerical research. The findings are not dedicated to a specific scenario; rather provide insight on hydrogen behaviour in case of release, dispersion and combustion. Possible safety strategies and recommendations on the safer use of hydrogen are also presented.

Hydrogen properties

Hydrogen is the simplest chemical element. It is a colourless, odourless, tasteless, flammable gaseous substance. As a fuel, hydrogen has high energy content by mass, nearly **three times the energy** content of **gasoline**—120 MJ/kg for hydrogen versus 44 MJ/kg for gasoline. However, due its low density the volumetric energy content of hydrogen is low if not compressed or in liquid state. Thus, a common practice for efficient storage, transportation and handling of hydrogen is its compression or liquefaction. This can increase the associated risks, especially, for unintended releases from pressurised storage. The increased risk, though, can be mitigated by using proper preventive and mitigation measures and performing personnel training.

The risks of hydrogen should be compared in relation to the risks of other conventional fuels, such as natural gas (87-98% methane). Table 7.1 provides some properties of hydrogen and methane that affect their dispersion and combustion. Hydrogen has lower density, calorific value by volume and auto-ignition temperature, while it has higher heat capacity, calorific value by mass, flame temperature, laminar burning velocity and molecular diffusivity. It has wide flammability limits (4-75% v/v) and low minimum ignition energy (0.02 mJ). The MIE corresponds to concentration around 23 % v/v H2 in air. For concentration levels closer to LFL (below 10 % v/v) and to UFL (more than 55 % v/v) the ignition energy of hydrogen is higher and similar to that of methane, as shown in Figure 7.1.

Figure 7.1. Ignition energy in respect with the concentration of the fuel in air (for hydrogen and methane)



Source: Ono et al., 2007 (for H_2) and (Bjerketvedt, Bakke and Van Wingerden, 1997[1]) (for CH_4).

Based on the comparative table, the wider flammability limits, the lower MIE for H_2 concentrations around 8-58% v/v, the lower auto-ignition temperature and the higher burning velocity and flame temperature compared to methane are the factors by which hydrogen is considered more dangerous. It should be kept in mind, though, that the associated risks of hydrogen use can be reduced to an acceptable level, comparable to other hydrocarbon fuels, by the adoption of appropriate safety measures.

Table 7.1. Comparison between hydrogen and methane properties

Property	Hydrogen	Methane
Molar mass (g/mole)	2.02	16.04
Vapour density (kg/m^3)	0.08	0.65
Specific heat capacity (kJ/kg/K) (at T='293.15' K)	14.4	2.21
Lower calorific value by mass (lower heating value, weight basis) (MJ/kg)	120	48
Lower calorific value by volume at 1 atm (MJ/m^3)	11	35
Higher calorific value by mass (MJ/kg)	142	53
Higher calorific value by volume at 1 atm (MJ/m^3)	13	39
Maximum flame temperature (K)	1800	1495
Explosive limits (vol % in air)	18.2-58.9	5.7-14
Flammability limits (vol % in air)	4.1-74	5.3-15
Lower limiting oxygen concentration for combustion (vol %)	5	12
Auto-ignition temperature (K)	833.15	873.15
Laminar burning velocity (m/s)	3.1	0.4
Molecular diffusivity in air (m^2/s)	6.110^{-5}	1.610^{-5}

Source: (Messaoudani et al., 2016[2]).

Vapour cloud dispersion

The accumulation and formation of flammable vapour clouds is a significant parameter in safety engineering. Hydrogen is lighter than air with a high diffusion coefficient. When hydrogen is released outdoors, wind and buoyancy force cause the mixture to rise and disperse. This behaviour is somewhat desirable for safety, as hydrogen will not accumulate near the ground, where ignition sources are more likely to be present. Similarly, in indoor/ confined spaces hydrogen tends to accumulate on the ceiling and on the top part of a facility. This rich-in-hydrogen layer below the ceiling can take on specific dimensions and thickness depending on the conditions and also flow into another part of the building. It should be noted that in compressed horizontal releases the momentum dominant region can be larger than ambient releases and buoyancy effects are evident at longer distances from the release.

Hydrogen distribution depends on the containment leak conditions, such as the leak diameter and pressure, the volume of hydrogen released and the ventilation characteristics of the location. Several experimental and numerical studies have been carried out to investigate hydrogen behaviour and understand the underlying phenomena. Next, we focus on certain studies that have provided insight on hydrogen vapour cloud dispersion, mainly in confined spaces.

(Gupta et al., 2009[3]) conducted experiments with helium release as hydrogen surrogate inside a semi-closed facility in an unventilated private garage showing that the risk (in terms of peak hydrogen concentration) is affected mostly by the **total mass released rather than the release flow rate**. However, variations in flow rates influence the mixing behaviour inside the garage that in turn changes the decay rates of gas concentrations. For low released volume (1.2 m^3) inside a 41.3 m^3 garage the peak concentration was little above the LFL (4.39 %).

The substitution of hydrogen with helium is a common practice in small dispersion experiments for safety reasons, because the two gases have similar dispersion behaviour, while helium is non-flammable.Since helium is expensive it is not appropriate for large containments. Simulation studies (He et al., 2016[4]), (Prabhakar et al., 2017[5]), (Giannissi et al., 2021[6]) compared the behaviour of the two gases and showed that the agreement between the results is very good. Thus, the use of helium as hydrogen surrogate in experiments is a valid approach and the findings are not expected to be affected. CEA performed a series of experiments in ventilated and unventilated small rooms to study helium distribution (as hydrogen surrogate for safety reasons) for several leak conditions (at ambient release pressure) (Cariteau and katschenko, 2012[7]), (Cariteau and Tkatschenko, 2013[8]). In (Cariteau and katschenko, 2012[7]) helium release through different nozzle sizes (5 and 20 mm) inside a closed facility was examined. The flow rate was ranged from 1 Nl/min to 350 Nl/min the main findings were:

- Distribution depends on Ri_v[1] number, which in turn depends on the facility volume and the leak velocity.
- The higher the volume and the lower the velocity the higher the Ri_v.
- At steady state for $Ri_v>1$ a stratified mixture is formed, for $Ri_v<1$ a stratified with homogeneous mixture on the top is formed and for Riv<<1 a homogeneous mixture is formed.

In (Cariteau and Tkatschenko, 2013[8]) helium was released through different nozzle sizes in a naturally ventilated facility. Different vent sizes were tested. The main findings are:

- Distribution depends on Ri_v number, which in turn depends on the facility volume and the leak velocity, and on the vent size and characteristics.
- $Ri_v>1$ result in a homogeneous layer on the top, for $Ri_v<1$ a homogeneous layer on the top increases, for $Ri_v<<1$ a homogeneous mixture is formed.
- The highest the vertical extension of the vent more quickly formation of the homogeneous layer

Based on the above, for a facility with **no ventilation,** the **larger the leak velocity** and the **smaller the volume** of the facility, the **more homogeneous** distribution inside the facility. For a **ventilated** facility with one vent, the **larger the leak velocity** and the **smaller the volume** of the facility the **larger the homogenous layer** in the upper part of the facility. The **greater** the vertical extension of the vent size the **slower the formation of the homogeneous layer**. Moreover, the thickness of the homogenous layer decreases with decrease of vertical extension of the vent and a more stratified mixture is formed in the lower part of the facility. In terms of safety, for the same total mass of hydrogen inside the enclosure a stratified mixture can lead to more severe explosions compared to homogeneous mixtures (Skjold et al., 2019[9]).

The pressure at the point of the release is another factor that influences hydrogen distribution. High-pressure releases will result in under-expanded jets and sonic flows. (Hooker, Hoyes and and Hall, 2014[10]) conducted experiments with compressed hydrogen release inside a ventilated facility and concluded that sonic flows lead to relatively uniform hydrogen distributions compared with subsonic releases at similar flow rates. The aim of the experiments was to evaluate the ventilation effect on hydrogen dispersion and thus different passive vent configurations were tested. The facility was also exposed to naturally varying wind and mimicked a warehouse with forklift trucks, a room with fuel cells, or a hydrogen storage room. The main findings of this work relevant to ventilation efficiency can be found in the section covering Ventilation.

High turbulence in the area of release can also affect the dispersion and lead to homogeneous mixtures (IFV, 2020[11]). Thus, the presence of obstacles in the environment where the leak takes place influences the dispersion of hydrogen but to a lesser degree compared to leak conditions. Obstacles in laminar flow can generate turbulence resulting in better mixing and uniform mixtures below the ceiling. On the other hand, in turbulent flow, obstacles disrupt vortices, causing the hydrogen jet to lose energy and decelerate, therefore reducing uniformity in distribution and leading to higher concentrations beneath the ceiling increasing the risks of explosion.

To define the hazardous zones, the downwind distance that mixture with a concentration above the Lower Flammability Limit (LFL) extends is a significant parameter. Based on recent experiments performed by Pro-Science (Grune et al., 2021[12]), for release pressure around 11.5 bar (ṁ=5 g/s, d=4 mm) the LFL distance of free jet is 2.7 m. For release pressure around 115 bar (ṁ=5 g/s, d= 1 mm) the LFL distance of free jet is little less than 2.5 m, while for the 21bar pressure (ṁ=1 g/s, d= 1 mm) the LFL distance is around 1.1 m. The results verify the dependence of the LFL distance to both the operating pressure and the leak size. Along with the experiments in a stagnant environment, (Grune et al., 2021[12]) conducted experiments in presence of co-flow, counter-flow and cross-flow highlighting the reduction of LFL distance with all three ventilation configurations (see Ventilation section).

Simple correlations can be used for a first estimation of the LFL distance. Based on the similarity law (Chen and Rodi, 1980[13]) in unobstructed jet releases in a stagnant environment the concentration at the jet centerline depends on the nozzle diameter and density. The following relation gives the released gas mass fraction with respect to the distance from the nozzle:

$$C^{m} = 5.4\sqrt{\frac{\rho_n}{\rho_a}}\frac{D}{x}$$

where C^m is the hydrogen mass fraction, ρ is the density, D is the nozzle diameter and x is the axial distance. Index n is for nozzle conditions and α for air. The above equation is valid provided that buoyancy effects are negligible. Thus, for buoyant gas releases, like hydrogen release, it stands only for distances close to the nozzle where momentum is dominant. Based on the similarity law, LFL distance increases proportional to leak diameter, so by decreasing the leak size you decrease proportionally the safety distance in unobstructed releases. Other factors like ventilation and wind can also affect the LFL distance and should be considered.

The similarity law can be expanded to compressed releases, if the density at the nozzle is properly computed. Considering that in high-pressure releases the pressure at the nozzle is higher than ambient, and the density of a gas increases with pressure, the similarity law implies that the axial distance of the LFL concentration is increased with increasing release pressure. This in turn means longer and more hazardous flames. Calculations in elab (https://fch2edu.eu/home/e-laboratory/)[2] show that for hydrogen release through a 5 mm nozzle from **350 bar** the 4% (LFL) distance is **32.6 m**, while for **ambient release** the LFL extends only to **2.5 m**.

Integral models can be also employed to predict the gas dispersion in simple geometries, like in HyRAM software[3] (Ehrhart et al., 2021[14]), (Groth and and Hecht, 2017[15]). More sophisticated tools, like CFD codes, can be used to predict hydrogen dispersion and flammable distances in the 3D domain in complex geometries, e.g. in presence of obstacles, where simple correlations and models will not work properly.

In unignited releases of hydrogen, the Pressure Peaking Phenomenon (PPP), first introduced by (Brennan and Molkov, 2013[16]) is also of concern in closed facilities, as it can result in overpressure exceeding enclosure or building structural strength limit in case of sufficiently high hydrogen release rate. Recent experiments by USN (Lach et al., 2020) demonstrated the relationship between ventilation area, enclosure volume, and release rate which may result in significant overpressures in an enclosure (max. measured overpressure of the examined cases was 8.05 kPA). The maximum release rate, hence TPRD diameter, should be regulated in RCS to protect humans and surroundings. The mitigation of the PPP can be achieved by either decreasing the TPRD diameter or increasing the area of the vents. However, the PPP mitigation measures should also account for tank-TPRD system rupture in case of fire. Similar work of (Lach and Gaathaug, 2021[17]) with ignited hydrogen release in confined space demonstrated that PPP from the jet fire is more hazardous compared to the PPP for unignited release from the same source, as it results in higher overpressures.

Ignition

In case of hydrogen leak, a flammable cloud may be formed that could be ignited. It has to be noted that 28.65 g of trinitrotoluene (TNT) is energetically equivalent to 1 g of hydrogen. Moreover, hydrogen is more susceptible to deflagration-to-detonation transition (DDT) than hydrocarbons (Rigas and P., 2013[18]) and (Lins and de Almeida, 2012[19]). The properties that play decisive roles in ignition are: flash point temperature, auto-ignition temperature, minimum ignition energy (MIE), the lower flammable limit (LFL) and the upper flammable limit (UFL). For ignition to occur certain criteria must be met: the gas or vapour cloud should be within its flammability range and an ignition source of sufficient energy should be present.

Ignition can be categorised as immediate and delayed ignition depending on the time when ignition occurs. **Immediate** ignition happens when a released jet ignites immediately after its leakage and results in jet fires or a fireball. The jet flame may be invisible and can injure people, damage objects and buildings, and possibly create secondary effects.

Delayed ignition is considered when the ignition occurs at some time after the leakage starts and when the vapour cloud has already been diffused and mixed with surrounding air. It is caused by an ignition source remote from the point of release. Delayed ignition can result in flash fire, deflagration and/or detonation. If the vapour cloud ignited is in the open, it could create a flash fire and in most cases no overpressure effects are to be expected- only heat effects (IFV, 2020[11]). In a confined space, an overpressure may be created, which could cause major damage in humans and buildings.

Ignition sources

For ignition to occur in the presence of a hydrogen flammable cloud, an ignition source has to be present to initiate the explosion. Some potential ignition sources are:

- Mechanical and electrical sparks
- hot surfaces, flames
- frictional heating
- adiabatic compression and shock waves
- electrical equipment, especially non-flameproof motors
- static electricity
- radio waves

The most common cause of ignition is an electrostatic discharge. Compared to spark discharges, brush discharges from electrical motors (having energy < 4mJ) are much less likely to cause an explosion (IFV, 2020[11]).

However, an early ignition can prevent elongated cloud formation that could lead to detonation. Although full elimination of ignition sources is a safe approach, it is not always possible and it should be considered in conjunction with the fact that if the cloud is not immediately ignited very large flammable clouds may be formed, especially in non-ventilated closed spaces, with the potential of severe explosions. At this point it should be noted that early controlled ignition (flaring) is usually not recommended as a safety measure in household applications of hydrogen. Early venting and hydrogen escape outdoors at high elevations without deliberate ignition should be sufficient and is the recommended approach rather than flaring. However, for depressurisation of pipelines flaring can be considered as the preferred option.

Ignition probability

The estimation of ignition probability is a key step in the quantitative risk analysis. To define the ignition probability for hydrogen releases we need to define the probability of a flammable atmosphere existing and then the probability of ignition of the flammable atmosphere.

In the study by (Moosemiller, 2011[20]), the probability of immediate ignition is the sum of the probability of auto-ignition and the probability of static discharge. Given that release temperature would be practically always lower than the auto-ignition temperature of hydrogen the probability of auto-ignition is assumed zero (IFV, 2020[11]). The ignition of static discharge depends on minimum ignition energy and release conditions, such as process pressure or release rate. Thus, the ignition probability for hydrogen release is given by,

$$P_{imm.ig} = 0.0024 \cdot \frac{(P)^{1/3}}{(MIE)^{2/3}}$$

where P is the pressure in psi and MIE is in mJ.

A delayed ignition probability is significantly affected by the vapour cloud size, the release duration and the vapour cloud location and the number of available ignition sources (Zhu, Jiang and Yuan, 2012[21]). In the study by (Moosemiller, 2011[20])a relationship has been developed in which the approximate probability of delayed ignition can be determined (IFV, 2020[11]) by,

$$P_{delayed} = 1 - \left[\frac{0.7}{(F_{MIE} \cdot F_{flow\ rate} \cdot F_{duration} \cdot F_{location})}\right], if\ (F_{MIE} \cdot F_{flow\ rate} \cdot F_{duration}) > 1$$

$$P_{delayed} = 0.3 \cdot (F_{MIE} \cdot F_{flow\ rate} \cdot F_{duration} \cdot F_{location}), if\ (F_{MIE} \cdot F_{flow\ rate} \cdot F_{duration}) < 1$$

$F_{location}$ in the above equations consists of the several sub-factors, such as $F_{room\ volume}$, $F_{ventilation}$, $F_{strategy}$ and $F_{electr.\ Classification}$. Relations to calculate these factors can be found in (IFV, 2020[11]).

In Purple book (Guidelines for Quantitative Risk Assessment in the Netherlands, Haag and Ale, 2005) the probability of delayed ignition caused by an ignition source accounts for the probability of the ignition source to be present and, thus, expressed by the following equation,

$$P(t) = P_{present} \cdot (1 - e^{-\omega t})$$

where P(t) the probability of an ignition in the time interval 0 to t (-), $P_{present}$ the probability that the source is present when the cloud passes (-), ω the ignition effectiveness (s-1), t time (s).

The ignition effectiveness, ω, can be calculated given the probability of ignition for a certain time interval. The Purple book gives a table with the probability of ignition for a time interval of one minute for a number of sources. However, those numbers are not well established and should only be used as a guideline.

Finally, in Purple book formulae to calculate ignition probability for a road or railway near the establishment or transport route under consideration and the probability of an ignition for a grid cell in a residential area in the time interval 0 to t are also given. For the ignition probability for a road or railway the average traffic density should be determined. The average traffic density is calculated based on the number of vehicles per hour, the length of the road or the railway section and the average velocity of the vehicle. For the ignition probability for a grid cell in a residential area the average number of people present in the grid cell is used. For more details, please refer to the Purple book.

Even though it is difficult to calculate the total as well as partial probabilities, because of lack of sufficient data (Tchouvelev et al., 2006[22]) and HYSAFE 2007 (Rodsaetre and Holmefjord, 2007[23]) have proposed a hydrogen ignition probability based on the leak rate and the pressure. Gas accumulation by confinement or extensive congestion is not considered. The proposed probabilities are presented in Table 7.2. However, in 2015 The UK Health and Safety Laboratory (HSE) concluded that no direct ignition probabilities could be derived for hydrogen from available literature.

Table 7.2. Hydrogen ignition probabilities

(Tchouvelev et al., 2006[22])			HYSAFE (Rodsaetre and Holmefjord, 2007[23])	
Hydrogen leak rate (kg/sec)	Immediate ignition probability	Delayed ignition probability	Hydrogen leak rate (kg/sec)	Immediate ignition probability
<0.125	0.008	0.004	0.01-0.1	0.001
0.125-6.25	0.053	0.027	0.01-1	0.001 + 0.001when P>100 bar
>6.25	0.23	0.12	1-10	0.01 + 0.01 when P>100 bar
Average	**0.097**	**0.05**	>10	0.1 + 0.01 or 0.02

Note: These figures are generic. In detail, the probabilities are application and location specific.

The **total ignition probability** is the sum of the average probabilities for immediate and delayed ignition. Based on (Tchouvelev et al., 2006[22])proposed probabilities of Table 7.2 the total ignition probability is estimated to be **14.7%.** This provides a complementary 85.3% probability of not igniting in case of accidental leak.

The probabilities proposed by (Tchouvelev et al., 2006[22]) are also used in (LaFleur et al., 2017[24]) and implemented in HyRAM risk tool.[4]

Consequences

In the case of ignition of a hydrogen cloud depending on the ignition delay the consequences could be jet fire, flash fire deflagration or detonation (see Ignition section). Ignition location also influences the explosion, as different conditions are met at different distances from the release (Houf et al., 2012[25]). Hydrogen concentrations determine the direction and spread of hydrogen flames. Flames burn upwards at 4 % v/v, since the propagation velocity of the flame is lower than the speed at which the hydrogen-air mixture rises, sideways at 6 % v/v and in all directions at 9 % v/v and over. The available amount of space necessary to develop the flame front is determined by the hydrogen concentration and the location of the ignition source in the confined space. The speed of hydrogen molecules in the plume travel is important. If the speed is greater than the speed at which hydrogen burns, the flame will not return in the direction of the release point. Therefore, upon ignition at LFL, only a fraction of hydrogen present burns, very little heat is produced and there is no build-up of pressure (Molkov, 2012[26]).

The explosion of a hydrogen-air mixture cloud results in the formation of a pressure wave. Hydrogen concentrations of up to 10 vol % result in hardly any overpressure. A mixture with near-stoichiometric conditions (30% v/v) is among the worst-case scenarios keeping all other parameters the same. Generally, concentration levels ranging from 25-42 % v/v are considered of great risk as high burning velocities are developed resulting in high overpressures. The magnitude of the generated overpressure in a confined space depends inter alia on hydrogen concentration, size and geometry of the space, the presence and size of any openings and the level of congestion of the environment.

In the deflagration of a free hydrogen-air gas cloud, the maximum overpressure is in the order of 10 kPa. An overpressure of 7 kPa is still considered not dangerous, as it is the threshold of people falling down to the ground (HySafe, http://www.hysafe.org, Hydrogen fundamentals).

To assess the magnitude of consequences in case of hydrogen ignition, i.e. pressure and thermal hazards, several experimental and modelling studies have been performed in the past. Based on a non-exhaustive literature review on hydrogen combustion and fire experiments, next, we discuss some of these studies and their main findings in terms of safety. More discussion and dedicated conclusions to the specific scenarios/applications are given in *Mapping Exercise* section.

Pressure hazards

In 2019, GEXCON performed gaseous hydrogen release inside a container with obstacles and vented explosions (Skjold et al., 2019[27]), (Skjold et al., 2019[28]). In (Skjold et al., 2019[27]) a homogenous mixture of 15 % v/v H2 was ignited inside a 20 m^3 ISO container with openings. The effect of obstacles was also examined. The lean mixtures and simple geometry configuration resulted in weak explosions and modest effect of the obstacle on flame acceleration and pressure development. The maximum measured overpressure was 7.7 kPa with pressure impulse 530–620 kPa·ms and was developed in the presence of obstacles. In (Skjold et al., 2019[28]) the vented explosion of non-homogeneous mixture was examined and the main findings of the work in terms of safety are:

- A stratified mixture is produced, which is more evident after the end of the leak, with peak values lower than near-stoichiometric mixture (about 15-28 % v/v in the deployed sensors).
- The stratified mixture inside confined spaces can lead to more severe explosions.
- Obstacles, like the pipe rack that can be used as hydrogen storage, can somewhat increase overpressure.
- Maximum overpressure 60 kPa (when the mixture ignited at peak concentration). The overpressure at most sensors is 40 kPa, which means 50% probability of eardrum rupture.

For H_2 release experiments from storage at a pressure 4 MPa through a 12 mm diameter hole and storage volume 5 m^3 (Daubech et al., 2015[29]) the LFL jet centreline distance was more than 17 m. Ignition of the cloud at 1.8 m, where hydrogen concentration was around 30% (near-stoichiometric mixture), generated a maximum overpressure of 8 kPa at 2 m downstream the ignition position (threshold of skin lacerations by missiles, window glass shatters, light injuries from fragments).

Experiments performed by FM Global (Bauwens, Chaffee and Dorofeev, 2011[30]) inside a 64 m^3 chamber to compare the combustion consequences among hydrogen, methane and propane. The experiments involved ignition of 18% vol. hydrogen–air, 9.5% methane–air and 4.0% propane–air mixtures at two different locations and two vent sizes. These experiments showed that, despite having similar laminar flame speeds, the hydrogen mixtures propagated at flame speeds significantly higher than the methane and propane mixtures. Due to the higher propagation speeds of the hydrogen flames, significantly higher overpressures (up to 30kPa) were generated during the vented explosions when compared to the methane and propane mixtures. Moreover, the **larger the vent size** the **lower the pressure** was.

The above finding on the dependence of overpressure on vent area is also supported by (Chen et al., 2020[31]), who showed that the deflagration overpressure decreases with the increase in the vent area. The raised vent location may affect the pressure development during explosion venting. Moreover, in the same study it was shown that with the increase of the volumetric blockage ratio inside the chamber, the maximum overpressure and flame velocity become higher. The behaviour of the non-homogenous hydrogen deflagration is controlled by the maximum hydrogen concentration in the chamber, but the maximum overpressure and flame velocity for the non-homogenous mixture are slightly lower than those for the homogenous mixture with the same maximum concentration. The maximum overpressure measured inside the empty chamber increases as hydrogen concentration increases from 15.3% to 20.2%.

The effect of blockage ratio on overpressure was also examined and verified by (Schiavetti and Carcassi, 2021[32]) examining different obstacle configurations. It was shown that **increasing the blockage ratio** the maximum **overpressure** also **increases**, nevertheless, for the tested configurations, the effect of repeated obstacles on the increase of maximum peak pressure is higher than that of increasing blockage ratio.

To similar conclusions was led the study of (Chen et al., 2020[33]) based on experiments inside a 27 m^3 chamber with different vent areas and different mixtures (uniform hydrogen-air mixtures with concentrations ranging from 15 % to 21 % and stratified mixtures with maximum concentrations equal to average values of uniform mixtures). Among their findings were those: both **maximum hydrogen concentration** and **hydrogen inventory** inside the chamber **affect the external pressures** during **non-homogenous** hydrogen deflagrations, but t**he maximum hydrogen concentration is the dominant factor.** Higher volumetric blockage ratio leads to higher external pressures. The **obstruction has a significant influence** on the external pressures during non-homogenous hydrogen deflagrations when the volumetric blockage ratio inside the chamber is large enough, but its effect is **much stronger for the homogenous deflagration**.

Fire and thermal hazards

The above studies examined the pressure hazards in case of hydrogen ignition. However, another consequence is fire and thermal hazards. The radiation heat flux in the case of a hydrogen fire may harm people and buildings depending on its magnitude and its dose.

In the case of an expanded jet fire the hydrogen flame length is proportional only to the leak diameter based on (Hottel and and Hawthorne, 1949[34]) and (Hawthorne, Weddell and and Hottel, 1949[35]). However, the work of (Kalghatgi, 1984[36]) that studied experimentally both with subsonic and sonic hydrogen jet flames concluded that for both flows: 1) the **flame length increases with the mass flow rate** at a fixed diameter, and 2) the **flame length increases with the diameter** at fixed mass flow rate.

In e-lab (https://fch2edu.eu/home/e-laboratory/) there is a validated correlation available that calculates the flame length and hazard distances depending on chosen hazard criteria for both expanded and under-expanded jets (subsonic and sonic flows, respectively). For instance, for storage at very high pressure, 350 bar, ambient temperature and 2 mm nozzle the flame length is 5.2 m, the no harm separation distance (70°C) is 18.2 m and the pain limit separation distance (5 mins, 115°C) is 15.6 m. The HyRAM tool also has the capability to calculate thermal hazards (heat flux and temperature maps) from hydrogen jet flames using well validated models of flame physics.

Another concern of hydrogen is the risk of transition to detonation (detonation propagation velocities are higher than speed of sound), which will under certain circumstances create a significant pressure impulse to the human and surrounding civil structures. A H_2-air mixture deflagration (subsonic burning velocities) is likely to eventually develop into detonation during accidents because hydrogen has shorter Deflagration to Detonation Transition (DDT) distance compared to other fuels (Li, 2018[37]), (Li et al., 2021[38]). Thus, in case of delayed ignition, where better mixing is achieved, or if the combustion is enhanced by external obstacles, the deflagration could develop into detonation with severe consequences.

Studies for hydrogen detonation in confined spaces have been performed with the aim to estimate the threshold for onset of detonation and the generated overpressure (Groethe et al., 2007[39]), (Kuznetsov et al., 2015[40]). However, no generic results are able to be extracted as they vary with the experimental conditions. For instance, in the experiments of (Groethe et al., 2007[39]) involving hydrogen combustion in a sub-scaled tunnel with the hydrogen premixed with air and confined in a plastic film barrier the maximum overpressure was 150 kPa and was measured at the outlet of the tunnel. On the other hand, in (Kuznetsov et al., 2015[40]) an experiment was conducted in a flat semi-confined layer with gradient hydrogen concentration and the measured overpressure was in the order of magnitude of 1 MPa.

Tank rupture

In the event of fire and failure of TPRD activation or unaffected TPRD due to localised fire, hydrogen tanks can rupture causing harm to humans and damages to structures. The level of harm and damages is assessed by pressure effects of the blast wave (pressure and impulse) and thermal effects by the fireball. Tank rupture is caused by pressure increase inside the tank that could not successfully be vented. Fire close or around the tank can lead to tank rupture.

(Makarov et al., 2021[41]) presented a brief review on hydrogen tank rupture experiments and the resulting fireball size. Two fire tests were performed in the USA (Weyandt, 2005[42]), (Zalosh and Weyandt, 2005[43]), (Weyandt, 2006[44]), (Zalosh, 23–27 April 2007[45]). The tanks considered in these tests were Type III[5] and Type IV[6] with volume 72.4 and 88 lt and pressure 34.3 MPa and 31.8 MPa, respectively. Two more experiments were performed in Japan (Yosuke et al., 2006[46]) on tanks Type III and IV with nominal working pressure 70 MPa. Finally, two tests with compressed hydrogen Type III tanks rupture in a fire were conducted by (Shen et al., 2018[47]). At both tests the tank pressure was 35 MPa.

The maximum fireball diameter based on the above experiments was 24 m resulting from 35 MPa storage pressure and 88 lt volume (1.89 kg). The time that tank withstood rupture varied based on experimental conditions from 6 min and 27 sec to 21 min and 21 sec.

(Makarov et al., 2021[41]) also presented correlations for the calculation of fireball size based on hydrogen tank mass showing a positive correlation. A conservative model that correlates fireball size from high-pressure gaseous hydrogen tank ruptures with hydrogen mass in power ⅓ is suggested in (Makarov et al., 2021[41]).

The leak-no-burst (LNB) safety technology (Molkov, Makarov and Kashkarov, 2019[48]) for explosion free in a fire tank that has been developed by HySAFER Centre of Ulster University may resolve the issue with TPRD failure, as it does not require TPRD (TPRD-less tank). This, in turn, reduces drastically the risk of blast wave, fireball, long flame and pressure peaking phenomenon in confined spaces. This technology provides a level of risk of hydrogen-powered vehicles below that of the fossil fuel vehicles (HyResponder, 2021[49]). The main breakthrough of the LNB technology is that in case of fire hydrogen leaks through tank walls safely as insignificant leak before tank walls exceed the load bearing limit preventing rupture from happening. This is achieved by using at least two composites with different thermal properties, an external part with lower thermal conductivity and an internal part with higher thermal conductivity. The thermal parameters of the liners and their thickness are such to allow melting of the liner before resin decomposition front reaches the load-bearing fraction of the wall thickness. As an additional safety measure, TPRD can also be integrated, but with a much smaller diameter resulting in the creation of a smaller flammable cloud in case of activation. The prototype of this technology has been successfully tested.

Safety strategies

The design and implementation of efficient safety strategies in hydrogen applications and infrastructures is a key element for the safer use of hydrogen technology. There are several prevention and mitigation measures that can be applied for hydrogen following certain criteria to address its behaviour. The principle of safe-by-design, e.g. for HFCV, is the fundamental risk prevention approach. The safe-by-design aims at addressing safety issues during the R&D and design phases of new technologies and can potentially reduce the need of mitigation measures, maintenance, etc. Nonetheless, since it is not always possible to exclude the possibility of equipment failure, human error or malicious attacks, the design of measures to reduce the consequences in case of an accident is mandatory.

General recommendations on safety strategies for hydrogen technology are:

- reduction of the inventory in storage facilities on-site refuelling stations
- use of safety distances
- installation of safety valves, such as excess flow valve, emergency control valve, pressure indicators in compressors
- reduction of the TPRD size (while using proper fire resistance to tank) to avoid hydrogen concentrations above LFL on the ceiling
- oblique TPRD orientation, e.g. at 45 degrees downwards
- perform regular inspections and maintenance in all components (and especially joint parts) in hydrogen systems to reduce the risk of a leak
- proper design, installation, use and maintenance of detection sensor and alarm system
- ventilation (natural or mechanical)
- ensure sufficient distance of main tunnel and elements, like dust collectors and exhaust fans, that can trap hydrogen in flammable concentrations
- elimination of ignition sources, if possible, close to the ceiling, where accumulation of hydrogen is expected
- limit congestion inside closed facilities as high blockage ratio accelerates the flame and leads to higher deflagration overpressure
- avoid obstacles on the ceiling that could lead to accumulation of hydrogen above LFL
- proper installation of fire protection walls and barrier walls in HRS
- use of fire suppression systems, such as water mist to mitigate the consequences in case of fire and explosion and/or prevent the fire spreading

The next sections present further details on the installation of detection sensors and on ventilation based on existing knowledge.

Detection sensors

Hydrogen detection sensors are risk mitigation devices. They can detect a flammable atmosphere in case of an accidental leak and dictate/initiate certain actions, like activation of shutdown valves or activation of the alarm system. Optimal installation of the sensors includes the selection of the appropriate sensor technology type, number and positioning, and their calibration and maintenance. General recommendations on the installation of hydrogen detection sensors are:

- Be able to **detect hydrogen leakage** and isolate the supply in an enclosed space **before the hydrogen concentration reaches 15%** (when more severe consequences occur if ignited). Generally, low alarm levels need to be considered equal to 10% of the LFL and/or 25% of the LFL.
- **Sensors should not be placed on a direct path of the airflow** from the air inlet to the exhaust fan.
- **Locations close to the floor may not be practical** since their expected concentration levels are on the borderline of practicality and reliable sensor detection threshold.
- **Locations below the enclosure ceiling** thus not obstructed by the ceiling piping and lighting fixtures or other objects are preferred.
- Use simultaneously different detection technologies, such as ultrasonic, electrochemical, etc. (HSE, 2017[50]) in compliance with ATEX regulations. Application of different gas/leak detection algorithms in addition to the use of a basic alarm threshold (e.g. low and high) is also recommended by UK HSE (HSE, 2017[50]).

Ventilation

Ventilation is considered a good practice to control health and safety hazards. Ventilation can be either natural or mechanical (using systems which are in compliance with ATEX regulations). Proper ventilation design and operating conditions are the key factors for an efficient system and are determined by the characteristics of hydrogen dispersion and combustion.

The EU-funded project, HyIndoor (www.hyindoor.eu), whose aim was to develop safety design guidelines, engineering tools and RCS recommendations for the safer use of hydrogen indoors, presented a series of ventilation strategies based on the conducted research. Next, we present some recommendations based on HyIndoor and other existing knowledge (Grune et al., 2021[12]), (Giannissi et al., 2015[51]), (Giannissi, Tolia and Venetsanos, 2016[52]):

- **Large openings** enhance ventilation (and the overpressure in case of ignition decreases with increasing vent size)
- **Vents with large vertical extension size** are preferred:
  - The larger the leak velocity and the smaller the volume of the facility the larger the homogenous layer in the upper part of the facility with one vent.
  - The larger the vertical extension of the vent size the slower the formation of the homogeneous layer.
  - Thus, vents with large vertical extension size promote the formation of homogeneous layers and provide better ventilation compared to vents of the same area but horizontally stretched (height < length).
- **Multi-vent** configurations provide much more efficient ventilation than single-vent configurations
- The larger height difference between multiple vents is, the more efficient is passive/natural ventilation
- Vertically stretched vents (height > width) provide better ventilation compared to horizontally stretched vents of the same area based on CFD simulations
- For single vent configuration, a **wall vent** can provide more efficient ventilation than a chimney vent of equal area
- If practical, the ventilation system should be designed to prevent concentrations exceeding LFL for realistic expected hydrogen release rates
- **Co-flow, counter-flow and cross-flow** can reduce the distance that mixture within H_2 lower flammability limit (LFL) extends
- **External wind** can either enhance or hinder ventilation depending on the vent configuration and the wind direction in respect to the vent. Several vents distributed on all sides of the enclosure (both at the top and the bottom) help to ensure that wind would enhance ventilation regardless of its direction
- Simple models can give reasonable predictions in multi-vent configurations.

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Notes

[1] $Riv=g*(\rho_{\alpha}-\rho_{0})/\rho_{0}*V^{1/3}/U_{0}^{2}$.

where V is the volume of the facility, U the velocity, ρ the density, index α is for air and 0 for release conditions.

[2] e-Laboratory is a virtual laboratory with tools for hydrogen behaviour and fuel cells (HFC) from a physical, an economic or a safety perspective. Free registration is required to get access.

[3] Available at: https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/hyram/.

[4] Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/hyram/.

[5] Type III tanks: metallic liners fully wrapped with fibre resin composite.

[6] Type IV tanks: polymeric liner fully wrapped with fibre resin composite (max. pressure 70 Mpa).

8

Mapping exercise

The mapping exercise presents scholarly output, including experimental and modelling studies, relating to six selected scenarios of hydrogen-related accidents. The main conclusions from the study of the literature and identified knowledge gaps are also discussed for each scenario.

Scenario 1 – Production: Leakage from the pipe connected to electrolyser

Hydrogen production can be onsite or offsite, with the former more suitable for refuelling stations that are far away from external hydrogen sources, together with a lowered expense for hydrogen transportation; while the later produces hydrogen at large scale that is then delivered through tube trailers, LH_2 trucks or hydrogen pipelines (Tian et al., 2021[1]). (Tchouvelev et al., 2006[2]) pointed out that on-site water electrolysis presents a lower societal risk as well as a lowered risk for individual harm exposure as compared with on-site steam methane reforming (SMR). Other technologies (Kalamaras and Efstathiou, 2013[3]) used for hydrogen production include oil/naphtha reforming and coal gasification etc.

Despite the fact that water electrolysis is a greener method[1] for hydrogen production if the electricity used is from a renewable source or fossil fuels equipped with carbon capture, utilisation or storage (CCUS) technologies, it only represents a very small proportion of world's hydrogen production (IEA, 2021[4]). Electrolysers for water electrolysis can operate under either acidic or alkaline conditions. **Alkaline electrolyser** including anion exchange membranes (AEM) is a more mature technology, with most large-scale plants (up to 165 MW) built between 1920s to 1980s in response to hydrogen demand for ammonia industry[2] (Krishnan et al., 2020[5]). Other technologies, including **proton exchange membrane (PEM)** and **solid oxide electrolyser cell (SOEC)** are gaining market traction as they expect to be either more flexible or efficient, and hence have a smaller footprint (IRENA, 2018[6]). Nonetheless, **alkaline products still dominate the market** and Bloomberg estimates them to account for 75-78% of the shipments in 2022. Being cheaper than newer technologies, alkaline electrolysis is also more suitable for large-scale projects, more of which are set to start construction in 2022 (BloombergNEF, 2022[7]).

Table 8.1. The three main types of electrolysers with their characteristic parameters and typical operating conditions

Type	Temperature (^{O}C)	Pressure (MPa)	Cold Start (IRENA, 2021)
Alkaline	60-220	<3.4	< 50 minutes
PEM	40-80	<3.4	< 20 minutes
SOEC	600-1 000	1	> 600 minutes

Note: Based on key performance metrics of the largest device available of European suppliers.
Source: (Gallandat, Romanowicz and Zuettel, 2017[8])

In some countries, code and standards on hydrogen generators are already in force.[3] For example, the Chinese standard defines a safety distance of **2 m between the electrolysers**. While determining the minimum distance, the size of the electrolyser and its production rate is of importance as well. This is because the size determines the production rate. Furthermore, international standard ISO 22734:2019 defines the construction, safety and performance requirements of hydrogen generators that use electrochemical reactions to produce hydrogen.

In general, the major risk factors of an electrolysis hydrogen production plant consists of: 1) a chemical component (electrolyser); 2) mechanical component (compressor. *etc*) and 3) storage component for temporary storage (Zarei, Khan and Yazdi, 2021[9]). Also noteworthy are 4) power electronics, and 5) the energy source. In the next sections, first, a holistic picture of risks associated with hydrogen production sites, quoting results from 3 independent sources, is provided. Then, the major risk contributor (compressor) is identified. Afterwards, a discussion on hydrogen pipeworks[4] within a production site focusing on pipes connected to electrolysers, is presented.

General concerns on hydrogen production site (Electrolysis)

Two risk analyses on hydrogen production site (Zarei, Khan and Yazdi, 2021[9]), (Kasai et al., 2016[10]) suggests that most root events that may lead to accidents can be either eliminated or reduced to low risk following current recommended safety measures, such as use **safety valves (**pressure relief valve *etc*) to provide extra security, **sensors** (Tchouvelev et al., 2021[11]) to monitor reaction conditions, **fire wall** (Schefer et al., 2009[12]) to reduce eventual loss following an explosion. Nonetheless, there are two scenarios that cannot be eliminated under current risk measures, namely the crashing of an aircraft/helicopter or collapse of a crane into the facility.

Moreover, **energy-related Service Accident Database** (ENSAD) recorded 43 accidents related to hydrogen production, which represents 25% of all hydrogen-related accidents between 1995 and 2014 (Spada, Burgherr and Rouelle, 2018[13]). None of these accidents recorded any hydrogen release. Calculations by the same authors also suggested the current practice of hydrogen production is associated with **a lower normalised risk**[5] for fire/explosion as compared with traditional energy productions (oil, coal and natural gas). Nonetheless, the accidents cost one life, 56 injuries and property damage at ca. 4.4 million euros.

Analysation of incidents in additional 2 databases (HIAD[6] 2.0 and H2tools) concludes that the risk associated with electrolysers are small compared to compressors and pressurised storage (FCH2JU, 2020[14]).[7] (Skjold et al., 2017[15]) suggest that **compressors** are the **major risk contributor in hydrogen production plants**.[8]

Database H_2tools recorded 5 accidents related to compressors Table 8.2, 2 resulted in fire, out of which one accident required emergency shutdown of the plant. It was suggested improving leak detection can prevent escalation and hence reduce the risk.

Table 8.2. Hydrogen compressors-related accidents in H2tools database

Accident causation	Additional lessons learnt	No. accidents
Failed pressure switch	Stop-valve at Storage vessel to prevent escalation	2
Damaged Component	Check components' H_2 compatibility	3

Pipeworks, focus on those connected to electrolysers

A Sandia report on a *hydrogen plant located near nuclear power plants* scenario (Glover, Baird and Brooks, 2020[16]) discussed potential hazards and risk associated with the pipeworks connected to the electrolyser. In the setting, a steam pipe enters the electrolyser at 0.5 MPa and the pressure was assumed to be maintained until reaching the separator vessels. After which the purified hydrogen is pressured in 2 steps to reach 2.2 MPa for delivery. A Bayesian statistical model was then developed based on hydrogen data for compressors, cylinders, hoses, joints, pipes and valves, with all other data coming from offshore oil industry. Connecting pipe leaking frequency ranging between $2.99 \cdot 10^{-9}$ m^{-1} $year^{-1}$ for very small leakage and $3.13 \cdot 10^{-10}$ m^{-1} $year^{-1}$ for rupture at 95% confidence level. These values **fall within the range advertised by the purple book** (Uijt de Haag and Ale, 2005[17])**,** suggesting a low risk of hydrogen leakage from the pipework connecting to the electrolyser.

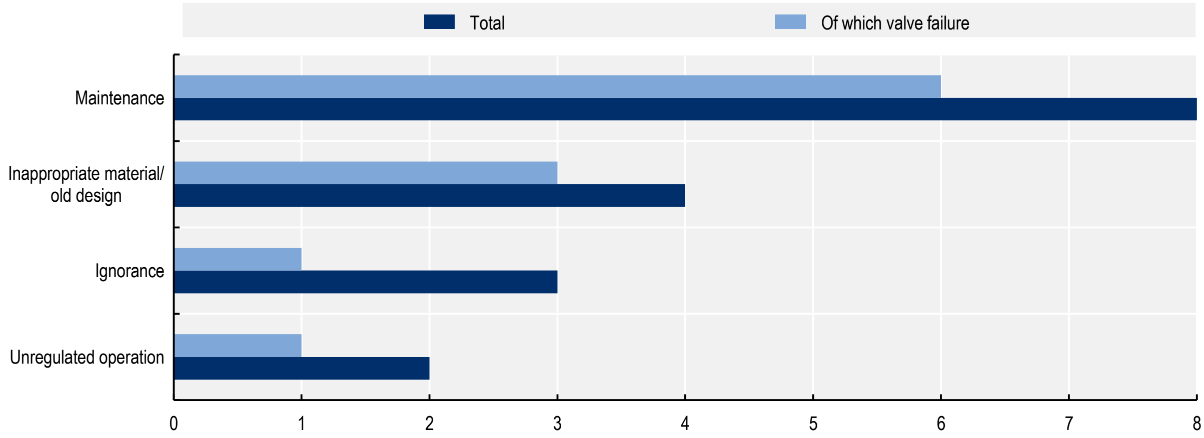
In addition, analysis on a laboratory accident together with a computational simulation (Ichard et al., 2012[18]) suggests that in a confined space[9] with good ventilation, **minor release of hydrogen should not cause major safety concerns** as long as current safety measures on hydrogen are followed, which include restrictions in the bottle/regulator system, significant distance to the ceiling, limited total gas inventory *etc*. The study reasoned that hydrogen mixes well with air and upon leakage so that hydrogen concentration drops below its ignition limit quickly. In their simulation, only 9% of the room has a hydrogen concentration above 4% (ignition limit) 30 s after leakage.

Hydrogen accidents data in database **HIAD 2.0** suggest that 84% of hydrogen-related accidents are of fire/explosion type (FCH2JU, 2021[19]). This is due to hydrogen's unique chemical properties such as tendency to escape due to small size, low ignition energy, and wide flammability range. It suggests that simulation work may be optimistic or that minor, unintended releases that caused no harm tend not to be reported. The latter is in line with a report from *Air Liquide* (Campbell, 2005[20]), which suggests that "**small leaks are hard to detect**".

For "worst-case scenario", a computational simulation of large-scale hydrogen jet fire[10] from pipework (Jang and Jung, 2016[21]) shows a rapid fire expansion from ignition to 3 s, and later on reaches equilibrium at 22 s. In addition to the fire, the simulation indicates radiation heat also causes critical consequences for humans as well as facilities. Another simulation[11] (Matthijsen and Kooi, 2006[22]) calculated the individual risk (IR) 10^{-6} contour (purple book) at 4.5 m for in-plant pipeworks i.e. a distance of 4.5 metres should be maintained to keep the risk of personal injury lower than 10^{-6} per year.

Finally, incident data relating to pipework failure from database H_2tools are summarised in Figure 8.1. In 17 accidents reported, 11 are related to valve failure highlighting the importance of regular preventive maintenance. All accidents (4) that involve fire/explosion and injuries were dated before the 1990s when modern valve design and safety regulations were not available. The only accident involving death (1992) was in a laboratory setting which lacked hydrogen detection sensors.

Figure 8.1. Analysis of hydrogen pipework-related accidents in H2tools database



Conclusions and knowledge gaps

The main conclusions based on the literature review related to Scenario 1 are:

- Alkaline water electrolysis represents a **mature technology** with most large plants built between 1920s-1980s.
- Risk analysis on hydrogen production plants and suggested that **most initiating events can be reduced/eliminated** following existing risk mitigation measures.
- Current hydrogen production presents **a lower normalised risk** for fire and explosion as compared to the production of oil, coal and natural gas.
- The Chinese standard requires a safety distance of **2 m between the electrolysers**.
- Three accident databases (ENSAD, HIAD 2.0 and H_2tools) were analysed: in ENSAD, no hydrogen release was reported for production site accidents; HIAD 2.0 data suggest **the risk associated with electrolysers are small** compared to compressors and pressurised storage; For H_2tools, no

accidents that can relate to Scenario 1 were reported after 1990. However, these databases do not provide complete coverage and so any observations should be taken with some caution.

- A Sandia report used Bayesian statistics to estimate the risk for leakage from pipelines connected to the electrolyser using hydrogen-specific leakage data; the estimated risk is **within the boundary** set by the Purple book ($5 \cdot 10^{-6}$ m^{-1} year $^{-1}$).
- Scientific studies suggest that minor hydrogen release should not cause safety concerns. Computational simulation calculated the IR 10^{-6} contour (distance for a 10^{-6} probability of injury each year) to be 4.5 m for in-plant pipeworks.

Gaps

Based on the above remarks, it can be concluded that current research identifies that risk associated with Scenario 1 is within the boundary set by the purple book. Nonetheless, we recommend an up-to-date review of available hydrogen accident databases to follow the current development and hence complement the literature review.

Scenario 2 – Pipeline transport: leakage from high pressure pipeline

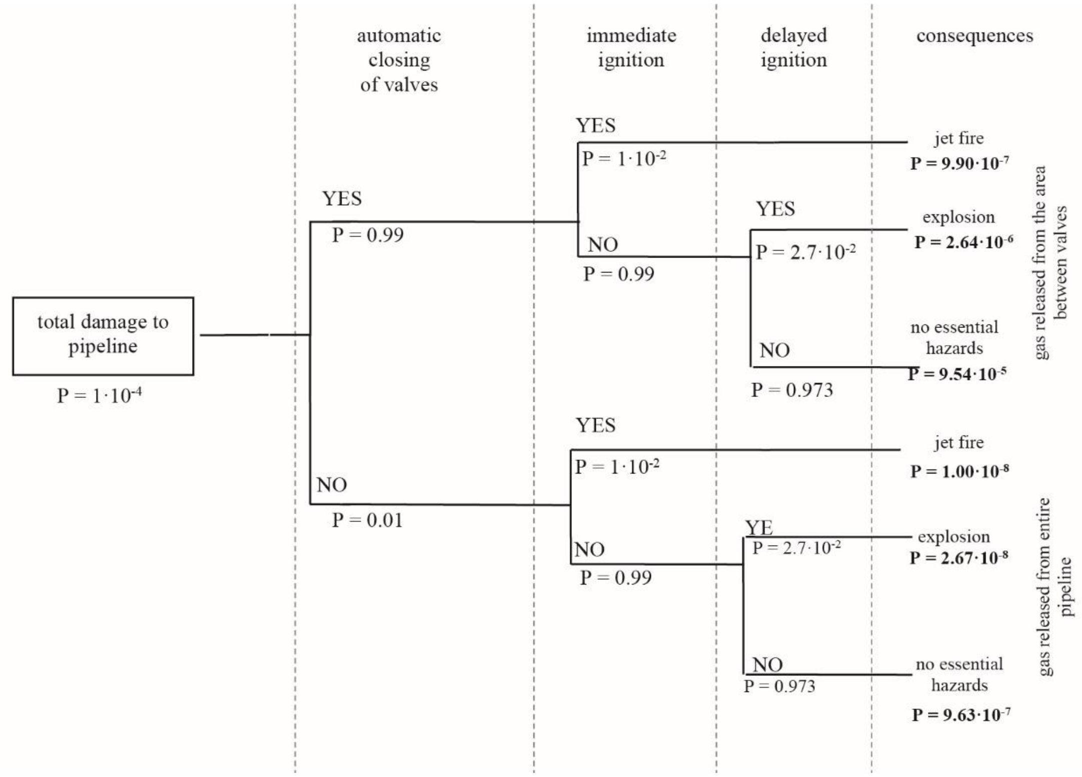
The studies included in this scenario analyse the transport of gaseous hydrogen through high-pressure pipeline and the safety measures that should be taken into account. The research focuses on ignition, leakage and explosion likelihood, the potential damages on buildings, people and the necessary safety distance to prevent these hazards. Quantitative research and experiments, alongside models verify the impact of the consistency and material of the tube, the ground soil, the internal flow and the position of the pipeline, whether buried or over ground, on the aforementioned hazards.

Hydrogen by nature is lighter than natural gas and air and its leakage from pipelines is approximately 1.3 to 2.8 times larger than methane leakage and four-times than air under the same conditions (Rigas and P., 2013[23]).

As evidence from Figure 8.2, hazards occurring on a hydrogen transport high pressure pipeline -likewise similar pipelines with flammable gases can lead to major consequences.

When analysing leakage rate and dispersion, it has to be considered that hydrogen diffusion in air is larger than natural gas. It presents a higher diffusion coefficient and greater volumetric flow rate compared to methane for the same pressure and leak size (Lowesmith et al., 2009[24]). Liquefied hydrogen confined, for instance, in a pipe between two valves, will eventually warm to ambient temperature, resulting in a significant pressure rise. However, transport pipelines do not transport liquified hydrogen. Standard storage system designs usually assume a heat leak equivalent to 0.5 %/d of the liquid contents. Considering liquefied hydrogen as an ideal gas, the pressure resulting from a trapped volume of liquefied hydrogen at one atmosphere vaporising and being heated to 294 K is 85.8 MPa. However, the pressure is 172 MPa when hydrogen compressibility is considered (Rigas and P., 2013[23]).

Figure 8.2. Event tree for damage to a hydrogen transport pipeline



Source: (Witkowski et al., 2017[25]).

An incident consisting in a pipeline failure can lead to several consequences, resulting in serious damage to humans and properties in the surrounding area. Many factors play a role in identifying a hazard area related to the damage, being: the type of failure, hole size, length, and operating pressure of the pipeline, in addition to the time to ignition, meteorological conditions, the ground soil, and the pipeline position. The flow in case of hydrogen leakage through a hole can be characterised to be either choked and or unchoked depending on the release speed (sonic or subsonic flow).

The release rate of high-pressurised hydrogen from a leak in the pipeline depends on the operating pressure, the pipeline diameter, and the length of pipeline from the supply point to the failure point. Due to large differences between the pipeline and its outside ambient, the flow conditions at the release become critical, so that a sonic flow will release from the failure point (Dagdougui et al., 2010[26]).

From the experimental point of view, to estimate the scale of damage to people and buildings caused by high-pressure hydrogen pipeline explosions (Russo, De Marco and Parisi, 2020[27]) conducted a probabilistic risk assessment. The release of hydrogen is simulated using the LimitState:SLAB model. The software tool is a slab analysis tool. To systematically automate the well-known yield line method. First, the size of the hydrogen-air cloud in the flammability range is evaluated and then the overpressure and impulse generated by the blast are evaluated through the Netherland Organisation for Applied Scientific Research (TNO) model. Finally, explosion effects on people and buildings are estimated through probit equations and pressure–impulse diagrams. The study (Russo, De Marco and Parisi, 2020[27]) took into account different relevant effects, from direct and indirect for people to different damages depending on the types of buildings. Proposals for mitigation and prevention systems are featured, alongside distance safety measures, considering both EU guidelines and HSE's.

The simulations were performed assuming various pipeline geometric characteristics and operating parameters (diameter, temperature, and pressure), various properties of the release source (e.g., hole diameter, distance from the compression station, and distance from the explosion centre), different atmospheric conditions (e.g., wind speed and Pasquill–Gifford atmospheric stability class), and explosive class. The blast probability was calculated using statistical data on the operating properties of pipelines for H2 transmission gathered from the available literature. The information from Air Liquide was used for the failure frequency of hydrogen pipelines per length of pipeline. The value was assumed to be 0.126/year/1 000 km. Finally, the data of the European Gas Pipeline Incident Group (EGIG) were used to determine the frequency of the various sizes of breach. It was defined as follows: a small breach is one with a hole diameter smaller than or equal to 0.02 m; a medium breach is one with the hole diameter larger than 0.02 m and smaller or equal to the diameter of the pipe; and rupture is when the hole diameter is larger than the pipe diameter.

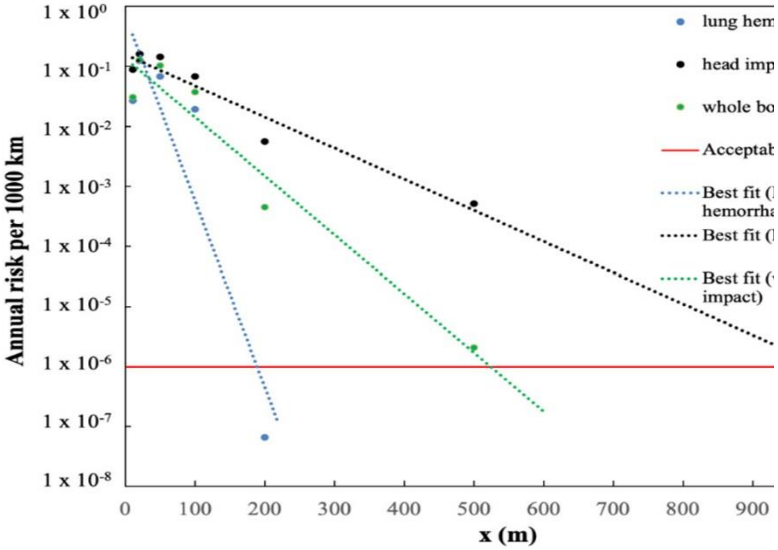
For what concerns blast damage to people, direct and indirect effects are generally distinguished. On the one hand, pressure-sensitive organs (e.g., lungs and ears) can be damaged by a change in pressure. On the other hand, a person can be indirectly involved in the explosion and suffer from indirect damage, such as the impact from flying fragments generated by structure damage or collapse. In addition, people can be thrown away from the overpressure, with a possible subsequent impact.

The European Industrial Gases Association (EIGA) defines harm criteria as being approximately a 1% chance of individual risk of serious injury or fatality and proposes the individual harm exposure threshold for determining safety distances of $3.5 \cdot 10^{-5}$ /year. The UK Health and Safety Executive (HSE) has specified risk criteria as follows: for workers, maximum tolerable risk is 10^{-3} per year; for the public, 10^{-4}/year; broadly acceptable risk, 10^{-6} /year. The Netherlands has its own tolerable risk criteria as detailed in section "Zoning safety measures" below.

A minimum safe hazard distance between pipelines and populated areas equal to 1 000 m is calculated from comparison with the harm criteria (see Figure 8.3) for certain types of pipeline. It should be pointed here that the safety distance of 1 000 m is prescriptive only.

In the study of (Russo, De Marco and Parisi, 2020[27]) and is calculated based on the particular assumptions made in the QRA. It can be considered as a conservative distance.

Figure 8.3. Annual risk per 1 000 km of damage to people vs. safety distance (m), in the case of blast strength 9 and atmospheric stability class F2



Source: (Russo, De Marco and Parisi, 2020[27]).

Zoning safety measures

In the Netherlands a zoning policy is in place as a safety measure to prevent major accidents and consequences to people and buildings. This follows an approach aimed at reducing the risk through safety measures at the source of risk. To determine the zoning policy and set the criteria limits for pipelines, the individual risk as a measure of the level of protection to each individual member of the public, and the societal risk as a measure of the disaster potential for the society as a whole. The first is determined with the risk fatality per year, i.e. the probability that an unprotected person residing permanently at a fixed location will be lethally wounded as a result of an accident occurring at a source of risk. The societal risk is the probability of exceeding a certain yearly amount of casualties.

For vulnerable object like schools and hospitals the individual risk limit is 10^{-6} / year

For less vulnerable objects the above number is a guidance value.

For transport routes the limiting frequency (Flim) per kilometre of pipeline for the occurence of an accident with death (N) casualties is: Flim x $N^2 = 10^{-2}$ (Laheij and Theune, 2010[28]).

A similar analysis completed by (Witkowski et al., 2017[25]) on hydrogen compression and pipeline transportation processes at the distance of 50 km and the pressure of 10 MPa upstream a pipeline, with safety issues for water electrolysis hydrogen productions, for selected hydrogen flow rates of 0.2, 0.5, 1.0, 2.0, and 2.8 kg/s. These hydrogen mass flow rates were determined by the possible working parameters of different types of compressors and the possible range of safe inner diameter of the pipeline for the transportation process determined similar consequences for human beings. In the case of the hydrogen jet fire, the zones with a fatal effect on humans extend from the location of the pipeline damage over a distance of approximately 120 m for a pipeline diameter of 250 mm. The zones presenting a hazard to human health and life will depend, among others, on the hydrogen pressure and the size of the pipeline damage.

(Houssin-Agbomso, G. and D., 2018[29]) verified the consequences of a specific high pressure gas release on a buried pipeline through a 12 mm diameter breach. The choice of the 12 mm hole size was determined by the fact that it constitutes a representative size of releases in buried pipes resulting from corrosion in the highest number of the 145 000 km long buried pipelines network across Western Europe. The latter element of the pipeline being buried is influenced by environmental factors that contribute in shaping the consequences of leakages occurring on buried high pressure pipes. The experiment therefore determines what were their behaviour and their impact on the soil – i.e., crater formation, or not, according to release parameters – in order to use the appropriate methodology for risk and consequences assessment. Thus, by changing several parameters – like nature of gas, initial gas pressure, type of soil – the threshold between crater formation and gas dispersion in the soil following such leakages was investigated. The crater is influenced by the following specific conditions: high pressure of the releasing gas, vertical upward orientation of the release, and a soil with low plasticity and low cohesiveness like a sandy soil, while it is independent of the nature of the releasing gas. For the other conditions, an uplift of the soil occurs and allows the evacuation of the gas reaching the ground surface with a low velocity and possibly quickly dispersed in the ambient air, for light releasing gases in most atmospheric conditions.

A similar simulation aimed at analysing the impact of different factors in a hydrogen leakage accident evidenced that (1) wind speed, ground roughness, tube pressure and leakage gap area have a great influence on the diffusion distance, wind speed being the most influential; (2) Wind speed, tube pressure and leakage gap area have a great influence on the overpressure distance, gap area being the most influential; (3) Gap area has a significant impact on the combustion distance. The impact of other variables on the combustion distance is very little or negligible; (4) the diffusion distance and overpressure distance reduce as the wind speed and ground roughness increase. In particular, tube pressure and gap area have a great impact on the consequences of the accident; wind speed and ground roughness have a negative correlation to hazardous distance; tube pressure and gap area have positive correlation to hazardous distance; wind speed and ground roughness do not affect combustion distance (Chen and Mao, 2017[30]).

Ignition probability

Since the infrastructural network for hydrogen relies on the same pipeline system of natural gas it might be useful to factor in the ignition probability and safety measures implemented for the transport of other gases.

The ignition probability is described as to be subdivided into direct/immediate and delayed ignition. Two main factors contribute in determining the probability of ignition pressure (p) in the pipeline and the diameter (D) of the pipeline, with a linear relationship existing among them. It has been affirmed that the $P_{ign} = pD^2$. Therefore the computed equation states that P_{ign} is 0.80 at the most with a P_{direct}:$P_{delayed}$ distribution of 0.75:0.25 (Spoelstra and Laheij, 2011[31]).

The effect caused by ignition depends on both the physical state of the transported substance and the type of incident occurring. In the event of rupture of an underground pipeline for a flammable substance such as gaseous hydrogen a jet fire will occur. In case of a delayed ignition a a plume fire for the gaseous hydrogen.

In the same process in case of a leakage the direct ignition will develop a jet fire with a substance in a gaseous physical state and a jet fire combined with a pool fire with a liquid substance. Should the ignition be delayed, both will develop a flammable cloud (National Institute of Public Health and the Environment (RIVM), 2009[32]).

The effects determined by the two accidents we should consider the air entrainment. With gas ruptures the event will form a crate with the mixture with air influencing the velocity of the jet fire. In comparison to vertical jet fires, horizontal jet fires with low momentum can increase ground level heat due to the tilting impact of winds (Spoelstra and Laheij, 2011[31]). However, mixtures of air and hydrogen in low concentrations, up to about 8 -10 vol%, have a lower risk of ignition than natural gas (DNVGL, 2020[33]). The main cause of pipeline rupture are external interferences, safety measures to reduce individual and societal risk are due to focus on reducing the probability of pipeline ruptures as the preemptive way to reduce the adverse effects generated (National Institute of Public Health and the Environment (RIVM), 2009[32]).

Frequency of failures

The frequency of possible failures are determined at $6.1 \cdot 10^{-4}$ /km/year. With a probability of leakage frequency at 0.75 and 0.25 probability for rupture. As rupture is the most probable incident to occur the failure frequency will be $1.5 \cdot 10^{-4}$/km/year mostly caused by external interference (Laheij and Theune, 2010[28]).

By combining historical data of number of incidents in a pipeline depth class and historical damage data and fracture mechanics we derive a function $fd = e^{-2.4 \cdot d-3.}$ (Laheij and Theune, 2010[28]).

To calculate this function, we use specific pipeline parameters: the diameter, pressure, depth of cover, wall thickness, yield strength and Charpy energy. An analysis using this function was conducted on the 12 000 kilometres in length Gasunie network and represented in the calculations by about 1.2 million data points based on the 1977-2005 historical failure data. The final prediction was a 0.7 rupture per year.

The number of leaks and outflow

Natural gas low pressure pipeline leaks mainly occur near the home, precisely in the connecting pipe, the metre connection and the indoor piping through the distribution materials such as iron, asbestos cement and steel. These are commonly the same materials to be used for the hydrogen distribution networks. The main difference with natural gas in terms of leak is related to the outflow volume which is greater with hydrogen. A small leak of around one litre per hour or less, the flow may be laminar and about 30% more hydrogen flows out based on volume. Larger leaks lead to a turbulent flow that releases 190% more hydrogen than natural gas (DNVGL, 2020[33]).

By analysing the H2Incidents database, a total of 53 incidents involving pipe ruptures were found with most of them leading to ignition subsequent to leakage. 35 of them lead to property damage with only 7 involving human life.

Conclusions and knowledge gaps

The main conclusions based on the literature review related to scenario 2 are:

- Scenario 2 analyses pipeline transport focusing on the consequences occurring in case of leakage from high and low pressure pipelines. The reports provide an overview of both impacts on the pipeline, buildings and people, and effects leading to the potential hazards. Main conclusions from all reviewed studies so far are:
- A **maximum value of $1.65 \cdot 10^{-3}$ death/year/1 000** km was obtained in the case of an explosive class with high ignition power (class 9), stable atmospheric conditions and assuming a failure frequency of hydrogen pipelines equal to 0.126/year/1 000 km.
- The individual risk creates a distance between the source of risk and its surroundings. Societal risk limits the population density around the source of risk.
- Crater formation from a 12 mm diameter breach in underground pipeline is studied. The 12 mm size was tested as it is most commonly considered as an accidental scenario of the buried pipelines network due to damage by pipe corrosion. It is impacted by high pressure of the releasing gas, **vertical upward orientation of the release**, and a soil with low plasticity and low cohesiveness like a sandy soil. There is **great influence of wind speed, ground roughness, tube pressure and leakage gap area on the diffusion distance and overpressure distance**.
- Since hydrogen gas is odourless, colourless, and tasteless, leaks are not detected by human senses. Therefore, as a safety measure to counter major consequences from hazards, the **use of hydrogen sensors** is recommended to successfully detect hydrogen leaks.
- **Walls collapse at overpressures of 14 kPa**,[12] and at **42 kPa**[13] **houses are largely destroyed**. Due to the higher reactivity of hydrogen, it is expected that a stoichiometric mixture of hydrogen is more likely to cause a detonation.
- By reviewing the literature we understand that there is no clear view of the sources that do or do not lead to ignition. Different sources with sufficient energy for ignition were tested but there was discontinuity of igniting a flammable mixture.
- **Hydrogen leaks are greater in volume flow than those of natural gas**. In case of leaks, the risk of hydrogen entering in a home depends on the concentration that can be built up: if the concentration of **hydrogen remains below 10 vol%, there is a lower probability of damage** because the likelihood of ignition is lower than with natural gas and because no explosion is likely to occur if ignition takes place. For c**oncentrations above 10 vol%, hydrogen presents a greater risk of damage** because the chance of deflagration is higher than with natural gas and the pressure builds up much faster.

- **Hydrogen spreads faster in confined spaces than natural gas**. Experiments and simulations have shown that in the case of a leak in a non-ventilated space, hydrogen initially accumulates at the top of a confined space due to the difference in density, and then mixes to form a homogeneous blend. With enough ventilation hydrogen escapes to adjacent spaces.

Gaps

- From the above findings, most of the experiments conducted out of labs used pre-existing infrastructure developed and built for natural gases that have different properties that might vary depending on the relative specific conditions.
- No statistics have yet been compiled for the leakage size distribution and detection in hydrogen distribution networks. The creation of a register of leaks and their extent in future hydrogen distribution networks might help.
- Further study is needed to confirm the effects of detonation in confined areas and to further establish the impact compared to natural gas.

Scenario 3 – Road transport: H_2 leakage in a confined space/ built environment

The following analysis investigates the properties of hydrogen in confined spaces and built environments. Hydrogen is less likely to cause a fire or explosion hazard in an open or well-ventilated space as it diffuses easily. However, it can cause a safety risk if it accumulates in a confined or poorly ventilated space. Therefore, the safety of FCVs and the related infrastructure, including hydrogen fuelling stations, tunnels, garages, parking, and maintenance workshops is relevant. Accidents in urban built areas also increase the likelihood of hydrogen leakage and the attendant risks. The articles summarised, therefore, describe the potential incidents arising out of hydrogen leakage in parking garages and road accidents involving hydrogen FCVs (HFCV) and some methods to mitigate such incidents.

Sensors in HFCVs

Regulatory attempts have already been proposed for certifying HFCVs to test their crashworthiness. For instance, the new Global Technical Regulation (GTR) proposes the performance-based test methodology for HFCV fuel system integrity certification. If this proposal is accepted, then HFCV's certification could depend on the system performance during barrier/ rollover crash tests. Under the proposed regulation, an FCV would fail the certification test if the hydrogen l**eakage rate exceeds 118-L/min** or if flammable mixtures develop within the car or the trunk within an hour of the crash.

Within the GTR methodology, certain additional experiments have been performed to analyse the capabilities necessary to detect the presence of flammable mixtures within the car or the trunk (Ekoto et al., 2011[34]). Through in-vehicle leakage tests the importance of sensors, both direct and indirect, were highlighted. Direct sensors measure the hydrogen concentration while indirect sensors or oxygen depletion sensors measure the depletion in oxygen levels. Both the sensors performed equally well once temporal drift corrections were applied. Some other findings from this experiment are as below:

- Duplicate in-vehicle (cabin and boot) dispersion characteristics were highly repeatable, with **mole fraction profile** variations **less than 0.01** at most sensor locations.
- Releases with **high amounts of convective mixing** had in-vehicle mixture distributions that were **far more homogeneous** than distributions from diffusion dominated releases with negligible jet exit velocity.

- **Porous diffusion boundaries**, such as seat cushions, natural ventilation to the ambient environment, present between adjacent compartments within the car **slowed the development of elevated H_2 concentrations.** However, H_2-rich mixtures eventually formed in elevated regions for both compartments if the upper edge of the diffusion boundary was located above the ventilation point.
- Although increased release rates led to more rapid threshold detection times and higher peak concentrations throughout the vehicle, even small leaks resulted in the rapid development of flammable regions. A simplified analytic analysis indicates these flow rates can easily be exceeded from small ruptures in moderately pressurised storage or delivery components unless appropriate control and mitigation measures are taken.

Ventilation in parking garages

Increase in the demand for H_2 fuel in the future will require high investments in the infrastructure sector. In this regard, parking hydrogen vehicles in residential garages pose a potential safety hazard because of the accidents that could arise from hydrogen leaks. The dispersion of hydrogen in a garage: with ventilation and without, has been analysed through numerical and experimental studies (Ehrhart et al., 2020[35]), (Choi et al., 2013[36]). The temporal and spatial evolution of hydrogen concentration as well as flammable regions in a parking garage have been predicted. The **volume of the flammable region** shows a **non-linear growth in time with a latency period**. The effects of the leakage flow rate and an additional ventilation fan have also been investigated to evaluate the ventilation performance to relieve accumulation of the hydrogen gas. It is found that **expansion of the flammable region is delayed** by the **presence of a fan via enhanced mixing** near the boundary of the flammable region.

(Merilo et al., 2011[37]) performed a series of experiments to investigate hydrogen release accidents in a vehicle garage with both mechanical and natural ventilation. Tests were performed with hydrogen release rates of 1.6 kg/h, 3.3 kg/h, 4.9 kg/h, and 6.7 kg/h and ventilation rates of 0.1 m^3/s, 0.2 m^3/s, and 0.4 m^3/s. The primary hazard was the deflagration of the hydrogen-air mixture and the burning of the hydrogen jet fire inside the garage. The maximum concentration of 17% v/v and overpressure of 0.77 kPa were produced with a 6.7 kg/h release rate and a ventilation rate of 0.1 m^3/s. The maximum average peak overpressure was 0.769 kPa. For all mechanical ventilation tests except the 6.7 kg/h release, the overpressures that resulted from the confined deflagrations were all very low and did not represent a risk to people or property.

Very recent experiments performed by USN, (Lach and Gaathaug, 2021[38]) investigate the ventilation efficiency in underground garages. Compressed hydrogen was released from underneath a car inside a semi-closed facility with forced ventilation. Two ventilation rates based on British standards (6 and 10 ACH) and several nozzle sizes were tested. Steady state and blowdown releases were considered. Based on the experiments it was found that:

- The **peak concentration** formed inside the garage is similar for **6 ACH**[14] **and 10 ACH** ventilation.
- The cloud becomes flammable (reaches the LFL) at **different times for each ventilation rate** for hydrogen releases with the same mass flow rate.
- The **residence time** of the flammable cloud is halved for a ventilation rate with 10 ACH.
- The **sufficiency of forced ventilation,** used today, on hydrogen concentration **was not conclusive** in the experimental geometry that was used.
- The ventilation rate in underground release **should be 10 ACH (or higher) for unignited hydrogen releases**, because lower ventilation rates will result in a longer duration of a flammable cloud.

(Hao et al., 2020[39]) studied the impact of no ventilation and mechanical ventilation on dispersion of hydrogen in a confined space using experiments. Two model cars of equal dimensions and having onboard hydrogen storage tanks with working pressure of 70 MPa mounted near the rear seats and the trunk were experimented upon. Vehicle A was equipped with **Type IV hydrogen tank**[15] **(non-metallic liner)** while Vehicle B was equipped with **Type III hydrogen tank (seamless metallic liner)**. The experiments were performed firstly with an Air Exchange Rate of 0.03 ACH which is considered to be the poorest ventilation and is descriptive of a tight wooden frame structure and sheltered from wind and temperature variations. The second experiments were performed with two fans and vents producing an air exchange rate of 6 ACH. For emergency ventilation 9 ACH is preferred. Fans with dimensions 120x120x38 mm (length, width, thickness), diameter 100 mm, air velocity 86.0 m^3/h at the speed of 1600 rpm were placed near the ceiling. Circular vent diameter was 100 mm. The discussions and findings surrounding parking state and idle state as covered in the study by (Hao et al., 2020[39]) are discussed below.

In most scenarios involving parking garages and repair workshops, vehicles are engaged in two states: i) parking state (including start-idle and shutdown process) and ii) idle state. Both these states have different impacts on the hydrogen leakage and volume of flammable concentrations:

Parking state (with a parking time of 8 hours)

Vehicles with Type III hydrogen tanks perform better than vehicles with Type IV hydrogen tanks (Hao et al., 2020[39]). Hydrogen is detected about 20 minutes and 50 minutes after leakage in Type IV and Type III respectively. As hydrogen concentration follows a **linear upward trend, after parking for 8 h**, the hydrogen leakage of vehicle A and vehicle B resulted in the detection of the highest hydrogen concentration in the poorly ventilated confined space, **at 125 ppm and 42 ppm**, respectively. However, both the values are **much smaller** than the **safety limit of 10 000 ppm required by GTR standards.** Additionally, after hydrogen gas was detected in the sealed chamber, the hydrogen concentration rose at a nearly constant rate. This means that 8 hours is enough to examine the hydrogen leakage of the vehicle without the need to further increase time. 8 hours could simulate the daily use of most vehicles. Interestingly, if the hydrogen concentration is raised at approximately **5.544 ppm/h (as for a car with Type II tank)**, it would require approximately **1 800 hours to reach the safety limit of 10 000 ppm.**

Idle state (with start-up and shutdown purge and idling time of 10 minutes)

When an HFCV is started, it goes through a start-up purge. Before a fuel cell engine starts, in order to supply the hydrogen into the anode rapidly or purge the air in the anode which permeated from the cathode during parking conditions, some hydrogen is supplied into the stack with pressure and then discharged from the tailpipe of the vehicle. This process is named as **"start-up purge process**." As a consequence, the **hydrogen concentration near the vehicle exhaust** outlet rapidly increased to **695 ppm (Type IV) and 232 ppm (Type III)**. Subsequently, the hydrogen gas can diffuse to other positions in the chamber. Next, the fuel cell engine automatically maintains an idling state for 10 minutes. **During idling, hydrogen concentrations do not increase** noticeably. Once the vehicle shuts down, the fuel cell engine automatically enters the **"shutdown purge process.**" In order to decrease the water produced by electrochemical reaction and adjust the humidity inside the fuel cell stack, during the shutdown process of the fuel cell engine, some hydrogen is supplied into the stack with pressure and then discharged from the tailpipe of the vehicle. As a consequence, this process rapidly raises the hydrogen concentration **near the tailpipe to 2356 ppm (Type IV) and 130 ppm (Type III; the two types operate at different pressures, hence the resulting difference in concentration)** and causes the hydrogen concentration at other positions to increase. However, under the action of mechanical ventilation, the hydrogen concentration in a confined space can be gradually decreased.

It can be conclusively stated that **ventilation reduces the hazard associated with hydrogen leakage in confined spaces** frequented by HFCVs. This is because firstly, the f**low structure and molar fraction of hydrogen is strongly influenced by ventilation parameters**. With a ventilation fan, the flammable region decreases as air volume of the fan increases. A **fan enables mixing of air near the flammable region** and thereby delays expansion of the flammable mixture. Secondly, in the **absence of ventilation, flammable regions increase with time**. It is important to note that the volume of the flammable region does not increase linearly with time, but increases rapidly after the initial latency period. It can be therefore stated that parking garages need a minimum ventilation requirement for both liquid and gaseous energy carriers, and should be an important consideration in building regulations.

Regulators must note that the extent of risk mitigated depends on several factors such as shape of the vent, type of ventilation (see also Hydrogen Safety Aspects section): i.e. natural or mechanical, and in the case of mechanical ventilation systems such as fans, the size, speed and location of the fan etc. Some findings from the study by (Hajji et al., 2021[40]) which can inform regulators on the parameters of ventilation and their impact on hydrogen stratification are as under:

- **Hydrogen flows in two directions**, parallel to the bottom of the car and to the ceiling. This results in development of flammable regions near the bottom of the car and closer to the top of the ceiling.
- Amongst the three generally prevalent configurations of ventilation openings- square, circle and triangle, the **square shape generates lower concentration** levels and presents the highest extraction efficiency which is equal to 56.06%. This proves that simple geometric shapes (square) are more adaptable to the evacuation of low-fuel gas density as hydrogen.
- Different **aspect ratios (R, length/height) of the vent have a distinct effect** on the hydrogen concentration; when R decreases, there is an increase of fresh air drawn and an increase of the hydrogen evacuation. When combining the two factors: aspect ratio and shape type, hydrogen **extraction of the transverse rectangular shape (R = 0.5) is more efficient and it presents better results than the others.**

Accident involving HFCVs

A vital issue for HFCVs is the safety concerns when hydrogen is leaking from a damaged vehicle after an accident.

(Sun and Zhiyong, 2018[41]) studied the major hydrogen consequences including impinging jet fires and catastrophic tank ruptures are evaluated separately in terms of accident duration and hazard distances. The hazards associated with hydrogen releases in a 70 MPa fuel cell car involved in an accident caused by collision on a city road (for instance due to tyre burst), would normally last for no more than 1.5 minutes due to the emptying of the tank (although a conservative value could be 3-5 minutes when considering first responder activities). For the probability of a successful fire extinguishment (assuming a fire is caused due to the collision), it is assumed that 50% of the fires will not be suppressed in time. It takes 30 minutes from the fire starting to the triggering of TPRD (4.2 mm diameter). The probability that the TPRD will fail is estimated at $2.22 \cdot 10^{-5}$. Given the improvement in modern hydrogen tank safety, the likelihood of TPRD failing is low.

First responders would be able to approach the vehicle, conservatively, **approximately two minutes after hearing the hissing sound** as the hydrogen hazards have been eliminated. For the safety of the general public, **a perimeter of 100 metres** is suggested to be set in the accident scene if no hissing sound is heard (Sun and Zhiyong, 2018[41]). However, the perimeter can be reduced to 10 metres once the hissing sound of hydrogen release is observed. For the first responders, if there's no sign of hydrogen release, they **should stand at least 10 m away** from the burning car, otherwise their risk of fatality would be over 50% in case of catastrophic tank rupture. Blast wave **overpressures greater than 1.35 kPa** would lead to temporary loss of hearing. Overpressure of 30 kPa is taken as the fatality criterion (50% probability of fatality from missile wounds).

To mitigate the risks of ignition and fire, studies, (Liu and Christopher, 2015[42]) have suggested the **use of a portable blower by first responders**. Ground effect blowers with **a diffuser flush to the floor effectively removes most of the hydrogen to create a safety envelope around the vehicle.** In terms of approach direction, first responders should avoid approaching the vehicle from the side opposite the blower. This is because these areas are where the hydrogen concentrations would still be close to the lower flammability limit even despite the presence of a blower. Hydrogen flame lengths can be considered as "fatal distance" and distance to 70℃ temperature boundaries can be considered "no harm distance". CFD simulations show that flame lengths from hydrogen jet impingement reach 8 metres and the 70℃ envelope is 10 metres. This means that first responders who deal with accidents must stand at least 8 metres away from a car to avoid fatalities and a perimeter of at least 10 metres should be set around the accident scene to protect the public. Some other issues, regulators could consider while drafting regulations related to emergency responses involving HFCV accidents are:

- Blowing from the **front** produces a higher safety margin.
- **Leak from under the centre** of the car is easier to control than leaks from the side.
- **Forced airflows of 10 m/s** can disperse hydrogen from around a car and in its interior to less than the flammability limit of 4 vol% hydrogen (assuming leak rate of 2000 NL/min).
- Ground effect blowers with the diffuser flush to the floor removed most of the hydrogen effectively to create a safety envelope around the vehicle.

Regulators can also consider using **lessons learnt from CNG vehicles** to determine the safety requirements for HFCVs. Comparison studies using CFD (Li and Luo, 2019[43]) between CNG and HFCVs show that the release duration for CNG vehicle is over **two times longer than that for hydrogen vehicle**, indicating that CNG vehicle jet fire accident is more time-consuming and firefighters have to wait a longer time before they can safely approach the vehicle. In the given experiment, for both hydrogen vehicles and CNG vehicles, the longest hazard distance near the ground occurs about 1 to 4 seconds after the initiation of the thermally-activated pressure relief devices. Afterwards the flames will shrink and the hazard distances will decrease. For firefighters with bunker gear, they must stand 6 m and 14 m away from the hydrogen vehicle and CNG vehicle, respectively. For the general public, a **perimeter of 12 m and 29 m** should be set around the accident scene for hydrogen vehicles and CNG vehicles, respectively.

Risk assessment on life safety and financial losses in case of FCV accidents

In the study by (Sun and Zhiyong, 2018[41]), the additional risks introduced by the flammable effects of hydrogen are calculated. The study considers "additional" risks rather than "overall" risks because the losses caused by hydrogen powered vehicles and conventional fuel vehicles are similar. As per the study, due to flammable effects of hydrogen, the risk of compensation for **fatalities and injuries** in the car accident is **$8x10^{-5}$/year**, and compensation costs will be less than 20 million dollars and 2 million dollars for fatalities and injuries, respectively. For r**epair and replacement loss**, the risk of compensation of less than 60 thousand dollars is **$8x10^{-5}$/year** and the risk of compensation less than 7 thousand dollars **is $2x10^{-4}$/year**. The risk of **environmental clean-up** cost is $2x10^{-4}$/year, while the cost is very small (700 dollars). The insurance premium of fatalities and injuries should be higher than that of property loss, to be taken into account in insurance pricing of FCVs.

The Hydrogen Safety Panel prepared a report for the Safety of Mobile Hydrogen and Fuel Cell Technology Applications in October 2019 to suggest future course of action for safer use of *inter alia* mobile refuelling and high-volume transport applications. These trailers with high pressure (upwards of 19 MPa[16]) hydrogen cylinders particularly those of composite construction require greater harmonisation of codes and standards (Hydrogen Safety Panel, 2019[44]).

Conclusions and knowledge gaps

The main conclusions based on the literature review related to Scenario 3 are:

- Hazards for Fuel Cell Vehicles (FCVs) are generally categorised into two, first being hazards associated with onboard hydrogen and piping systems mostly in the rear of the vehicle and second, hazards related to the onboard battery mostly in the front of the vehicle. The hazards can be associated with each other.
- An **immediate ignition of continuous release** of hydrogen will result in a j**et fire**, while a **delayed ignition** could lead to a **flash fire or an explosion** if in confined space. For an instantaneous release in the case of catastrophic rupture of a hydrogen tank the **violent depressurization from the high pressure** tank will create an outward blast wave and fragment projectiles.
- Hydrogen FCVs could become more publicly acceptable if the general public perceives their safety as comparable to that of the now generally accepted of CNG cars.
- Storing a hydrogen fuel cell car in a garage can pose a safety hazard if there is a **build-up of flammable mixture** within the vehicle and/or the garage structure and an ignition source is present. Ventilation- both natural and mechanical- should be considered for the design of garages, repair workshops etc.
- Significant research has also gone into studying dispersion of hydrogen in confined spaces. Hydrogen **tends to accumulate below ceilings and roofs where it can reach flammable concentrations**. Further, the manner in which hydrogen forms layers: uniform or stratified with varying concentrations, will also impact the safety assessment especially in confined spaces such as residential units.
- To calculate the risks posed by hydrogen fuelled systems, probability of ignition is required. Ignition probability is still unknown and more research is required in the field. However, given hydrogen's low ignition energy, its ignition probability is higher than that of other flammable gases if no additional measures are taken. Current studies reveal a number of mitigating and management measures such as limiting release of hydrogen, preventing leaks from escalating, personal protections and emergency response. The importance of overpressure relief valves and flow restrictors is also stressed.
- **Valves are the best way to limit leaks**. Once a leak is detected, ventilation, prevention and management of ignition sources, and implementation of safety distances are some key measures which most studies emphasise.
- (Hao et al., 2020[39]) demonstrate that the hydrogen emission for vehicles with Type IV fitted hydrogen tanks fare worse than vehicles with **Type III tanks.** Regulators can consider incentivising the use of Type III tanks in HFCVs to reduce risks.
- For vehicles parked in enclosed spaces, the purge process is a crucial factor because emissions are highest in this state. Parking and idling present less risk from leaking hydrogen as the hydrogen concentration is stable and does not rise with idle time. Car idle times can be determined based on this and the fact that vehicles should avoid multiple purge processes in confined spaces. If the purge process control strategy is not optimised, it could lead to hydrogen concentrations in an enclosed space to exceed the safety limit of 1%.

Gaps

1. Ventilation

In addition to ensuring adequate ventilation in parking garages and enclosed spaces, ventilation should also be considered for tube-trailers transporting hydrogen. More tests need to be performed to verify that vent openings will be adequately sized for credible hydrogen leaks to ensure that hydrogen is not trapped in an enclosure around the cylinders or the pipelines. If there is a roof on the cylinder enclosure of a trailer, the benefits of hydrogen detection sensors should be considered to alert operators and avoid them from opening a door to a flammable mixture.

2. Sensor Location

Although the importance of sensors in HFCVs has already been established, the issue of location of the sensor still requires detailed analysis. Hydrogen distribution strongly depends on release characteristics such as release rate and location. Pinhole leaks from moderate source pressures would produce unacceptably high in-vehicle hydrogen concentrations. Sensors should optimally be located high above the release point. However, much of the sensor's efficacy would depend on the final vehicle orientation in a crash involving rollovers and therefore further research would be required to take this into account.

3. HFCV Design

i) The main sources of leakage included hydrogen permeation through hydrogen storage vessels, hydrogen leakage in the high-pressure valve, and hydrogen leakage in pipelines and joints. For instance, a concern remains over the robustness of safety valves and the likelihood that they would inadvertently open during impact. However, more research is required on material compatibility, valve performance etc.

ii) Since the highest hydrogen concentration in an enclosed space is noticed to be caused by the purge process, controlling the hydrogen emissions occurring due to the purge process is critical to the improvement of hydrogen safety of vehicles in a garage. This could be done by improving the hydrogen utilisation rate of a fuel cell engine by using components such as a hydrogen circulation pump and optimising air compressor control strategy. Mixing the appropriate amount of air into the FCV exhaust gas to dilute the hydrogen concentration by optimising the pipeline design could also be considered. However, these interventions would require further analysis.

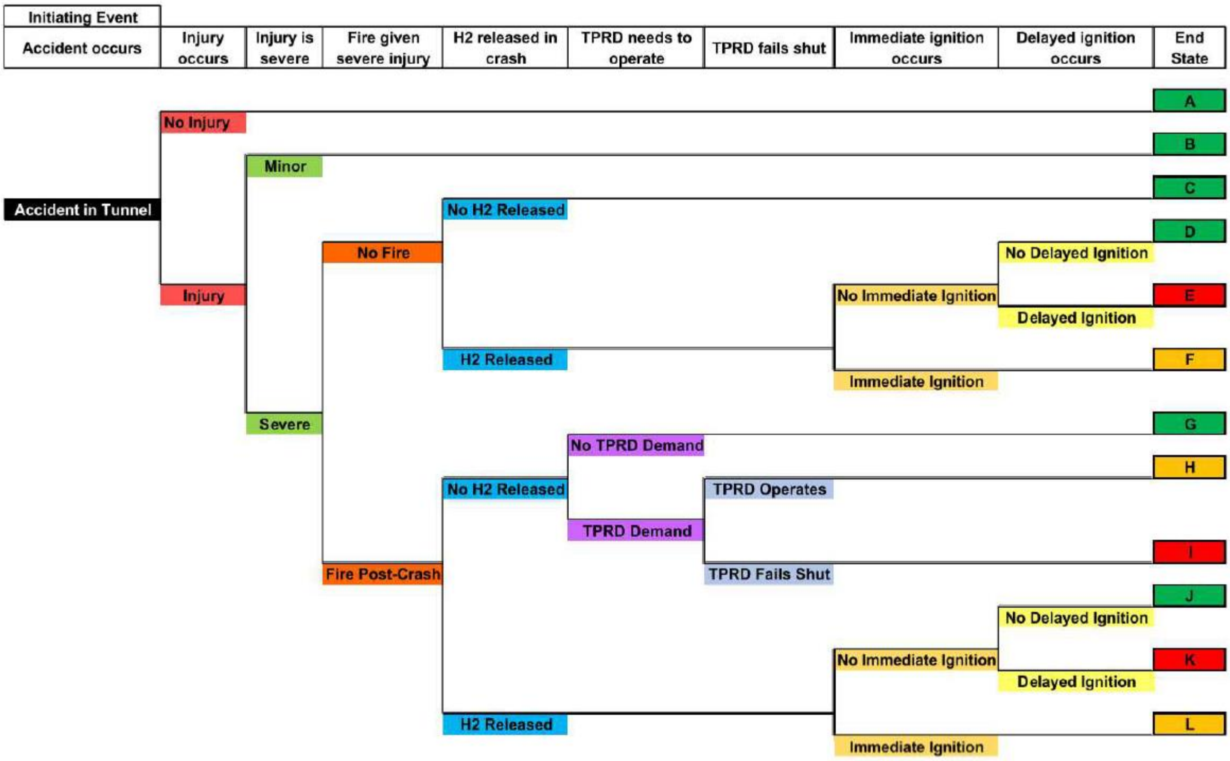
Scenario 4 – Mobility and partially confined spaces: Examples of this scenario include a hydrogen city bus driving in a tunnel involved in a collision accident

This scenario examines the possible hazards from a hydrogen vehicle crash inside a tunnel. A hydrogen vehicle crash can lead to the release of hydrogen and possibly to its ignition. The gas can form flammable clouds and fill the semi-enclosed space of the tunnel. Overpressures can occur as a result of ignition of a cloud of released flammable gas but also as a result of unignited releases of pressurised gas.

(LaFleur et al., 2017[45]) and (Ehrhart et al., 2019[46]) performed a thorough risk assessment investigating a number of possible scenarios involving a hydrogen vehicle crash inside a tunnel: as can be seen in Figure 8.4, t**he most likely consequence of a crash is that there will be no additional hazard from the hydrogen fuel** (98.1–99.9% probability). If the hydrogen does ignite, it is most likely to result in a **jet flame** from the pressure relief device released due to a hydrocarbon fire (0.03–1.8% probability).

An older risk study (Middha and Hansen, 2009[47]), examines releases from hydrogen cars (containing 70 MPa[17] gas tanks releasing either upwards or downwards or liquid hydrogen tanks releasing only upwards) and buses (containing 35 MPa gas tanks releasing upwards) for two different tunnel layouts and a range of longitudinal ventilation conditions. The worst-case deterministic evaluation of each of the scenarios involved the tunnel filling with stoichiometric hydrogen gas clouds of varying size resulting in very high overpressures (the highest pressure seen was almost 12 barg[18] for a 1 000 m^3 gas cloud). However, this assumes that the full gas inventory is being mixed homogeneously at stoichiometry, something considered unrealistic by the authors of the study. In fact, very moderate worst-case explosion pressures were predicted when the actual reactivity of the clouds was taken into account, even in cases in which the flammable gas cloud sizes were large. The risk assessment suggested a maximum expected pressure level of 10-20 kPa above ambient.

Figure 8.4. Event sequence diagram for a hydrogen vehicle accident



Source: (Ehrhart et al., 2019[46]).

The **shape of the tunnel**, the **ventilation regime** and the different **properties of the vehicle thermal pressure relief device (TPRD)** are potentially important parameters in determining explosion risks and appropriate mitigation measures. In regard to the tunnel's shape, larger and 'taller' tunnels are considered safer. Findings from HyTunnel , a project established within HySafe, the European Network of Excellence on Hydrogen Safety (Kumar et al., 2009[48]) have shown that the increased ceiling height associated with arched cross-section tunnels reduces the hazard associated with the release of hydrogen, due to increased dilution of the hydrogen stream and a reduction in the momentum of the impinging jet. However, it was noted that the presence of blockage elements, e.g. light armatures or fans, could add some turbulence to flame propagation and make explosions more severe.

For some tunnel tests, obstacles representing vehicles were used to investigate turbulent enhancement. In a series of large-scale hydrogen deflagration and detonation experiments (Groethe et al., 2007[49]) obstacles representing vehicles were used to investigate turbulent enhancement during the release of hydrogen and homogeneous hydrogen mixtures (9.5%, 20% and 30%) inside a 1/5-scale model tunnel. It was found that the presence of vehicle models had no effect in the deflagration, possibly due to the small blockage ratio (cross-area blockage ratio of 0.03).

Tunnel inclination and slope are of interest as well: an older numerical study by (Mukai et al., 2005[50]) found that a 2% slope in a long horseshoe-shaped tunnel resulted in hydrogen collecting near the tunnel ceiling for several dozen minutes, whereas in underwater tunnels with a trough slope, hydrogen is rapidly cleared from the tunnel. In addition, a series of fire experiments and numerical simulations of a carrier loaded with hydrogen FCEVs in a full-scale tunnel (Seike, Ejiri and Kawabata, 2014[51]) showed that even a modest tunnel inclination (2%) hastened the thermal fume propagation of the FCV fires.

An **effective tunnel ventilation regime** is likely the most important preventive measure against hydrogen hazards. In the study by (Mukai et al., 2005[50]), 60 m^3 hydrogen (approximately 5.08 kg) leaked inside a tunnel was immediately carried away from the leaking area under the ventilation velocities of 1 m/s and 2 m/s. A study of a horseshoe-shaped tunnel by (Koutsourakis, Tolias and Giannissi, 2021[52]) showed that for slopes up to 5 % the slope effect on hydrogen dispersion is negligible and no special treatment is required for inclined tunnels. The same study tested also whether the 'stack-effect' resulting from inclination inside a tunnel might hazardously cancel out the ventilation. In almost all cases examined the ventilation was proven to be much stronger: ventilation overwhelmed any buoyancy effects. This led to flammable gas concentrations being significantly lower.

There are, however, limits to the positive effects of ventilation. (Wu, 2008[53]) studied the effect of ventilation on the upstream back-layering and the downstream flame from an ignition of hydrogen inside a tunnel. For a smaller hydrogen release rate the tunnel ventilation system could eliminate the upstream back-layering (the smoke flow moving against the ventilation) and control the downstream flame. For a larger rate of hydrogen release (0.25 kg/s and a velocity of 50 m/s) however, the tunnel ventilation system could not provide sufficient air flow. If hydrogen is released at a high enough rate, even in a well-ventilated tunnel, it may produce a near homogeneous mixture at close to stoichiometric conditions, with a corresponding increased explosion hazard (Kumar et al., 2009[48]). Yet, this "worst case scenario" has been considered unrealistic elsewhere (Middha and Hansen, 2009[47]).

(Mukai et al., 2005[50]) also noted that hydrogen with a concentration close to low flammability limit might flow into the power collector portions of electrostatic dust collectors, or at the exhaust fan of the model tunnels for a brief time period. Thus, the distance between the main tunnel and these elements has to be sufficient for the hydrogen to diffuse and mix with the surrounding air. Ventilation can also potentially have negative effects: Simulations performed to test the effect of a 'push' or a 'pull' fan in underground mines have showed that, especially for the 'pull' configuration, in the case of a hydrogen leak, the lower concentration region is being drawn or forced back inside the higher concentration part of the cloud (Angers et al., 2013[54]). This results in higher overpressures in the vicinity of the release point. In experiments testing the effect of different ventilation configurations on unignited horizontal hydrogen jets in the air, (Grune et al., 2021[55]) there were a few cases when low velocity counter-flow ventilation (1.5 m/s) led to a minor increase of the safety distance. The effect was reversed under a stronger flow velocity, which led to a significant reduction of the safety distance. In Grune's experiments, **cross-flow ventilation** led to the strongest reduction of the safety distance.

(Giannissi et al., 2021[56]) carried out CFD simulations based on experiments involving hydrogen release inside an enclosure and tested different ventilation configurations based on the experiments conducted by (Grune et al., 2021[55]). The aim was to study the efficiency of mechanical ventilation in case of a high-pressure hydrogen release and provide recommendations on the modelling of ventilated hydrogen dispersion. Simulations agreed with experimental data showing that both co-flow and counter-flow configurations enhanced the mixing and led to a reduction of the longitudinal distance of LFL (compared to the case without ventilation). Attributes of the TPRD, such as its **diameter**, can also make a difference when it comes to hazard mitigation. (Hussein, Brennan and Molkov, 2020[57]) investigated the release and dispersion of unignited hydrogen in a naturally ventilated covered car park through three different TPRDs with diameters of 3.34, 2.00 and 0.50 mm. A TPRD diameter of 0.5 mm was the safest choice for this particular scenario, since it produced a much more limited flammable cloud than in the other cases. However, the size of the unignited cloud due to the smaller TPRD should be weighed against the potential increase in risk due to longer emptying times in a fire. A risk trade-off needs to be made between the risk of pressure vessel burst and the effect of a smaller flammable cloud.

(Bouix et al., 2021[58]) conducted a set of tests in a real tunnel in France investigating a scenario of a jet fire following the activation of a TPRD. It was found that the temperature of the combustion products of the hydrogen flame, measured near the top of the vault, was much lower with TPRDs with smaller diameter. In a study by (Shentsov, Makarov and Molkov, 2021[59]), releases from TPRDs with diameters of 0.5 and

0.75 mm did not result in a flammable layer formation under the parking ceiling (3.12-3 m height), but releases from TPRDs with a diameter above 0.75 mm did, especially in the absence of mechanical ventilation. In the same study, it was also noted that releases from TPRDs toward obstacles tend to prohibit hydrogen mixing with air and promote the accumulation of a flammable cloud; it was therefore recommended not to park an FCEV with its TPRD directed towards obstructions.

The effect of TPRD **orientation** on flammable cloud formation inside a naturally ventilated parking area was also studied by (Hussain, Midhat and Balachandran, 2019[60]). It was found that **a downward TPRD release at an angle of 30° and 45° directed the hydrogen away from the car**, whereas a downward release at 0° briefly surrounded the car doors and passenger escape routes with a flammable cloud. (Shentsov, Makarov and Molkov, 2021[59]) also considered a release angle of 45° to be the overall safest solution. (Bouix D. et al., 2021b[61]) studied upward and downward gas releases following TPRD activation and noted that when the TPRD was directed downwards, the area around the chassis maintained high levels of gas volume. The conclusion was that it is safer not to place the TPRD completely perpendicular to the ground.

Where applicable, it is helpful to perform comparisons between hydrogen fires and hydrocarbon fires. (Seike, Ejiri and Kawabata, 2014[51]) found that the thermal fume from an FCV fire travelled faster than that of a gasoline vehicle fire. (Li, 2019[62]) in a study of fire and explosion hazards of alternative fuel vehicles in tunnels showed that hydrogen jet fires normally are characterised by longer flame lengths and higher heat fluxes compared to fires resulting from the ignition of compressed natural gas. In Li's numerical study, the flame length increases along with the increasing diameter of the PRDs and can rise up to the height of 40 m. The heat flux can reach 45 kW/m2 for GH2 at 10 m from the fire (compared to 14 kW/m^2 for Compressed Natural Gas).The possibility of fire spreading quickly inside a tunnel can therefore be high, as with other vehicle fuels.

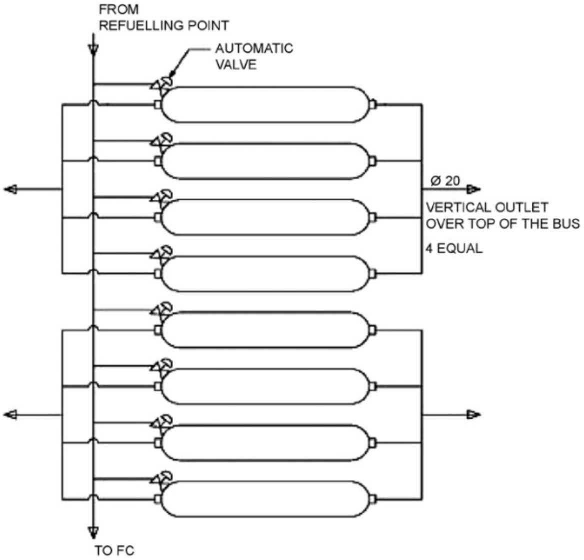
Nevertheless, research has shown that a hydrogen fire poses fewer hazards than a hydrogen explosion: a numerical analysis of hydrogen release, dispersion and combustion in a tunnel by (Li et al., 2021[63]) suggested that the deliberate activation of TPRD can mitigate the consequence of a tunnel accident. If hydrogen is ignited right after being injected in the tunnel it forms a jet fire whose Heat Release Rate (HRR) decays with the injection rate. The region of the combustion cloud is limited to the jet fire near the injection and the ceiling. In the case of delayed ignition however, the pressure wave propagates through the detonatable hydrogen cloud. Then, the blast wave decays the unburnable region at a lower speed resulting in a lower overpressure to the surrounding cars. This pressure wave may have severe effects on the human body: for example, in this study it reaches 800 kPa, which can cause lung damage and severe damage to ear drums.

In a combined experimental and modelling study by (Houf et al., 2012[64]) all three of the fuel-cell vehicle's onboard hydrogen tanks were simultaneously released through three TPRDs toward the road surface. Computational fluid dynamics simulations were used to model the release of hydrogen from the fuel-cell vehicle and to study the behaviour of the ignitable hydrogen cloud inside the tunnel. By increasing the ventilation rate the peak flammable volume, as well as the time required for dilution below the lower flammability limit, were reduced. Simulation results showed that overpressure peaked at an ignition delay of around 5 seconds. Ignition delays of about 4 to 8 seconds resulted in overpressures near or above the fatality threshold level.

Most studies of hydrogen vehicles inside tunnels are focused either on hydrogen cars or on FCEVs in general without specifying the type of vehicle. It is expected that by the end of July 2022 there will be additional findings that will address hydrogen buses from within the HyTunnel project. It is worth noting however, that there is an older CFD simulation study (Venetsanos et al., 2008[65]) examining hydrogen releases from non-articulated single deck city buses in urban environments and tunnels. Working pressures of 20, 35 and 70 MPa for hydrogen[19] and 20 MPa for natural gas were examined. The gas was stored in eight cylinders, each containing either 5 kg hydrogen or 21 kg natural gas (Figure 8.5). Three cases were considered: 1) only one PRD is open and all automatic valves are closed; 2) all automatic valves are open and therefore the gas from all cylinders is released; 3) (worst case scenario), all PRDs and automatic valves are open and the gas from all cylinders is released.

For the tunnel scenario only Case 1 and Case 3 were examined, as consequences of Case 2 were expected to lie somewhere in between. In both Case 1 and Case 3 the flammable cloud shape was similar for all hydrogen storage pressures but the shape of the natural gas cloud was significantly different. In Case 3, hydrogen reached the tunnel ceiling and dispersed along the ceiling towards both tunnel openings. The flammable volume was 1.34 times larger for Case 3 and 73 times larger than that of methane. For Case 3, the methane flammable cloud, also ascended towards the ceiling, but it extended much further transversely and less so longitudinally, surrounding the bus. The authors note that critical cases in tunnels may lead to a fast deflagration. For methane, for Case1, the predicted flammable mass is much lower compared to hydrogen, whereas for Case 3, the predicted methane flammable mass is much higher compared to hydrogen. Additionally, it was noted that with turbulence generating features, e.g. obstacles, there is the possibility of a detonation. The authors' conclusion is that hydrogen storage systems should be designed to avoid simultaneous opening of all PRDs. They also recommended that, in order to mitigate the consequences from the hydrogen release, either the number of PRDs opening should be limited or their vents to the atmosphere should be restricted.

Figure 8.5. Assumed storage system arrangement for hydrogen bus



Source: (Venetsanos et al., 2008[65]).

Another accident scenario revolved around the possibility of TPRD failure, something that would lead to a tank explosion. (Bouix et al., 2021[58]) performed tank explosion experiments to determine the size and progression of the blast wave and the propagation velocity of the reactive wave. To examine the reactive wave, a line of thermocouples was placed along the axis of the tunnel near the ceiling. The thermocouples' response allowed the identification of two regimes: the first one was probably reactive with an average velocity of about 25 m/s and the second one corresponded to the convection of the burnt gas cloud by the flow in the tunnel and had an average velocity of 3.5 m/s.

Traditional models for blast wave decay inside tunnels are derived from studies involving high explosives. (Bouix et al., 2021[58]) used an older model derived from the study of TNT explosions (Silvestrini, Genova and Leon Trujillo, 2009[66]) to determine the extent of the contribution of chemical energy to the blast wave from the explosion of a hydrogen-filled tank: it was estimated at 12%. (Molkov et al., 2020[67]) finding them to be non-appropriate to describe blast wave decay after hydrogen tank rupture presented a universal correlation for blast wave decay after hydrogen tank rupture in a tunnel fire. The validated CFD model was then applied to perform numerical experiments. This model however, has not been used in other studies.

A numerical study by (Shentsov, D. and W., n.d.[68]) made a preliminary exploration of the possible consequences from a blast wave following a tank explosion inside a tunnel. The article attempted to quantify risk by determining 'no-harm', 'injury' and 'fatality' zones and scenarios within different types of 150 m long tunnels according to maximum overpressures predicted: these were to 1.34 kPa, 16.5 kPa and 100 kPa, respectively and described as temporal loss of hearing, 1% eardrum rupture probability and 1% fatality probability respectively. The conclusion was that people in the tunnel would encounter fatality in the field that is nearer to the explosion. Further from the 'fatality' zone threshold (40 m from the point of the explosion), all cases of tunnel area and mass combinations examined in the simulations fall into the 'injury' zone but in most cases examined in which tank mass is above 0.58 kg (regardless of the tunnel cross-section) are above the 'injury' threshold for the whole length of the tunnel. All cases were well below the "fatality" threshold of 100 kPa but the "no-harm" limit was not obtained at 140 m (10 m away from the tunnel exit) in any tunnel type examined and for all hydrogen mass inventories down to 0.58 kg. There is therefore no "no-harm" zone.

A solution to problems posed by the possibility of tank rupture could be found in the leak-no-burst tank, which is developed as part of the HyTunnel project (Kashkarov, Makarov and Molkov, 2021[69]). In case of a fire, heat is transferred through the composite overwrap of the tank, melting a polymer liner. This initiates controlled hydrogen microleaks, keeping pressures in check. With this technology a tank rupture will not occur.

Conclusions and knowledge gaps

The main conclusions based on the literature review related to Scenario 4 are:

Scenario 4 examined the scenario of a traffic accident involving a hydrogen city bus or car inside a tunnel.

- A risk analysis conducted by (LaFleur et al., 2017[45]) showed that a hydrogen accident within a tunnel is most likely to be a **minor crash**, which has no additional consequence due to **no hydrogen release** (probability of 94.1%).
- Of the scenarios in which hydrogen does ignite, by far the most likely consequence is a **jet flame** resulting from the release of hydrogen through the TPRD due to the heat from a typical accident-related hydrocarbon fire. The possibility of fire propagating inside a tunnel is high.
- Suitable **ventilation** of a tunnel can significantly reduce the probability of an explosion. However, there may be the possibility that even in a well-ventilated tunnel, **a high release rate of hydrogen could produce a near homogeneous mixture at close to stoichiometric conditions**, with a corresponding increased explosion hazard. Similarly, a large fire may reach the tunnel ceiling and spread under it, which could result in serious damage to the tunnel equipment and structures along the ceiling. Ceiling design and mitigation measures are important.
- The ventilation regime should be planned with great care since, **under certain circumstances, ventilation can have adverse effects**, as it has been shown to happen with **low velocity counter-flow ventilation** (Grune et al., 2021[55]) and with **'push' or 'pull' fans** (Angers et al., 2013[54]).
- In a study by (Mukai et al., 2005[50]) it was found that there is a possibility that there is a brief time in which hydrogen with a concentration at about low flammability limit flows into the power collector portions of electrostatic dust collectors, or at the exhaust fan of the model tunnels. The distance between the main tunnel and these elements has to be sufficient for the hydrogen to diffuse and mix with the surrounding air.

- **Obstructions** inside the tunnel and particularly at the level of the tunnel pose a potential risk in respect to possible fast deflagration or transition to detonation.
- In a scenario involving TPRD activation, flammable gas venting to the environment must be considered and the time delay prior to ignition becomes a parameter. **Ignition delays can result in dangerously high overpressures**. An immediate ignition poses fewer hazards compared to a delayed ignition. Therefore, the deliberate activation of TPRD can mitigate the consequences of a tunnel accident and also reduce the risk of tank rupture.
- Storage systems involving more than one TPRDs should be designed to **avoid simultaneous opening of all TPRDs**. In addition, **either the number of TPRDs openings should be limited or their vents to the atmosphere restricted**.
- **TPRD size and orientation** are important factors that can limit the formation of flammable clouds under the ceiling of a tunnel or a closed parking lot. **Small TPRD sizes (< 1 mm)** are generally recommended**.** Vertically downwards release direction should be avoided to reduce the flammable cloud under the car and around the car doors. Release direction backward **at 45º angle** is recommended.
- The **possibility of a TPRD failing** with an explosion ensuing can cause **severe consequences**: there is currently ongoing interest on the matter with numerous studies published.

Gaps

Although lots of research has been performed investigating the safe use of hydrogen vehicles inside tunnels and other confined spaces, some gaps have been identified. A relatively recent review article by Sandia (Glover, Baird and LaFleur, 2020[70]) identified the following gaps in research:

- **Temperature and thermal effects to structures**, or, in other words, how a hydrogen fire or explosion can damage the tunnel. In particular, the risk study by Sandia (LaFleur et al., 2017[45]) mentioned the potential degradation of structural epoxy at 90°C, or its melting at 140°C.
- It also has to be noted that hydrogen explosions are more likely to produce an oscillatory pressure-time profile than hydrocarbon explosions, which may have implications for the structures subjected to a hydrogen explosion (Kumar et al., 2009[48]).
- Experiments or numerical studies involving **vehicles of different size or class** can be performed, since, as the vehicular class increases so does the amount of stored fuel. Several different classes of vehicles were evaluated in the studies, including hydrogen cars and buses, liquid hydrogen cars, and multiple hydrogen cars on a cargo truck. The possible effects of deflagration or detonation on structural components of a tunnel can also be different for each of the different hydrogen vehicle classes.
- A series of experiments were performed to show that the spontaneous ignition of released hydrogen is caused by transient shock formation and mixing associated with rupture of a burst disk between compressed hydrogen and air (Dryer et al., 2007[71]). However, the study was conducted in ambient conditions outdoors. Further research can evaluate the effect that ventilation inside a tunnel has on the results.
- Closer collaboration between the hydrogen industry and research organisations is needed for knowledge transfer, e.g., maximum allowable TPRD diameter, TPRD orientation, tank heat resistance, etc.
- However, dedicated research projects on hydrogen safety inside tunnels, like the **HyTunnel-CS** EU-funded project (https://hytunnel.net/), are still ongoing. Gaps like hydrogen dispersion and combustion inside tunnels resulting from leakage from bus and train along with thermal effects on tunnel structure are expected to be closed within this project.

Scenario 5 – Mobility and partially confined spaces: accidents at a hydrogen refuelling stations

This particular scenario looks into accidents and safety concerns emerging from hydrogen fuel stations, alongside with risk assessments and case studies which help identify safety aspects and input for hydrogen related standards and regulations.

Based on studies by (Sakamoto et al., 2016[72]) it has been possible to understand the **nature of accidents and incidents at hydrogen fuelling stations** in Japan and the USA within the time period 2004-2014. The collected data included the incidents and accidents involving several types of hydrogen fuelling stations.[20] **Most types of accidents and incidents were small leakages of hydrogen**, but some had led to serious consequences, such as fire. Most of the leakages occurred at the joint parts due to **inadequate torque and inadequate sealing**. Other causes included design error of the main bodies of apparatuses and human error. One of the characteristics of HRS accidents in Japan was the high percentage of leak accidents occurring at pipe joint sections (whereas accidents due to design error, that is, poorly planned fatigue, were common in the United States).

Several experiments aimed at defining safety measures to strengthen levels of safety at hydrogen refuelling stations (Nilsen and Rikheim, 2003[73]), (Kikukawa, Mitsuhashi and Miyake, 2009[74]), (Hecht and Ehrhart, 2021[75]). Several authors (Nilsen et al., 2003; Kikukawa et al., 2008) mentioned the necessity to **install a fire protection wall along station boundaries** and that, whenever possible, hydrogen processing systems or storage at high pressures should be placed outdoors in well ventilated areas. (Hecht and Ehrhart, 2021[75]) further highlighted that, via his work on simulations of liquid hydrogen dispersion and **flame behaviour to study distances of separation from bulk liquid hydrogen storage, the exposure distances are meant to prevent fire spread, so firewalls can be used to mitigate** this hazard and reduce the necessary distance (exposures: the furthest distance to a heat flux of 20 kW/m^2 (6 340 BTU/hr-ft^2), the visible flame length, or an overpressure of 70 kPa).

(Nilsen and Rikheim, 2003[73]) further remarks that if, for some reason, hydrogen systems have to be located indoors, it is very important that the **risk of leaks and gas accumulation is assessed**. In addition, (Kikukawa, Mitsuhashi and Miyake, 2009[74]) highlights how, **in densely populated areas**, where large safety distances may be impossible to achieve, **stricter requirements to quality, inspection and protection of refuelling stations against impact should be implemented**. Moreover, (Nilsen and Rikheim, 2003[73]) argues that **fences around the units may lead to reduced safety distance requirements** if they are designed so that flammable concentrations will not reach outside these barriers.

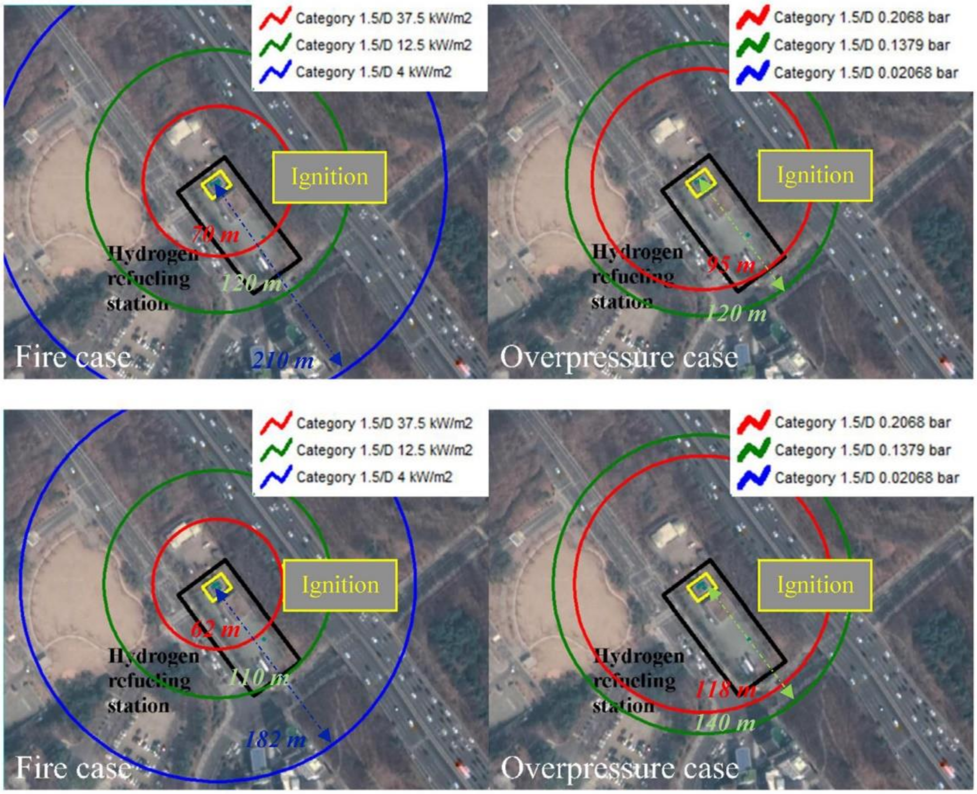
(Gye et al., 2019[76]) performed a quantitative risk assessment (QRA) of a high-pressure hydrogen refuelling station in an urban area with a large population and high congestion between the instruments and equipment considering the following main accident scenarios 1) catastrophic rupture of the tube-trailer with release pressure equal to 100 bar, 2) leakage from the dispenser with release pressure 70 Mpa[21] and leak size 0.11, 1.11 and 11.11 mm). They concluded that **leakage from dispensers and rupture from tube-trailers are the main contributions to the hydrogen refuelling station risks**.

This conclusion is further confirmed by (Yoo et al., 2021[77]). Their study showed that the catastrophic rupture of a tube trailer and a liquefied hydrogen tank are the **worst accidents** because they **induce fires and explosions.** (Gye et al., 2019[76]) argue that to decrease the risk, mitigation, and safety barrier system with certain detectors, such as **Emergency Detection System (EDS),** also confirmed by (Yoo et al., 2021[77]), which will cause an immediate shutdown in an emergency situation deemed necessary. In agreement with the previous authors is (Khalil, 2017[78]) who underlines the need for high sensitivity detection devices that can **detect leaked flammable** as well as the use of pressure and temperature sensors in all confined spaces containing flammable gas systems.

Latest research in the field derives from (Yoo et al., 2021[77]), which aimed to perform a **quantitative risk assessment (QRA) of GHRSs and LHRSs**. A comparative study was performed to enhance the decision-making of engineers in setting safety goals and defining design options. The effect of vapour cloud fire classified by the level of heat radiation (4 kW/m^2) resulted in first-degree burns to people remaining in the area indicated by the blue circle or within 210 and 182 m downwind from the centre of the accident for the GHRS and LHRS, respectively (Figure 8.6) **Severe damage with high heat radiation (37.5 kW/m^2) occurred near the station within 70 m (for GHRS) and 62 m (for LHRS) from the centre of the accident,** which can damage equipment and reach 100% lethality within 1 min inside the area of the red circle Figure 8.6. In addition, sufficient energy to induce ignition on wood and plastic classified by a heat radiation level of 12.5 kW/m^2 was present within 120 m and 110 m for the GHRS and LHRS, on the basis of the experiments' conditions.

- Considering both the worst-case scenarios, **fire occurring in the GHRS had a greater effect on the surrounding people and buildings than the LHRS**, whereas a greater explosion effect was observed for the LHRS owing to the formation of a LH_2 pool on the ground.
- · **The results of the risk assessment indicated that the LHRS had a lower risk than the GHRS.** The following supplemental safety measures are proposed to risk the risk level at GHRS & LHRS: detachable coupling, hydrogen detachment sensor, and automatic as well as manual ESD buttons.

Figure 8.6. Worst-case scenario for the GHRS (top) and LHRS (bottom)

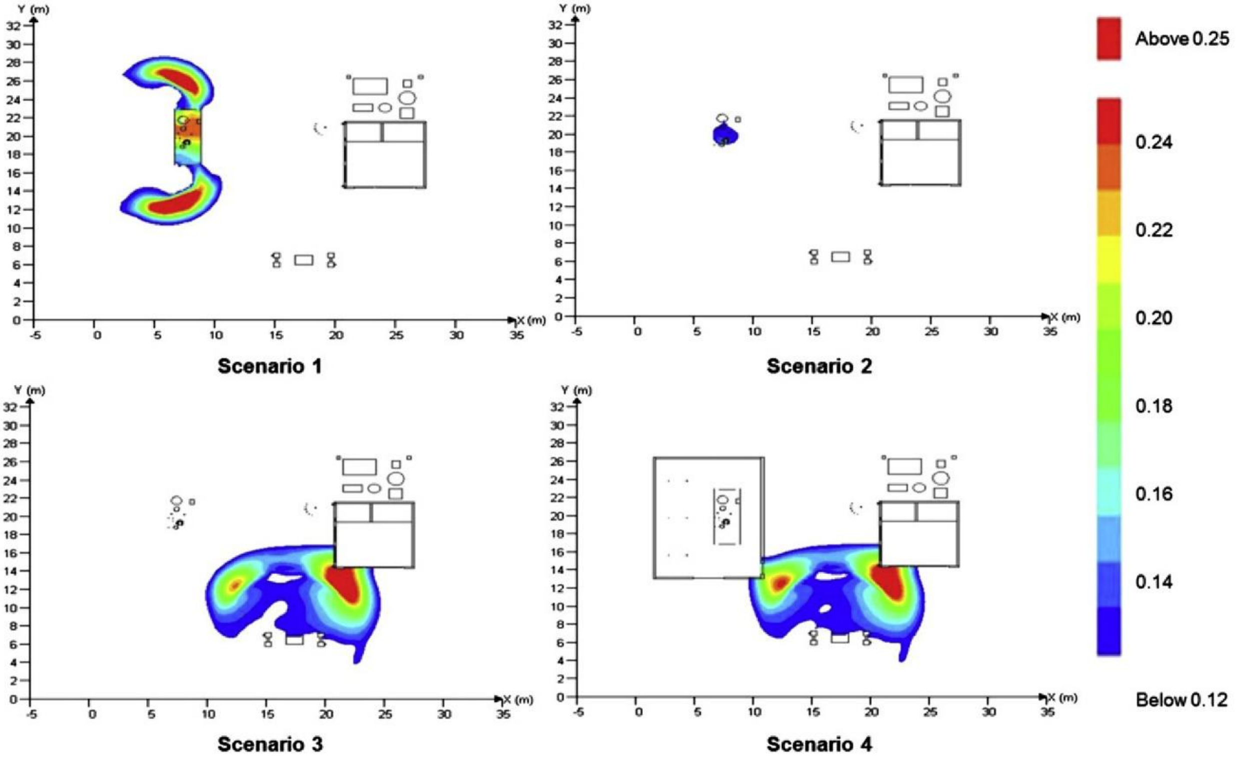


Source: (Yoo et al., 2021[77]).

When it comes specifically to safety distances of hydrogen refuelling stations, (Kim et al., 2013[79]), examined a simulation of hydrogen leak and explosion given conditions of a set of pressures, 10, 20, 30, 40 MPa[22] and a set of hydrogen ejecting hole sizes, 0.5, 0.7, 1.0 mm, using a commercial CFD tool, FLACS

(Figure 8.7). The simulations are based on real 3D geometrical configuration of a hydrogen fuelling station that is being commercially operated in Korea (Figure 8.8).

Figure 8.7. Simulation of experiment scenarios

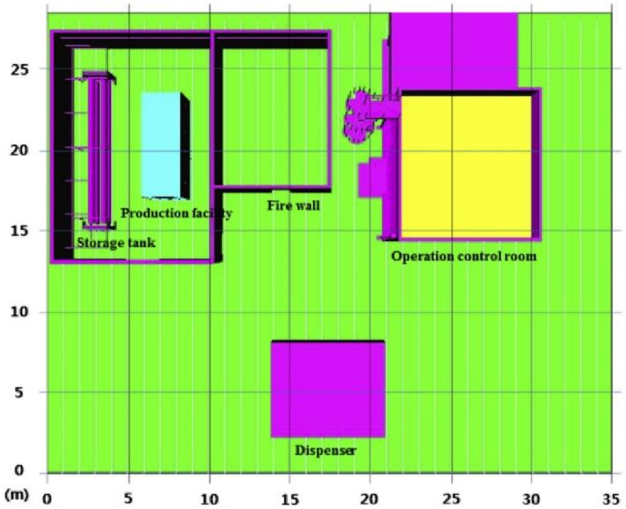


Source: Simulation of hydrogen leak and explosion for the safety design of a hydrogen fuelling station in Korea (Kim et al., 2013[80])

It was found that under scenario 1 (explosion taking place in storage tank) hydrogen storage tank should be configured 5 m further away from the current location of the hydrogen production facility. Next, in scenario 2, an explosion which takes place in a production facility, the explosion does not affect other facilities (placed at a distance of approximately 10 m). **In scenario 3, an explosion takes place in the dispenser, it does not reach the hydrogen storage tank nor the hydrogen production facility.** In Scenario 4, dispenser with protective wall, it was found that the maximum pressures at the protective wall and operation control room are 0.23 and 0.27 bar. **The protective wall and operation room should remain at an additional distance of 2 m away from the dispenser (**the difference between scenario 3 and 4 is whether a protective wall is installed or not).

Also, (Russo et al., 2018[81]) presented a study on a hydrogen station to be installed with the aim of determining safety distances. Results of calculations of safety distances for dispenser and compressor show that the **most severe scenario,** corresponding to a leak size equal to 100% of pipe diameter **has higher frequency compared to other leak sizes due to higher probability of ignition, although the exact value of ignition probability remains uncertain.** Moreover, the study also found out that **safety distances are reduced when safety systems are effective and activated within a short notice**, by employing for instance a dispenser which operates in parallel with an emergency shutdown function that interrupts the flow of hydrogen gas. **Pressure indicator** or switch shall monitor the compressor to initiate its shutdown whenever necessary.

Figure 8.8. Facility-distance layout of a hydrogen fuelling station as considered in the experiment



Source: Simulation of hydrogen leak and explosion for the safety design of a hydrogen fuelling station in Korea (Kim et al., 2013[80]).

(Takeno et al., 2007[82]) performed an experimental investigation on the hypothetical scenario of dispersion and explosion of high-pressurised hydrogen gas (40 MPa) which leaks through a large-scale break in piping and blows down to the atmosphere. In the worst-case scenario case (pipe diameter = 10mm, H_2 pressure = 40MPa, time = 0.85 s), an overpressure greater than 50 kPa was detected at 10 m away from the ignition point. Through these experiments, it was clarified that the **explosion power** depends not only on the **concentration** and **volume** of hydrogen / air pre-mixture, but also on the **turbulence characteristics before ignition**.

(LaChance et al., 2009[83]) conducted an analysis to support development of risk-informed separation distances for hydrogen codes and standards, the minimum separation distances between a bulk gaseous hydrogen storage facility and other facilities that help reduce the potential for injury and facility damage. The hydrogen-specific data was utilised to generate system leakage estimates for a 20.7 MPa and 103.4 MPa facility. For a 0.1% leak size, the system leakage frequency is $3 \cdot 10^{-2}$/year and $6 \cdot 10^{-2}$/year for the 20.7 MPa and 103.4 MPa systems, respectively. What emerges from these values is that a **0.1% leak would be anticipated during the lifetime of these facilities.** Larger and less frequent leak sizes of at least 1% should be used as the basis for separation distances to reduce the likelihood of accidents involving humans. If evaluated on a cumulative distribution basis, leaks equal to or less than 0.1% of the component flow area were estimated to represent 95% of the system leakage frequency. This allows us to conclude that s**eparation distances based on the size of leak would guarantee that they cover the majority of possible leakage events**.

(Khalil, 2017[78]) used a visual flowcharting methodology to develop a probabilistic model to quantify occupational risks of fire and explosion events initiated by leaks that ignite within enclosed spaces. The case study applied to HRS served as an example for demonstrating functionality of the proposed probabilistic model. The proposed probabilistic model is a solid simulation tool for training relevant stakeholders to better understand potential occupational risks associated with ignition of leaked flammable gases within confined spaces in a wide variety of industrial settings. The research showed that, for these analyses scenarios, **small leakage**[23] **from the compressors** is associated with an **intolerable occupational risk** frequencies, which exceed both the acceptance criterion at $1.0 \cdot 10^{-4}$ /year and NFPA's guideline at $2.0 \cdot 10^{-5}$/year.

(Honselaar, Pasaoglu and Martens, 2018[84]) conducted an inter-comparison among the QRAs of permitted HRSs in the Netherlands revealing major inconsistencies on different areas of the QRA including for instance the application of failure scenarios. Their conclusion was that it is recommended to **develop specific QRA guidelines for HRSs**. It should be clear for permitting authorities what the HRS consists of and how it operates. A checklist of HRS sub-systems and components and an extensive description of sub-systems, components, preventive and mitigation measures, configurations (including piping and instrumentation diagrams) and input parameters is recommended. **Establishing a national, independent review function for QRAs of HRSs is also advisable.** Such an entity would have the potential to become a centre of expertise that could collect existing and future QRAs of HRSs to monitor the latest developments and progress towards the consistent application of the approach as well as provide guidance to permitting authorities on how to apply the approach for HRSs.

(Kodoth et al., 2019[85]) described the importance and need of verification of life parameters in QRA to reduce uncertainty linked with the risk calculation. Failure frequency estimation is one of the important measures of risk quantification. In traditional reliability assessment, **mean time to failure (MTTF) is one of the most used life parameters in QRA**. It is **observed that two stations can have similar survival time but small to large differences in the usage** (i.e., number of fillings). If the failure rate is estimated as a function of time, the mean failure rate will be approximately the same for both stations. On the other hand, if the failure rate is estimated by the number of fillings, the failure rate will vary depending on the actual usage of the station. The actual usage conditions are discarded when using the survival time and this may lead to uncertainty in the failure estimation. This leads to another conclusion that the **failure rate estimated as a function of number of fillings** is more reliable and realistic than the estimation based on survival time. Moreover, the number of fillings i**s more representative of the true failure rate**. This means that the survival time does not always represent the actual usage of the HRSs.

(Kodoth et al., 2020[86]) further conducted leak frequency analysis for hydrogen-based technology using Bayesian and frequentist methods. The leak rate is estimated to be 0.16/year, 0.20/year and 0.42/year based on the time-based,[24] leak-hole-size, and non-parametric methods, respectively. This paper proposed **leak rate estimation** using time-based evaluation methods that utilise historical HRS accident information. In addition, leak frequency estimates from another two methods (non-parametric and leak-hole-size) were examined. In the non-parametric approach, the leak frequency was estimated based on a Bayesian update. It can be observed that there is **no major margin between the results resulting from the time-based and leak-hole-size methods**. The asset manager can pick the most appropriate leak rate data based on the data on accidents and method availability. One of the possible solutions is to consider a conservative value for the design, in which case, t**he non-parametric model leak rate of 0.24/year** can be used. The base value selected can be used in design to set performance standards for the availability and reliability in the operation maintenance of HRSs. **If the leak rate is estimated to be high, inspections activities shall be more frequent to limit the unrevealed leak time** (evaluated from the estimated leak frequency) and increase the process of safety. Moreover, the unrevealed leak time can be used to the specification of hydrogen sensors to detect leaks of hydrogen. This will ensure the component and process serve requirements in the performance standard, leading to increased process safety in HRSs.

The National Institute for Public Health and the Environment in the Netherlands performed a QRA in 2016 to assess the risk and identify the impact distances in hydrogen refuelling stations (National Institute for Public Health and the Environment, 2016[87]). The calculations were conducted with the tool, SAFETI-NL 6.7. **The direct ignition probability of gaseous hydrogen was assumed equal to 1** and of liquid hydrogen equal to 0.9**.** It is also assumed that hydrogen will ignite in the first 20 seconds after the release of the gas. The main assumption for the modelling were:

- 0.001 probability of failure of the emergency shut-off device. A higher value of 0.01 was also examined.
- Same failure frequencies as for LPG discharge hose were used.

- 1 000 kg of hydrogen per day were assumed.
- Compressor works for 10 hr/d.
- Both 35 and 70 MPa can be refuelled at the delivery column and there were also two buffer storages of 44 and 95 MPa.

The estimated distances to 10^{-6} risk contours were 30 m for the LH2 delivering via tank and for the gaseous hydrogen dispensing system supplied by pipeline or local production, while they were 35 m for gaseous hydrogen delivering via tube or cylinder trailer. For gaseous hydrogen with delivery via pipeline or tube trailer, the risk after about 50 metres was 10^{-9}, whereas for LH2 supplied by a tanker a risk of 10^{-9} was reached at 270 m. The proposed QRA distances can be further reduced with the use of proper safety measures. Moreover, an ignition probability equal to 1 that is used is overly conservative. QRA with lower ignition probability and taking also into account certain preventive and mitigation measures are recommended to be carried out to re-evaluate the risk.

(Hecht and Ehrhart, 2021[75]) calculated minimum distance (given by a safety factor of 2) from outdoor LH2 refuelling stations to exposures, like compressor, buildings, human. The estimated distances were lower than 30 m for all group of exposures based on NFPA-2 (including overpressure criteria too), i.e. group 1 – the furthest distance to an average mole fraction of 8%, a heat flux of 4 732 kW/m2 or an overpressure of 5 kPa, group 2–- the furthest distance to a heat flux of 4 732 kW/m2 or an overpressure of 16 kPa, and group 3 – furthest distance to a heat flux of 20 kW/m^2 , visible flame length or an overpressure of 70 kPa. These distances should not be confused and compared directly with the values presented in (National Institute for Public Health and the Environment, 2016[87]), because different assumptions were made in the two studies, e.g. in (Hecht and Ehrhart, 2021[75]) a leak diameter of 1% of the flow area and maximum operation pressure of 1.2 MPa were assumed. Moreover, (Hecht and Ehrhart, 2021[75]) haven't calculated the distances based on risk contours, but based on the furthest distance to selective hazardous criteria of the abovementioned exposure groups.

Conclusions and knowledge gaps

The main conclusions based on the literature review related to scenario 5 are:

Scenario 5 examined the scenario of accidents at hydrogen fuel stations. The main findings are:

- Most of the leakages in accidents involving hydrogen fuelling stations in Japan and USA up to 2016 occurred at the joint parts due to inadequate torque and inadequate sealing, which therefore needs to be carefully designed and supervised.
- The catastrophic rupture of a tube trailer and a liquefied hydrogen tank are the worst accidents of hydrogen refuelling stations, because they induce fires and explosions.
- In terms of safety measures it is recommended to maintain risk within accepted levels for liquid hydrogen fuelling stations, the research pointed out that hydrogen storage tanks should be configured at least 5 m further away (based on the conditions outlined in the experiment) from the current location of the hydrogen production facility and a protective wall surrounding the dispenser shall be implemented as a physical barrier protecting from the expansion of a potential explosion. Walls/fences around the units may lead to reduced safety distance requirements if they are designed so that flammable concentrations will not reach outside these fences. However, careful design is required, because obstructions and confinements may lead to more severe explosions in case of ignition. If the leakage frequency is estimated to be high, the inspection interval should be more frequent to reduce the unrevealed leak time.[25]

- Fire occurring in the GHRS had a greater effect on the surrounding people and buildings than the LHRS, whereas a greater explosion effect was observed for the LHRS owing to the formation of a pool of LH2 on the ground: the results of the risk assessment indicated that the LHRS had a lower risk than the GHRS.
- It is to notice how the proper design of a gas and flame detection system would increase the chance to detect the leaks at an early stage. This is especially true if in a compressed hydrogen gas fuelling station the ultrasonic technology is used properly to detect leakage at an early stage even with small hole diameter. The complete gas and flame detection system could activate immediately the safety solution in order to avoid the formation of hazardous conditions.
- In terms of life parameters in QRA to reduce uncertainty associated with the risk calculation, (Kodoth et al., 2019[85]) argues that the failure rate estimated as a function of the number of fillings is more reliable and realistic than the estimation based on survival time. The number of fillings is more illustrative of the true failure rate as it takes into account the station's usage and loading.
- To reduce the potential for significant consequences to a person at the site boundary due to expected accidents, (LaChance et al., 2009[83]) demonstrates that larger and less frequent leak sizes of at least 1% should be used as the basis for distances between a bulk gaseous hydrogen storage facility and other facilities that help reduce the potential for injury and facility damage.
- (Khalil, 2017[78])'s research points out how the probabilistic visual flowcharting based model for consequence tool can simulate what-if accident scenarios and quantify sensitivities of the predicted frequencies of occupational risks to different values of inputs to this model. The HRS case study showed that those accidents involving H2 small leaks (SL) in the compressor's room could lead to undesirable occupational risk frequencies that exceed the $1.0 \cdot 10^{-4}$//year acceptance criterion and in excess of the $2.0 \cdot 10^{-5}$/year risk value proposed by NFPA as a guideline driven by the comparative risk to gasoline refueling stations. The predicted frequencies of risks associated with the base case SL scenario can be summarised as follows:
    - Fire-related injuries: $6.62 \cdot 10^{-4}$/year (Best Estimate) and $4.26 \cdot 10^{-3}$/year (Upper Bound)
    - Explosion-related injuries: $1.12 \cdot 10^{-3}$/year (Best Estimate) and $3.85 \cdot 10^{-3}$/year (Upper Bound)
- The proposed model could find application as a training tool for first responders to fire and explosion events which are subsequent to leaks of flammable gases.

Gaps

Based on the mapping exercise the following gaps are identified:

- It would be helpful to further analyse qualitatively the most recent accidents and incidents that took place at hydrogen refuelling stations involving small leakages of hydrogen to provide an update vision on leakage-type-based analysis at hydrogen fuelling stations using natural gas and other resources and offsite-type hydrogen fuelling stations.
- The need for establishment of a national, independent review function for QRAs of HRSs in the Netherlands along with developing specific QRA guidelines for HRSs is revealed. Further analysis into more advanced countries on this end such as Japan could be useful to facilitate the successful implementation of such recommendations.
- Closer collaboration between the hydrogen industry, standardisation institutes eg: NEN/PGS and research organisations is needed for knowledge transfer, e.g. separation distances via optimisation of piping diameters.

Scenario 6 – Domestic use: Safety of hydrogen in buildings with focus on hydrogen based residential heating

This scenario relates to safety issues that arise from the local production and/or storage of hydrogen, followed by its distribution for domestic use. The following aspects of this scenario were considered, a) risks that arise due to hydrogen gas leaks during the distribution of hydrogen by low pressure distribution networks into the houses for heating and cooking and b) the accumulation of hydrogen in a house in the case of a leak and possible prevention and mitigation measures.

Hydrogen leaks from a low-pressure distribution network

An investigation into past gas leak incidents from natural gas distribution networks in the UK determined that **most leaks occur in the connecting pipe, followed by the gas meter connection and the indoor piping**, i.e. in and near the house. Most reported leaks occur from network components made of **materials such as grey and ductile iron, asbestos cement and steel**. In the case of the UK, these materials, besides steel, are already being removed from the gas distribution network as part of the ongoing Iron Mains Risk Reduction Replacement Programme, so they should not be an issue in the future (V. D. Noort et al., 2020[88]).These findings are supported by (Mouli-Castillo et al., 2021[89]), who investigated gas leak incidents in the UK and who report that the majority of public reports of gas escapes are related to faulty metal joints in piping. They suggest that replacing the currently used UK gas network piping, which is composed of approximately 74% polyethylene and 26% metal parts, with a **100% polyethylene network** would amount to a 2.5 factor reduction in reported flammable gas escapes and a 3.5 factor reduction in "gas in building" events for both natural gas and hydrogen. This benefit is only applicable to releases upstream of the gas metre, which compose 85% of the currently reported natural gas releases, as the replacement of the metallic components of domestic pipework was not considered within the scope of this risk assessment (Mouli-Castillo et al., 2021[89]). Tests are ongoing to understand the implication of long-term use of hydrogen in polyethylene (PE) pipelines (ERM and HSL, 2019[90]), although past research on the long-term exposure of polyethylene to a hydrogen atmosphere suggests that the tensile behaviour and the microstructure of the polymer are not significantly affected even in the long term (Castagnet et al., 2012[91]).

Due to the nature of hydrogen, the outflow volume of hydrogen from a pipeline leak will be greater than in the case of natural gas for the same mass flow. When the gas leak is small (around 1 L/h or less), the gas outflow may be laminar and, as a result, about 30% more hydrogen than natural gas will flow out based on volume. However, for larger leaks, the gas flow becomes turbulent and 190% more hydrogen than natural gas is released based on volume (V. D. Noort et al., 2020[88]).

Risk modelling conducted by DNV GL on behalf of Netbeheer Nederland, was used to study and compare the release and dispersion of natural gas and hydrogen from a low-pressure distribution pipeline in the open air and underground (V. D. Noort et al., 2020[88]). Experiments are being conducted as part of the H21 research programme, taking place in the UK, to support and validate the results of this risk analysis model.

The risk modelling concluded that due to its lower density, **hydrogen will rise faster when blown off or leaked into the open air than natural gas**. This does not lead to higher risks, as the amount of energy released is approximately the same and initial calculations of the safety contours around a leak in a distribution pipe show that they are lower than for natural gas. The contour of the gas cloud is similar to that of natural gas (V. D. Noort et al., 2020[88]).

In the case of hydrogen ignition in an open space and at low concentrations (<10 % v/v hydrogen in air), a fire will break out, but **no overpressures will occur at concentrations below 10% hydrogen** (V. D. Noort et al., 2020[88]). Any leak of pure hydrogen will of course result in concentration over 10% in a certain volume immediately neighbouring the leak, but for small leaks these volumes will be small. Further modelling work was conducted by DNV GL on the heat radiation – and the lethality – of a flare fire that could occur in the event of a rupture in an underground low-pressure distribution pipeline that is then exposed to the open air. In all four standard operation scenarios examined in this work, the **heat radiation of hydrogen**, and therefore the lethality and risk resulting from this heat radiation, is **lower than that of natural gas under identical conditions** (Table 8.3) (Coster, Triezenberg and Beks, 2018[92]).

Table 8.3. The results of calculations of the heat radiation and the site-specific risk (SSR)

Results cover both hydrogen and natural gas leaks from an exposed pipeline of four different configurations for a pipeline failure rate of 3.74·10-5 km-1 year-1

		Hydrogen		Natural gas	
Gas pressure (bar)	Pipeline diameter (mm)	Peak heat (kW/m^2)	Distance SSR (m)	Peak heat (kW/m^2)	Distance SSR (m)
0.1	63	83	10^{-6}: n/a 10^{-7}: n/a 10^{-8}: 3.3	60	10^{-6}: n/a 10^{-7}: n/a 10^{-8}: 4.5
0.1	110	101	10^{-6}: n/a 10^{-7}: 0.1	105	10^{-6}: n/a 10^{-7}: 2.4
8	110	38	10^{-6}: n/a 10^{-7}: n/a 10^{-8}: 6	57	10^{-6}: n/a 10^{-7}: 10 10^{-8}: 17
8	114	37	10^{-6}: n/a 10^{-7}: 3.6	56	10^{-6}: n/a 10^{-7}: 10.6

For larger hydrogen gas leaks, the overpressure increases on ignition from hydrogen concentrations above 10% v/v and with a stoichiometric mixture (around 30% v/v) overpressures can occur that exceed 10 kPa.[26] Due to the high reactivity of hydrogen, it is expected that a stoichiometric mixture of hydrogen is more likely to cause a detonation than natural gas. Further study is needed to confirm this and to further establish the possible impact compared to natural gas.

Overall, based on the results of this study, the risks of natural gas and hydrogen are expected to be comparable in the case of free flow in the open air (V. D. Noort et al., 2020[88]).

For underground releases, the outflow of hydrogen through the soil can be accurately described with models, provided that the soil composition and its permeability are known. Besides soil composition, permeability is also influenced by the weather conditions (rain, freezing weather). At equal pressures, hydrogen is more likely to cause crater formation than natural gas. This can occur mainly at higher pressures in the gas distribution system (>200 kPa) and not at low pressures (<20 kPa). Crater formation could be favourable, as it ensures that the hydrogen is released into the atmosphere faster and does not diffuse underground into confined spaces. Overall, in the case of underground leaks, the chance of an unsafe situation is expected to be lower if a permeable top layer is present, but if the top layer is impermeable (e.g. due to the nature of the soil or due to freezing weather), the likelihood of hydrogen migrating into buildings increases (V. D. Noort et al., 2020[88]).

A more in-depth investigation of gas leaks from pipes under open and covered surfaces was conducted as part of the H100 project (ERM and HSL, 2019[90]). A series of eight generic flow regimes were analysed, focusing on the distance to which hydrogen gas can travel to a minimum hazardous flux level and how this distance changes if methane gas is used instead of hydrogen. The switch from methane to hydrogen makes minimal difference to the range at which significant gas dispersion will occur in the case of leaks from uncovered pipes. In cases where the leak is covered, however, the release range of hydrogen may be significantly larger. Horizontal distances travelled below ground from the point of release were found to be typically 6%-25% further for hydrogen compared to natural gas across the range of conditions tested.

The most serious potential consequences (large hydrogen flow rates) are associated with (very rare) hydrogen gas releases into large open channels that lead directly into vulnerable buildings. Such an unlikely scenario might occur due the presence of a service duct that is not properly sealed where it enters a property. When such an easy route is present, a 25% increase in hydrogen travel distance compared to methane may occur.

An experiment conducted by the HyDelta consortium studied the extent of the entry of air to a hydrogen distribution pipeline in the event of a pipe fracture (Lueb, 2021[93]). During this experiment, pipes with diameters of DN100 (114.3 mm outer diameter) and DN200 (219.1 mm outer diameter) were filled with hydrogen and then their ends were opened to the air to simulate a pipe rupture. The hydrogen/air ratios in the pipes were measured before and after the opening of the pipe ends. As expected, after the leakage occurred, the hydrogen contained in the pipes flowed out immediately. Explosive hydrogen/air mixtures were then observed in both the DN100 and the DN200 pipes as the air entered the pipes. The explosive concentrations persisted for the entire duration of the experiment (90 minutes). The air inflow was faster in the case of the DN 200 pipe than in the DN 100 pipe. As a result, the explosive mixture formation was slightly faster in the case of the DN 200 pipe. The effect of wind was negligible during the experiment. Further experiments should be conducted in the future to investigate the effect of the entry of air in a natural gas pipeline and compare the risk to the risk from hydrogen.

In the Netherlands, the HyDelta consortium is currently filling in the knowledge gaps that inhibit the use of hydrogen in the existing Dutch natural gas infrastructure. As part of the project, a variety of factors that might affect the use of hydrogen in the infrastructure were studied. One such factor was the leak tightness of the pipeline connections during hydrogen transport and whether the same requirements that are currently applied to natural gas can also be applied to hydrogen (Lueb and Kooiman, 2022[94]). The leakage rates of three gases, natural gas, hydrogen and nitrogen, were measured as they were flowing through the service lines at pressures of 3, 10 and 20 kPa. The measurements were subsequently combined with a theoretical assessment of the risk arising from small hydrogen leaks, such as those that might occur under the currently used leak tightness guidelines. The study concluded that it is not necessary to have stricter tightness requirements for hydrogen than for natural gas when it comes to new service lines. However, in the case of the currently used connecting pipes, the leakage rate of hydrogen was 1.83 times higher than the leakage rate of natural gas. As such, the suggestion was made that the tightness requirements should be stricter, ensuring that the maximum permissible leakage rate for hydrogen is 74% of that of natural gas.

In another study conducted by the HyDelta consortium (Lueb and Kooiman, 2022[95]), the compatibility of currently used pressure regulators with hydrogen was tested. 40 pressure regulators, that had been previously removed from the natural gas distribution network, were tested with hydrogen and 10 of these regulators were further tested with natural gas. Based on the results of these tests, it was concluded that the existing domestic pressure regulators can be safely used with hydrogen, and it is therefore unnecessary to replace the regulators as part of the conversion to hydrogen. It was however observed that the under-pressure shut-off valve in several of the tested regulators closed prematurely when hydrogen was used, increasing the likelihood of more failures occurring. Additionally, an increase in the valve shut off pressure was observed when hydrogen was used. As all hydrogen appliances will be equipped with a flame protection device, that should be sufficient to mitigate the safety risk.

A study was carried out to determine the risks that might arise during the purging of the Dutch natural gas pipelines with hydrogen and to determine the appropriate purging speed to be used to safely displace the natural gas (Lueb, 2021[96]). Pipes of diameters DN100 and DN200 that were 200 metre long, were initially filled with 100% natural gas. Hydrogen was then introduced into the pipes at different flow rates. It was determined that the purging of the natural gas in the pipes with hydrogen, including flaring, could be carried out safely. A purging speed of 0.2 m/s was sufficient to safely purge the natural gas with hydrogen in both types of pipes. However, as in practice purging the network pipes might be more difficult than purging the test pipes, a minimum purging speed of 0.4 m/s is suggested, to ensure that the pipes are completely purged of natural gas. For a shorter purging process, a purging speed of 1.0 m/s is suggested as optimal.

Hydrogen dispersion and accumulation in a house following a leak

Experimental testing of the leak rates of methane and hydrogen from various gas joints and fittings currently used in domestic gas installations in the UK was conducted as part of the Hy4heat project (Ryan and Roberts, 2020[97]). The tests showed that **hydrogen was compatible with all of the fittings and pipes tested**. Components that displayed no leaks when methane flowed through would also not display any leaks when hydrogen flowed through and components that displayed a leak with methane would also cause a hydrogen leak. It can therefore be considered safe to use the same materials and fittings for internal pipework for hydrogen as is currently used for methane, at least in the short term, in the context of a community trial. The hydrogen that leaked from damaged components was larger in volume than methane under the same conditions (1.2:1 volumetric leak ratio between hydrogen and methane for small leaks along threads and 2.8:1 from large leaks from drilled holes), however, as hydrogen has less than one-third of the energy of methane on a volumetric basis, the amount of energy outflow is, in every case, less for hydrogen than for methane. Furthermore, the measured concentration of hydrogen within flammability limits resulting from a large leak in a domestic room, was only 1.3 -1.8 times higher that of natural gas, evidence that hydrogen dissipates more quickly than methane under the same leak conditions.

In another set of experiments conducted as part of the Hy4heat project, the dispersion and accumulation of hydrogen and methane when they are released within confined spaces in residential buildings was examined (Simpson, Allason and Johnson, 2020[98]). The confined spaces that were considered were kitchen cupboards and an inset metre box. Gas releases from holes ranging from 0.6 mm to 7.2 mm diameter with a pressure of 10 kPa were examined. Based on these tests it was determined that releases of both methane and hydrogen generally formed layers of nominally uniform concentration above the point of their release. In all releases of hydrogen and methane into the metre box, **flammable concentrations were only observed in the wall and floor cavities**. No flammable concentrations of either gas were observed in the rooms of the house. For hydrogen, the highest release rate tested (18.6 m^3/h through a 7.2 mm hole) produced highly reactive hydrogen concentrations above 30% v/v within a high-level layer in the kitchen. Hydrogen concentrations of 30% v/v have a burning velocity about a factor of 5 higher than the worst case for methane. This can have a significant effect on the severity of any subsequent explosion, even where some venting is available through weak parts of the structure such as windows.

Further tests conducted using different combinations of vent openings in the cupboard and kitchen wall, showed that the **addition of a ceiling vent, ducted to the external wall**, was very beneficial in reducing the maximum concentration of hydrogen seen within the kitchen and the presence of cupboard vents helped reduce the concentration of hydrogen in the cupboards. The resulting recommendation from these tests was, therefore, that for community trials, **venting in any cavity should be made mandatory**, as specified by Building Regulations ADJ (i.e. an exemption should not be granted for hydrogen appliances).

The dispersion of hydrogen in a gas metre box was also studied by DNV GL on behalf of Alliander N.V. (Bierling, Vlap and Bahlmann, 2020[99]). In a series of measurements, 100% natural gas and 100% hydrogen were released into a metre box at flow rates ranging from 1 to 25 lt/hr to simulate a flammable gas leak from the piping connected to the gas metre. The tests were performed initially with the ventilation grilles of the box open and then they were repeated with taped grilles, so as to simulate metre boxes that do not have ventilation openings. Most tests with open ventilation grilles were carried out once, so the measurements that were obtained only give an indication of the concentrations of natural gas and hydrogen in the metre cupboard. Duplicate or triplicate measurements must be made to ensure that the measured gas concentrations are statistically substantiated.

The tests of natural gas and hydrogen leakage, with open ventilation grilles, showed that, with increasing leakage rates, the gas concentration in the cabinet increased proportionally. The gas concentration eventually levelled off at approximately 2 % v/v, for both natural gas and hydrogen. The measured gas concentration of hydrogen was greater at the same leakage rates than the measured gas concentration of natural gas, but only by a factor of approximately 1.02. The measured gas concentrations were comparable except in the case of the 3 L/h leakage rate where the measured concentration of hydrogen was 3.7 times higher than that of methane. Because hydrogen is much lighter than natural gas, it was expected in advance that hydrogen would rise faster, so that it would disperse more quickly through the top ventilation grid. However, the tests showed that this was not the case. The hydrogen concentration in the box was comparable to the natural gas concentration, at the same leakage rates. The researchers could not give an explanation to this and suggested that further tests will need to be conducted. Furthermore, for some tests for both natural gas and hydrogen, a sinusoidal trend was seen in the measured gas concentrations. This could be a side-effect of chimney effect taking place in the box or could be caused by vortex formation in the box. Additional tests would have to be performed to determine the actual cause. In the tests with taped grates, and therefore no ventilation, higher gas concentrations were detected than in the tests with open grilles, but the measured gas concentrations remained below 4% v/v for both types of gas.

At the domestic property level, gas dispersion and accumulation tests have also been conducted, to determine the risks that arise by hydrogen leaks in various locations within a house. Such tests have been conducted both as part of the Hy4heat project (Simpson, Allason and Johnson, 2020[100]) and as part of the HyHouse study (Crowther et al., 2015[101]). During the Hy4heat experiments, hydrogen and methane were released within a two-story domestic property. The release sites were the basement of the house and the kitchen boiler cupboard. Based on the results of these tests, it was determined that having the kitchen door open, in experiments where methane or hydrogen were released in the boiler cupboard, resulted in higher explosive gas concentrations in the rooms outside the kitchen whilst not having much effect on the concentrations measured at the high point in the kitchen. For hydrogen gas releases in the basement, a minimum gas flow rate of 25.5 m^3/h through a 10 mm diameter release orifice was required to generate significant flammable concentrations. It should be noted that while the inclusion of furniture and other obstacles is unlikely to have any effect on the accumulation of gas within the property, it is known to have a significant effect on the potential explosion severity in natural gas explosions. Given the increased reactivity of hydrogen mixtures, it is important to take this effect into account when assessing the experimental results and the potential risk.

A mitigation measure that was tested was the **addition of a ceiling vent**[27] which had the effect of reducing the maximum concentration of hydrogen seen within the kitchen. Other mitigation measures, such as air bricks added to the basement, showed less conclusive results, with some smaller vent tests recording an increase in the maximum hydrogen concentration. The tests undertaken with the larger vent size in the basement did demonstrate a reduction in maximum hydrogen concentration, however, as the results were inconclusive, this could be an area that requires further investigation. The potential effect of atmospheric wind conditions on the results of the venting experiments was not considered and future experiments should study the impact of wind speed and direction on the air flow through the house to better quantify the effects of the mitigation measures tested (Simpson, Allason and Johnson, 2020[100]).

In the HyHouse project (Crowther et al., 2015[101]), test gases were injected into a two-storey farmhouse at different flow rates and the concentration and distribution of those gases throughout the house was measured. The following test gases were used: 100% Natural Gas, 100% Hydrogen, 3% v/v Hydrogen (97% Natural gas), 10% v/v Hydrogen (90% Natural gas), Town gas (50% Hydrogen, 25% CO_2 and 25% Natural gas). A range of leaks were simulated from locations in the living room, the kitchen and the cupboard under the stairs. This was complemented by several high-rate gas releases to simulate a leaking hydrogen vehicle or gas main, using 100% hydrogen and 100% natural gas.

Significant flammable gas stratification was observed in the downstairs rooms of the property, with increasing definition at higher injection rates and thus higher gas concentrations. Flammable gas stratification was evident at different levels of house air tightness. At hydrogen injection rates under 39.5 lt/min, as would be expected from a minor gas leak, hydrogen gas concentrations within the property did not exceed the lower flammability limit (LFL) for hydrogen. For 79 lt/min 100% hydrogen injections, hydrogen concentrations did reach the LFL in the room of injection, but concentrations throughout the rest of the house did not reach the LFL until the very end of the injection period. This suggests that flammable concentrations are unlikely to be achieved during short term, low-rate releases, even in properties with low air permeability rates (e.g. ~3 $m^3 h^{-1} m^{-2}$).

Overall, the flammable gas concentrations resulting from the release of hydrogen in the HyHouse project were found to be, on average, about 1.6 times greater than the concentrations resulting from methane releases. Based on these concentrations from HyHouse, the ignition likelihood of hydrogen (for the same energy release rate) was estimated to be greater than that of methane by a factor of 4. When only the large gas releases were considered, this factor was reduced to 2. This difference in ignition probability is primarily due to the ignition energy being approximately one order of magnitude lower for hydrogen than for methane (Mouli-Castillo et al., 2021[89]).

The concentrations observed in HyHouse would not lead to flammable gas concentrations that would result in severe structural damage if ignited. The large releases of hydrogen and methane were shown to result in flammable gas concentrations that are likely to induce a similar overpressure if ignited. In such a case, the associated **potential to cause severe structural damage was comparable for hydrogen and methane**.

Experiments conducted as part of the Naturalhy project (Lowesmith et al., 2009[24]), simulated the release of methane / hydrogen mixtures in a test rig designed to represent a typical domestic room of dimensions 3 m (length) by 3 m (width) by 2.3 m (height). Four different gases were used in the experiments: 100% methane and mixtures of hydrogen and methane which contained 10%, 20% and 50% v/v hydrogen. In all cases, the gas concentrations (of either methane or hydrogen) measured at different locations within the enclosure but at the same height, were the same. The gas accumulation was uniform in the horizontal plane but only varied with height above the floor. The recorded gas concentrations increased with time until a steady state concentration was reached which prevailed until the gas release was terminated.

Gas concentrations were very low (less than 1% v/v) for all sensors located at low heights within the enclosure (1.1 m or lower). All sensors located 1.6 m or higher gave similar results, indicating uniform gas accumulation between 1.6 m and the ceiling. Between these two regions, the gas concentration varied significantly with height. The formation of a uniform gas layer was observed at an early stage after gas release, and the gas concentration in the layer increased until a steady state concentration was reached. After the gas release was terminated, high gas concentrations persisted for some time close to the ceiling but at lower heights, the concentrations were significantly lower and gas accumulation was quickly dispersed.

A mathematical model was developed to compare the absolute gas concentration levels achieved during the experiments while taking into account the effect of different wind conditions and the different heights of ventilation openings. The predictions of the model showed good agreement with the experimental data, demonstrating that the model performs well for upward directed, relatively low momentum, releases of buoyant gas. Consequently, the model was used to investigate the influence of changes in the hydrogen content in the released methane/hydrogen mixture on the gas accumulation. Raising the percentage of hydrogen resulted in an increase in the volume flow rate of the gas released into the enclosure, leading to a rise in the gas concentration and an increase in the volume of the region in which the gas accumulates. However, the rise in hydrogen content also led to enhanced gas buoyancy which in turn led to an increase in the ventilation air flow. Consequently, the rise in concentration was not as great as might otherwise have been expected.

While hydrogen dispersion tests have been successfully carried out in two-storey houses, the applicability of the test results to other types of accommodation, such as flats or bungalows, might require further investigation (Mouli-Castillo et al., 2021[89]).

The hydrogen dispersion tests have been further supplemented by gas ignition potential tests and consequence assessments. Experiments have been conducted to assess and compare the potential for household electrical items to ignite hydrogen or methane mixtures with air (Crewe, Johnson and Allason, 2020[102]). The items used in these experiments included white goods in new and used condition, plugs and switches, light fittings and extractor fans. In the majority of the tests, no ignition occurred with either hydrogen or methane or ignition occurred with both hydrogen and methane. Very **few domestic appliances caused hydrogen to ignite, but not methane**. These included **hair dryers, toasters, vacuum cleaners, tumble dryers and irons**. Nearly all of these appliances can only be used with a human operator present, who would most likely be able to smell a gas release. For this reason, the **odourisation of hydrogen to lower the detection threshold** is the priority of various currently ongoing projects (Mouli-Castillo et al., 2021[103]).

The consequence assessment of potential hydrogen gas ignitions within structures constructed from varying types of material such as glass, wood, concrete and metal, concluded that **for concentrations of around 15-20% v/v hydrogen, the consequences of an ignition would be roughly comparable to those of a 10% v/v methane ignition** (Hardy et al., 2021[104]). Towards the higher end of this concentration band, the hydrogen ignition starts to become more severe than methane. **Beyond 20% v/v (up to around 40% v/v) the consequence of a hydrogen ignition gets progressively more severe**. The **presence of obstructions within the combustion zone** could cause turbulence of flammable gas mixtures leading to **increased peak overpressure for both hydrogen and methane**. Peak overpressures for hydrogen can be higher due to the faster flame speed. There was no evidence of hydrogen exhibiting a general transition from deflagration to detonation in a pseudo domestic environment. A general detonation was only achieved using chemical detonators.

As part of the Naturalhy project, a series of large-scale explosion experiments involving methane/hydrogen mixtures was conducted in a 69.3 m^3 enclosure to assess the effect of different hydrogen concentrations on the resulting explosion overpressures (Lowesmith et al., 2011[105]). The tests studied methane, 80:20 methane: hydrogen and 50:50 methane: hydrogen mixtures. The results showed **explosion severity (overpressure) increased with increasing hydrogen fraction**. This increase was small when adding up to 20% v/v hydrogen to the methane, however the increase became significant when 50% v/v hydrogen was added. For the vented confined explosions studied, it was also observed that the **addition of obstacles** within the enclosure, to simulate the congestion caused by furniture, equipment and pipework, resulted in **increased flame speeds and overpressures** above the levels measured in an empty enclosure. Predictions of the explosion overpressure and flame speed were made using a modified version of the Shell Global Solutions model, SCOPE. Comparisons of the model predictions with the experimental data showed generally good agreement.

Hydrogen odourisation

One of the main mitigation measures suggested for the early detection of hydrogen gas leaks is the **odourisation of hydrogen**. Research has been conducted to identify odorants that are effective when added to hydrogen and are also compatible with hydrogen appliances (Mouli-Castillo et al., 2021[103]), (Murugan et al., 2019[106]). Tests conducted in the UK, determined that **Odorant NB**,[28] which is a blend of 78% t-butyl mercaptan and 22% dimethyl sulphide and which is currently used for natural gas, is also **effective for hydrogen**. Other odorants, such as **THT**,[29] have also been tested and were found to be **effective and compatible with network components and hydrogen appliances** (Murugan et al., 2019[106]), (Top and Teunissen, 2020[107]) However, both NB and THT were shown to be **incompatible with fuel cells** due to the sulphur that they contain, which causes significant degradation to the fuel cell components (Murugan et al., 2019[106]).

Conclusions and knowledge gaps

The main findings based on the literature review related to scenario 6 are:

Due to increased interest in the residential use of hydrogen for heating, large research projects and demonstrations are currently underway, mainly in the UK and the Netherlands, which aim to investigate the possibility of substituting natural gas with hydrogen for heating. Experiments conducted as part of these projects are currently filling in the knowledge gaps when it comes to the safe delivery and use of hydrogen in residential buildings. Below are summarised the main findings of these projects, along with the recommendations they make to minimise the risk from the use of hydrogen in houses.

Hydrogen distribution network

Based on findings from the H100 project, it has been concluded that switching to hydrogen without any changes to the current UK gas network and infrastructure would lead to a doubling in the risk of fatalities resulting from severe structural damage (relative to the risk from the use of methane in the current gas network). As **most observed flammable gas leaks are caused by metallic network components**, by switching to a **100% polyethylene network** and by implementing **additional mitigation measures downstream of the gas meter**, a 100% hydrogen network could be as safe as the currently used natural gas network (Mouli-Castillo et al., 2021[89]) Figure 8.9.

Hydrogen usage in buildings

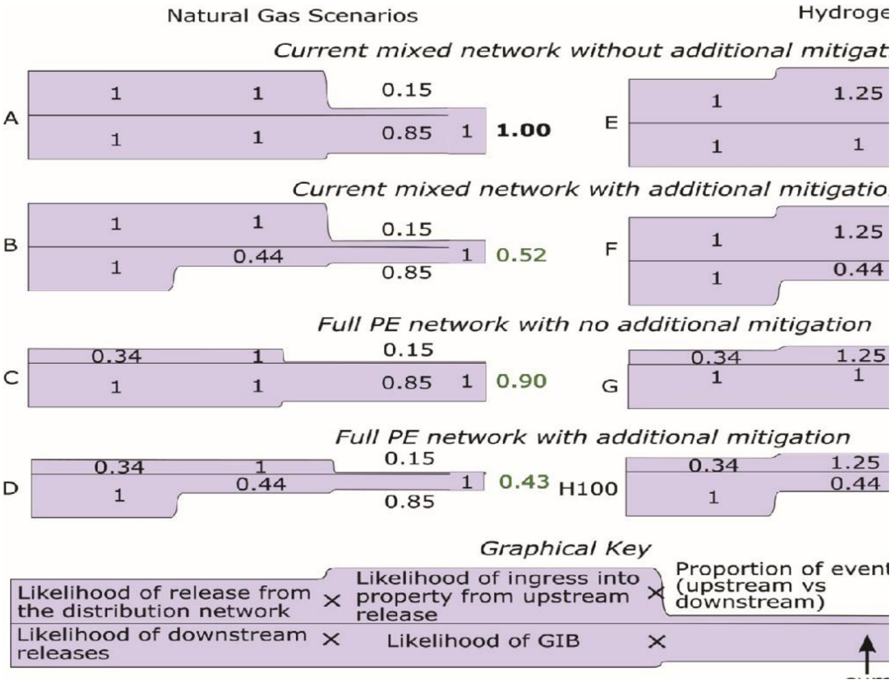
Based on the results of hydrogen dispersion experiments, **small hydrogen leaks** (97% of currently reported natural gas leaks in the UK are from holes no larger than two millimetres) **should not create sufficiently large flammable clouds to produce injuries**. **Medium sized leaks** (from holes between three and seven millimetres in size) could produce flammable gas clouds in small rooms, notably those with the door closed and / or rooms with poor ventilation. However, as noted by the experts, these leaks are **most often caused by third party damage and rarely occur spontaneously**, so generally the appropriate steps are readily taken to stop the development of the leak, i.e. opening windows, closing the emergency control valve (ECV) and alerting the gas company. **Large leaks** (from holes greater than seven millimetres) can produce high gas concentrations in large areas of a house. A significant percentage of these leaks arise from third party damage, including malicious intent. The likelihood of such leaks could be **reduced by implementing the appropriate mitigation measures**, such as the introduction of **excess flow valves** to the household piping and the installation of **flame failure devices** to all hydrogen appliances (Brown et al., 2021[108]).

Recommendations from pilot studies

- The introduction of **two excess flow valves (EFVs)**. This would help reduce the likelihood of large hydrogen leaks developing into a hazardous scenario by a factor of 4 (i.e. the flow of gas will be stopped before a flammable atmosphere can develop). This reduced likelihood will then be similar to the likelihood of hazardous scenarios that can ensue in the current UK natural gas network (Mouli-Castillo et al., 2021[89]).
- The first EFV should be either **in the service pipe or immediately after the emergency control valve**. The second EFV should be either **integrated in the hydrogen gas metre** (Brown et al., 2021[108]) **or added upstream of the metre** (Mouli-Castillo et al., 2021[89]). The gas metre should be installed outside of the property, where possible, and comply with current best practice and BS6400-1:2016 (Brown et al., 2021[108]). Since in the Netherlands the gas metres are inside the house, some initial research has been conducted on the effectiveness of **ventilation for the gas metre cabinets** (Bierling, Vlap and Bahlmann, 2020[99]), but further information is needed to better understand potential risks.

- The installation of **Flame Failure Devices (FFDs)** in all hydrogen appliances to reduce the likelihood that appliances will be, unwittingly, left on whilst unlit. A significant cause of current fires and explosions (about 40% of all of those occurring downstream of the emergency control valve) is the absence of FFDs, particularly on hobs (Brown et al., 2021[108]), (Mouli-Castillo et al., 2021[89]).
- There should be **non-closable vents** with an **equivalent area of 10,000 mm²**, located as close to the ceiling level as possible and no more than 0.5 m below the ceiling level in all rooms with gas appliances or hydrogen-carrying pipes installed (Brown et al., 2021[108]).
- All the **cupboards and other appliance compartments** (e.g. boilers) where hydrogen appliances are present **should have vents** (Brown et al., 2021[108]).
- An **odorant** of the same effectiveness should be added to hydrogen as is currently used for natural gas (Brown et al., 2021[108]).
- **Hydrogen detection alarms** should be installed where residents are unable to smell the gas odorant (Brown et al., 2021[108]).
- **Mechanical crimp fittings** should be used in pipework instead of soldered joints, which are weaker and more prone to leakages (Mouli-Castillo et al., 2021[89]).
- Concerning the potential use of hydrogen for cooking, a stronger flexible pipe could be installed at the rear of the cooker to limit the likelihood of damage when the cooker is displaced. Additionally, the cooker should be fixed to the wall using a chain and Rawl bolts to limit the loading on the flexible cooker connection (Mouli-Castillo et al., 2021[89]).
- As a lot of the required infrastructure for the use of 100% hydrogen for domestic heating is not yet installed and would require years of preparation, it has been suggested that, in the short term, a **20% blend of hydrogen with natural gas** could be used for heating and would still be **compatible with the existing infrastructure and heating appliances** (Castek and Harkin, 2021[109]).

Figure 8.9. Risk factor calculations based on the likelihoods of events determined in our assessment



Note: The scenarios A, B, C and D correspond to the risks that arise by the use of natural gas, and scenarios E, F, G and H100 are scenarios corresponding to the use of hydrogen in the gas network. Scenario A is the current use of natural gas in the UK network. Scenario H100 is representative of the H100 100% hydrogen network.
Source: (Mouli-Castillo et al., 2021[89]).

Gaps

As most of the studies on the residential use of hydrogen that were covered in this report are still on-going, it is likely that some of the current gaps in our knowledge concerning hydrogen safety will be addressed in the near future.

The projects covered in this report focused on the use of hydrogen in properties that are masonry-built and that contain a standard range of ignition sources. This is suitable for the UK needs, as it corresponds to the majority of domestic settings in the UK. However, the applicability of the results to other types of accommodation might require further investigation. Such kinds of accommodation are blocks of flats, high-rise buildings, houses in multiple occupation, mechanically ventilated buildings and buildings that contain an atypical number of ignition sources (Brown et al., 2021[108]), (Mouli-Castillo et al., 2021[89]).

There is not currently sufficient information on the safety concerns associated with the use of 100% hydrogen in the internal pipework of houses. Additionally, as there is currently a limited number of heating appliances available that run on 100% hydrogen (and these appliances are still largely part of various demonstration projects and have only been in operation for the past 2-3 years), it is unknown what the impact from the use of hydrogen will be on the maintenance requirements of the heating systems. As the current demonstration projects continue and more information on the use of hydrogen is compiled, evidence on this impact should be obtained over the next 5 years (Castek and Harkin, 2021[109]).

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Notes

[1] However, one should note that each (hydrogen) production route depends also on the geographical region, process configuration (IEA, 2021[4]).

[2] In the 1940s, the world’s largest water electrolysis plant was built in Rjukan, Norway (Hydrohub, 2020).

[3] This includes: Canadian Hydrogen Installation Code - BNQ, design code for hydrogen station GB50177-2005 (China), hydrogen technologies code - NFPA2 (USA) etc.

[4] That is, pipeworks that transports hydrogen at a pressure between atmospheric pressure to 3.4 MPa (Table 3).

[5] A measure of risk created by mathematically adjusting a value in order to permit comparisons.

[6] HIAD: Hydrogen incident reporting database.

[7] Fuel cells and hydrogen joint undertaking, https://www.fch.europa.eu.

[8] Nonetheless, compressors at hydrogen production plants operate at a lower pressure as hydrogen is prepared for transportation either by pipelines (usually between 2-5 MPa) or road tube trailers (legal limit at 20 MPa in China and 25 MPa in the United States).

[9] This is related to Scenario 1 as electrolyser units (alkaline, PEM) are located indoors.

[10] More applicable to pipework connected to a hydrogen vessel where a large inventory is available.

[11] Nonetheless, the software Safeti (Det Norske Veritas) is applicable to for hazardous substances in general, not specifically validated for hydrogen.

[12] 14 kPa = 0.14 bar = 140 mbar.

[13] 42 kPa = 0.42 bar = 420 mbar.

[14] Air changes per hour.

[15] For details on different tank types please check section 2.4.

[16] 1MPa = 10 bar.

[17] 70MPa = 700 bar.

[18] 12 bar above atmospheric pressure, 12 bar = 1200 kPa.

[19] It is worth noting that currently, heavy duty hydrogen vehicles, such as buses and trucks in Europe typically use gaseous hydrogen compressed to 35 MPa, while a pressure of 70 MPa is the norm for hydrogen cars.

[20] In Japan, onsite-type hydrogen fuelling stations using natural gas and other resources and offsite-type hydrogen fuelling stations, in the USA, some hydrogen fuelling stations considered in this study were of the offsite type.

[21] 70MPa = 70,000 kPa = 700 bar.

[22] 1 Mpa = 10 bar.

[23] Nonetheless, risk for medium and large leakage meet the acceptance criterion at $1.0 \cdot 10^{-4}$ /year.

[24] A method which uses information on HRS accidents over time.

[25] Unrevealed leak time is calculated as a function of leak rate and inspection interval. Unrevealed leak time is one area within safety and risk management of hydrogen stations that has not yet been addressed in any other research paper. The authors believe that in addition to process safety time, unrevealed leak time is an equally critical parameter that needs to be considered in the engineering safety designs. It determines the time period when the leak exists at the installation due to an unrevealed leak failure.

[26] 10kPa = 100 mbar.

[27] Ducted to the external wall of the kitchen.

[28] NB: a blend of two chemicals, t-butyl mercaptan (TBM) and dimethyl sulphide.

[29] THT: a chemical, Tetrahydrothiophene.

Part II Regulatory review

9

The hydrogen regulatory landscape

This chapter provides an overview of the hydrogen energy law and regulations across several countries. It presents the regulations related to hydrogen technologies in different scenarios/applications during the entire hydrogen life cycle.

The report consists of a study of the hydrogen energy law and regulations across several countries. It presents the regulations related to hydrogen technologies in different scenarios/applications during the entire hydrogen life cycle. It presents main findings and guidance with regard to hydrogen regulations complementing the review study on hydrogen safety and risks under the Outputs of Component B of the project.[1]

The review section on hydrogen safety regulations summarises and discusses existing (mandatory) regulations in ten countries: Australia, China, England, France, Germany, Japan, the Netherlands, Norway, the Republic of Korea and the United States. An introduction to each hydrogen legal framework is provided. The review investigates regulations falling into six distinct scenarios or Value Chain elements (outlined below) selected at the behest of the Dutch Ministry of Economic Affairs and Climate Policy. They are of particular interest as they cover use of hydrogen technology in densely populated areas requiring specific safety and risk management measures.

- Scenario 1 – Production: hydrogen leakage from pipes connected to electrolysers;
- Scenario 2 – Transport pipelines: hydrogen leakage from high-pressure pipeline;
- Scenario 3 – Road transport: hydrogen leakage in confined spaces/built environments;
- Scenario 4 – Mobility and partially confined spaces: examples of this scenario include a hydrogen city bus driving in a tunnel is involved in a collision traffic accident;
- Scenario 5 – Mobility and partially confined spaces: accidents (ISO, 2020[1])[2] at a hydrogen refuelling station;
- Scenario 6 – Domestic use: safety of hydrogen in buildings with focus on hydrogen cooking stoves and boilers.

From the review, it appears that:

- There is no dedicated regulatory framework in most of the countries for most of the scenarios/applications analysed. However, in some countries guidelines for the safe use of hydrogen in some scenarios/applications, like e.g. refuelling stations, are published. Moreover, international codes and standards for hydrogen equipment and installations and national codes and standards for some scenarios/applications have been developed in some countries.
- Hydrogen production via electrolysis, as a more mature and well-developed technology, has a more concrete legal framework compared to the rest of the scenarios.
- Domestic use of hydrogen is the application with the least specific regulations in the countries analysed as well as the least developed economic or environmental case.
- Several countries intend to revise their legislation and amend it for hydrogen in the coming years according to their strategic roadmap for hydrogen.
- There are multiple levels of authorities and an absence of a unified permit system, and this may hinder the energy transition. Integration and simplification appear highly desirable.
- There is clear need for harmonisation and consistent approaches to the hydrogen safety regulations and permitting processes. International co-operation between national regulators would facilitate the use and faster adoption of hydrogen-based technologies.

Overview and discussion

The review of regulatory framework across countries revealed the absence of a specific regulatory framework for hydrogen applications in the countries considered. Several countries intend to revise their legislation or amend it to take account of the increased deployment of hydrogen according to their respective strategic roadmaps for hydrogen. From the country-specific review, strengths and weaknesses on regulatory aspects emerged that enable and hamper, respectively, the energy transition to hydrogen. These are summarised (Box 9.1).

Box 9.1. Emerging strengths and weaknesses from the countries in this study

Strengths

- Australia has already developed a number of hydrogen projects relating to all the different parts of the hydrogen life cycle. These projects are providing valuable information to policymakers to support, complement and enhance the pathway to realising the country's considerable potential in hydrogen. It is anticipated that the legislation will be amended by 2023 subject to federal and territorial government processes and approvals to better incorporate and clarify requirements for hydrogen, including formalised standards.
- China shows a good practice of developing a set of technical regulations and standards. The establishment of technical regulations helps to prevent market failures. It has hydrogen specific, legally binding technical regulations for 4 of the 6 scenarios of the H2 value chain considered here and has recently developed one standard regarding hydrogen use in domestic settings. Regarding scenario 4 &5, its technical regulations were updated and improved after 2020 that is a few years after its implementation of large-scale hydrogen projects. In addition, regarding scenario 1-5, the country also developed a set of not legally binding national standards that reflect the lessons learnt from its hydrogen practices.
- In England, hydrogen is currently a nascent area of energy policy, with the industry looking to the UK Government to provide capital and revenue support, regulatory levers, and incentives. There is still reliance on existing high hazard gas management law and regulation. The good practice is that the Government has launched a Hydrogen Strategy for a hydrogen transition putting hydrogen development as a priority.
- France's hydrogen regulatory framework is improving in order to meet the objectives set in the national strategy plan until 2030. In 2021, the first French text to create a legal regime for hydrogen was created. Hydrogen production is now divided into three categories; renewable hydrogen (including water electrolysis hydrogen), low-carbon hydrogen (a CO2 emission threshold must be reached for hydrogen to be considered renewable or low carbon) and carbon-based hydrogen (the hydrogen produced with fossil fuels). This is of course the recognition that hydrogen production needs to be fully and attentively discerned. Additionally, France developed technical regulations for the use and layout of HRSs, for instance under Order 22/10/18 to promote safety and environmental protection.
- Germany's energy transition is progressing. This can be witnessed through legislative changes for pipeline transport and for increased incentives for increasing HRS. Good practices from Germany include vesting the power for permitting at the local level with the individual states (Länder). States are considered best equipped to handle the unique challenges that may arise due to local environment, industry, safety etc. Digitisation of application process has already begun which helps in speeding the permit time.
- Japan has the advantage of having designated government policy, including "Strategic Roadmap for Hydrogen and Fuel Cells" (2011) and "Basic Hydrogen Strategy" (2017) formulated by the government and supporting the uptake of hydrogen, coupled with a public acceptance of hydrogen projects in the domestic-energy mix. The government is tackling deregulation for hydrogen stations for the popularisation of hydrogen fuel cell vehicles, and technical standards for hydrogen stations that allow customer/drivers to self-refuel. Arrangements for hydrogen tank fuelling - self-service hydrogen stations - were added to Article

7-4 of the GHPGSO in 2020. In 2018, the Japan Petroleum Energy Center (JPEC) released the Self-hydrogen Station Guidelines (JPEC-TD 0004). In the sector of hydrogen domestic use fuel cells that are released for such purposes (though not limited to hydrogen) are subject to the Fire Service Act and the Electricity Business Act.

- The Netherlands is demonstrating good practices in hydrogen technology development and makes forward steps for the development of national regulatory regime. There is a lot of legislation; however it does not everywhere sufficiently take into account hydrogen as an energy carrier for the energy transition. There are general restrictions within the broader Dutch regulatory framework and two very particular hydrogen regulations, the PGS35 for hydrogen fuel stations and the requirements for hydrogen fuel cells (soft law), are published. Even though, there is essentially no single comprehensive piece of legislation for new hydrogen usage in the energy transition the Netherlands Hydrogen technology development is on its way and pilot and demonstration projects are ongoing. This development is also receiving positive support from the local population and public acceptance is a key factor in accelerating the deployment of new technologies. In line with the 2021 OECD recommendations on agile regulatory governance to harness innovation (6 October 2021), successful, future-proof regulation can only be developed in cooperation with other national jurisdictions and stakeholders.
- In Norway, in addition to a national framework, the municipality is responsible for permitting related to hydrogen projects and for coordinating with other authorities as it sees fit. This is a good practice because the municipality is best aware of the local conditions. Further, the municipality is responsible for consulting other regulatory agencies when it deems fit. This reduces uncertainties for the operator who only needs to make the application before the municipality and not to individual agencies.
- The Republic of Korea not only declared ambitious plans for hydrogen inclusion into its economy by a specified date but puts all best efforts to achieve these plans by establishing a legal framework for permitting, where local government is involved, developing hydrogen specific technical standards, providing a wide range of state support to businesses willing to participate in hydrogen development. There are a number of hydrogen pilot projects on the basis of territorial economic zones, provided with a variety of incentives. Big market players like Hyundai as well as state utility companies actively participate in such projects. Also, the Government actively supports foreign partnership and knowledge exchange as well as local knowledge hubs involvement.
- The regulatory landscape in the United States largely depends upon the adherence to codes and standards. Different states and local legislations have developed different requirements. An exception can be found in the California Fire Code which was developed by the state of California to provide a set of rules for hydrogen refuelling stations. The rules included in the California Fire Code are sufficiently comprehensive: they include requirements for dispensing systems and approved equipment and list separation distances.

Weaknesses

- There is currently no legal framework in Australia targeted specifically at hydrogen production, transport, or domestic use. The existing legal framework requires to be adjusted.
- The Chinese hydrogen sector heavily relies on government subsidies, and this is unfortunately not a sustainable long-term driving force. Therefore, a better and more supportive regulation regime is required for sustainable growth in the sector. Furthermore, since many stakeholders are involved in the permit-issuing process for hydrogen-based technologies, the process can be slow and hinder private investment. It is estimated that for a small-scale hydrogen station, it

would take up to 6-8 years for the investor to recover his investment and for a petrol station, it would take up to 2-3 years.

- There is lack of dedicated regulatory and policy structure in England. Dedicated hydrogen legislation and policy lag behind the initial implementation of low-carbon hydrogen production that can be seen only in some areas. This means that elements of the hydrogen production, transport, storage, and distribution process often fall within the scope and remit of various other rules and regulators, while other aspects remain without clear or specific regulation.
- France's energy transition is progressing, but some gaps are present and need to be filled to keep pace with hydrogen technology and facilitate its use. The French legislator has not yet associated the notion of "manufacture in industrial quantities" in hydrogen production installations subject to environmental regulations of ICPEs with a specific numerical threshold which therefore could be strengthened.
- In Germany, despite the initiatives, legislation is lagging, and authorities do not have regulatory support or technical expertise to efficiently handle the hydrogen transition.
- In Japan, hydrogen has generally been used as an industrial gas, and the business environment and infrastructure to utilise it as an energy carrier has not been sufficiently developed. Existing regulations on the handling of high-pressure gas or flammable gas, such as HPGSA, consider hydrogen as a flammable gas and regulate it accordingly. These regulations are not therefore specific to hydrogen in its new context and so are not suitable therefore for the regulation of hydrogen as energy carrier.
- In the Netherlands, laws of different levels of governance and practices and expertise that need to be brought together in a relatively short period of time set obstacles to a fast progress in regulating nationally the rapidly developing hydrogen technology. More efficient ways may need to be found to regulate in current circumstances, given also the 2021 OECD recommendation that there would be benefit in bringing international partners, stakeholders, and enforcement considerations onboard in order to create a regulatory regime more supportive of innovation.
- Norway is yet to have a well-defined legal and regulatory framework for hydrogen projects in the scenarios described above. Legislation which can simplify development of hydrogen in the six scenarios still needs to be developed.
- In the United States, both DoE and the industry recognise that there is a lack of appropriate regulations and standards, and that further research and development is necessary. The attitudes towards precaution between the United States and Europe are fundamentally different. The EU follows a more stricter approach to the precautionary principle than the United States.

Among the examined applications in this review, hydrogen production via electrolysis, as a more well-developed technology, has more mature legal frameworks. Domestic use of hydrogen has the least number of specific regulations in the countries analysed. Only China and England (UK) are the two countries that have shown effort in regulating this sector.

This next section presents a summary of the existing regulatory framework in the countries analysed for the six examined applications.

Production facilities

China has legal binding standards for the safe design and maintenance of hydrogen production stations that set restrictions on maximum allowable storage capacity, operation conditions, safety equipment, technical specifications of pipework, safety requirements, such as minimum ventilation rate, separation, and safety distances, etc. South Korea has developed codes that cover most of the above requirements for hydrogen production and storage facilities. In Japan, the above requirements of the hydrogen production facilities are set under the regulation of high-pressure gas facilities. In the United States, hydrogen production facilities are managed by the OSHA standard and NFPA-2 which among other issues defines safety and separation distances and requirements for safety systems. In Germany and Norway, permits related to building, construction and operation of the stations are required and risk assessment should be performed and submitted to the regulatory authorities' prior operation. In France production facilities are subject to environmental regulations specific to "classified facilities for the protection of environment."

Across the EU, notification of the regulatory authority is required for storage of more than 5 tonnes. There is a requirement to draw up a written safety policy for the prevention of hazardous accidents. Storage greater than 50 tonnes requires a safety report and emergency plan to be prepared, submitted to and assessed by the Competent Authority. In many countries, including the EU and Japan, hydrogen production, *per se* is not subject to any specific legislation as the focus is on the maximum stored inventory. Regulations covering high pressure or flammable gases and regulations for other gas producing facilities, respectively, are applied.

Pipelines

Regulations have been amended to allow hydrogen to be transmitted though pipelines in some countries, like Australia and Germany, while in others, like the Netherlands, the law does not provide yet the possibility to inject, transport, or distribute any amounts of hydrogen through the natural gas infrastructure under the Gas law,[3] but allows it in new pipelines Thus, no pertinent regulatory framework has been developed in all countries. In UK, hydrogen transport through pipelines requires permission and must adhere to pipeline requirements for design, safety systems, construction, installation, operation, maintenance, and decommissioning as well as to industry codes. In Japan, even though the transport of hydrogen is limited to short distance uses, there are safety regulations for the pipe layout and the pipe materials. However, many of them are still being verified. In the United States, which has the largest existing gas pipeline system, regulations for flammable gases in hydrogen pipelines are applied. Finally, the American Society of Mechanical Engineers provides standards for piping and transportation pipelines and China has developed a Chinese code with general requirements that pipelines have to follow.

Road transport and mobility in confined spaces

Most countries currently apply to hydrogen the regulations that were developed for other flammable gases. Within Europe, Road transport is regulated via the ADR agreement that concerns the International Carriage of Dangerous Goods by Road. ADR requires no amendment for hydrogen as it is already fully incorporated. Australia also applies the Dangerous Goods Safety (Road and Rail Transport of Non-explosives) Regulations 2007 and the Australian Dangerous Goods Code. Training of transport company employees on the associated risks of these goods is obligatory in France.

Restrictions on transport of dangerous goods in tunnels apply within Europe based on road tunnels classified by ADR. Tank carriage of hydrogen is forbidden in tunnel categories B, C, D and E. This means that hydrogen in tanks cannot be delivered through all tunnels, e.g., in the Netherlands the transportation is allowed only in 5 tunnels. In Japan, the passage of vehicles carrying explosive or flammable dangerous goods is prohibited or restricted in long tunnels (over 5 000 m long) and underwater/waterfront tunnels. No specific restrictions were found for FCEV entering tunnels, revealing the need to develop regulations, standards, and codes for FCEV in confined spaces.

Hydrogen refuelling stations

Even though the countries analysed in this report have several hydrogen refuelling stations already deployed in their territory, a solid regulatory framework is lacking in EU countries and Australia, while Japan, China, and the United States have regulated hydrogen stations and their equipment (dispenser, compressor, storage) for both compressed and liquid stations. More specifically, Japan, which possess the largest number of refuelling stations worldwide, and China, have regulations which indicate the technical specifications of materials and equipment, prevention and mitigation measures, and detailed safety distances from site boundaries and different components of the stations, vulnerable objects as well as oxygen facilities.

The state of California in the United States, has developed a comprehensive set of rules for hydrogen refuelling stations, including requirements for dispensing systems and approved equipment (cylinder, containers, tanks, pressure relief devices, hoses, compressors, hydrogen generators, dispensers, detection systems, electrical equipment and others). Moreover, the separation distances from a hydrogen refuelling station as defined in NFPA-2 are applied. In the Netherlands, the PGS35 series has been published to provide guidelines on the design, construction, maintenance and management of hydrogen delivery installations.

In the remaining countries, in the absence of specific legislation and guidance on the permitting procedure, the variety of national and international standards and codes is followed and/or HRS facilities are compared on a par with LNG and LPG facilities. Finally, the review showed that since HRS are capable of producing and storing hydrogen at different capacities, the requirements related to land use and general operability are often unclear. For instance, in Germany, rules vary depending on whether an HRS has the ability for onsite production of hydrogen and the accompanying storage limits.

Domestic use

Hydrogen is not regulated for domestic use in most of the countries reviewed. In Australia there is no regulation allowing domestic use of pure hydrogen, because existing gas appliances are only suitable to take a blend of hydrogen (up to 10 or 20%). China's policies and regulations support hydrogen blending in existing natural gas grids and has published a groups of standards for natural gas/hydrogen mixing stations. It is also currently completing the review on how to bring hydrogen into the gas network. In Japan and South Korea domestic use of hydrogen involves fuel cell systems. In both countries hydrogen fuel cells are subject to regulations that apply to fuel cells in general. In England, in the absence of hydrogen related rules and regulations the Gas Safety (Management) Regulations 1996 (GSMR), which concerns the flow of gas through the network are applied. Pursuant to the GSMR the concentration of hydrogen that can be injected onto the England gas network and consequently be supplied to domestic homes should be no greater than 0.1% molar volume. Currently, tests are being conducting to increase the hydrogen blend to up to 20%. If successful, the regulations will need to be amended to allow for this richer in hydrogen blends. The law in the Netherlands does not yet provide for the possibility to inject, transport, or distribute any amounts of hydrogen through the natural gas infrastructure. There are no regulations specifically targeting the domestic use of hydrogen in the United States. Such use is however not prohibited as can be seen by the existence of small-scale pilot projects.

Codes and standards related to scenarios

Good practices for safety in the different hydrogen applications

For fixed installations, including pipelines, common legal safety instruments included:

- Prior notification to the regulatory of the installation, activity, location, and hydrogen capacity
- Licensing or prior approval (permitting) of the installation prior to operation, incorporating:
  - Period inspections or checks on safety during operation;
  - Notification of accidents and incidents involving loss of containment of hydrogen.
- Operator risk assessments

- Safeguarding against impact / trespass
- Specified safety distances from vulnerable populations, buildings – but no consensus on those distances based on hydrogen inventory or activity
- Specification of installation materials of construction
- Specification of design and configuration of installation, including:
    - Safety devices – pressure relief valves, gas detection and alarms, automatic shutdown systems, ventilation (design and rate of air change);
    - Fire protection, fire walls or blast protection to vulnerable building;
    - Operational controls.
- Fire precautions and building fire resistance
- Means of escape

For vehicles transporting hydrogen:

- Authorised and codified standards of design and construction
- Certification of design conformity
- Periodic structural examination inspections
- Visible labelling and information
- Driver training and certification
- Firefighting equipment and information cards for emergency services

For road tunnels:

- Restrictions on passage of hydrogen transportation vehicles, including escorts, restricted times of use or prohibition of use
- Means of escape in the event of fire

Key takeaways

The review found a wide variety of regulatory approaches across the countries assessed with no consensus as to the most efficient and effective format for a national regulatory framework. Equally, some governments have developed new specific standards and codes covering design, location and safe operation of hydrogen facilities whilst others have adopted or amended existing legal instruments, particularly those relating to compressed or high-pressure flammable gases such as methane, LPG or LNG. Similarly, some countries have developed their own national technical standards and guidelines to specify minimum standards of technical safety compliance whilst others adopted existing industry standards and codes to support minimum standards of safety compliance. These soft laws can be considered as precursors for mandatory regulations and in absence of relevant hard law they are often handled as such.

International standards that cover hydrogen production via electrolysis, technical specifications for storage and transportation, detection apparatus, installation and operation of refuelling stations, and others are already available. Australia has released a set of standards on hydrogen quality, storage, transportation and usage that are currently being applied. China has published 31 national standards regarding hydrogen, covering its full life-cycle, while South Korea has developed its own codes for refuelling stations. The Netherlands has also published PGS35 series to provide regulations on the design, construction, maintenance and management of hydrogen delivery installations.

The fragmentation of the regulatory and standardisation framework for hydrogen applications across different countries can be attributed to the following elements:

- different uses of hydrogen. Hydrogen can be a chemical feedstock, a chemical process gas, or a gaseous or liquid energy carrier.
- national, European and international regulations covering the safety of chemical industry processes, supply chains of flammable chemicals, and of handling fuels already exist.
- depending on the specific hydrogen applications, its handling is covered by existing RCS framework.
- permitting authority can vary depending on the application, e.g., for the sectors geographically determined, as in the case of delivery infrastructure, the authority is locally determined. In the case of applications which concern global trade, such as FCEV, global consensus mechanisms have been put in place to harmonise safety requirements and facilitate adoption worldwide.
- RCS harmonisation has been attempted in the past, and in several cases failed, for the reasons above. Common internationally methodologies might conflict with already existing national regulations covering a broader set of hazards and other fuels, which cannot be changed a posteriori.

Some good progress is being made in developing practices, codes, policy, and regulation and this should be continued if market opportunities and strategic needs as well as stated development plans are to be addressed and realised. The key areas for development might be production, storage and distribution. Hydrogen production via electrolysis has more mature legal frameworks compared to other applications, while domestic use of hydrogen has the least number of specific regulations in the countries analysed.

Technical regulations managing related hazards (flammable/explosive) are broadly relevant and are being used and revised in the light of developing data, technology, and market knowledge in order to fill the current regulatory gaps. Given the hazard context, very good progress has been made in several segments of the hydrogen life cycle and value chain, with the domestic heating component being the least well developed and facing the biggest challenges in terms of engineering and public acceptance. Other segments are already close to market or already in place, requiring regulatory refinement and a growth in the necessary investment support and planning and delivery processes for wider roll-out.

Multiple levels of authorities and an absence of a unified permit system first at national level and later on at international level might slow down the energy transition. Laws with simplified administrative procedures will facilitate the construction and operation of hydrogen infrastructure. It is essential to develop a proportionate and consistent regulatory framework not only to build a level of trust with investors and reduce uncertainty about legal compliance but also to promote a sustainable development of the hydrogen energy industry. The existing international standards and national codes can provide useful guidelines for policymakers and can contribute to the development of regulations.

From the review in the countries analysed in this report some good and bad practices were identified, which could be better considered as early strengths and weaknesses/gaps. Some appear to be good developments preparing for appropriate policy and regulation as knowledge deepens. Others are just reflections of the current state of development of technology, policy and regulation or even reflection of the national cultures and current or perceived industry, regulator and/or public concern.

The strengths are:

- perform risk assessment to be granted building and operation permits for facilities that store hydrogen above a specified volume amount. The publication of a risk guidebook at national or international level would provide greater levels of confidence and would accelerate the process.
- rest the power for permitting at the local level with the individual states. States are best equipped to handle the unique challenges that may arise due to local environment, industry, safety etc. It should be stated that for effective permitting state authorities should have adequate skill development, and mechanisms for improved coordination and communication between the different authorities including through digital tools is necessary.

- digitisation of application process for permitting to speed up the permit time.
- develop regulations in cooperation with other national jurisdictions and stakeholders.
- develop sufficiently comprehensive codes and standards for equipment and applications that are not covered by existing codes and standards.

The weaknesses are:

- lack of dedicated regulatory and policy structure as well as technical expertise to efficiently handle the hydrogen transition.
- laws of different levels of governance and practices and expertise that needs to be put together in a relatively short period of time.
- in hydrogen production facilities there is often no legal or administrative distinction between localised and centralised production and also no distinction among the different production processes. This hinders building production facilities onsite hydrogen refuelling stations and as a result, permitting obstacles for simplified processes, zoning, and permitting requirements arise.

It should be noted, though, that several countries intend to revise their legislation to take account of the increased deployment of hydrogen according to their strategic roadmap for hydrogen.

There is a clear need for consensus and consistent approaches to the regulation of hydrogen in the technologies involved in the energy transition and international co-operation between national regulators would facilitate common technologies and safety systems. EU legislation would also facilitate transportation and trade across countries. It is clear, though, that this is a quite challenging task as already existing national regulations covering similar applications (e.g., handling of fuels or safety of chemical industry processes) could conflict with the new hydrogen regulations and careful revision might be required. Clear and less complex permitting processes should be developed that would reduce the time required for approval. Regulations, standards and codes should be revised regularly based on innovations and technology advancements in equipment and safety devices and on evidence-based improved knowledge.

Finally, guidance material and special training programmes[4] for H_2 fires and hazards should be designed and distributed to fire authorities. In the sector of hydrogen vehicle mobility, such as parking and tunnel use it is crucial to develop regulations, codes, and standards and an international programme and training for first responders and emergency services, as currently FCEVs are not distinguished from other vehicles.

Table 9.1. Summary of the review findings

		Australia	China	England (UK)	France	Germany	Japan	NL	Norway	South Korea	United States
Are there any Regulations[1] developed specifically for H2?	Production[2]	-	✓	-	✓	-	-	✓	-	-	-
	Pipeline transport	-	-	-	-	Transi-tional	-	✓	-	-	-
	Road transport and mobility	✓	✓	✓	✓	✓	✓	✓	✓	✓(fuel cells)	✓
	Mobility in confined spaces	-	-	-	✓	-	-	-	-	-	-
	Refuelling station	-	✓	-	✓	-	✓	-	-	✓	✓
	Domestic use	-	-	-	-	-	-	-	-	✓(fuel cells)	-
Nature of regulation	Production	P	P	P	P	P	P	P	P	P	P
	Pipeline transport	P	P	P	P	P	P	P	P	P	P

		Australia	China	England (UK)	France	Germany	Japan	NL	Norway	South Korea	United States
permissive (P) or restrictive (R)	Road transport and mobility	P	P	P	P	P	P	R	P	P	P
	Mobility in confined spaces	P	P	R Exceptions apply	P	P	P	R	P	P	P
	Refuelling station	P	P	P	P	P	P	P	P	P	P
	Domestic use	P	P	P	No	No	P	P	No	P	N/A
In lack of specific regulation developed is hydrogen handled as flammable gas?	Production	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Pipeline transport	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

1. This refers only to mandatory rules (laws) that have been designed specifically for hydrogen (codes and standards, guidelines or other soft laws are not included). Specific hydrogen regulations mean regulations that have been developed and are applied only for hydrogen applications. Other regulations, i.e. regulations for flammable gases, which in some countries are applied also for hydrogen, are not taken into account in this question.
2. Hydrogen production via water electrolysis.

Reference

ISO (2020), *ISO 19880-1:2020(en)*, https://www.iso.org/obp/ui/fr/#iso:std:iso:19880:-1:ed-1:v1:en:term:3.53. [1]

Notes

[1] Component B of the project aims at consolidating and improving knowledge in relation to the safety risks associated to the use of hydrogen, and, on this basis, develop recommendations and guidance with regard to adequate risk-management in the application of hydrogen in different scenarios, and to the development of appropriate regulations and regulatory processes for the use of hydrogen. An extensive literature review, review on hydrogen pilot projects across several countries, review on hydrogen incident database, targeted risk assessments and this output on regulatory review across several countries will be the basis for the final output with guidance materials for permit-issuing authorities.

[2] The ISO/TS 19880-1:2016 defines incident as any “unplanned event that resulted in injury or ill health of people, or damage or loss to property, plant, materials or the environment or a loss of business opportunity.” For the purpose of scenario 5, accidents also include incidents as defined in the ISO. https://www.iso.org/obp/ui/fr/#iso:std:iso:19880:-1:ed-1:v1:en:term:3.53

[3] The Gas law, applied in natural gas pipelines, does not allow injection of hydrogen and thus it is currently illegal to transport hydrogen in existing natural gas infrastructure. However, in new pipelines hydrogen transportation is allowed based on the Pipeline Decree.

[4] Within the EU funded project, HyResponse, the first comprehensive training program for first responder for safer deployment of FCH systems and infrastructure has been developed. There is also a follow up EU-funded project, HyResponder which aims to develop and implement a sustainable trainer the trainer programme in hydrogen safety for responders throughout Europe, supporting the commercialisation of hydrogen and fuel cell technologies by informing responders involved in the permitting process, improving resilience and preparedness, and ensuring appropriate accident management and recovery.

10

Review of hydrogen safety regulations

This section examines the hydrogen legal framework in ten countries: Australia, China, England, France, Germany, Japan, the Netherlands, Norway, the Republic of Korea and the United States. The review investigates the general legal framework and regulations relating to six distinct accident scenarios.

Australia

A legislative package of reforms that will enhance the inclusion of hydrogen within the national energy regulatory framework of Australia is underway. Under the National Hydrogen Strategy, the Federal Government is working with the legislative bodies of each State and Territory in amending the National Gas Law, National Energy Retail Law and subordinate instruments. While the expedited process to develop a suite of uniform laws which will address all aspects (including safety foremost) of a hydrogen industry is still in progress, Standards Australia released a set of standards relating to hydrogen quality, storage, transportation, and usage that are currently being applied. Existing regulatory arrangements and protections continue to work as intended.

General legal framework for hydrogen

Australia has recognised hydrogen as a significant opportunity for growth, investment, and energy transition. Launched in 2018, the *National Hydrogen Roadmap* provided a comprehensive strategy for realising the opportunity to build a potentially clean, innovative and safe hydrogen industry in Australia. The report was developed in parallel with the *National Hydrogen Strategy* to ensure that the reform process will meet the needs of the energy transition.

The Strategy outlined an adaptive approach that equips Australia to scale up quickly as the hydrogen market evolves. It identified 57 joint actions, involving governments, the industry and the community, that represent the first steps to support this hydrogen-based emerging industry. While investment and interest have fluctuated over the last decades, specific legislation, regulations and standards are yet to be introduced. The major inhibitor is the design of Australia's federal system (and the devolution to and from states and territories to the federal level) and the complexity found in creating new federal legislation. Once the governments, its advisors and agencies succeed to reach, through the Council of Australian Governments' (COAG) processes, agreed laws and standards, the legal framework surrounding hydrogen can be very robust, effective and long- lasting.

The preliminary review of the laws in Australia's jurisdictions identified approximately 730 pieces of legislation and 119 standards potentially relevant to hydrogen. Under the National Hydrogen Strategy, Federal, state and territory governments are currently reviewing and reforming the legal and regulatory framework to bring hydrogen, bio-methane and other renewable gas blends within the scope of the national gas regulatory framework. This includes amendments to:

- the National Gas Law (NGL), the National Gas Regulations, the National Gas Rules (NGR), procedures and other subordinate instruments made under the NGL and/or NGR;[1]
- the National Energy Retail Law (NERL), the National Energy Retail Regulations and the National Energy Retail Rules (NERR).[2]

Jurisdictional officials, the Australian Energy Market Commission (AEMC), and the Australian Energy Market Operator (AEMO) have each been tasked with progressing various aspects of the reforms. Jurisdictional officials will identify and develop amendments to the NGL, NERL and regulations, the AEMC will identify and develop amendments to the NGR and NERR, and AEMO will identify and develop amendments to the procedures and other AEMO-made instruments required for settlement and metering in the facilitated and regulated retail gas markets. Energy Ministers agreed to an expedited process to complete these reforms. A draft legislative package is to be presented to Ministers for approval and draft rules following in the latter part of 2022. The National Gas Framework legislation was amended in 2022 to take hydrogen within its scope. An AEMO report was published on 8 September 2022 addressing gas blends and usage areas.

Finally, the Australian Government is reviewing legal frameworks and standards relevant to hydrogen industry development and safety. The review will determine:

- if existing regulatory frameworks will enable industry development and ensure safety;
- any amendments required to ensure appropriate regulation.

Relevant consultations were run throughout the years 2021-22 and a final component from AEMC and involving relevant stakeholders was concluded in mid-October 2022.

Existing regulation for the six scenarios

Regulation and policy momentum in support of hydrogen industry development is considerable in Australia. Nearly all Australian states and territories have published hydrogen specific strategies and/or road maps. An overarching legal framework is currently under preparation. The new measures intend to take effect by Energy Ministers and subsequent passage through the South Australian Parliament by 2023.

While the regulatory package is being prepared, the Standards Australia organisation, working together with the Australian government, helped facilitating the development and adoption of internationally aligned standards in Australia. At the same time, the Standards Australia committee ME-093 Hydrogen Technologies, without being responsible for enforcing regulations or certifying compliance with standards, prepared a set of standards for use covering most aspects of the emerging hydrogen industry. To date, the following Australian standards (Table 10.1) have been published and are in force (Standards Australia, 2021[1]).

Table 10.1. List of Australian standards used for hydrogen regulation

Scenario 1 – Production
• AS 22734 Hydrogen generators using water electrolysis – Industrial, commercial, and residential applications (ISO 22734:2019, MOD) • AS 16110.1 Hydrogen generators using fuel processing technologies, Part 1: Safety (ISO 16110-1:2007, MOD) • AS ISO 16110.2 Hydrogen generators using fuel processing technologies, Part 2: Test methods for performance • SA TS 19883 Safety of pressure swing adsorption systems for hydrogen separation and purification (ISO/TS 19883:2017, MOD) • AS ISO 14687 Hydrogen fuel quality – Product specification
Scenario 2 – Transport pipelines
• AS ISO 16111 Transportable gas storage devices – Hydrogen absorbed in reversible metal hydride
Scenario 3 – Road transport
• SA TR 15916 Basic considerations for the safety of hydrogen systems (ISO TR 15916:2015, MOD)
Scenario 4 – Mobility and partially confined spaces: tunnels
• AS ISO 19881 Gaseous hydrogen – Land vehicle fuel containers
Scenario 5 – Mobility and partially confined spaces: refuelling stations
• AS 19880.3 Gaseous hydrogen – Fuelling stations, Part 3: Valves (ISO 19880-3:2018, MOD) • AS ISO 19880.8 & Amendment 1 Gaseous hydrogen – Fuelling stations, Part 8: Fuel quality control • AS ISO 19880.5 Gaseous hydrogen – Fuelling stations, Part 5: Dispenser hoses and hose assemblies
Scenario 6 – Domestic use
• None

Scenario 1 – Production

Australia is well-placed to produce and use significant quantities of hydrogen. The National Hydrogen Strategy estimates that Australia has 262 000 square kilometres of land that is highly suitable for hydrogen production using renewable electricity. This is about 3% of Australia's total land area and is larger than the average Member State of the European Union.

This amount of land could theoretically support tens of thousands of gigawatts of renewable energy projects. Currently three new Australian gas generators have announced plans to install hydrogen-ready gas turbines at their plants. As a highlight, NSW is set to become home to Australia's first dual fuel capable hydrogen/gas power plant following an AUD 83 million funding agreement for the Tallawarra B project in the Illawarra, planning to deliver enough electricity to power around 150 000 homes at times of peak demand (NSW, 2021[2]).[3]

The main methods used to produce hydrogen in Australia are:

- Electrolysis (extracting hydrogen from water using electricity);
- Thermochemical reactions using coal (coal gasification) or natural gas (steam methane reforming – SMR).

Ideally, the focus should be on the production of green hydrogen. However, scaling green hydrogen is still under development. Any hydrogen production facility is governed by existing energy, water, gas and environmental regulations such as the Gas Regulations 2012, the Gas Act 1997 & National Gas Amendment (Regulation of Covered Pipelines) Rule 2019.

According to the Gas Regulations 2012's safety and technical requirements:

- Gas infrastructure should be designed, installed, operated, and maintained to be safe for the gas service conditions and the physical environment in which it will operate and so as to comply with any applicable requirements of AS/NZS 4645, AS/NZS 1596 and AS 2885 or achieve, to the satisfaction of the Technical Regulator, the same or better safety and technical outcomes; and
- Gas installations should be designed, installed, operated, and maintained to be safe for the gas service conditions and the physical environment in which it will operate and so as to comply with any applicable requirements of:
    - AS/NZS 5601 and AS/NZS 1596, in the case of a liquefied petroleum gas installation;
    - AS/NZS 5601, in any other case.

Scenario 2 – Transport pipelines

The Australian Energy Regulator (AER) regulates pipeline services in all jurisdictions except Western Australia where the Economic Regulation Authority holds this responsibility. Under the current regulatory framework, all pipelines are assumed to transport natural gas. In the case of pipeline transition from transporting natural gas to transporting hydrogen, the NGL and the NGR will provide the framework, the requirements, and the obligation for regulation of pipeline services (AEMC, n.d.[3]).

There are two frameworks: one for schemed pipelines set out in Parts 8-12 of the NGR and the second for non-scheme pipelines in Part 23 of the NGR. Part 8 to 12 of the NGR regulate covered pipelines, having two forms of regulation available for them (full or light) (AEMC, n.d.[4]). Part 23 of the NGR regulates those pipelines that are not classified as covered.

Currently, the maximum percentage of hydrogen injected into the natural gas' pipelines is around 10%. Recommended options for setting and allowing updates of upper limits on the volume allowed to be blended are being considered, with focus on eventually using 100% hydrogen in Australian gas pipeline networks.

For the reason above, the regulatory framework that is applied and implemented to the oil and gas industry is periodically revised with consideration of the hydrogen applications in pipeline transport. For instance, in 2021 the South Australian Petroleum and Geothermal Energy Act 2000 was amended to allow hydrogen and its derivatives to be transported though pipelines.

Scenario 3 – Road transport

Road transport requirements for hydrogen are covered by the Dangerous Goods Safety (Road and Rail Transport of Non-explosives) Regulations 2007 and the Australian Dangerous Goods Code – Edition 7.7. More specifically, attention should be given to the following:

- The design and construction of the valves by one of the following methods:
  - placed inside the neck of the pressure receptacle and protected by a threaded plug or cap;
  - protected by caps. Caps must possess vent-holes of sufficient cross-sectional area to evacuate the gas if leakage occurs at the valves;
  - protected by shrouds or guards;
  - pressure receptacles are transported in frames, (e.g., bundles); or
  - pressure receptacles are transported in an outer packaging. The packaging as prepared for transport must be capable of meeting the drop test specified.
- The design of the pressure relief devices:
  - it must be arranged to discharge freely to the open air in such a manner as to prevent any impingement of escaping gas upon the pressure receptacle itself under normal conditions of transport.
- The design of the portable tank:
  - it must be located under maximum filling conditions in the vapour space of the shell, be arranged to prevent an unacceptable amount of leakage of liquid in the case of overturning or entry of foreign matter into the tank.
- Leak testing gas cartridges and fuel cell cartridges:
  - the closures (if any), and the associated sealing equipment must be closed appropriately and checked for the correct mass. The leak detection equipment must be sufficiently sensitive to detect at least a leak rate of 2.0 x 10-3 mbar.l.s-1 at 20°C. Any gas masses not in conformity with the declared mass limits or that show evidence of leakage or deformation, must be rejected.
- The vacuum-relief devices used on portable tanks intended for the transport of substances must comply with the flash point criteria.
- Portable tanks must have a pressure-relief device approved by the competent authority:
  - The relief device must comprise a frangible disc preceding a spring-loaded pressure-relief device. The space between the frangible disc and the pressure-relief device must be provided with a pressure gauge or suitable tell-tale indicator for the detection of disc rupture, pin holing, or leakage which could cause a malfunction of the pressure-relief system. The frangible disc must rupture at a nominal pressure 10%.
  - The necessity of exceptional inspection and test when the conditions indicate it, the extent of which should not exceed the 2.5-year.
  - Internal and external examinations.
- The design, construction, and installation of the piping.
- All piping must be of a suitable material. Only steel piping and welded joints must be used between the jacket and the connection to the first closure of any outlet. The method of attaching the closure to this connection must be to the satisfaction of the competent authority or its authorised body.
- Decontamination of cargo transport units after unloading and before removal of placards.

Scenario 4 – Mobility and partially confined space: tunnels

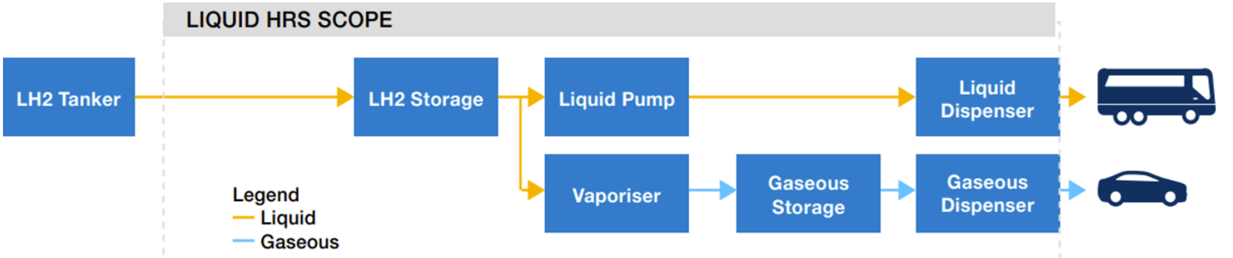
Australia is gearing up towards the hydrogen mobility, already planning and implementing significant investments in the future in car manufacturing, particularly hydrogen-based fuel-cell electric vehicles ("FCEVs"). Until recently the lack of infrastructure had been the biggest impediment for hydrogen mobility in Australia (Australian Hydrogen Council, 2022[5]). Given the increase in demand, it is critical that hydrogen installations are correctly designed, installed, and maintained to minimise risk of fires and explosions. In absence of specific regulations for hydrogen fuel cars in confined spaces, like tunnels, Australia is currently developing the Hydrogen Safety Code of Practice (the Code), in order to provide principles for mobility and requirements for confined spaces.

Scenario 5 – Mobility and partially confined spaces: refuelling stations

In Australia, there is a small number of operational hydrogen refuelling stations. All stations have similar equipment but employ different designs depending on how the hydrogen is produced, delivered, stored, and dispensed:

- Gaseous hydrogen refuelling station (GHRS)
- Stations are in operation and under construction for light-duty vehicles (passenger vehicles), heavy-duty vehicles (trucks and buses), and material handling equipment. Stations dispense hydrogen as a compressed gas at pressures of 70 MPag for light-duty vehicles and 35 MPag for other vehicles.
- Liquid hydrogen refuelling station (LHRS)
- At liquid hydrogen refuelling stations, tanker trucks pump hydrogen into an above-ground tank where it is kept at cryogenic temperatures. Liquid hydrogen is vaporised, compressed, and stored in above-ground cylinders for dispensing[4]. As customers fuel their vehicles, the gaseous hydrogen cylinders are refilled. Liquid storage generally requires more space than gaseous storage.

Figure 10.1. Liquid hydrogen refuelling station (HRS) SCOPE



The currently operating facilities have been designed and constructed following the variety of Australian and international standards and codes listed in the Table below.

Standards Australia has released the "Technical Specification – Hydrogen – Storage and Handling" in 2022 in which a specific Australian Standard on hydrogen storage and handling as well as on specifications for hydrogen refuelling stations have been published. Key standards, codes and documents identified as relevant to hydrogen refuelling stations which were previously accepted have been summarised below (see Table 10.2).

Table 10.2. Key international standards applicable to hydrogen refuelling stations

Document / series	Description
ISO 19880 series	International Standards Organisation (ISO) Technical Committee (TC) 197, has been tasked with the development of the ISO 19880 series which aims to define the minimum requirements applicable for the safety and performance of gaseous hydrogen stations.
SAE J2601 series	SAE J2601 (along with J2799) provides guidance on the fuelling hydrogen (SOC) without violating the operating limits of the internal tank temperature or pressure.
SAE J2799 series	The intent of SAE J2799 is to enable the harmonised development and implementation of hydrogen fuelling interfaces for Fuel Cell Electric Vehicles (FCEVs).
NFPA 2	NFPA 2 provides fundamental safeguards for the generation, installation, storage, piping, use and handling of hydrogen in compressed gaseous gas (GH2) form or cryogenic liquid (LH2) form.

Scenario 6 – Domestic use

The Australian government is currently completing the review on how to bring hydrogen into the gas network. The review will consider:

- options for a framework to set and update the volume of hydrogen that can be blended in gas networks. Activity is underway to trial hydrogen blending. Nine projects are expected to be operational by 2025;
- the economics of blending and the eventual use of 100% hydrogen in Australian gas networks.

At the moment, there is no regulation allowing 100% use of hydrogen in residential buildings as existing gas appliances are only suitable to take a blend of hydrogen (up to 10 or 20%). The domestic use of hydrogen lies behind various pilot projects the most recent of which took place on 1 July 2022, by the Australian Gas Infrastructure Group ((n.a.), 2022[6]).[5] Fuller life cycle deployment, including blended and pure hydrogen distribution and domestic use are being considered but may be some way off, given issues of public acceptance, infrastructure and regulatory development.

Authorities and institutions in charge of regulating hydrogen

Table 10.3 lists the state safety regulatory bodies of Australia.

Table 10.3. Key state safety regulatory bodies

State	Regulatory bodies/documents
Australian Capital Territory	• WorkSafe Act • Australian Capital Territory Planning and Land Authority
New South Wales	• SafeWork NSW • NSW Fair Trading
Northern Territory	• NT WorkSafe
Queensland	• Petroleum and Gas Inspectorate of Resources Safety and Health Queensland • Workplace Health and Safety Queensland • Resource, Safety and Health Queensland • Electrical Safety Office
South Australia	• SafeWork SA • Office of the Technical Regulator • Office of Consumer and Business Services
Tasmania	• WorkSafe Tasmania • Office of the Tasmanian Economic Regulator
Victoria	• WorkSafe Victoria • Energy Safe Victoria
Western Australia	• Energy Safety • Department of Mines, Industry Regulation and Safety

China

China’s push for hydrogen technology is illustrated in the newly published Long-Term Plan for the Development of Hydrogen Energy (2021-2035), which outlined a road map of major milestones for the coming years. Although China does not yet have a well-defined legislative framework for hydrogen, its national technical committee 309154 have drafted and published 31 national standards regarding hydrogen, covering its full life cycle. The country's incorporation of hydrogen energy into its national energy management system, publication and enforcement of development plans, encouragement of scientific and technological innovation and strengthened financial support promote a sustainable development of the hydrogen energy industry.

General legal framework for hydrogen

Hydrogen was first written about in the *Government Work Report* (national level)[6] in 2019, where a plan to increase hydrogen refuelling station (HRS) capacity was mentioned. A year later, in the *Energy Law (draft for comments,* 2020*)* hydrogen was listed as a form of energy for the first time. There is, in general, little legislation that specifically relates to hydrogen. Hydrogen has been traditionally defined as a hazardous chemical and is therefore regulated as such (work safety law 2020). The law emphasises safety planning, personnel training and safe handling[7] of hazardous chemicals. It also requires compliance with a number of legally binding *National Standards.*

Since the publication of *the action plan for energy technology revolution and innovation 2016-2030*[8] by the National Development and Commission, a fast development in the hydrogen energy sector was observed. By 2019, China makes up 1/3 of global sales in hydrogen vehicles and by 2020, 21 out of its 34 provincial level administrative divisions have issued subsidy policies for the construction of hydrogen refuelling stations. Specifically, the maximum subsidy for a newly built fixed hydrogen station can be as high as 8 million Chinese yuan, ca. 40% of the total cost (Meng et al., 2021[7]). For hydrogen vehicles, the subsidy is at 6% (Zhao et al., 2020[8]).

By 2022, China has completed the construction of over 250 hydrogen refuelling stations (Statista, 2023[9]), making it the country owning most hydrogen stations worldwide. However, Government subsidies are unfortunately not a sustainable long-term driving force and therefore it is important to lay a foundation for a good industrial ecology after the initial development.

Authorities and institutions in charge of regulating hydrogen

Table 10.4 illustrates the institutions responsible for legislation on hydrogen. At national level, the *Standardization Administration of China* (SAC) oversees a number of technical committees that draft national standards. The *National Technical Committee 309* is responsible for developing standards for hydrogen technologies.

The enforcement of standards is carried out by:

1. the department of construction at provincial level for hydrogen-related constructions (Mao, 2014[10]);
2. the administration for market regulation at local level for road vehicle related standards; and
3. the department of emergency management at local level for the handling of hazardous chemicals.

Table 10.4. Hydrogen regulation in China

Hydrogen	• as a hazardous chemical: Ministry of Emergency Management • usage in road vehicles: Ministry of Industry and Information
	• as a form of energy: National Energy Administration (NEA)

Existing regulation for the six scenarios

The subsequent subsections review legally binding national standards that are related to the specified scenarios following the inherently safer design concepts. In case no legally binding standards exist, the review focuses on recommended national standards (not legally binding) or industrial standards. The standards reviewed are listed in the Table 10.5.

Table 10.5. List of Chinese national standards reviewed in this report

Scenario 1 – Production
• GB 50177-2005 Design code of hydrogen station (legally binding) • GB 4962-2008 Technical safety regulation for gaseous hydrogen use (legally binding)
Scenarios 2 and 3 – Transport pipelines and Road transport
• GB 50316 Design code on industrial metal pipes (legally binding) • NB/T Tube trailers • GB 4962-2008 Technical safety regulation for gaseous hydrogen use (legally binding)
Scenario 4 – Mobility and partially confined spaces: tunnels
• GB/T 24549-2020 Fuel cell electric vehicles – safety requirements • Technical standards for fire protection of road tunnel
Scenario 5 – Mobility and partially confined spaces: refuelling stations
• GB 50516-2010 Technical code for hydrogen fuelling station (2021, legally binding)
Scenario 6 – Domestic use
• Technical codes for natural gas/hydrogen mixing stations

Scenario 1 – Production

The legally binding national standard "GB 50177-2005 Design code of hydrogen station" specifies criteria to be met in the design and maintenance of hydrogen production stations and hydrogen supply stations.[9] GB 4962-2008 Technical safety regulation for gaseous hydrogen use provides additional information on how hydrogen should be handled at production sites.

(1) Restrictions:

- Quantity: the maximum volume for a single hydrogen storage cylinder set should not exceed 30 000 m^3.
- Control operating conditions to minimise hazards: a preferred pressure difference less than 0.5 kPa for hydrogen and oxygen outputs pipes.

(2) Facilities and equipment design:

- Equipment
  a. Electrolyser: automatic as well as manual hydrogen concentration analysers for oxygen (by-product). Alarm for hydrogen detection.[10]
  b. Compressor: equip with safety alarm, safety valves and safety-lock[11] mechanism.
  c. Hydrogen cylinder/tanks: equip with pressure metre, pressure relief valve, hydrogen release pipe (at highest point); connector for nitrogen input.
  d. Hydrogen detectors in places with the possibility of hydrogen accumulation: hydrogen concentration should not exceed 1%.
  e. Detailed requirement on materials to avoid hydrogen embrittlement.
- Pipe works
  a. Seamless steel.
  b. Welded joints. Screw joints are allowed for equipment and valves connections.

  c. Flame arrestor for hydrogen vent.
  d. Protective outer pipe, e.g., if it is unavoidable for sections to be built under railway.
- Ventilation
  a. Ventilation in rooms with explosion risks[12] should be no less than 3 air changes per hour.[13]
  b. Ventilation facilities for emergency response should have a capacity of no less than 12 air changes per hour. They should respond to signals sent by hydrogen leak detectors.

(3) Safer Location:

- Outdoor installation when possible.
- Access control:
  a. Hydrogen and oxygen compressors should not be in the same room.
  b. Rooms with explosion risk should not have direct access to rooms without such risk.
  c. A minimum of two exits for rooms with explosion risk, one exit must lead directly outside.14
  d. Underground piping should not go through outdoor-storage area, not buried together with other pipes and buried at least 0.7 m in depth.
- Safety barriers:
  a. External wall should be fire resistant and with height no less than 2.5 m.
  b. A barrier wall with height no less than 2 m for hydrogen filling facilities.
  c. Fire resistant walls for control rooms.
- Internal and external safety distances:

Table 10.6. Internal and external safety distances

Other buildings (depending on their fire resistance level)	12-16 m
Electrical substations	25 m
Storage facilities	13-20 m
Civil buildings	25 m
Important public buildings	50 m
Flammable gas (depending on volume)	12-25 m
Oxygen gas cylinders (depending on volume)	10-14 m
Open fire or spark sites	30 m
Liquid cylinders (depending on volume)	12-25 m
Coal or coke (depending on weight)	6-8 m
External railway	30 m
Internal railway	5-10 m
External Major Road	20 m
Internal Major Road	5-10 m
Enclosure Wall	5 m

Scenarios 2 and 3 – Transport pipelines and road transport

No technical regulations exist that specifically address hydrogen pipelines. Legally binding national standard “GB50316 Design code on industrial Metal pipes” sets out general requirements (e.g., on material, welding, and fabrication) that pipelines have to follow.

A recommended standard for the energy sector NB/T 10354-2019 *Tube Trailer* specifies the material, design, fabrication, testing-methods, signs, documentation, storage, and transportation etc. There is only one provision[15] that specifically addresses hydrogen, however, there is an appendix specially addressing compressed natural gas.

In addition, section 6 storage (6.3.18-6.3.20) of the legally binding national standard GB 4962-2008 *Technical Safety Regulation for Gaseous Hydrogen Use* specifies a few terms specific to the transportation of hydrogen by tube trailers.

(1) Restrictions:

- Quantity: 1000-4200 L water volume for single hydrogen tank/cylinder (general).
- Control operating conditions to minimise hazards:
  - Operating pressure not greater than 20 MPa;
  - Temperature between -40°C to 50°C.

(2) Facilities and equipment design:

- Pressure relief valve on both ends for every hydrogen tank and there should be no hindrance to gas release.
- Leave space on one end of the cylinders for thermal expansion and contraction.
- Pressure and temperature meters.
- Fire extinguishers no less than 4kg on both sides of the vehicle.
- Facilities to avoid undesired movement of both hydrogen tanks and the vehicle.
- Flexible hoses should be used to connect hydrogen tanks.

Scenario 4 – Mobility and partially confined spaces: tunnels

Hydrogen fuel vehicles are a subclass of electrical vehicles and hence follow the recommended national standard *GB/T 24549-2020 Fuel cell electric vehicles – Safety requirements*.

(1) Restrictions:

- Control operating conditions to minimise hazards:
  - Hydrogen concentration in exhaust gases should be less than 4%.[16]
  - For passenger vehicles heavier than one metric tonne, external hydrogen concentration in an enclosed space should remain less than 1%.

(2) Facilities and equipment design:

- Hydrogen detector:
  - At least one hydrogen detector above hydrogen tanks;
  - Alarm the driver when internal hydrogen concentration reaches 2%;
  - Shut down hydrogen supply (from the leaking tank(s)) when internal hydrogen concentration reaches 3%, and
  - Alarm the driver when hydrogen detector(s) are not in normal working conditions.
- Thermal insulating shield for hydrogen tanks and pipes that may be affected by heated components (e.g., exhaust pipes).
- Ground strap to protect electrical components in the event of a power surge or short circuit.
- Pressure relief devices (PRDs) should vent outside the vehicle, but not (a) in the direction in which the vehicle moves, or (b) towards emergency exits (if applicable).
- The vehicle should not be able to move when fuelling.
- Ability to empty fuel tank when desired.

(3) Safer Location:

- Hydrogen tanks together with hydrogen pipe works should not be located in passenger cabins, luggage cabins or other places with poor ventilation.

Hydrogen vehicles and vehicles carrying hydrogen are not specifically addressed in the standard, meaning that they receive no special treatment and therefore are allowed to go into tunnels. The Standards are focused on tunnel design and operation to reduce the risk for severe tunnel accidents.

Scenario 5 – Mobility and partially confined spaces: refuelling stations

For this scenario, the legally binding national standard ‘GB 50516-2010 Technical code for hydrogen fuelling station’ (2021 edition) applies:

(1) Restrictions

- Quantity: total hydrogen inventory no greater than 8 000 kg with a single tank containing no greater than 2 000 kg hydrogen.
- Control operating conditions to minimise hazards:
    - Hydrogen flow rate (via dispensers) should be less than 7.2 kg/min.
    - Vehicle hydrogen tank’s temperature should remain less than 85°C after fuelling.

(2) Facilities & Equipment design:

- Hydrogen compressor:
    - Safety valves between the H2 entrance and exit on the one hand and the first set of shut-off valves on the other.
    - Alarm for abnormal pressure at the entrance and exit as well as a mechanism for emergency shut-off.
    - Alarm for lubricating oil system (abnormal pressure and temperature).
    - Alarm and emergency shut-off mechanism for cooling system.
    - Port nitrogen purging.
    - Barrier no less than 2 m around hydrogen compressors.
- Storage:
    - Pressure relief valves.
    - Pressure meter and sensor.
    - Hydrogen leak alarm with video recording functions.
    - Hydrogen vent pipe.
    - Port nitrogen purging, nitrogen concentration no lower than 99.2%.
    - Barrier no less than 2 m around storage facilities.
- Dispensers:[17]
    - Emergency release coupling on the flexible hose connection. Activation of emergency release (680 N) should automatically shut down hydrogen supply.
    - Crash posts around dispensers.
    - Independent hydrogen supply systems dispensers.
    - Measure vehicle’s hydrogen pressure, stop fuelling if the pressure is less than 2.0 MPa or above nominal pressure.
    - Pressure relief valves.

(3) Safer Location

- External safety distances regarding hydrogen storage, the compressors and dispensers, and the hydrogen vent. Fire resistant walls when the distance between hydrogen facilities and external buildings is less than 25 m or 1.5 times.
- Separate entrance and exit.
- Internal safety distances programmable logic controller (PLC) for compressors.
- No less than 0.03 m between hydrogen tanks in the same set; no less than 1.5 m between sets.
- Outdoor installation for dispensers.

Scenario 6 – Domestic use

Policies and regulations supporting hydrogen blending in existing natural gas grids can accelerate the shift into a hydrogen economy. Research suggests a volume ratio of up to 15-20% does not require major adjustment of existing gas grids (IEA, 2018[11]). Very recently in 2021, China published a group standard I/CAS XXX-202X *Technical codes for Natural gas/Hydrogen mixing stations.*

(1) Restrictions:

- Quantity: Total hydrogen inventory no greater than 8 000 kg with a single tank containing no greater than 2 000 kg hydrogen.
- Control operating conditions to minimise hazards:
    - Natural gas pressure 0.05 - 0.1 MPa before mixing; gas mixture transporting temperature between -20oC - 50oC;
    - Requirement on hydrogen quality (see Table 10.7);
    - Natural gas flow speed should not exceed 20 m/s;
    - Hydrogen flow speed should not exceed 15 m/s;
    - Mixing uniformity should be no less than 95%;
    - Hydrogen/natural gas mixture flow speed should not exceed 20 m/s.

(2) Facilities & Equipment design:

- Gas mixer:
    - Nitrogen purging ports for both hydrogen and natural gas input pipes. Oxygen content in purging nitrogen should be less than 0.5% (volume ratio);
    - Design pressure for pipes and valves should be 1.1 times or greater than maximum allowable working pressure;
    - Ventilation area ≥ 4% of mixer's bottom area. Explosion vent for mixers larger than 1.5 m3;
    - Use flange joints to connect hydrogen and natural gas pipes;
    - Vent pipes.
- Alarm:
    - Distinct gas detectors for different flammable gases (hydrogen, natural gases and methane);
    - Local and transmission pressure gauges for hydrogen storage;
    - Fire detection for hydrogen storage.
- Emergency shut off system: reaction time less than 3 seconds (from when signals are sent).
- Parking: Flat parking sites for tube trailers. Concrete walls for fire protection. Tube trailers should not use or bypass fire exits.

(3) Safer Location:

- External and internal safety distances.
- Fire resistant barrier walls with height no less than **2.5 m** around the production site.
- At least one exit with width no less than **4 m** at production sites.

Additional data on specific standards and regulations

This section contains additional data on specific standards and regulations which provide a background to the safety and regulatory considerations of several scenarios/applications described above.

Table 10.7. Quality requirement on hydrogen for hydrogen/natural gas mixing stations

Oxygen volume fraction/10-2 = 0.40
(N2 + Ar) volume fraction/10-2 = 0.60
Free water (mL/40L) = 100
Total Sulphur content (mg/m3) = 100
H2S (mg/m3) = 20
CO2 mole percent (%) = 4.0

Table 10.8. Additional national standards (recommendations) related to the 6 scenarios

Scenario 1

- GB/T 40061-2021 Technical specification for liquid hydrogen production system
- GB/T 37563-2019 Safety requirements for pressurised water electrolysis system for hydrogen production
- GB/T 37562-2019 Technical conditions of pressurised water electrolysis system for hydrogen production
- GB/T 34539-2017 Safety requirements on hydrogen-oxygen generator

Scenario 2

- GB/Z 41117-2021 Fasteners - Fundamentals of hydrogen embrittlement in steel fasteners

Scenario 3

- GB/T 40070-2021 Technical requirements for storage and transportation of liquid hydrogen
- GB/T 34542.1-2017 Storage and transportation systems for gaseous hydrogen - Part 1: General requirements
- GB/T 34542.2-2018 Storage and transportation systems for gaseous hydrogen - Part 2: Test methods for evaluating metallic material compatibility in hydrogen atmosphere
- GB/T 34542.3 -2018 Storage and transportation systems for gaseous hydrogen - Part 3: Test method for determination of the susceptibility of metallic materials to hydrogen gas embrittlement (HGE)

Scenario 4

- GB/T 40045-2021 Fuel specification for hydrogen powered vehicles - Liquid hydrogen (LH2)
- GB/T 26779-2021 Hydrogen fuel cell electric vehicle refuelling receptacle
- GB/T 37154-2018 Fuel cell electric vehicles - Test methods of hydrogen emission
- GB/T 37244-2018 Fuel specification for proton exchange membrane fuel cell vehicles - Hydrogen
- GB/T 35544-2017 Fully-wrapped carbon fibre reinforced cylinders with an aluminium liner for the on-board storage of compressed hydrogen as a fuel for land vehicles
- GB/T 35178-2017 Fuel cell electric vehicles - Hydrogen consumption - Test methods
- GB/T 34872-2017 Technical requirement of hydrogen supply system for proton exchange membrane fuel cells
- GB/T 34537-2017 Hydrogen and compressed natural gas (HCNG) blended as vehicle fuel
- GB/T 34593-2017 Test methods of hydrogen emission for fuel cell engine
- GB/T 34544-2017 Safety test methods for onboard low pressure hydrogen storage devices for small fuel cell vehicles

Scenario 5

- GB/T 40297-2021 Seamless austenitic stainless-steel pipes for high pressure hydrogenation unit
- GB/T 34425-2017 Fuel cell electric vehicles - Hydrogen refuelling nozzle
- GB/Z 34541-2017 Safety operation management regulation for hydrogen fuelling facilities of hydrogen vehicles
- GB/T 34583-2017 Safety technical requirements for hydrogen storage devices used in hydrogen fuelling station

France

The French regulatory framework for hydrogen is being updated and strengthened to meet its national hydrogen strategy objectives by 2030. Hydrogen production installations (by electrolysis) and recharging facilities are now subject to detailed environmental regulations specific to ICPE.[18] In areas such as domestic use, installations are subject to the regulations applicable to any installation using a fuel gas in a residential building and therefore need further consolidation.

General legal framework for hydrogen

The French hydrogen legal framework was rapidly reformed following the so-called "hydrogen deployment plan for the energy transition" (Ministère de la Transition écologique et de la Cohésion des territoires, 2018[12])[19] launched on June 1, 2018. The objective of this plan was to support innovation and promote decarbonised hydrogen industrial deployment projects in France to foster the energy transition. The legal framework for hydrogen is now laid down in the Law-decree 2021-167 of 17 February 2021 (French Government, 2021[13]),[20] which came at a time when businesses wanted to exploit the potential of hydrogen.

Authorities and institutions in charge of regulating hydrogen

At the national level, it is the Ministry for Ecological Transition (*Ministère de la Transition écologique*) that proposes the national hydrogen plan and its objectives. At the departmental level, the prefect has the power to issue general prescriptions to authorise the hydrogen installations. The minister in charge of classified installations (currently the Minister for Ecological Transition) can also issue general prescriptions orders.

The requirements are rules to be respected by the operator during the construction, operation, and rehabilitation of the facility. The objective of these rules is to ensure the preservation of the environment, human health and safety and resources.

The French Environment and Energy Management Agency (*Ademe*) is responsible for encouraging "the development of clean technologies and savings" (French Government, 2023[14]).[21] It thus encourages the development of hydrogen and fuel cells by issuing tenders for projects, which, if successful, would qualify for a state subsidy.

Existing regulation for the six scenarios

Table 10.9 lists French regulations reviewed in this report.

Table 10.9. List of French regulations

Scenario 1 – Production
• Code de l'environnement (Environmental Code) • Law-decree 2021-167 of 17 February 2021 • The Seveso III Directive 2012/18/EU
Scenarios 2 and 3 – Transport pipelines and Road transport
• Amended decree of 29 May 2009 on the transport of hazardous goods by land • Code de l'environnement (Environmental Code) • Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods makes the ADR, ADN and RID applicable within the EU • UN Recommendations on the Transport of Dangerous Goods (vol. I & vol. II)
Scenarios 4 and 5 – Mobility and partially confined spaces: tunnels and refuelling stations
• Order of 12 February 1998 on the requirements for installations classified for the protection of the environment

subject to declaration under heading no. 4715 • Order of 22 October 2018 relating to the general requirements applicable to installations classified for the protection of the environment subject to declaration under heading no. 1416 (hydrogen gas distribution station) of the nomenclature of classified installations • United Nations for Europe (UNECE) R 134 Europe (UNECE), 2015
Scenario 6 – Domestic use
• Not applicable

Scenario 1 – Production

Law-decree 2021-167 of 17 February 2021 (French Government, 2021[13])[22] was published in the Journal Officiel on 18 February 2021. It created a Book VIII in the Energy Code, entitled “Provisions relating to hydrogen” – which brought significant changes to the legal framework. It is the first text to create a legal regime for hydrogen in France).

In the law, hydrogen production is divided into three categories: renewable hydrogen (including water electrolysis hydrogen), low-carbon hydrogen (a CO_2 emission threshold must be reached for hydrogen to be considered renewable or low-carbon) and carbon-based hydrogen (the hydrogen produced with fossil energies).

At the same time, it is clarified how production and recharging facilities are subject to environmental regulations specific to “classified facilities for the protection of environment” (known as ICPE). These are regulations applicable to hydrogen production installations which use electrolysis. Regulation on ICPE imposes procedures prior to the construction and operation of installations and then monitoring during the operation.

Code de l’environnement (Environmental Code) adds in R511-9 and its annexes of the Environmental Code that ICPEs related to hydrogen production are, according to paragraph 3420-a, those that “[m]anufacture in industrial quantities by chemical or biological transformation of inorganic chemicals” (French Government, 2023[15]).[23] These are installations for the “manufactur[ing of hydrogen] in industrial quantities” by chemical transformation. The French or European legislator does not associate the notion of "manufacture in industrial quantity" with any precise numerical threshold. The French Ministry of Ecology, however, provides some clarification on the concept. Two main criteria stand out, commercial and environmental.[24]

A hydrogen installation generally also falls under the heading 4715 hydrogen (Ineris, 2014[16]).[25]

The storage of hydrogen falls under the following regimes: declaration when the quantities likely to be present in the installation are greater than or equal to 100 kg but less than 1 000 kg. Authorisation if the quantities are greater than or equal to 1 000 kg.

Another code provision worth mentioning is L512-8, 9, 10 et R512-50, 51, 52 of the Environment Code (French Government, 2021[17]),[26] which sets out the procedure required for the installation. The declaration is the simplest formality. It consists of notifying the administration of the setting up of an ICPE. It applies to installations that present a danger, but one that is relatively low.

In the case of hydrogen, most installations are subject to the authorisation system, which requires an authorisation application file to be drawn up, including an impact study and a hazard study. This file is examined by the administration and a prefect issues a permit order (the procedure lasts 9 to 12 months). Seveso regulations also apply to hydrogen installations.

The Seveso thresholds are specified in the ICPE nomenclature in article R511-10 (French Government, 2015[18]).[27] Two thresholds are identified as low and high thresholds in heading 4 715 (Ineris, 2014[16]).[28] For hydrogen, the low threshold corresponds to a storage of 5 000 kg and the high threshold to a storage of 50 000 kg.

Scenarios 2 and 3 – Transport pipelines and road transport

The framework for hydrogen transport pipelines and road transport is spread across the international, European and national level. At the international level, there is the UN Recommendations on the Transport of Dangerous Goods (Vol. I & vol. II).

At the European level, the Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods makes the ADR, ADN and RID applicable within the EU. Here, the specific exemptions for road and rail transport (according to ADR) of hydrogen see a threshold of 333 kg if the gas is refrigerated and 333 L if it is compressed. The mass taken into account is that of the gas alone without its packaging, the volume corresponds to the volume of water in the container.

At the national level, there is the amended decree of 29 May 2009 on the transport of hazardous goods by land (known as the "TDG decree") (French Government, 2009[19]).[29] Additionally, there is the Code du Travail: General information and training obligation. (Articles L4141-1 to L4141-5) (French Government, n.d.[20])[30] All companies handling dangerous goods are obliged to train their employees on the risks of these goods in accordance with articles L4141-1 et seq. of the Labour Code. More specifically, for employees who are required to participate in transport operations, the company must provide training on the risks and dangers specific to the transport of dangerous goods and on the reactions to adopt for their safety, that of other people, the safety of the environment and of property (1.3 and 1.10 of the ADR).

Lastly, the Code environnemental: L554-6 AND 7 and R555-4 determines that the pipelines concerned by the regulations on pipelines for the transport of hazardous material are pipelines for the transport of natural gas or similar hydrocarbons or chemical products, as well as the installations and equipment required for the operation of the pipeline.

Gas distribution installations are also concerned. For most hydrogen pipelines, the prefect of the department in which they are located will be responsible; if they cross several departments, each prefect is responsible for the sections that cross their department.

Scenarios 4 and 5 – Mobility and partially confined spaces: tunnels and refuelling stations

(Ineris, 2018[21]) defines all the provisions applicable to installations classified for environmental protection subject to declaration with periodic inspection for heading no. 1416 "hydrogen gas distribution station for land vehicles". It concerns installations for recharging vehicles equipped with fuel cells, consisting of hydrogen storage, a distribution area and, if necessary, a production area. Under Article 2.2. of the Order of 22 October 2018, layout rules are described.

These say that: the dispensing area shall be located outside, and its equipment likely to contain hydrogen is at a minimum distance of 14 metres for a maximum flow rate of 120 g/s and 10 metres for a maximum flow rate of 60 g/s, including in the event of a hose rupture, from the site boundary, the ventilation devices, any storage, or installation of flammable, combustible, or oxidising materials other than hydrogen. For additional changes in distancing of the dispensing area, please refer to Table 10.10.

Table 10.10. Changes in the distancing of the dispensing area

Change in distance of the dispensing area	Situation in which the distance is reduced
Distances of 14 and 10 metres are reduced to 10 metres for a maximum flow rate of 120 g/s and 8 metres for a maximum flow rate of 60 g/s, including in the event of a hose rupture as well as if the anti-ripping system is designed to ensure an upward orientation of the gas flow of more than 45 degrees.	In the event of a hose rupture. If the anti-ripping system is designed to ensure an upward orientation of the gas flow of more than 45 degrees.
The distance of 8 metres is reduced to 6 metres.	If the distribution terminals are designed to respect a maximum flow rate of 20 g/s even in case of hose rupture.

The dispensing area and its equipment that may contain hydrogen are at least 5 metres from parking spaces, excluding spaces used by vehicles being filled or waiting to be filled and vehicles used in the operation of the installation.

The vent of the dispensing unit is located at least 3 metres above the highest point of the equipment in the dispensing area, or of the above-mentioned wall if applicable. Subject of the inspection will be:

- compliance with the installation distances;
- presentation of proof that the characteristics of the walls are fireproof when the distances are not respected and presence and distance of the vent.

Order 12/02/98 (French Government, 1998[22])[31] defines the general requirements applicable to hydrogen storage. Article 2.1.1. specifies the layout rules for liquid hydrogen storage tanks:

- The installation must be located at least 20 metres from the property line. It is forbidden to store or use liquid hydrogen in buildings. Article 2.1.2. deepens on specific requirements for gaseous hydrogen arguing that the installation must be located at a distance of:
    - if it is located in the open air or under a canopy, at least 8 metres from the property line or any building;
    - if the room containing the installation is enclosed, 5 metres from the property line or any building.

The distances of 8 to 5 metres between the building and the storage of hydrogen gas containers are not required if they are separated by a solid wall without openings, made of non-combustible materials and with a 2-hour fire rating, with a minimum height of 3 metres and extended from the storage by a canopy made of non-combustible materials with a 1-hour fire rating, with a minimum width of 3 metres projected on a horizontal plane.

This wall must be extended on either side and on the storage side by return walls without openings, made of non-combustible materials, and fireproof to 1 hour, with a height of 3 metres and a length of at least 2 metres.

Article 2.4. aims at clarifying what fire reaction and resistance characteristics hydrogen gas storages must have. They are: 2-hour fire-resistant walls and high floors, non-combustible light roofing, interior doors with a 2-hour fire rating and fitted with a door closer or self-closing device, door leading to the outside, flameproof to 2 hours, M0 class materials (non-combustible).

Closed premises must be equipped at the top with devices allowing the evacuation of hydrogen, smoke and combustion gases released in the event of a fire (skylights on the roof, opening doors on the façade or any other equivalent device). The manual opening controls are to be located near the accesses. The smoke extraction system must be adapted to the risks of the particular installation.

Article 4.2.1. describes the requirements specific to liquid hydrogen. The installation must be equipped with fire-fighting equipment appropriate to the risks and in compliance with the standards in force, a standardised 100 mm diameter fire hydrant with the necessary equipment to set up a large nozzle and two small ones, 1 x 50 kg powder extinguisher on wheels, 2 x 9 kg powder extinguishers, 1 x 6 kg CO^2 extinguisher.

This equipment must be placed near the installation, maintained in good condition, and checked at least once a year. The personnel must be trained in the use of fire-fighting equipment. In the event of fire in the vicinity of the installation, measures must be taken to protect the installation.

Article 4.2.2. presents the requirements specific to gaseous hydrogens. The installation must be equipped with fire-fighting equipment appropriate to the risks and in compliance with the standards in force, in particular 1 x 50 kg powder extinguisher on wheels and 1 x 40 mm water tap, equipped with a nozzle that can be brought into service instantly.

This equipment must be located near the installation, maintained in good condition, and checked at least once a year. Staff must be trained in the use of fire-fighting equipment. In the event of fire in the vicinity of the installation, measures must be taken to protect the installation.

Scenario 6 – Domestic use

Hydrogen is not being used (nor regulated) for residential scope. Currently, only LPG or NG gas fuels are regulated.

Additional national standards (recommendations) related to the 6 scenarios

This section contains additional data on specific standards and regulations which provide a background to the safety and regulatory considerations of several scenarios/applications described in the main body of this report.

Hydrogen vehicles regulations

The main regulation concerning hydrogen vehicles is the United Nations for Europe (UNECE) R 134 Europe (UNECE) published in 2015[32] and updated in 2016, 2017 and 2018. In July 2022, it will replace the European regulations 79/2009 and 406/2010, which currently set out the specific technical specifications for hydrogen vehicles.

Focusing on safety, it deals with the specifications and approval tests of components, in particular tanks and their safety components. It also sets out the requirements for overall safety in the vehicle, including the maximum concentration of hydrogen in the ambient air in and around the vehicle (4%) or the permissible leakage rate in normal operation or after a crash test. It is taken as a reference by the latest European regulations (EU 2018/858 and 2019/2144) and is harmonised with other relevant standards and regulations.

Germany

Regulations related to dangerous and hazardous substances govern hydrogen production, storage, distribution, refuelling stations, and vehicle usage. However, multiple authorities and an absence of a unified permit system is hindering the energy transition in Germany. Some states have already recognised the problem and are strategizing to simplify the supply chain related to hydrogen. A new law aims to integrate hydrogen pipeline transport with existing natural gas pipelines with simplified administrative procedures for operators.

General legal framework for hydrogen

Hydrogen is recognised as an alternative fuel in Germany under the Alternative Fuel Infrastructure Directive.[33] Several steps are being taken for the expansion of hydrogen production and the accompanying infrastructure network for its transportation, distribution, and usage. The target of the German Federal Government is to reduce greenhouse gas emission by 55% by 2030 and by 80-95% by 2050 (Bundesministerium für Wirtschaft und Klimaschutz, 2022[23]). Hydrogen produced from green sources is certified accordingly in Germany although no national level certification for hydrogen origin exists. This remains a key barrier for deployment of clean hydrogen at a national level. The involvement of several regulatory organisations increases the chances of delays due to reduced coordination and longer permit processes.

Authorities and institutions in charge of regulating hydrogen

Depending on the application, different authorities are responsible for granting permits related to setting up and operating hydrogen facilities. The Building Authorities at the individual *Länder*[34] are responsible for granting construction permits and for carrying out the necessary assessments. Regulatory requirements can also be different, although the extent and impact of such changes are not clear. However, for road worthiness of hydrogen vehicles and road transport both the local and national authorities have a deciding role.

Existing regulation for the six scenarios

Table 10.11 lists German National Standards reviewed in this report.

Table 10.11. List of German national standards reviewed

Scenario 1 – Production
• Baugesetzbuch – German Building Code • Baunutzverordnung – Federal Land Utilisation Ordinance • Bundes-Immissionsschutzgesetz – Federal Emission Control Act • Betriebssicherheitsverordnung – Ordinance on Industrial Safety and Health
Scenarios 2 and 3 – Transport pipelines and Road transport
• Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods makes the ADR, ADN and RID applicable within the EU • Individual rules of the states • Rules and codes imposed by the Federal Ministry for Transport and Digital Infrastructure
Scenario 4 – Mobility and partially confined spaces: tunnels
• Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods makes the ADR, ADN and RID applicable within the EU • Individual rules of the states • Rules and codes imposed by the Federal Ministry for Transport and Digital Infrastructure
Scenario 5 – Mobility and partially confined space Hydrogen: refuelling Stations
• Baugesetzbuch – German Building Code • Baunutzverordnung – Federal Land Utilisation Ordinance • Bundes-Immissionsschutzgesetz – Federal Emission Control Act • Betriebssicherheitsverordnung – Ordinance on Industrial Safety and Health
Scenario 6 - Domestic use
• Not applicable

Scenario 1 – Production

Production of hydrogen in Germany can be through centralised or localised processes with some procedural simplifications for the latter. The (German Government, n.d.[24])[35] (*Baugesetzbuch)* and (German Government, n.d.[25])[36] (*Baunutzungsverordnung*) govern land use requirements for centralised hydrogen production. Small-scale production and pilot plants which do not produce hydrogen at an industrial level are exempt from land use permits.

Land use regulations are the same regulations which govern the production of chemicals at an industrial level. Industrial or centralised hydrogen production plants can only be constructed in industrial and commercial areas with additional restrictions being imposed if the plant disturbs or is incompatible with the specific nature of the area. There is no evidence to show inconsistent application or interpretation of the German Building Code by the municipalities.

Permits related to construction and operation are granted by the Building Regulatory Authorities. The application process is governed by the Federal Emission Control Act (Umwelt Budesamt, 2020[26])[37] and also involves a step for public participation. Both building permits and environment impact assessments are covered under this application process. There are exemptions from EIA for those sites where the production value is under 200 tons subject to the discretion of the regulatory authority and the pre-existing local conditions. The process for permit is unified, i.e., only one permit for building, operating and construction. In several states, permits on emission protection applications are now being given digitally. The digital permit system has been created by the state of Lower Saxony.

However, the requirements for building permits vary per federal state and are governed by the respective State Building Ordinances. For instance, building permits for stationary vessels with 5 m^3 storage capacity do not need building permits in North Rhine Westphalia[38]. The general rule is that permits applications should be decided within a maximum period of seven months. For facilities with small storage quantities (under 3 tons), the maximum period is 3 months. However, delays due to incomplete documentation or non-performance of legal and regulatory obligations typically makes the process take 12-15 months.

The Federal Emission Control Act exempts permit requirements for plants and installations that are being constructed for research and development of new feedstocks, fuels, or processes in laboratories or in pilot plants (non-industrial production). However, these plants still require environmental compliance and the environmental impact of opening such facilities should be minimum.

Barring the above exemption, all industrial scale production needs to fulfil the application process. The application must fulfil the following minimum requirements before a construction, operation and building permit can be granted:

- Definition of the scope of the project,
- Expert opinion[39] of an authorised inspection body in accordance with the (German Government, n.d.[27])[40] (TÜV, DEKRA). The report shall consist of the description and assessment of planned facilities, operating procedures, procedures related to safety requirements, and fire and explosion protection. Further, a risk assessment is also mandated under the Ordinance. Provisions of the Ordinance on Hazardous Substances should also be fulfilled;
- Documentation related to processes, safety equipment, construction drawings, site plan;
- Public announcement and public display of plans, replies to objections after public announcement.

Safety requirements are regulated through the Hazardous Accidents Ordinance and are set based on the risk assessment performed under the Ordinance on Industrial Safety and Health, and the quantity of hydrogen being produced at the facility. For facilities where the production is greater than 5 tons, the operator must draw up a written concept note for the prevention of hazardous accidents. For production greater than 50 tons, the operator must prepare a safety report, emergency plan, public announcement (via internet or local news) of the safety measures. The operator must also appoint an accident officer and an emission control officer (although it can be the same person holding both responsibilities).

Both internal and external safety distances are not fixed and depend on the local conditions and the risk assessment of the individual facility. The Ordinance of Industrial Safety and Health is the relevant regulation for determining safety distances.

The Federal Land Utilisation Ordinance allows hydrogen storage only in industrial areas and in some rare cases in commercial areas. However, refuelling stations without onsite production but (including hydrogen) which also store hydrogen are allowed even in residential areas. This creates regulatory inconsistency.

Scenarios 2 and 3 – Transport pipelines and road transport

Germany does not impose additional conditions for the road transportation of hydrogen and regulations governing transport of hazardous goods are applied.

Operators transporting hydrogen, like other dangerous goods, need to appoint a dangerous goods officer who has an ADR training certificate. The driver of the transport vehicle must also have an ADR training certificate specific for hydrogen transportation. Vehicles must be clearly marked for transport of hydrogen.

The pressure receptacle must have a safety factor (ratio between burst pressure and nominal fill pressure) of 3.

Approval for hydrogen powered vehicles is similar to those for conventional fuel vehicles. Rules related to maintenance are also similar to those applicable to conventional fuels. Manufacturers, however, are required to prepare maintenance manuals specific to hydrogen vehicles. The individual components of the vehicle have to undergo rigorous tests as required under European and national frameworks. This is equally true for cars, trucks, buses, bikes and motorcycles.

Road route planning is the responsibility of the State transport department. Rules for dangerous goods such as those related to use of bridges and ferries and parking in residential spaces at certain times or on public holidays also apply.

Parking is allowed in underground garages as long as there is no explicit prohibition by the owner of the garage. Since hydrogen vehicles are treated on par with electric vehicles, parking spots dedicated to electric vehicles can be used. Access restrictions for reasons of noise and emissions may also be removed.

High safety requirements (ADR) have restricted the increase of payload of hydrogen trailers and restricted the cylinder/tube volume. Improvements in transport technology means that more hydrogen can be transported at lower costs. However, regulatory restrictions are preventing this from happening. Recently, an ordinance has been passed giving operators the option to use existing natural gas pipelines for hydrogen.

Scenario 4 – Mobility and partially confined spaces: tunnels

Restrictions on transport of dangerous goods in tunnels apply based on road tunnels classified by ADR.[41] For instance, there is no restriction for Category A tunnels. Tank carriage of hydrogen is forbidden in tunnel categories B, C, D and E. Hydrogen in cylinders can pass through in tunnel categories A, B and C. Additional conditions such as time restrictions may be applicable. The conditions are regulated by the Federal Ministry of Transport and Digital Infrastructure.

At present no restrictions are imposed on hydrogen powered cars travelling through any kind of tunnel. Information on restrictions (if any) related to movement of hydrogen powered trucks and buses is not available publicly.

Scenario 5 – Mobility and partially confined spaces: refuelling stations

The rules governing the construction and operation of HRS present some uncertainty. For one, each federal state has its own rules with respect to building requirements. Secondly, since HRS can produce and store hydrogen at different capacities, the requirements related to land use and general operability are often unclear.

The permitting process is required to be completed within 3 to 7 months depending on how complex the facility is. However, this extends to up to 15 months.

Once a binding land use plan is prepared, a hydrogen refuelling station is permissible as long as it does not contravene the terms of the land use plan. Under the German Building Code, a building permit is required for erecting a facility. An HRS with onsite production is allowed only in industrial and commercial areas and subject to additional local conditions (if any exist).

Rules vary depending on whether an HRS has the ability for onsite production of hydrogen and the accompanying storage limits and are summarised below:

- When the storage limit is under 3 tonnes, a building permit under State Building Regulations and an operation and construction permit under Ordinance for Industrial Safety and Health is needed – irrespective of the production capabilities.

- When the storage limit is more than 3 tons but under 30 tons and the facility does not have onsite production, a simplified procedure under the Emission Control Act applies.
- When the storage limit is more than 30 tons and the facility has onsite production, no simplified process exists. All the provisions as applicable to production of hydrogen at an industrial scale are applicable.
- A risk assessment must initially be performed before the permit is granted and subsequently on a regular basis according to the Ordinance on Industrial Safety and Health. The risk assessment determines the specific safety requirements and distances applicable to that permit.

Scenario 6 – Domestic Use

Present regulation does not support hydrogen in domestic use.

Japan

Japan has the advantage of having a designated government policy, such as "Strategic Roadmap for Hydrogen and Fuel Cells" (2011) and "Basic Hydrogen Strategy" (2017), formulated by the government, supporting the uptake of hydrogen, coupled with a public acceptance of hydrogen projects in the domestic-energy mix (Miho, Mihoko and Kimiharu, 2021[28]). Japan relies on existing regulations (HPGSA, HPGSCA etc...) related to high pressure gases and flammable gases to regulate its hydrogen industry.

General legal framework for hydrogen

The High-Pressure Gas Safety Act (HPGSA) (Japanese Government, n.d.[29]),[42] which regulates the safety of high-pressure gas, plays a central role. The detailed content of the HPGSA is in the General High Pressure Gas Safety Ordinance (GHPGSO) (Ministry of International Trade and Industry, n.d.[30]).[43] The regulations with more specific figures are the Exemplified Standards.[44] The HPGSA, GHPGSO and Exemplified Standards cover high-pressure gases. Hydrogen is specified as one of the high-pressure gases and as a flammable gas. Therefore, the same regulation is applicable to hydrogen as to one of the other high-pressure gases. Still, there are some hydrogen-specific provisions in GHPGSO covering compressed hydrogen stations (e.g., in GHPGSO, Article 7-3).

Authorities and institutions in charge of regulating hydrogen

The responsible legislator institutions at the national level are the National Diet (in charge of the Law), the Cabinet (Cabinet Orders), and the Minister of Economy, Trade and Industry (METI) (Ministerial Ordinances, Public Notices, Circular Notices (Internal Rules)), whilst the permitting institution is represented by the prefectural governor at the provincial level.

Existing regulation for the six scenarios

Table 10.12. List of Japanese regulations reviewed

Scenario 1 – Production
• The High-Pressure Gas Safety Act (HPGSA) • General High Pressure Gas Safety Ordinance (GHPGSO) • Exemplified Standards
Scenarios 2 and 3 – Transport pipelines and Road transport
• The High-Pressure Gas Safety Act (HPGSA) • General High Pressure Gas Safety Ordinance (GHPGSO) • Exemplified Standards

• the Road Transport Vehicle Act Safety Standards • Hazardous materials in the Japanese Fire Service Act
Scenarios 4 and 5 – Mobility and partially confined space: tunnels and refuelling stations
• Road Act • The Building Standard Law • The High-Pressure Gas Safety • General High Pressure Gas Safety Ordinance (GHPGSO) • The Fire Services Act • JPEC-S0003
Scenario 6 – Domestic use
• The Fire Service Act • The Fire Prevention Ordinance of the Fire Service Act • The Electricity Business Act • General High Pressure Gas Safety Ordinance (GHPGSO) • The Fire Services Act

Scenario 1 – Production

Japan defines the "Production of high-pressure gas" as "compressing, liquefying or otherwise treating, and filling containers with high pressure gas". Among the production equipment (excluding pipeline for production), gas equipment refers to the parts passed through the gas of the high-pressure gas being produced, including the raw material gas and low-pressure gas before reaching the state of high pressure (pumps, compressor, towers and vessels, heat exchanger, pipes, joints and connectors, valves, and other associated accessories) (High Pressure Gas Safety Institute of Japan (KHK), 2016[31]).

There are no specific regulations to electrolysers in the High-Pressure Gas Safety Act (HPGSA) (Japanese Government, n.d.[29])and the General High Pressure Gas Safety Ordinance (GHPGSO) (Ministry of International Trade and Industry, n.d.[30])[45] (compressors, pumps, evaporators and other treatment equipment, pipes, storage tanks, etc.).

For instance, rather than hydrogen-specific regulations, GHPGSO Article 6 (1) (Ministry of International Trade and Industry, n.d.[30]) includes leakage control provisions for high pressure gases containing hydrogen.

To prevent leakage, there are provisions that include the installation of emergency shut-down devices in the pipes (Article 6 (1)(xxv),[46] structures to prevent stagnation,[47] the installation of gas leak detection and alarm system,[48] an explosion-proof construction,[49] and the strength of high-pressure gas facilities.

Regarding the structure to prevent stagnation, the room in which the manufacturing equipment is installed shall be of a well-ventilated structure or shall have forced ventilation by openings in two or more directions, or by ventilation equipment, or their combination.[50]

Explosion-proof construction is needed to prevent nearby electrical equipment from becoming an ignition source in the event of flammable gas leakage.

Furthermore, high pressure gas facilities should be equipped with a pressure gauge and a safety device that can immediately restore the pressure to below the limit if the allowable operating pressure in the facility is exceeded.[51]

When it comes to high pressure gas facilities' strength, there are tests on pressure resistance (Ministry of International Trade and Industry, n.d.[30]),[52] the airtightness of the construction (Ministry of International Trade and Industry, n.d.[30])[53] and pipes wall thickness (Ministry of International Trade and Industry, n.d.[30]):[54]

- GHPGSO, Article 6 (1) (xi) and Exemplified Standards, Article 7 regulate that the high-pressure gas facilities should pass the pressure resistance test with certain requirements (Definitions of high-pressure gas) to ensure that they can withstand up to 1.25 times or more than the normal pressure[55] for 5-20 minutes.

- GHPGSO Article 6 (1) (xii) and Exemplified Standards, Article 7 regulate that the high-pressure gas facilities should pass the airtight construction test with certain requirements (Definitions of high-pressure gas) to ensure that they can withstand up to pressures above the normal pressure for 10 minutes or more.
- Regarding pipe wall thickness, see Definitions of high-pressure gas.
- The standards for materials used for the pipes of high-pressure gas facilities must be:
    - Stainless steel (SUS316);
    - JIS G4311 (heat-resistant steel bars and wire rods) (limited to SUH660);
    - JIS G4312 (Heat-resistant steel sheet and strip) (limited to SUH660),[56] or
    - ASME Section ii Part A (1998) SA-479 and SA-312 (limited to Type XM-19).[57]
- HPGSA and Enforcement Order of HPGSA regulate **the amount of production** which requires a **permission** issued by the prefectural governor. Under HPGSA, gases are classified by type into two classes: hydrogen is a flammable gas and therefore, a Class 2 gas (GHPGSO, Article 2 (1) (i)).
- Therefore, when the amount of hydrogen produced is 100 Nm^3/day or more, the permission by the prefectural governor is required,[58] as well as when the amount of hydrogen stored is 1000 Nm^3/day or more[59] as shown in Table 10.13.

Table 10.13. Categories for permissions for high pressure gas production and storage

Classification	Gas type	Amount of production that requires the permission by the prefectural governor	Amount of storage that requires the permission by the prefectural governor
Class 1 gas	Helium, xenon, neon, radon, argon, air, nitrogen, krypton, carbon dioxide, fluorocarbon (flame retardant)	300 Nm^3/day or more	3 000 Nm^3/day or more
Class 2 gas[1]	Gas other than Class 1 gas	100 Nm^3/day or more[2]	1 000 Nm^3/day or more

1. Class 2 Gas is more hazardous than Class 1 Gases, the standard for the quantity of production required to qualify is smaller.
2. The amount of hydrogen generally handled at a hydrogen station is more than 100 Nm3/day.

Regarding safety distance,[60] because storage and treatment facilities of a high-pressure gas production site encounter a large risk of disasters and a large impact on their surroundings in the event of a disaster, to ensure safety, a distance of at least Class 1 Equipment Setback (High Pressure Gas Safety Institute of Japan (KHK), 2016[31])[61] and Class 2 Equipment Setback (High Pressure Gas Safety Institute of Japan (KHK), 2016[31])[62] must be maintained.

Class 1 Equipment Setback refers to the minimum distance to be maintained from the exterior of the storage equipment or processing equipment of a high-pressure gas production facility to Class 1 Protected Properties.[63] Similarly, Class 2 Equipment Setback is the minimum distance from Class 2 Protected Properties.[64] The Equipment Setback is determined by the storage or processing capacity and its calculation is as it is shown in Table 10.14.[65]

Table 10.14. Calculation of equipment setback for flammable gas (X is the storage capacity (in cubic meters for compressed gas and in kilograms for liquefied gas) or processing capacity)

Class / X	0≦X<10 000	10 000≦X<52 500	52 500≦X<990 000	990 000≦X
Class 1 Equipment Setback	12v2 m	3/25v(X+10,000) m	30 m	30 m
Class 2 Equipment Setback	8v2 m	2/25v(X+10 000) m	20 m	20 m

The high-pressure gas facilities for the production of flammable gases containing hydrogen must be installed at no less than the distances indicated from the following facilities (Table 10.15):

Table 10.15. Safety distance of the high-pressure gas facilities for the production of flammable gases containing hydrogen

Class / objects	Safety distance
Class 1 Protected Properties	Class 1 Equipment Setback or more
Class 2 Protected Properties	Class 2 Equipment Setback or more
Between high pressure gas installations for the production of flammable gases, including hydrogen and high-pressure gas facilities for the production of flammable gases other than the production facilities	5 m or more
Compressed hydrogen station treatment and storage facilities	6 m or more
High pressure gas facilities for oxygen production facilities	10 m or more
Facilities that handle fire	8 m or more
The storage tank	1 m or 1/4 of the sum of the largest diameters or more
The dangerous goods facility	20 m or more[1]

1. The Regulation of Dangerous Goods Ordinance, Article 12.

Scenarios 2 and 3 – Transport pipelines and road transport

Transport pipelines

Currently, pipeline transport of hydrogen is limited to short distance uses, as a means of transport between plants in Japan. Three projects exist for the installation of hydrogen pipelines.[66] However, there are no long-distance pipelines such as those in the United States or Europe, the longest being 1.2 km.[67]

Short-distance transport of a few kilometres is exempt from the High-Pressure Gas Safety Act, as the pressure during transport is less than 1 MPa, which is the requirement for high pressure gas.[68]

The provisions for transport through high pressure pipelines are in GHPGSO, Article 6 (1) (xliii), which provides a set of regulations regarding pipe installations and pipe properties. The GHPGSO of 1966 provided for the following regulations on pipes. Article 6 (1) (xliii) covers high-pressure gases including hydrogen.

Regarding the location of pipes

- Pipes should not be installed where there is a risk of landslides or unequal subsidence of the ground;
- Pipes above ground level should be installed 30 cm or more from the ground surface;[69]
- Pipes below ground level should be installed 60 cm or more from the ground surface.[70]

Regarding pipes strength

- GHPGSO, Article 6 (1) (xliii) and Exemplified Standards, Article 7 regulate that the pipes should pass pressure resistance test with certain requirements (see section on Additional national standards (recommendations) related to the 6 scenarios) to ensure that they can withstand up to 1.25 times or more than the normal pressure for 5-20 minutes;
- GHPGSO, Article 6 (1) (xliii) and Exemplified Standards, Article 7 regulate that the pipes should pass the airtight construction test with certain requirements (see section on Additional national standards (recommendations) related to the 6 scenarios) to ensure that they can withstand up to pressures above the normal pressure for 10 minutes or more;

- Regarding pipes wall thickness, see Definitions of high-pressure gas.

  Regarding materials

- For the protection of outer surfaces when pipes are buried underground, the outer surface of the pipes must be protected by a paint covering or asphalt mastic or similar coating by a combination of asphalt or coal tar enamel or similar coating material and jute (Hessian cloth), vinylon (or vinalon) cloth, glass mat or glass cloth, or similar coating material.[71]

  Regarding measures to absorb stresses

- When pipes are installed underground, the pipes should be supported in the soil uniformly and with suitable frictional forces, whereas when they are installed above ground, bent pipes should be installed to absorb stresses (the amount of expansion and contraction). To not exceed the temperature of normal use, when pipes are installed above ground, measures such as painting silver paint on top of anti-corrosion paint should be taken to prevent abnormal temperature rises. Pipes communicating between establishments shall be equipped with telephones, intercoms, etc., to allow for reporting in case of an emergency.[72]

  Regarding safe distances

- In crossings of public roads where vehicle traffic is particularly heavy, the depth of buried pipelines shall be at least 1.2 m.[73] Regulations on the safety distance of pipelines could not be found. Although there have been some demonstrations of pipeline laying in Japan, most of the pipelines are on factory premises and are not long-distance as in other countries, which may explain the lack of pipeline safety distance regulation in Japan.

A chief gas engineer shall be appointed when installing pipelines with a continuous extension of more than 500 m ((n.a.), n.d.[32]).[74]

Notification establishing detailed technical standards for the location, structure and equipment of manufacturing facilities and manufacturing methods provides the following safety distances from the pipes as it is shown in the tables below (if the normal pressure is less than 1 MPa, the horizontal distance shall be 15 m less than the following safety distances, respectively).

Table 10.16. Safety distance from the pipes when pipes are buried

Objects	Safety distance
From buildings	1.5 m
From underground shopping centres and side roads	10 m
From water supply facilities, where there is a risk of high-pressure gas contamination	300 m

Table 10.17. Safety distance from the pipes when pipes are installed above ground[1]

Objects	Safety distance
From railways	40 m
From roads	40 m
From schools	72 m
From social welfare facilities	72 m
From hospitals	72 m
From urban parks	72 m
From facilities capable of accommodating more than 30 000 people	72 m

From hotels and other buildings intended to accommodate an unspecified number of people with a total floor area of 1 000 m^2 or more	72 m
From main buildings and platforms of stations with an average of more than 20 000 passengers per day	72 m
From important cultural properties	72 m
From water supply facilities, where there is a risk of high-pressure gas contamination	300 m
From evacuation airspace and evacuation roads for times of disaster	300 m
From houses	40 m

1. Gas Business Act Enforcement Regulations, Article 1 (2) (ii).

Regulations pertaining to odour control measures

The Gas Business Act, Article 21 and the Ministerial Ordinance Establishing Technical Standards for Gas Facilities, Article 22 provide regulations on odorant measures when gas is supplied through pipes.

When supplied by low pressure (~0.1 MPa ((n.a.), n.d.[33]) [75]), it is necessary to provide odorant measures so that the gas can be detected by odour. This does not apply to large gas supplies that are used to supply large quantities of gas at medium (0.1 MPa~ 1 MPa ((n.a.), n.d.[34])[76]) or higher pressure, or where appropriate leak detection equipment has been installed by appropriate means.

Road transport

The provisions for road transport are GHPGSO, Article 49, 50, which regulate high pressure gas including hydrogen. Based on these articles, the temperature of the filling container should be kept below 40°C at all times by avoiding sunlight, covering the vehicle with a sheet and choosing a shaded area for parking.

Composite containers that are 15 years old must not be filled, stored, or moved. Proper measures should be applied to prevent filling containers from tipping over (e.g., filling containers should be stacked horizontally. For liquefied gas, vertical stacking is recommended to prevent the safety valves from being used by the liquid and becoming inoperative.).

When parking, except when loading or unloading the filling containers, areas where Class 1 and 2 protected properties[77] are densely located should be avoided and a safe place with light traffic should be chosen.

Scenarios 4 and 5 – Mobility and partially confined spaces

No hydrogen-specific regulations related to tunnel have been found. In long tunnels (over 5 000 m long) and underwater/waterfront tunnels, the passage of vehicles carrying explosive or flammable dangerous goods is prohibited or restricted (Road Act, Article 46). Tunnel requirements are as below,[78] though those requirements are written in a Circular Notice (Internal Rules) (Ministry of Land, Infrastructure, Transport and Tourism, 2005[35]).

- The tunnel premises structure must be possible to sustain wind speeds of 2 m/s or more in order to prevent heat from rising back up from the point of accident.
- There must be no congestion that stagnates for more than 11 minutes (i.e., the vehicle must be able to pass through the tunnel in 11 minutes) before the hydrogen is released from the hydrogen vehicles.

When it comes to hydrogen stations, there are four equipment configurations: the dispenser, the storage tank, the accumulator, and the compressor, each of which is regulated under GHPGSO. The March 2005 amendments to the GHPGSO set out Article 7-3 as technical standards for specific compressed hydrogen stations. Regarding performance requirements for hydrogen dispensers and constraints on the filling process, Exemplified Standards such as 55-2 and 59-4 refers to JPEC-S0003. In Japan, the fuelling protocol standard in compliance with national legislation, which is called JPEC-S0003 was developed by

Japan Petroleum Energy Center (JPEC) based on SAE J2601. However, JPEC-S0003 is modified for the Japanese regulation. (i.e., The normal pressure at hydrogen stations is 90 MPa to 100 MPa in the United States because the protocol is based on the assumption that the normal pressure is sufficiently high for the maximum filling pressure of the on-board container, 87.5 MPa. On the other hand, the normal pressure at hydrogen stations in Japan is less than/equal to 82 MPa because national regulation, GHPGSO Article 7-3 stipulates that the upper limit of the normal pressure is 82 MPa.)

For on-site production facilities, the same regulations as in production plants are applied. The provisions on production regulations are applicable to both production facilities and hydrogen stations. As of December 2022, there are approximately 164 hydrogen stations in operation in Japan (Kato et al., 2016[36]).[79]

GHPGSO Article 6 contains the provisions for production facilities excluding cold evaporators, compressed natural gas stations, liquefied natural gas stations, and compressed hydrogen stations, and most provisions in Article 6 are applied mutatis mutandis in Articles 7-3(1) (i)and 7-3(2)(i).

Regarding standards for materials for high pressure gas equipment, the compressor must be made of (i) Stainless steel (SUS316) or (ii) SCM435 Steel.[80]

Pipes must be made of (i), (iii) JIS G4311 (heat-resistant steel bars and wire rods) (limited to SUH660), JIS G4312 (Heat-resistant steel sheet and strip) (limited to SUH660),[81] (iv) ASME Section ii Part A (1998) SA-479, SA-312 (limited to Type XM-19).[82] The valves must be made of (i), (iii), (iv), (v) JIS H3250 (2010) copper and copper alloy rods (limited to C3604 and C3771).[83]

The dispenser must be protected against damage to hoses due to accidental starting of vehicles (Ministry of International Trade and Industry, n.d.[37]).[84] To ensure that hydrogen does not stagnate on the roof – if installed –, the dispenser shall have a structure on the roof (Ministry of International Trade and Industry, n.d.[38]):[85]

- where the lower surface of the roof is horizontal and flat, and
- that allows leaking gases to pass from the lower face to the upper face where the lower face of the roof is sloped or has an indentation.[86]

Flame detectors must be installed and if a flame is detected, an alarm is activated to stop the operation of the onsite production facility and prevent leakage of compressed hydrogen (Ministry of International Trade and Industry, n.d.[39]).[87]

A liquid storage tank must have a pressure relief valve and criteria for releasing liquefied hydrogen. Liquid storage tanks for inflammable gases, including hydrogen, which have a storage capacity of 1 000 tonnes or more, must use reinforced concrete, steel and reinforced concrete, metal, earth, or a combination of these. Liquid dikes must be made of corrosion- and rust-resistant metal. The earth fill is to be sloped no more than 45° to the horizontal.

The surface must be protected by concrete or other means to prevent run-off due to rainfall. The width at the top of the embankment should be at least 30 cm (Ministry of International Trade and Industry, n.d.[40]).[88] Gas storage tanks must have measures to prevent temperature rise (water[89] or fire hydrants (Ministry of International Trade and Industry, n.d.[41]).[90]

Flame detectors must be installed at the accumulators and if a flame is detected, an alarm should be activated to stop the operation of the onsite production facility. A firewall must be installed to prevent the accumulators from being heated by a fire that occurs outside the premises of the compressed hydrogen station (Ministry of International Trade and Industry, n.d.[42]).[91] Overflow prevention valves must be at the outlet of the accumulator (Ministry of International Trade and Industry, n.d.[43]).[92]

The pressure relief valves in the pipes receiving compressed hydrogen from the accumulator monitor the hydrogen pressure and automatically open when the pressure exceeds the set pressure, reducing the pressure before the relevant safety device is activated. Small and safe amounts of hydrogen are released (Ministry of International Trade and Industry, n.d.[44]).[93] If the pressure relief valves are not activated, the safety valves are activated when the set pressure of the safety valve is reached. Large quantities of hydrogen are released in a short time (Ministry of International Trade and Industry, n.d.[45]).[94]

The compressor must have emergency shutdown devices (Ministry of International Trade and Industry, n.d.[46])[95] and ventilation systems (Ministry of International Trade and Industry, n.d.[47]).[96] The compressor must be installed in a room with a steel plate casing or non-combustible construction, and the room should be provided with a ventilation system with sufficient ventilation capacity.[97] Reinforced concrete barriers with a minimum thickness of 12 cm shall be placed between the compressor or liquefied hydrogen boosting pump and the sending gas evaporator connected to it, the accumulator, the liquefied hydrogen storage tank and the sending gas evaporator and the dispenser.[98]

The Regulation of Dangerous Goods Ordinance Article 27-5 outlines the installation standards for hydrogen stations: location, structure or equipment of dispenser, liquefied hydrogen pipes, and gas pipes etc. Reformers for the production of hydrogen by reforming from dangerous goods must be installed outdoors where there is no risk of collision with vehicles.

The MC formula method in SAE J2601 is added to JPEC-S0003 (2021), which calculates the rate of pressure increase in response to the supply fuel temperature, enabling filling to be carried out under appropriate filling conditions. Exemplified Standards 59-4, which refers to JPEC-S0003, stipulates that when compressed hydrogen is filled into fuel equipment containers, the rate of pressure rise should be monitored by a pressure transmitter installed in the dispenser and the rate of pressure rise and the pressure tolerance range should be set in advance in accordance with JPEC-S0003.

GHPGSO Article 7-4 stipulates technical standards for compressed hydrogen stands that allow customers to fill themselves with compressed hydrogen and enable the operation of hydrogen stands under remote supervision. In addition, requirements have been established in Circular Notices (Ministry of Economy and Trade and Industry of Japan, n.d.[48])[99] to allow one safety supervisor to serve concurrently at more than one hydrogen station, provided that the station is limited to compressed hydrogen stations as defined in GHPGSO Article 7-3 and mobile compressed hydrogen stations as defined in GHPGSO Article 8-2. On the other hand, hydrogen stations with remote monitoring are not included in the list of hydrogen stations where a safety supervisor can serve concurrently at more than one hydrogen station due to the lack of experience in operating hydrogen stations with remote monitoring.

GHPGSO, Article 7-3 (2) provides the following safety distances as it is shown in Table 10.18:

Table 10.18. Safety distance

Objects	Safety distance
From the storage area	8 m, 6 m (for less than/equal to 40 MPa), to the site boundary
From the dispenser	8 m, 6 m (for less than/equal to 40 MPa), to the road boundary of a public road
Between the compressed hydrogen station treatment and storage facilities and high-pressure gas facilities for the production of flammable gases other than the production facilities	6 m
Between the compressed hydrogen station treatment and storage facilities and high-pressure gas facilities for oxygen production facilities	10 m

Regarding the mobile manufacturing equipment, in addition to a pressure-operated safety valve the accumulator must be also provided with a safety valve that operates below 110°C (Ministry of International Trade and Industry, n.d.[49]).[100] The safety distance of the mobile compressed hydrogen fuel station is shown in Table 10.19.

Table 10.19. Safety distance of the mobile compressed hydrogen fuel station[1]

Object	Safety distance
From class 1 Protected Properties	15 m
From class 2 Protected Properties	10 m
From the dispenser	8 m (40 MPa~ 82 MPa), 6 m (~40 MPa)
From the high-pressure gas facilities for the production of flammable gases other than the production facilities	6 m
From high pressure gas facilities for oxygen production facilities	10 m
From the facilities that handle fire	8 m

1. Manufacturing facilities with treatment facilities for filling fuel equipment containers fixed to vehicles using compressed hydrogen as fuel with compressed hydrogen, which can be moved with respect to the ground surface. GHPGSO, Article 2(1)(xii)(xxvi), Article 8-2 (2) (ii).

Scenario 6 – Domestic use

ENE-FARM, a fuel cell system for domestic use that uses hydrogen, was released in 2009. Fuel cells for domestic use, including but not limited to hydrogen, are subject to the Fire Service Act and the Electricity Business Act. Under the Fire Service Act, installation of fuel cells requires notification of equipment installation in accordance with the Fire Prevention Ordinance of the Fire Service Act, Article 44 (1) (xi).

When the Fire Prevention Ordinance of the Fire Service Act was amended to take into account fuel cells for domestic use, there were no practical applications for hydrogen fuel cells, so hydrogen fuel cells are not yet listed in the list of fuel cells to which the technical standards apply.[101]

Under the Electricity Business Act, there are regulations such as compliance with technical standards,[102] safety regulations,[103] appointment and notification of a chief engineer,[104] and required notification of a construction plan.[105] In 2004, a certification system for household fuel cell systems came into effect. The voluntary standard, Technical Standards and Inspection Methods for Small Fuel Cells for Stationary Use describes this certification.

Additional national standards (recommendations) related to the 6 scenarios

This section contains additional data on specific standards and regulations which provide a background to the safety and regulatory considerations of several scenarios/applications above.

Table 10.20. The legal structure of the High-Pressure Gas Safety Act

The Law (National Diet of Japan, etc.)
• The High-Pressure Gas Safety Act
Other related laws
• The Fire Services Act (METI) • The Building Standard Law (Ministry of Land, Infrastructure, Transport, and Tourism) • Fire Service Act (Ministry of Internal Affairs and Communications) • The Industrial Safety and Health Act (Ministry of Health, Labour, and Welfare) • Road Transport Vehicle Act (Ministry of Land, Infrastructure, Transport, and Tourism) • Road Act (Ministry of Land, Infrastructure, Transport, and Tourism) • Air Pollution Control Act (Ministry of the Environment) • Gas Business Act (METI)
Cabinet Orders (the Cabinet)

• Enforcement Order of the High-Pressure Gas Safety Law	
Ministerial Ordinances (established and made public in the official gazette by METI)	
Case	**Provisions**
• Hydrogen stations (compressed hydrogen stations) to be constructed in urban areas	• General High Pressure Gas Safety Ordinance • Container security regulations • Designated Equipment Inspection regulations
• Construction of a hydrogen production plant or hydrogen station in a petrochemical complex	• Industrial Complex Safety Regulations
Public Notices (established and made public in the official gazette by METI)	
• Public Notice Related to the Enforcement Order of the High-Pressure Gas Safety Law • Seismic Resistant Design Code for High Pressure Gas Facilities, etc.	
Circular Notices (Internal Rules) (issued to the prefectural governors by METI)	
• Application and Interpretation of the High-Pressure Gas Safety Act and the Related Ministerial Ordinances • Exemplified Standards	

Source: (High Pressure Gas Safety Institute of Japan (KHK), 2016[31]).

Definitions of high-pressure gas

Substances falling under any of the following categories (High Pressure Gas Safety Institute of Japan (KHK), 2016[31]) are called high pressure gas subject to the High-Pressure Gas Safety Act. (Pressure is referred to as the gauge pressure.) High-pressure gases are defined as compressed gases with a hydrogen state of 1 MPa or more and liquefied gases with a hydrogen state of 0.2 MPa or more (High Pressure Gas Safety Institute of Japan (KHK), 2016[50]).

Table 10.21. Definitions of high-pressure gas

Definition	Details
Compressed gas	• Gas pressure of 1MPa or greater at the normal operating temperature • Gas pressure of 1MPa or greater at 35°C
Compressed acetylene gas	• Gas pressure of 0.2MPa or greater at the normal operating temperature • Gas pressure of 0.2MPa or greater at 15°C
Liquefied gas	• Gas pressure of 0.2MPa or greater at the normal operating temperature • Temperature for the gas pressure to reach 0.2MPa is below 35°C
Other (liquid hydrogen cyanide, liquid bromomethane, liquid ethylene oxide)	• Pressure greater than 0Pa at 35°C

Regarding pipes wall thickness, Outer diameter to inner diameter ratio of 1.5 or less: $t=PD/ (2an + 0.8P)$,[106] Outer diameter to inner diameter ratio exceeding 1.5: $t=D/2(1- \sqrt{(an-P)/(an+P)})$.[107]

Under pressure resistance test of pipe, in principle, they shall use Water. Liquid requirements when liquids other than water are used are i) Below the boiling point, ii) In the case of flammable liquids, their flash point is higher than 40°C and they are tested near room temperature. Where it is inappropriate to fill the water for compelling reasons, they can use air or other non-hazardous gases.[108]

The airtight construction test of pipe to ensure that gases inside the equipment do not leak is conducted using air or other safe gas at pressures above the normal pressure. They should use air and other non-hazardous gases at temperatures not likely to cause brittle fracture.

The Netherlands

Hydrogen production in the Netherlands is mature and well-developed. The Dutch government has recognised that a solid regulatory framework is key to the development of the hydrogen economy. The Ministry of Economic Affairs and Climate Policy has identified that one of the main policy issues will be the transition of the natural gas infrastructure from natural to green gas and low carbon hydrogen. Currently, at least ten legislative texts and six governmental institutions can be relevant when it comes to different aspects of the transition to hydrogen. Except for general restrictions within the broader Dutch regulatory framework and two very particular regulations, the PGS35 for hydrogen fuel stations and the requirements for hydrogen fuel cells (soft law), there is currently no mandatory, specific, regulation for new hydrogen usage in the energy transition. Hence, there is a wide range of legislation, however these often do not consider explicitly hydrogen as an energy carrier for the energy transition. Legislative clarity, alignment of existing multiple regulatory goals and existing legal provisions and rules and guidance are being worked on to ensure consistent interpretation of legal framework with the Environment and Planning Act. This includes how relevant authorities should use their competencies regarding hydrogen.

General legal framework for hydrogen

The national government is working on bundling and modernizing the regulations for the living environment into the new Environment and Planning Act (version in English) – which is supposed to enter into force on January the 1st 2024. In the meantime, the relevant authorities have to figure out how they could process requests for permits when for some of the applications the national regulation is ambiguous. In 14 municipalities, new hydrogen gas stations have been built, and a number of authorisations for hydrogen gas stations are pending. According to the existing legislation this has to be done by using a risk analysis that in most cases is, based on the ministerial memos on calculating such risks and local and regional expertise in the environmental domain. Hydrogen refuelling stations are in nearly all cases in breach of the prevailing land use development plan, if only because most development plans do not consider the possibility of using hydrogen as a fuel. For other applications more regulatory clarity seems necessary to make and speed up the transition. The different authorities and stakeholders operate in silos to discuss relevant developments and how to enable and support safe energy transition, hence the approach with national guidance (*Richtsnoeren waterstofveiligheid*). The guidelines are being used as the safety framework for four such hydrogen projects. Two of these fall under the Green Deal H2 districts. The “Generic guideline for hydrogen safety” provides starting points for how to handle hydrogen safely. Specifically for the four projects there is also the 'Supplementary safety guideline'. This guideline gives substance to the agreements made within the Green Deal H2-Neighbourhoods about guaranteeing safety. The Netherlands Authority for Consumers and Markets (ACM) has developed a framework to facilitate pilots for the domestic use of hydrogen (Authority for Consumers and Markets, n.d.[51]).[109] In addition, the Ministry of Economic Affairs and Climate Policy has appointed the State Control of the Mines (SodM) as the supervisory body for the safety of the pilots (Ministry of Economy and Climate, 2022[52]).[110]

Authorities and institutions in charge of regulating hydrogen

The basis of the Dutch regulatory framework is stipulated in its constitution. The constitution establishes four different levels of government: the local (*gemeente*), regional (*provincie*), the national government (Rijksoverheid) and the entity water boards (*waterschappen*) each with their own tasks, policies, and regulations. This is in line with the principle of subsidiarity,[111] i.e. the different levels function in a hierarchy where the local and regional government are subsidiary to the national government (Government of the Netherlands, 2022[53]) and issues are dealt with at the most immediate or local level that is consistent with their resolution.

There are around 344 local municipalities (*gemeente*) subject to changes in the Netherlands. The responsibilities of the local municipalities include keeping track of who lives in the municipality, provide benefits to those who cannot support themselves, responsible for the housing of schools, make zoning plans, provide subsidies and the regional municipalities (*provincie*) are responsible for the layout of the province ensuring the implementation of regional economic policy. For example, they can decide where to locate business parks.

At the moment of writing, the national government (*Rijksoverheid*) consists of 12 ministries. The ministries are under the political leadership of a minister and a secretary of state. The civil service of each ministry is headed by a secretary-general. Under the responsibility of the ministries are about 160 organisations (Government of the Netherlands, 2022[53]).

The national government is the primary policymaker and regulator with regards to safety. The regulations focus on activities, (operating) facilities or the living environment, and function by issuing permits.

When authorising a permit, the responsible government takes the public interests into consideration related to the national regulation – examples of public interests for energy related projects are safety, durability, reliability, and affordability. Which government (*bevoegd gezag*) authorises a permit differs per regulation. For instance, mining activities need a permit from the national government, (operating) facilities which work with large quantities of hazardous substances need an environmental permit (*omgevingsvergunning*) which is in far most cases issued by the regional government (Province). Local government (*gemeenten*) deal with small facilities with limited amount of hazardous substances.

Whereas the process for regulation and permits starts prior to the activity, inspection and control come into play throughout the activity. The organisation that carries out the inspection also differs per regulation. For mining activities there is a national inspection (in Dutch jargon: *rijksinspectie* (Government of the Netherlands, 2016-2021[54]). For the above-mentioned (operating) facilities there are different inspections, there is an environmental inspector (*omgevingsdienst* (Kortekaas, n.d.[55])[112]), a national inspector for occupational safety (Inspectie SZW (Nederlands Arbeidsinspectie, n.d.[56])[113]) and the safety region (*veiligheidsregio*).

There are several channels through which hydrogen-based initiatives can get into contact with the authorities, which affect the point in time at which authorities first get involved on a project. Hydrogen initiatives can make use of the Environment Desk, which allows them to get into contact with the relevant authorities concerning questions on licensing and to get information on licensing procedures. In other cases, companies may be referred by the municipality. For environmental inspection there is a rule of thumb (InfoMil, n.d.[57]): whichever government (*bevoegd gezag*) issues the permit will be responsible for enforcement. Next to their above-mentioned responsibility as inspector, the safety region (*veiligheidsregio* ((n.a.), n.d.[58])[114]) is mainly responsible for incident control (predominantly fire) and coordination when a disaster or crisis occurs. The country is divided into twenty-five safety regions (Groenen, n.d.[59]).[115] Permits are normally necessary to operate and in most cases also to build a hydrogen gas station. The procedure takes several steps, which may be lengthy as common procedures applied for environmental permits: a request by a party, drafting a safety report, which needs to have an advice from the safety region and the enforcement department of the permit-giving organ. Individual domestic use of hydrogen (for instance, boilers) is regulated via private parties (sellers and buyers), also in terms of liability.

For a hydrogen filling station, a Wabo environmental permit must be applied for in all cases (Bor, Appendix 1, Part C, category 4.4, paragraph L) and usually also a building permit (Rijksoverheid, 2022[60]). In the classification of the Activities Decree, a hydrogen filling station is a type C establishment (no permit is required for type A, type B only requires notification, type C requires a permit). The competent authority follows the extensive Wabo procedure. Moreover, the initiatives are almost always conflict with the prevailing zoning plan, if only because hydrogen refuelling is usually not mentioned within spatial planning in the zoning plan.

Various licensors and regulators may be involved in their role in hydrogen. For instance, for licensing and supervision of the aforementioned pilots, the following public authorities are relevant:

- Authority for Consumers and Markets (ACM);
- State Supervision of the Mines (SodM);
- Radiocommunications Agency (AT);
- Environmental Services (ODs) and Regional Implementation Services (Ruds);
- Safety Regions (VRs);
- Construction and Home Supervision (BWT);
- Human Environment and Transport Inspectorate (IlenT);
- Labour Inspectorate;
- Ministry IenW;
- Ministry of Economic Affairs and Climate.

To summarise, every level and type of government will be confronted, to differing extents, with the challenges of the energy transition. Either when making policy or regulation, when authorizing permits, when inspecting and when something (inevitably) goes wrong. Hence, there is the Energy Transition Policy Principles and the Hydrogen Guidelines (*Richtsnoeren*).

Existing regulation for the six scenarios

Hydrogen is not comprehensively regulated in the following laws and regulations:

- Building Decree 2012. There are currently no established requirements for hydrogen applications in buildings, law on quality assurance for building, the underlying governmental decrees (AMvBs) and requirements of private parties.
- There are numerous other existing acts, decrees and rules, e.g. (Brzo [Seveso], increased risks premises Decree [Bevi], General Permitting Act [Wabo], Environmental Act, Spatial Planning Act capturing hydrogen as chemical in a classical manner. The Environment and Planning Act will be a complete integrated replacement of the mentioned existing laws and regulations to be a law that governs how the environment and land use is managed.
- The Dutch Gas Act and its supporting schemes: currently, there are no regulations governing the supply of hydrogen to customers in urban areas. There is also no legal foundation for network operators to participate in hydrogen pilot projects, even though they are frequently involved in them. Currently, the Dutch competition law authority (ACM) and SodM use established guidelines, rather than regulation, to carry out their natural gas monitoring responsibilities. In 2021 the ACM issued a 'toleration policy' note to promote energy transition, which, however, requires certainty on the safety criteria to effectuate hydrogen projects. The Gas Act is being transferred into an Energy Act.
- The Dutch government signed the 2015 Paris Agreement and is currently drafting the Dutch Climate Agreement to implement it. Hydrogen is a critical energy carrier for all transition options in the Draft Climate Agreement (HyLAW, 2019[61]). Within this agreement, the use of hydrogen is seen as cross-sectoral solution for a climate neutral society.
- Currently, hydrogen rules are mostly focused on industry and related operations such as production and transportation. However, except for general restrictions within the broader Dutch regulatory framework and two very particular regulations, the PGS35 (PGS 35, 2021[62]) for hydrogen fuel stations and the requirements (NEN, 2020[63])[116] for hydrogen fuel cells (soft laws), there is essentially no targeted regulation for new hydrogen usage in the energy transition. The current environmental law and decrees include hydrogen. However, they do not include much on the implication of the energy transition in instrumentation. Other policies are under development, for

instance, the PGS38 is currently under development, which is an informative document with guidelines for the safety of multi-fuel stations (HyLAW, 2019[61]).

- Regulations and standards for safety, interoperability, and compatibility, among other things, are needed to help with the energy transition. Electricity and gas cannot be separate any longer; the energy system must be viewed as a whole. This necessitates complementary legislation, which law proposals such as "STROOM" and "*Wet Voortgang EnergieTransitie*" aim to achieve. Interoperability and integration are hampered by the lack of a clear single authority (e.g., energy storage, power-to-gas and gas-to-power).
- It has been recommended to Dutch policymakers to agree on an integrated energy transition policy to boost hydrogen infrastructure, which enables an efficient green and renewable energy system in line with the goals of the forthcoming Dutch Climate Agreement (*Klimaatakkoord*) (HyLAW, 2019[61]).

Table 10.22. List of applicable legislation in the Netherlands

Scenario 1 – Production
• Besluit risico's zware ongevallen 2015 (Decree on the risks of serious accidents) Storage (>5000 kg), http://wetten.overheid.nl/BWBR0036791/2015-07-08) • Wet ruimtelijke ordening Wro (Spatial Planning Act), http://wetten.overheid.nl/BWBR0020449/2016-04-14 • Wet algemene bepalingen omgevingsrecht Wabo, http://wetten.overheid.nl/BWBR0024779/2016-07-01 • Bevi (Premises external Safety Decree) • Wabo (Permitting Act) • Omgevingswet, https://zoek.officielebekendmakingen.nl/dossier/33962/stb-2016-156?resultIndex=15&sorttype=1&sortorder=4. Note: this will take effect in 2024 and supersede and integrate most other legislative requirments mentioned here.
Scenarios 2 and 3 – Transport pipelines and Road transport
• Pipelines External safety Decree (Bevb) • Transport on hazardous substances (Annex 2 article 3 Wet Vervoer gevaarlijke stoffen (Annex 2 article 3), http://wetten.overheid.nl/BWBR0007606/2015-04-01 • Wet vervoer gevaarlijke stoffen (Law on transport of dangerous goods), http://wetten.overheid.nl/BWBR0007606/2015-04-01 • Wet ruimtelijke ordening Wro (Spatial Planning Act), http://wetten.overheid.nl/BWBR0020449/2016-04-14
Scenario 4 and 6 – Mobility and partially confined spaces: tunnels and domestic use
• Regeling energie vervoer, https://wetten.overheid.nl/BWBR0041050/2023-02-17 • Energy for Transport Registry, https://www.emissionsauthority.nl/topics/registry---energy-for-transport/energy-for-transport-registry-rev
Scenario 5 – Mobility and partially confined space Hydrogen: refuelling Stations
• PGS35 – Among the different Publications on Dangerous Substances (PGS) publications, PGS35 is Related to hydrogen, http://www.publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS35.html • Besluit infrastructuur alternatieve brandstoffen (Decree Alternative Fuels Infrastructure), http://wetten.overheid.nl/BWBR0039567/2021-07-01 • Wet ruimtelijke ordening Wro (Spatial Planning Act), http://wetten.overheid.nl/BWBR0020449/2016-04-14 • Wabo (Permitting Act)

Scenario 1 – Production

Hydrogen production in the Netherlands is mature and well-developed, having been conducted for more than 50 years. The chemical and petrochemical industries are the primary producers and users of hydrogen (centralised production) (HyLAW, 2019[61]). Hydrogen is used as a feedstock and, more recently, as an energy carrier.

The Netherlands produces the second-largest amount of hydrogen in Europe, after Germany. Most of the hydrogen in the Netherlands is being produced from natural gas.

Regardless of the type of hydrogen production (PEM, alkaline, reforming) or the presence (or lack) of hazardous compounds in the process, a hydrogen production plant is treated as a standard chemical manufacturing facility. Hence, hydrogen production is not subject to any specific legislation, and it is treated the same as any other inorganic gas producing facility.

Localised hydrogen production and storage is also governed by the European Commission the same as other forms of hydrogen production. As hydrogen is an industrial gas, hydrogen synthesis and storage are considered a chemical processes with emissions. When hydrogen is produced through electrolysis, downstream emissions are negligible (upstream emissions are only negligible in the case of renewable energy). However, production of hydrogen by electrolysis is not distinguished from other means of producing hydrogen (Delpierre et al., 2021[64]).[117]

This makes the administrative activity of building Hydrogen Refuelling Stations with localised hydrogen production unnecessarily complex. As a result, permitting obstacles for simplified processes (as opposed to "*uitgebreide*" processes[118] in Dutch), zoning, and permitting requirements arise.

There is no legal or administrative distinction in the Netherlands between localised and centralised hydrogen production (HyLAW, 2019[61]). As a result, applying for the "extended WABO procedure" is always required. Developers' costs rise as a result.

Hydrogen production permitting requirements are subject to:

- Risk assessments (Brzo 2015)
- Health and safety requirements (ATEX)
- Integrated environmental obligations (IED)
- Environmental impact assessment procedures (SEA and EIA)

Because of the aforementioned requirements, small production units are just as difficult to build as large ones. This substantially inhibits the development of localised production units, such as Hydrogen Refuelling Stations that produce hydrogen on-site. As a result of this complexity, requests are processed and interpreted in a non-uniform manner. The key conclusion about the barriers to hydrogen production is that small-scale (localised) hydrogen production is legally equivalent to large-scale (centralised) hydrogen production.

Scenario 2 – Transport pipelines

Since the 80s, hydrogen pipelines (hundreds of km) have been used in and between industrial clusters as chemical product. The Bevb (Pipelines External Safety Decree) and NEN 3650 Technical Standard for transport pipelines apply.

The law for natural gas (Gas Law) in the Netherlands itself does not yet provide for the possibility to inject, transport, or distribute high amount of hydrogen through the natural gas infrastructure (HyLAW, 2019[61]). A number of studies have been conducted in order to investigate if the methane network can technically and safety wise be used to transport hydrogen, and this has been confirmed and concluded. In addition, many projects, pilot-projects and initiatives have been developed or are in the process of being constructed and developed. A few examples are listed below:

- The Yara-Dow H2 pipeline, which became operational in 2018 and is the first natural gas pipeline converted to hydrogen pipeline in the Netherlands. This is a retrofit of a former natural gas pipeline, linking the hydrogen industry;
- There are three "Hydrogen Valleys" designated by EU in the Netherlands (the Europe's Hydrogen Hub: H2 Proposition Zuid-Holland/Rotterdam, the HEAVENN in province of Groningen and Hydrogen Delta a Dutch-Belgium crossboarder industrial cluster), i.e. a geographical area hosting

an entire hydrogen value chain, from production to distribution and from storage to local end-use. These "Hydrogen Valleys" have applications in industry, mobility and the built environment;

- The mobility market is being developed in the northern part of the country with hydrogen refuelling stations and several hydrogen buses already in operation;
- Gasunie is developing the National high pressure hydrogen grid;
- Gasunie is developing a terminal for the import of green ammonia, including storage and loading facilities and a connection to the so-called (Dutch) Hydrogen Backbone;
- In the World's first practical test (pilot) in Lochem, 12 monumental homes in the Berkeloord district are supplied and heated with hydrogen via the existing natural gas network.
- Green hydrogen has been planned to be produced offshore on an operational platform and transported to shore via existing former natural gas pipelines.

The Dutch government has recognised that a solid regulatory framework is key to the development of the hydrogen economy. The Minister of Economic Affairs and Climate Policy stated that one of the main policy issues will be the transition of the natural gas infrastructure from natural to green gas and low carbon hydrogen. The policy agenda will include studies looking into the role of the national gas infrastructure company Gasunie in the hydrogen chain. No specific legislation has been adopted for hydrogen which means that the existing laws on regulation of gas, and those applying to the energy, transport, and heating sectors, apply in the context of hydrogen projects (Jonk, Rietvelt and Schapink, 2021[65]).[119]

Scenarios 3 and 4 – Road transport and mobility and partially confined space: tunnels

Hydrogen transport via road (in the form of gas tanks, metallic cylinders and composite vessels – in gas, liquid or solid phase) is critical for the development of hydrogen energy infrastructure, such as transporting hydrogen to hydrogen refuelling stations or hydrogen for industrial use (e.g., the glass industry).

The regulations for moving hydrogen are transparent and uniform (ISO, 2021[66]):[120]

- In the Netherlands the relevant authorities refer to the ISO standards for technical and safety requirements of cylinders and tubes, and to other Dutch standards by the Dutch standardisation Institute (NEN).
- TheADR (UNECE, n.d.[67])[121] regulates the international transportation classified goods. This also holds for hydrogen in cylinders, tubes, trailers, and tank vehicles. The ADR defines hydrogen as category B/D, which indicates that transporting such goods through tunnels classified as B, C, D, or E is prohibited (Honselaar, Pasaoglu and Martens, 2018[68]). This can easily be understood since these are all tunnels below water level. Hydrogen road transport follows the obligatory Hazmat routing in order to avoid water tunnels, resembling other classified goods.

The concerns surrounding the distribution of hydrogen include the legal status of hydrogen as a fuel and the procedures for certification of hydrogen fuel.

The way RED II (European Commission, n.d.[69]) is implemented in the Netherlands is critical for safeguarding national interests in how "green" is defined. TheCertifHy project (Clean Hydrogen Partnership, n.d.[70]) provides the necessary building blocks for this transposition (Konda, Shah and Brandon, 2011[71]). When operating a filling station, determining the quality of hydrogen is still a problem. These are issues since sampling and quality assessment are complicated and not yet possible (to carry out widely) on site.

Legislation applicable:

- PGS35 (PGS 35, 2021[62]);
- Decree Alternative Fuels Infrastructure (Government of the Netherlands, 2017-2021[72]);

- Transport on hazardous substances (Annex 2 article 3 Wet Vervoer gevaarlijke stoffen (Annex 2 article 3) (Government of the Netherlands, 2015-2023[73]);
- Law on transport of dangerous goods (Government of the Netherlands, 2015-2023[73]).

The Transport of Hazardous Goods Act is the umbrella legislation concerning the transport of dangerous goods (HyLAW, 2019[61]). The Environmental Management Act and the Wet Safety Regions also concern road planning. Decree on external safety of transport routes falls under multiple laws such as the Transport of Hazardous Substances Act, Environmental Management Act, Safety Regions Act, General Environmental Law Act, and Spatial Planning Act.

In the Netherlands, the usage of hydrogen as propulsion for person cars, buses and trucks is unrestricted, this often raises a sense of uncertainty among those who are new in the field. Furthermore, for emergency services, FCEVs are now not distinguished from other vehicles. In the Netherlands, there is a general absence of regulations, codes, and standards in the sector of vehicle mobility[122] inside confined spaces, such as parking and tunnel regulations. This could lead to concerns about safety.

Transportation possibilities by boats and trains seem unclear in terms of technical development, safety concerns and desirability from relevant authorities. For instance, the railway tracks run through the highly populated main cities of the Netherlands where the relevant authorities, heads of municipalities, are concerned about the safety, in part due to the lack of information about this new energy source, relevant preventive measures and responsive actions in the case of an accident.

Scenario 5 – Mobility and partially confined spaces: refuelling stations

For hydrogen refuelling stations in the Netherlands a quantitative risk assessment is used for permitting. The rules governing the operation of HRS are present in the Dutch PGS35 guidelines. This directive is for the occupationally safe, environmentally safe and fire-safe application of installations for the delivery of hydrogen to vehicles and equipment. The PGS35 applies to hydrogen delivery installations on land, including the associated and/or necessary auxiliary equipment, with a maximum delivery pressure of 350 bar or 700 bar of gaseous hydrogen for road vehicles with European type approval.

In 2015, a new set-up of the PGS guidelines was started: the PGS New Style. A PGS New Style means that measures have been established with a risk approach. This means that an analysis has been made of the risks associated with activities involving the hazardous substance. The situations in which things can go wrong and lead to undesired, dangerous consequences are described in scenarios. Targets have been formulated for these scenarios aimed at managing the risks. At mobile and movable filling stations, the hydrogen supply consists of hydrogen bundles. These are several interconnected gas cylinders with hydrogen with a water volume of 50 l and a pressure of 200 bar. The risk is always a combination of the severity of the consequences (effect) of an (unwanted) event and the probability (chance) of the event occurring: risk = probability × effect. The probability is indicated with the numbers 1 for small chance to 5 for the greatest chance. The effect is indicated by the letters A for small effect through E for the largest effect. Low-risk scenarios are not included in the PGS guideline. The medium to high-risk scenarios is described in this PGS guideline.

Scenario 6 – Domestic use

For (the injection of) hydrogen to be used through the gas grid, technical improvements as well as changes in legislation, codes, and standards for the gas value chain are required to comply with the Paris 2015 Agreement. The Dutch high pressure gas grid is technically capable of distributing (pure) hydrogen, according to studies from prominent research institutions, but currently the natural gas law in the Netherlands does not yet provide for the possibility to inject, transport, or distribute a sizable amount of hydrogen through the Dutch natural gas grid (HyLAW, 2019[61]). Hydrogen can be transported, though, through newly-constructed pipelines under the Pipeline Decree (for above 16 bar) and below 16 bar for utility and distribution systems under the spatial planning law. Some consider that making an underground pipeline for hydrogen requires different materials, especially for certain elements, such as connections between pipelines and valves, as hydrogen is very light.

Norway

Much like other European nations, Norway relies on existing regulations related to high pressure gases, hazardous, and flammable substances to regulate its hydrogen industry. Depending on the intended application, some simplification processes are already present in the regulatory system. In addition to this, with most of the licensing and permitting functions lying with the municipalities (and in exceptional cases the Norwegian Directorate for Civil Protection, DSB), the regulatory process is relatively simpler because of better coordination facilitated by the municipality. The discretion of engaging other authorities and the task of coordination with other departments such as fire safety, occupational safety etc. lies with the municipality.

General legal framework for hydrogen

In Norway, it is generally recognised that costs for operators and regulators involved in hydrogen projects could be prohibitive if the goal was to prevent all incidents and accidents. Therefore, there is an acceptance of a limited residual risk (e.g. fatality risk outside the property of a facility may be up to 10^{-5}/year).

Thus, even if the operator has done everything right, accidents may happen. If a severe accident happens it will therefore be important for the operator to ensure that the risk documentation of the facility is of good quality confirming that the risk is well understood, and that the site has operated according to the procedures and standards described in the risk reports and internal governing documents, permits etc.

If there are significant weaknesses in the documentation that may indicate that the site risk was not properly understood, or procedures and requirements not followed, the operator or those responsible may risk fines, or at worst, face criminal prosecution for negligence.

Authorities and institutions in charge of regulating hydrogen

For most land facilities handling dangerous substances in Norway, the DSB is the regulator. All permits and necessary assessments for opening and operating hydrogen facilities are the responsibility of the concerned municipality.

When the expected production or storage is above the prescribed limit, additional permissions in the form of notification need to be obtained from the DSB. Information about regulations and guidance around the use, handling, storage, and transportation of dangerous goods (including hydrogen) have been summarised below.

Existing regulation for the six scenarios

Table 10.23. List of Norwegian regulations reviewed

Scenario 1 – Production
• The Planning and Building Act • Rules as decided by the local municipalities • Major Accidents Regulation • Equipment for potentially explosive atmospheres (ATEX) • National guideline on production and treatment of flammable, reactive and pressurised substances
Scenarios 2 and 3 – Pipeline transport and Road transport

- Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods makes the ADR, ADN and RID applicable within the EU
- National guidelines for sustainable and coordinated housing, spatial and transport planning

Scenarios 3 and 4 – Road transport and mobility and partially confined spaces: tunnels

- Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods makes the ADR, ADN and RID applicable within the EU
- Regulation (EU) No. 134/2014
- Regulation of road transportation of dangerous goods, 1. July 2009

Scenario 5 - Mobility in confined space: refuelling stations

- Planning and Building Act (2008). [Plan og bygningsloven]
- Control of Major Accident Hazards Involving Dangerous Substances, Regulation, 2016
- Fire and Explosion Prevention Act [Brann– og eksplosjonsvernloven]
- Regulation on handling of inflammable, reactive and pressurised substances, and equipment and facilities used in the handling of such substances [Forskrift om håndtering av brannfarlig, reaksjonsfarlig og trykksatt stoff, samt utstyr og anlegg som benyttes ved håndteringen]
- National Guidelines, tapping of dangerous substances [Temaveiledning om omtapping av farlig stoff, last updated September 2016

Scenario 1 – Production

Centralised production of hydrogen needs a land use plan and a corresponding land use permit, both of which are the responsibility of the municipality. Hydrogen production facilities are treated in the same way as facilities which manufacture flammable substances.

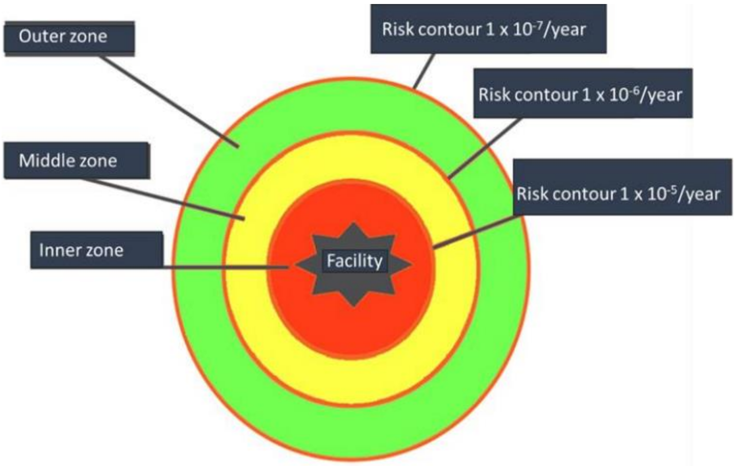
The permit for building a hydrogen facility is governed by the Norwegian Planning and Building Act (Government of Norway, 2008[74])[123] and is granted by the competent municipal authority.

The Municipality may also enlist the services of other departments such as fire safety, occupational safety etc. Once the building is constructed, an operations permit is granted for actual production to start. This too is granted by the municipality. The permit is granted in less than a year with statutorily fixed maximum response times.

For facilities handling dangerous substances a risk assessment will be required to document risk contours for land-planning purposes.[124] An example of risk-based assessment for hydrogen production-land use plan can be found in Figure 10.2.

- Areas with annual individual fatality risk higher than 1x10^{-5} would be defined as an inner zone to be controlled by the company for land planning purposes. This area should normally be kept within the property limits and fenced to prevent unauthorised access.
- Beyond the inner zone a middle zone with annual fatality risk higher than 1x10^{-6} should be defined, within which e.g., no private homes, shops or hotels would be accepted. Public roads and industry/offices will however be acceptable.
- Outside the middle zone an outer zone with individual fatality risk above 1x10^{-7} should be defined, here private homes, shops and smaller guest houses will be accepted. Particularly vulnerable objects (kindergartens, schools, hospitals, larger arenas, shopping malls and hotels etc.) should be outside this outer zone. In addition to the individual risk criteria the ALARP (As Low as Reasonably Practicable) principle also applies, i.e. that the risk shall be reduced to the lowest level that with reasonable effort can be achieved.

Figure 10.2. Illustration of tolerable fatality risk for various zones



Source:
https://static1.squarespace.com/static/5d1c6c223c9d400001e2f407/t/5eb553d755f94d75be877403/1588941832379/Report+D.3+Safety+and+regulations+Lloyds+Register.pdf, p. 41.

All three steps related to land use, building and operation permit are handled by a single authority and therefore there is less need for coordination or risk of duplicity of processes. The required environment impact assessment, risk and safety assessment are integrated within these three steps, and it is the municipalities who have to coordinate with other agencies if they so require. However, the permit system is handled by individual municipalities and there is a likelihood of different interpretation of requirements. This is because each municipality has the freedom to enlist the services of other departments. Secondly, each municipality has its own infrastructure and resource constraints. This could mean different standards of documentation and assessments especially when the facility is located in a densely crowded area.

For tank storage up to 5 t, details on tank placements, operational activities, and information about the tanks being used for storage and about the pipeline system need to be provided to the municipality. When a plant stores more than 5 t of hydrogen, the Major Accidents Regulation applies and a special consent from DSB is needed. Small volumes of hydrogen up to 55 litres may be stored in private homes and up to 10 litres may be stored in garden and boat houses and garages.

The ATEX (European Commission, n.d.[75])[125] regulation and national guidelines on production and treatment of flammable, reactive and pressurised substances require a zone map to be prepared. Depending on the risk assessment, restrictions on the use of adjacent spaces- such as construction of schools, hospitals, kindergartens, may be imposed. The National Guideline also elaborates on preventive safety requirements such as ventilation. There is also an obligation to exchange information on emergency plans with neighbouring enterprises.

For localised production all the requirements and permits as for centralised production are applicable. However, if a localised production unit produces under 100 kg of hydrogen in a year, they are exempted from declaration/ notification of the activity.

Scenario 2 – Transport pipelines

Possibilities for mixing hydrogen into natural gas, to use pipeline networks intended for natural gas transportation, are being looked at. This will make it possible to use the huge European natural gas network to store and transport hydrogen. Transportation of hydrogen through road is governed by the Norwegian Public Roads Administration which is a national authority through its national regulation (Government of Norway, 2009[76]).[126] However, there is no evidence of earmarked routes for hydrogen transport. The restrictions related to tunnel transport are the same as those applicable for Germany (see Section 1.4.) and are governed by ADR.[127]

Scenario 3 and 4 – Road transport and mobility and partially confined spaces: tunnels

Currently, cars, buses, motorcycles, bikes, and quadricycles powered by hydrogen are not subject to any additional burdens as opposed to conventional vehicles. For instance, hydrogen powered cars and bikes can be driven inside a tunnel without restrictions. The same is true for parking in underground and closed parking spaces, transportation inside ferries etc. While all such vehicles are classified as hydrogen internal combustion vehicles and FCV, the approval process remains the same as those applicable for conventional fuel vehicles. However, specific test requirements as specified under Regulation (EU) No. 134/2014 exist.

The approval of cars, buses, trucks etc. is carried out by the Directorate of Public Roads. The specific approval of individual vehicles is carried out by the Norwegian Public Roads Administration through its local traffic offices or registered car dealers.

The DSB has also issued a document for practical applicability of hydrogen road transport.[128] For example, one tunnel, the Hvaler tunnel, is closed each time a hydrogen transport vehicle has to pass through. However, it must be noted that the Hvaler tunnel is subsea and runs 3.7 kms long. There are no restrictions on transport over bridges.

Scenario 5 – Mobility and partially confined spaces: refuelling stations

The individual municipalities are responsible for issuing permits related to land use, building and operation of refuelling stations. The DSB has to be notified before the development of the project. In case the HRS is designed to store more than 400 litres of hydrogen, a special permission from DSB is needed.

Environmental impact assessments are integrated in the permit system and the Pollution Prevention Act places an obligation to inform the municipality of subsurface fuel tanks. The applicable regulation is the Norwegian Planning and Building Act. The local fire department and the Norwegian Public Roads department may also assist the municipality in the permit issuance process.

The operator/applicant must document that they have the necessary competence. It is also necessary to provide a map, spatial plan, documentation on spatial limitations, drawings, description, specifications, procedures, risk assessment, mounting instructions, control arrangements, area classification, explosion prevention document, etc.

The local neighbourhood needs to be informed of the installation of a refuelling station. In addition to this, special requirements can be added related to noise and danger zones, agricultural, and reindeer herding protection. There are no limitations to the areas where HRS facilities can be installed even when there is an onsite production facility.

However, the application process is scrutinised more carefully when the perceived risk is higher. A risk assessment shall include systematic mapping of hazards and unwanted events. The level of detail depends on the individual fuel station, its size, complexity, and the neighbouring conditions. Safety distance depends on the tank size. HRS facilities are regulated much the same way as LNG and LPG facilities.

For operation permit, it is necessary to document operator competence, and control/inspection before and during installation. Final control is to be carried out by an independent inspector and is required for the final documentation. This shall include the final inspection report, land disposal plan, any spatial restrictions, and any special requirements to be included in the final operation permit. This documentation will, finally, be submitted to the municipal plan and building authority, which may provide a final or temporary/conditional permit to operate the HRS.

Tankers carrying hydrogen for refilling HRS should have enough space to drive away unhindered and without the need for additional manoeuvres in case of emergencies. The safety distance from traffic and buildings is a minimum of 5 metres for permanent stations and minimum of 12 metres for mobile stations.

Scenario 6 – Domestic use

Current regulations do not support hydrogen for domestic use.

The Republic of Korea

According to Korea's Hydrogen Economy Roadmap (Korean Ministry of Trade, 2019[77]),[129] the main focus of the hydrogen agenda is the transportation and electricity sectors, which is in line with the country's competitiveness in FCEVs and stationary fuel cells. Thus, the Hydrogen Law adopted to ensure the Roadmap's implementation (one of the first H_2 dedicated laws in the world) provides for licensing and a certification framework as well as safety arrangements with respect to manufacturing hydrogen products (fuel cells production). At the same time, the Korean Green New Deal and the Hydrogen Law support the development of other H_2 innovative technologies as well as H_2 utilisation.

General legal framework for hydrogen

Korean hydrogen law designated the Korea Standards Association (KSA) as the central organisation to certify fuel cell and other hydrogen final products technologies. However, the certification of the hydrogen production technologies still remains with the Korea Gas Safety Corporation (KGS) which is the central government authority that tests and certifies high-pressure gas equipment. Currently there is no specific law that regulates the certification of hydrogen production and handling equipment such as SMRs and compressors, storage tanks, etc. Instead, the 'High-pressure Gas Safety Law (HPGSA)' is temporarily applied for the certification of this equipment. KGS and MOTIE are currently working on the Hydrogen Safety Act which is expected to be announced soon. According to the HPGSL, all hydrogen-related equipment rated at over 10 bar design pressure is considered high-pressure gas equipment and will need to be certified by KGS. On the other hand, equipment below 10 bar design pressure is considered low-pressure gas equipment. The Korea Occupational Safety and Health Agency (KOSHA) regulates low-pressure gas equipment and fuel cell certification.

The Republic of Korea's legislation for the purposes of this document[130] stems from two areas:

- Korea's strategic plans for hydrogen economy transfer, laid out in Korea's Hydrogen Economy Roadmap and reflected in the Hydrogen Economy Promotion and Hydrogen Safety Act (HEPHSA) (Republic of Korea, 2020[78])[131] where among investment and other hydrogen economy stimulation matters, legal basis for the establishment of safety management tools like hydrogen-related business permits, manufacturing facilities and product inspections as well as completion/ maintenance inspections of hydrogen-powered facilities are laid out. Such measures are augmented by appropriate penalties as well as mandatory insurance coverage.
- And high-pressure gasses safety 4-layers legislation: (1) High Pressure Gas Safety Control Act (HPGSCA) (Republic of Korea, n.d.[79])[132] (scope, terms, definitions), (2) High Pressure Gas Safety Control Act Enforcement Decree (Republic of Korea, n.d.[80])[133] (defining approval procedures), (3) High Pressure Gas Safety Control Act Enforcement Rule (establishment and revision of standards), (4) and detailed technical standards, KGS Codes.

Manufacturing permits and licenses for hydrogen products such as hydrogen production facilities, mobile fuel cells, and fixed fuel cells which are required under the HEPHSA refer to the safety inspections and pre-registration technical opinion of the KGSC, which conducts a technical review and issues a manufacturing licence to domestic hydrogen product manufacturers. The KGSC conducts a technical review and a factory inspection, and then the MOTIE registers the company to manufacture hydrogen products.

No KGS Code, which provide for more specific information on safety measures, is available in the public domain. KGS Codes need to be purchased from Korea Gas Safety Corporation according to the relevance to the subject of interest, including hydrogen.

Authorities and institutions in charge of regulating hydrogen

Coordination of efforts of responsible ministries and local governments as well as overseeing issues related to industry promotion, distribution, and safety is performed by the "Hydrogen Economy Committee," chaired by the Prime Minister.

National level. (Ministry of Trade Industry and Energy, n.d.$_{[81]}$)[134] (MOTIE) is the main executor of the Republic's H2 Agenda supported by other ministries according to the sector (Ministry of Land, Infrastructure and Transport, Ministry of Environment, etc.).

Subordinate level. ((n.a.), n.d.$_{[82]}$) (KGSC),[135] a government testing, inspection, education, and research organisation that is under the control of the MOTIE. KGSC supports integrated solutions for hydrogen safety management including hydrogen safety policies, safety management for hydrogen vehicles, and hydrogen safety training and public relations.

KGSC offers a variety of safety management services including risk management, system management and integrity management. The organisation also assists with manufacture registration, explosive-proof equipment certification, gas product certification and system certification. KGSC seeks to achieve the lowest level of gas accident indicator and implement comprehensive hydrogen safety management measures by 2025.

Existing regulation for the six scenarios

Table 10.24. Lists Korean regulations reviewed

Scenario 1 – Production

- Hydrogen Economy Promotion and Hydrogen Safety Act
- The High-Pressure Gas Safety Act
- Korea Gas Safety Corporation Codes[1]

Scenarios 2 and 3 – Transport pipelines and Road Transport

- Hydrogen Economy Promotion and Hydrogen Safety Act
- The High-Pressure Gas Safety Act

Scenarios 4 and 5 – Mobility and partially confined space: tunnels and refuelling stations

- Hydrogen Economy Promotion and Hydrogen Safety Act
- The High-Pressure Gas Safety Act
- Korea Gas Safety Corporation Codes[1]

Scenario 6 – Domestic use

- Hydrogen Economy Promotion and Hydrogen Safety Act
- Korea Gas Safety Corporation Codes[1]

1. Code for Facilities, Technology, and Inspection for Fuel Vehicles Refuelling by Type of On-Site Hydrogen Production (KGS FP216 2021) and Code for Facilities, Technology and Inspection for Vehicles Refuelling by Type of Compressed Hydrogen Delivery (KGS FP217 2021).

Scenario 1 – Production

The Hydrogen Plan acknowledges that production of hydrogen by electrolysers is not developed in the country yet.[136] However, HEPHSA provides for a range of general terms with regards to hydrogen equipment with enough space to let electrolysers in in the future. HPGSCA also gives general terms, and the electrolyser could fall under the "specified equipment" term.

In any case, production as well as storage of the hydrogen requires going through the permitting procedures prior to the construction and operation of installations and then monitoring during the operation by KGSC. In addition to permitting and licensing, all hydrogen involved producers shall provide for hydrogen safety training and shall have a dedicated Safety Manager on site.

All technical requirements with respect to installation, including layout standard (distances from significant objects), foundation standard, storage facility standards (materials of storage facilities, construction, installation), piping facilities (materials of piping facilities, thickness of piping facilities, etc.), accident prevention facility standards, damage control facilities are provided in KGS Codes (Korea Gas Safety, 2020[83]), (Korea Gas Safety, 2020[84]).

Safety distances

KGS Codes (Korea Gas Safety, 2020[83]), (Korea Gas Safety, 2020[84]) established that the distance from the external surface of a processing facility or storage facility of high-pressure gas to a protected installation (exclusive of protected installations in the business place and in industrial complexes) shall not be less than as specified in Table 10.25 and Table 10.26.

Table 10.25. Classes of protected installations

Class 1 Protected installations	Class 2 Protected installations
• Schools, kindergartens, children's nurseries, playrooms, children's playgrounds, teaching institutes, hospitals (inclusive of clinics), libraries, youth training centres, halls for the aged, markets, public baths, hotels, inns, theatres, churches, and public halls, • Buildings (exclusive of temporary buildings) accommodating people of which total floor area of the independent parts is not less than 1 000 m3. • Wedding halls, funeral service halls, exhibition halls and other similar buildings which can accommodate 300 persons or over, • Children welfare centres or welfare centres for the handicapped which can accommodate no less than 20 persons or over, and • Buildings designated as "designated cultural properties" in accordance with the Cultural Properties Protection Act.	• Houses • Buildings (exclusive of temporary buildings) accommodating people of which total floor area of the actually independent parts is 100 m2 to but not including 1 000 m2

Note: Definition of protected installations according to para 1.3.17 of KGS FP216 2021.

Table 10.26. Safety distances from protected installations

Processing capacity or storage capacity[1]	Class 1 Protected installation (m)	Class 2 Protected installation (m)
10 000 and less	17	12
Over 10 000 to 20 000	21	14
Over 20 000 to 30 000	24	16
Over 30 000 to 40 000	27	18
Over 40 000 to 50 000	30	20

1. Daily processing capacity or storage capacity is m3 for compressed gas and kg for liquefied gas, according to KGS FP216 2021.

Also, there are some safety guidelines on storage of hydrogen in Korea Occupational Safety and Health Agency Technical guidelines for the safety of hydrogen storage facilities D27-2021:[137]

- **The material of storage** containers and piping handling hydrogen must be at least killed steel (Killed carbon) (Nesbitt, 2007[85])[138] Use of killed steel exceeding 50 mm in thickness or low-alloy steel exceeding 38 mm in thickness. Cast iron-based materials should not be used for storage containers and piping.
- Hydrogen storage facilities should be installed in the **location priority,** in the following order:
  - Outdoor installation
    - The outdoor area is surrounded by a roof and up to two walls to protect the facility from rain and snow. The structure of these walls should be explosion-proof walls such as concrete, and the roof should be made of non-combustible materials.
  - Installation in an independent building with ventilation requirements:
    - The exhaust opening of the ventilation system is to be installed at a high position on the roof or exterior wall; the air intake opening of the ventilation system should be installed on the outer wall but at the floor level; the area of the air intake and exhaust openings shall be 0.1 m^2 per 30 m^3 of the indoor volume; the air discharged from the discharge opening is discharged to a safe area in the atmosphere.
  - Installed in **a special room** in the building (capacity of storage container is allowed up to 425 m^3)
  - **Installed in a mixture with other facilities in a general building**, not a special room (only storage containers with a capacity of 85 m^3 or less are allowed)

Regarding the safety distance, the following applies:

- The safety distance from outdoor hydrogen storage facilities according to exposure targets and types should follow based on the capacity of the storage container.
- When a hydrogen storage facility with a capacity of less than 85 m^3 is exposed to other facilities and installed in the same building as other facilities, the following safety measures shall be taken:
  - Installing a ventilation system;
  - Maintaining a safe distance of 6 m from flammable liquids and oxidizing substances;
  - Maintaining a safe distance of 15 m from other combustible gas storage;
  - Maintaining a safe distance of 15 m from the air intake opening of the air compressor and cooling or ventilation equipment, and
  - Providing facilities for preventing falling objects.
- If two or more hydrogen storage facilities with a capacity of 85 m^3 or less are exposed to other facilities and installed in the same building at the same time, in addition to the safety measures in paragraph (2), a safe distance of 15 m between each hydrogen storage facility should be maintained.

Scenario 2 – Transport pipelines

According to the Hydrogen Economy Roadmap, the pipeline as a major transportation means for hydrogen is to be considered in the future. As many articles on the Korean energy system reveal, there is not currently a well-developed pipeline system in general. However, as transportation of hydrogen is regulated by the High-Pressure Gas Safety Control Act, which requires transportation of dangerous gases, including hydrogen, through tube trailers and specialised pipes, the tubes of such trailers and pipes shall be subject to HEPHSA and HPGSCA as well as consequent safety KGS codes.

Scenario 3 – Road transport

According to the Hydrogen Economy Roadmap, the Republic of Korea focuses on utilisation growth of carbon free fuel cell transport including cars/taxes, trucks, trains, ships, with specific numerical targets for years 2030 and 2040. Article 36 of HEPHSA establishes that companies willing to produce hydrogen fuel cells or hydrogen related components must receive approval from the local district authority. There is also a stretch to foreign companies - exporters of hydrogen fuel cell related components (including Korean companies based abroad), which shall register their business with the Ministry of Energy, pursuant to Article 38 of HEPHSA. Thus, safety requirements shall also stem from HPGSCA and consequent safety KGS codes, where relevant.

Scenario 4 – Mobility and partially confined space: tunnels

There is no specific restriction on hydrogen fuel cell vehicles to enter tunnels or other confined places however, as hydrogen fuel cell production is under HEPHSA umbrella thus standards provided in KGSC Code will apply. Also, it should be mentioned that, there is a definite interest from the Republic of Korea academia with respect to this subject (Ryu and Lee, 2021[86]).[139]

Scenario 5 – Mobility and partially confined space: refuelling stations

According to the government's Hydrogen Economy Roadmap announced in 2019, the Republic of Korea plans to install 1.2 thousand hydrogen refuelling stations and produce 6.2 million fuel cell electric vehicles (FCEVs) by 2040. As was mentioned above, cell production as well fuel stations establishment are regulated by state: production cannot be launched without permits and technical compliance whereas fuelling stations can be located only in the places prescribed by The Minister of Trade, Industry and Energy which gives the operator request and receives back an installation plan (the Hydrogen Law).

Also, in addition to safety distances mentioned in the Scenario 1 KGS Codes (Korea Gas Safety, 2020[83]), (Korea Gas Safety, 2020[84])[140] provide for distances from one high-pressure gas facility to another high-pressure gas facility's external surface to be:

- not less than 5 m to a high-pressure gas facility in another combustible gas manufacturing installation.
- not less than 10 m to a high-pressure gas facility in an oxygen manufacturing installation.

A storage facility, processing facility, compressed gas facility or filling facility shall maintain a safety distance not less than 10 m from its external surface to the business place boundary (the boundary of the depot if the business place is installed in a bus depot, or the opposite end if the business place boundary borders on a sea, lake, river, road, etc.). However, in case a protection wall is installed around the processing facility or compressed gas facility, a safety distance not less than 5 m may be maintained.

A filling facility shall maintain a distance not less than 5m to the boundary of a road in conformity to the Road Act.

A storage facility, processing facility, compressed gas facility or filling facility shall maintain a distance not less than 30 m from a railroad.

Performance of gas facilities

Safety of gas facilities' performance is evaluated for its pressure-proof and gas tightness according to standards, provided by KGS Codes FP216 2021, para 2.4.5:

- Piping, tubes, hoses, piping systems, etc. shall undergo gas tightness test at a pressure not less than the normal pressure after their installation and there shall not be any abnormality for them to be able to safely transport high pressure gas.

- High-pressure gas facilities (exclusive of gas cylinders) shall undergo pressure-proof test at a pressure not less than 1.5 times (1.25 times for the case in which it is difficult to perform pressure-proof test with water and the pressure proof test is performed with a gas such as air or nitrogen) the normal pressure and be free of any abnormality.
- High-pressure gas facilities subject to super-high-pressure (the normal pressure of high-pressure gas facilities of which metal part temperature under pressure is -50 ℃ to 350 ℃ inclusive is not less than 98 MPa) and super-high-pressure piping may be tested at a pressure not less than 1.25 times the normal pressure (1.1 times the normal pressure with a gas such as air in case the operating pressure can be sufficiently controlled).
- In the case of the piping of which fluid is high-pressure gas containing hydrogen, the piping shall conform to American Petroleum Institute (API), Recommended Practice 941 to prevent hydrogen attack in its high-temperature operating conditions.
- Accident prevention
- Standards for accident prevention are provided in para 2.6 of KGS Code FP216 2021 and para 2.6 of KGS Code FP217 2021, where the following measures are provided for:

Installation of overpressure safety devices

Overpressure safety devices shall be installed to immediately return the gas pressure to the normal or under when the pressure in a storage facility, processing facility or compressed gas facility exceeds its normal pressure.

Selection of overpressure safety devices

- Safety valves to be installed to prevent the pressure rise of gas or vapor;
- Rupture discs to be installed when installation of safety valves is not appropriate due to abrupt pressure rise, leakage of toxic gas, corrosiveness of fluid or properties of reaction products;
- Relief valves or safety valves to be installed to prevent the pressure rise of liquid in pumps and piping, and
- Automatic pressure controllers (devices which control pressure in high-pressure gas facilities by a method which reduces the amount of gas inflow into the high-pressure gas facilities when their internal pressure exceeds their normal pressure) which can be installed in parallel with safety devices.

Installation locations of overpressure safety devices

- Pressure vessels, etc. of which pressure rise may exceed the design pressure due to internal and external factors;
- Discharge side of compressors (each stage in the case of multistage compressors) or pumps of which pressure rise may exceed their normal pressure due to their closed discharge side;
- Piping in which liquid is shut off by two or more valves and which is in danger of being ruptured due to the thermal expansion of the liquid being heated by an external heating source;
- High-pressure facilities or piping of which pressure rise may exceed the design pressure due to failure in pressure control, abnormal reaction, or closed valves in addition to (1) through (3) above;
- The final stage of a compressor or parts directly subject to the pressure when the pressure exceeds the normal pressure in other gas facilities.

Installation of detection and alarm systems

Gas leak detection and alarm systems shall be installed for filling installations as follows:

- A detection and alarm system shall detect leaked gas, activate the alarm, automatically shut off the gas passage and have the following functions:
    - The alarm shall be automatically activated at a present gas leak in response to the electric signals of the detection elements of contact combustion type sensors, diaphragm galvanic cell sensors, semiconductor sensors or sensors of other types. In this case, detection and alarm systems for combustible gas shall not be activated by cigarette smoke and those for toxic gas not by miscellaneous gases such as cigarette smoke, machinery washing oil gas, kerosene gas, exhaust gas and hydrocarbon gas.
    - The alarm concentration shall not be over 1/4 of the lower explosion limit (LEL) depending on the installation location and ambient temperature. The accuracy tolerance of the detection and alarm system shall not be over ±25% of the alarm concentration set value.
    - The time to be taken from detection to transmission shall not be normally over 30 seconds at a concentration equal to 1.6 times the alarm concentration.
    - The alarm accuracy of a detection and alarm system shall not be degraded even when the voltage fluctuation of the power is ±10 %.
    - The scale of the indicator for combustible gas shall clearly indicate 0 to the LEL. In principle, the detection and alarm system shall continue to sound the alarm even if gas concentration in the atmosphere is changed after the transmission of alarm, and the alarm shall be stopped only when it has been checked or the measures have been taken.

Installation of emergency shutoff devices

Filling installations shall be provided with emergency shutoff devices[141] near filling facilities and in the places distanced by 5 m or more from the filling facilities in accordance with the following standard to effectively shut off gas leakage in emergency cases (Korea Gas Safety, 2020[84]):

A manual emergency shutoff device shall be installed near a filling facility or at a place distanced not less than 5 m from the filling facility. When this device is operated, supply of power and gas to the compressor, pump and filling facility shall be automatically cut off.

In case the emergency shutoff device is operated, or power supply is cut off, the compressor and pump shall be stopped. In this case, only when the compressor and pump are manually operated, they shall be operable.

An automatic valve which can cut off gas supply to the compressor in one of the following cases shall be installed upstream of the compressor:

- The emergency shutoff device is operated;
- The power supply device is out of order;
- The power being supplied to the compressor is cut off, or
- The pressure at the suction of the compressor is dropped to below the set pressure.

A valve which automatically shuts off in one of the following cases shall be installed in the piping between a compressed gas facility and a filling facility:

- The power for the filling facility is cut off, or
- The emergency shutoff device of the filling facility is activated.

Shutoff mechanism and function of emergency shutoff device

The operating power source of an emergency shutoff device[142] shall be hydraulic power, pneumatic power, or electric power (whichever shall be available with an emergency power source in the case of power failure) or a spring depending on the construction of the shutoff valve. The location from which an emergency shutoff device can be operated shall be a location distanced not less than 5 m from the external surface of the relevant storage tank (outside the tank dike if such a dike is installed) and a location safe from massive efflux of liquefied gas. In addition, the location shall be a location from which the relevant shutoff operation can be swiftly carried out depending on the surrounding circumstances (Korea Gas Safety, 2020[84]).

The shutoff mechanism shall be able to shut off the fluid in a simply, firm and swift way.

In case a manufacturer manufactures an emergency shutoff device, or a repairman repairs it, the emergency shutoff device shall undergo the leak test of the valve seat by hydrostatic test in accordance with the standard stipulated in KS B 2304 (General Rules for Inspection of Valves), and the valve seat shall not leak. However, in case the leak test is performed with pneumatic pressure such as air pressure or nitrogen pressure, the leak rate shall not exceed 50 mL×[nominal diameter (mm)/25 mm] (330 ml if 330 mm is exceeded) per minute at a differential pressure of 0.5 MPa to 0.6 MPa.

Indication of opened or closed state of emergency shutoff device

In case a signal lamp, which indicates the opened or closed state of an emergency shutoff device, is to be installed, the installation location shall be the instrument room related to the send-out or transfer operation of the storage tank or a similar location.

Scenario 6 – Domestic use

Hydrogen Economy Roadmap mentioned plans for hydrogen fuel cells to be used for residential purposes. Therefore, all requirements including permitting and technical regulation which applies to fuel cells as well as their refuelling indirectly apply here too. Also, the Korean Ministry of Land, Infrastructure and Transport (MOLIT) announced on December 30, 2019 three cities – Ansan, Ulsan and Jeonju/Wanj – as hosts for hydrogen pilot projects (Yoon, 2019[87]).[143]There are no specific regulations for the use of hydrogen in residential buildings, however, real-time safety management approach is mentioned in the news on numerous occasions (Yoon, 2019[87]).[144]

United Kingdom (England)

England does not have a well-defined legislative framework for hydrogen nor specific policies or regulatory regimes to support hydrogen safety related issues. While the Hydrogen Strategy, published in August 2021, outlines a roadmap of key archetypes and milestones that the government expects to see in terms of the production and use of hydrogen across the 2020s, it suggests that an initial network regulatory framework is not expected to be in place until 2025 at the earliest. Until then, existing rules and regulations are being applied.

This case study is focusing on England. Similar but varied terms apply in Scotland, Northern Ireland, and Wales. The variations between the devolved parts of the United Kingdom are not included in this research.

General legal framework for hydrogen

Hydrogen is expected to have a substantial role in the decarbonised UK energy system over the coming decades. Total UK consumption of hydrogen is anticipated to increase from 0.7 million tonnes (Mt) in 2020 to between 3-19 Mt by 2050 (Dodds et al., 2020[88]).[145]

The importance of hydrogen to the UK's future energy system and industry is reflected in government policy. In November 2020, the UK government published its Ten Point Plan for a Green Industrial Revolution (HM Government, 2020[89]),[146] which proposed a target of having 5 GW of low carbon hydrogen production capacity by 2030 (and 1 GW by 2025). Building on this, one month later, the Energy White Paper set out the UK's strategy for the energy transition over the next decade, which amplified the role that the government predicts for hydrogen to play in its energy mix (HM Government, 2020[90]).[147]

In the same month, Scotland became the first country in the United Kingdom to publish a hydrogen policy statement, setting out Scotland's vision for hydrogen and how to maximise its massive potential. Hydrogen was also included in the Industrial Decarbonisation Plan and the Transport Decarbonisation Plan in early 2021.

In August 2021, the future role of hydrogen was consolidated in the long-awaited and first ever UK Hydrogen Strategy, which reinforced prior commitments but also set forth a roadmap for how these commitments are intended to be achieved over the 2020s (Majumder-Russell, Rihoy and Mitchell, 2021[91]).[148] According to the Strategy the UK Government aims to have:

- An initial network regulatory and legal framework in place between 2025-2027, and
- a long-term network regulatory and legal framework in place between 2028-2030.

There is limited legislation that specifically relates to hydrogen. Instead, hydrogen projects must navigate the existing legislative landscape that applies to gasses more generally. Hydrogen is captured under the definition of "gas" in the Gas Act 1986 (the "Gas Act") and is therefore regulated as part of the gas network *("…any substance in a gaseous state which consists wholly or mainly of- (i) methane, ethane, propane, butane, hydrogen or carbon monoxide; (ii) a mixture of two or more of those gases; or (iii) a combustible mixture of one of more of those gases and air" (Section 48(1) Gas Act 1986))"*. Beyond this, hydrogen falls under non-specific regulatory regimes (like transportation, safety regulations, environmental, permitting).

The Gas Act also confers powers on the Gas and Electricity Markets authority, operating through the Office of Gas and Electricity Markets ("Ofgem"). It follows that Ofgem will be the economic regulator in respect of hydrogen for the UK gas market. Anyone engaging in gas supply, gas shipping or gas transportation, or who participates in the operation of gas interconnectors, or provides smart metering in respect of gas must have a licence to do so under the Gas Act.

The licences include measures relating to the safe operation of the gas network and provisions relating to price controls. Licences also contain provisions in relation to the safe operation of gas networks transporting hydrogen.

An entity wishing to transport hydrogen (or carry out another activity regulated by the Gas Act) through gas pipelines may therefore require a licence and as part of this must demonstrate a credible plan to commence licensed activities and permit a risk assessment to be carried out by Ofgem as part of the process for obtaining the licence.

Further, a gas licensee, and consequently a hydrogen licensee, must also comply with various UK-specific industry codes, such as the Uniform Network Code, the Independent Gas Transporter Uniform Network Code, the Supply Point Administration Agreement, and the Retail Energy Code.

Authorities and institutions in charge of regulating hydrogen

There is no specific regulatory body that has full, or most, ownership of hydrogen regulation. Instead, a number of regulators would have responsibilities depending on the activity in question. The list that follows is not exhaustive (see Table 10.27).

Table 10.27. Regulatory bodies in England

Regulatory body	Role
Local Authority / Town and Country Planning Authority	• Regulates the use of land • Undertakes Environmental Impact Assessment • Usually has the role of the hazardous substance authority in relation to storage
Health & Safety Executive	• Assesses local authority decisions and signs off driver training
UK Vehicle Certification Agency	• Approves hydrogen transport vehicles
Oil and Gas Authority	• Regulates new pipelines and decommissioning
Ofgem	• Regulates the gas network

Existing regulation for the six scenarios

Hydrogen, like other gases, is regulated from a health and safety perspective. The Health and Safety Executive ("HSE") requires compliance with the following regulations (Table 10.28):

Table 10.28. List of regulations applied in the England for existing scenarios

Scenario 1 – Production
• Directive 99/92/EC also known as "ATEX 137" or "ATEX Workplace Directive" • Directive 2014/34/EU (also known as "ATEX 114" or "ATEX Equipment Directive" • Environmental Impact Assessments (EIA) • Town and Country Planning Act • Hazardous Substances Act • COMAH (2015) Regulations
Scenario 2 – Transport pipelines
• Pipeline Safety Regulations (1996) • Gas Safety Management Regulations (GSMR)
Scenario 3 – Road transport
• International Carriage of Dangerous Goods by Road ("ADR") • Pressure Equipment (Safety) Regulations 2016
Scenario 4 – Mobility and partially confined spaces: tunnels
• International Carriage of Dangerous Goods by Road (ADR)
Scenario 5 – Mobility and partially confined spaces: refuelling stations
• Hazardous Substances Act • COMAH (2015) Regulations • Alternative Fuels Infrastructure Regulations 2017
Scenario 6 – Domestic use
• Gas Safety (Management) Regulations 1996 • 1990 Gas Appliance Directive (GAD) 90/396/CCE

Standards

At present, there are no safety standards specifically designed for hydrogen (e.g., general guidance on the safety of hydrogen systems can be found in the International Standard Organisation's Technical Report ISO/TR 15916:2004 or ISO 22734-1:2008, which covers hydrogen generators using the water electrolysis process for industrial and commercial application etc). The same stands for the implementation of standards directly adopted from industrial standards that are, therefore, not totally suitable (e.g., Safety of Set Back distances which are all based on the use of gases, and often gases other than hydrogen).

Scenario 1 – Production

There are almost no abundant natural sources of pure hydrogen in England, which means that it has to be manufactured. The most common hydrogen production route is using steam methane reformation from natural gas (blue hydrogen). Hydrogen can also be produced through electrolysis (green hydrogen) when the electricity comes from renewable sources.

At present an estimated 10-27 TWh of hydrogen is produced in the United Kingdom, mostly for use in the petrochemical sector. There is currently only a very small amount of electrolytic hydrogen production in the United Kingdom, mostly for use in localised transport projects or trials for different uses of hydrogen, such as blending into the gas grid.

There is no legislation that regulates hydrogen in England. The current hydrogen production is subject to European safety rules.

These include a duty within **ATEX** and more specifically within the Directive 99/92/EC (also known as 'ATEX 137' or the ATEX Workplace Directive' that refers to minimum requirements for improving the health and safety protection of workers at risk from explosive atmospheres) and the Directive 2014/34/EU (also known as "ATEX 114" or "the ATEX Equipment Directive" that refers to the equipment and protective systems intended for use in explosive atmospheres).[149] According to the European Directives, the operator or employer should eliminate and reduce risks from explosive and dangerous substances. The EU Directives have been embedded into the UK legal system, and this has been realised through the Dangerous Substances and Explosive Atmosphere Regulations (DSEAR). Thus, despite UK exit from the European Union ATEX regulations are still valid in UK, since they are already part of UK law.

The operator or employer must classify areas where hazardous explosive atmospheres may occur into zones. The classification given to a particular zone, and its size and location, depends on the likelihood of an explosive atmosphere occurring and its persistence if it does. The operator or employer must have a plan on how to deal with accidents, incidents, and emergencies, and provide sufficient instruction and training. Operations must comply with any environmental permit and planning conditions.

Other typical examples of legislation required for hydrogen production include Environmental Impact Assessments (EIA), the Town and Country Planning Act, the Hazardous Substances Act and COMAH (2015) Regulations. The primary regulators are the Health & Safety Executive (HSE), the Environment Agency and relevant local authorities.

The Planning (Hazardous Substances) Regulations 2015 and/or **the Control of Major Accident Hazards Regulations 2015 ("COMAH")** regulate the storage of hydrogen. The Planning (Hazardous Substances) Regulations require that installations storing more than two tonnes of hydrogen require planning consent from the local planning authority.

This is only issued once HSE has reviewed the siting of the facility with respect to neighbouring vulnerable developments such as residential property, schools, hospitals etc. HSE provides three zone maps of the hazard contours around installations which are granted permission.

The local planning authority must use these risk maps when determining whether to allow additional or changed development within the three zones. Depending on the quantities involved. COMAH sets a high bar of requiring operators to take all measures necessary to prevent a major accident and limit consequences for human health and the environment.

The operator must notify HSE of any installation with more than five tonnes of hydrogen. Facilities with more than 50 tonnes must prepare and submit a Safety Report to HSE before the site becomes operational. Operators are required to have in place various strategies, including safety plans, emergency plans and a Major Accident Prevention Policy.

Scenario 2 – Transport pipelines

On the transport side, there is no relevant regulation that specifically addresses hydrogen. Instead, operators must navigate the existing legislative landscape that applies to gases more generally. Pipeline transport is captured under the **Pipeline Safety Regulations (1996) (PSR)** which concerns pipeline integrity.

These regulations set out requirements in respect of pipeline design, construction, installation, operation, maintenance, and decommissioning. For example, pipelines should be equipped with emergency shut down valves and its design should take account of the need for maintenance access. PSR imposes general duties in relation to all relevant pipelines and additional duties with regard to major accident hazard pipelines (e.g., for the gas transportation and distribution network, major accident hazard pipelines are defined as those operating at pressures in excess of 7 bar).

While PSR is principally concerned with pipeline integrity, **Gas Safety Management Regulations (GSMR)** deals with the management of the flow of gas through the network. GSMR requires gas conveyors to prepare a safety case and have it submitted and formally accepted by HSE before conveying gas. The framework for assessing the GSMR safety cases within which the HSE assessors exercise professional judgement is provided by the Gas Safety Assessment Manual (SCAM). The manual includes acceptance criteria and document submission details.

Schematically, if a party plans to transport hydrogen through a pipeline, it requires a transporter licence issued by Ofgem under the Gas Act 1986 (or a shipping licence where the hydrogen is transported through another transporter's pipeline network). The party transporting hydrogen must adhere to pipeline requirements for design, safety systems, construction, installation, operation, maintenance, and decommissioning (Pipeline Safety Regulations 1996) as well as to industry codes (such as the Uniform Network Code, Retail Energy Code and Smart Energy Code), which are binding on operators through conditions of licences issued by Ofgem. Finally, it must also co-operate with its local distributor within the National Transmission System.

Piping should preferably be routed above ground; if underground pipe work is unavoidable, it should be adequately protected against corrosion. The position and route of underground piping should be recorded in the technical documentation to facilitate safe maintenance, inspection, or repair. Underground hydrogen pipelines should not be located beneath electrical power lines. Pipeline should be cleaned before being placed into service using a suitable procedure for the type of containment, which provides a level of cleanliness required by the application.

Scenario 3 – Road transport

At present, hydrogen is transported via road using high pressure gaseous tube trailers and cryogenic liquid cargo trailers. The European Agreement concerning the **International Carriage of Dangerous Goods by Road (“ADR”)** regulates the transport of hydrogen, which is classified as a dangerous good under Annex 5 of the ADR.

The CDG Regulations place general duties on everyone with a role in the carriage of dangerous goods, which includes hydrogen, and specific duties on those in the transport chain, i.e., consignors, carriers, loaders, packers, etc.

These duties cover: classification, packing and tank provisions; consignment procedures including documentation and vehicle marking; construction and testing of packaging, containers, and tanks; carriage, loading, unloading, and handling; vehicle crews, equipment, operation and documentation (including training); and construction and approval of vehicles. Drivers transporting hydrogen must be appropriately trained, and vehicles must meet specifications required for hazardous cargoes.

The **Pressure Equipment (Safety) Regulations 2016** apply to the design and manufacture of tanks, cylinders and tubes used to transport hydrogen. Existing standards need to be revised to allow higher vessel capacities, both in terms of volume and pressure.

Scenario 4 – Mobility and partially confined spaces: tunnels

Hydrogen transport is prohibited through ten road tunnels in England based on its classification under the European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR). Other than that, no hydrogen codes, standards or regulations are designed to cover specifically the safety of hydrogen in confined spaces. Thus, existing legislation and general practices are being borrowed to cover that gap. (e.g., when using hydrogen in confined spaces, the employment of a hydrogen detection system for early detection of leaks is essential to facilitate the activation of alarms, safety operations and, where necessary, the safe evacuation of people) (HySafe, 2009[92]).[150]

Scenario 5 – Mobility and partially confined spaces: refuelling stations

Hydrogen refuelling stations are not specifically targeted nor regulated in England's national legislation. Until specific national safety rules are developed, general rules were being applied, centralised legislation is being followed and local planning approval is required (e.g., hydrogen storage over 2 tonnes will require consent from the Hazardous Substances Authority in accordance with the Planning Regulations. Storage above 5 tonnes (or less if other dangerous substances are stored on-site such as LPG, gasoline, diesel) will transit within the scope of Control of Major Accidents Hazards (COMAH) Regulations and need specific requirements. Also, according to the Alternative Fuels Infrastructure Regulations 2017, connectors for motor vehicles for the refuelling of gaseous hydrogen must comply with the ISO 17268(c) gaseous hydrogen motor vehicle refuelling connection devices standard (HM Government, 2017[93]).

Scenario 6 – Domestic use

In the absence of hydrogen related rules and regulations the following apply:

- **Gas Safety (Management) Regulations 1996** – concerns the flow of gas through the network. Pursuant to the GSMR the concentration of hydrogen that can be injected onto the England gas network and consequently be supplied to domestic homes should be no greater than 0.1% molar volume.
- Currently, tests are being conducting to increase the hydrogen blend to up to 20%. If successful, the regulations will need to be amended to allow for this richer in hydrogen blends (HSE, 2007[94]).[151]
- Similar restraints apply for all appliances sold after 1993 that must comply with the 1990 Gas Appliance Directive (GAD) 90/396/CCE, which demonstrates that they can operate on a wider range of gas quality than specified in the GSMR and specifies a gas composition of 23% hydrogen.

United States

The United States does not currently have a comprehensive centralised hydrogen regulatory regime. Regulations referring to flammable gases are applicable. What is more, enforcement of codes and standards is extremely decentralised since they vary from jurisdiction to jurisdiction and are difficult to coordinate or synchronise. Some standards are also old and obsolete. DoE and the US industry recognise that there is a lack of appropriate regulations and standards, and that further research and development is necessary to fulfil the US government's ambitious hydrogen plans. Nevertheless, there are some key U.S. documents for hydrogen safety that provide the necessary fundamental safeguards, most notably NFPA 2, also known as the Hydrogen Technologies Code (2023) and the California Fire Code (2019).

General legal framework for hydrogen

The United States does not currently have a comprehensive centralised hydrogen regulatory regime. Disparate regulations, which mostly generally refer to flammable gases, are scattered throughout the Code of Federal Regulations (CFR). Most of them are part of the Hazardous Materials Regulation (49 CFR, 100-185). Decisions about which standards are most appropriate for government use are left to the discretion of individual entities, including city, county, and state governments and port and tunnel authorities.

Agencies can use externally developed standards in a wide variety of ways, including adoption (by incorporating the standard in an agency's regulation or by listing or referencing it by title), strong deference, basis for rulemaking, regulatory guides, guidelines (advisory only), deference in lieu of developing a mandatory standard (ISO, n.d.[95]).[152]

Authorities and institutions in charge of regulating hydrogen

The main institutions responsible for hydrogen safety on a federal level are:

- the Occupational Safety and Health Administration (OSHA),
- the Department of Transportation (DoT) and its operation administrations, especially the Pipeline and Hazardous Materials Safety Administration (PHMSA).

Existing regulation for the six scenarios

Table 10.29. List of hydrogen standards and regulations in the United States

Scenario 1 – Production	
Regulations • OSHA 29 CFR 1910.103: Hydrogen • OSHA 29 CFR 1910.119: Process safety management of highly hazardous chemicals • OSHA 40 CFR Part 98 Subpart P- Hydrogen production	Important codes and standards • ASME B31.12: Hydrogen piping and pipelines • NFPA 2: Hydrogen Technologies Code • NFPA 55: Compressed gas and cryogenic fluids code. • CGA H-Series: Hydrogen components and systems • CGA S 1.1-1.3: Pressure relief device standards
Scenario 2 – Transport pipelines	
Regulations • PHMSA 49 CFR 192: Transportation of natural and other gas by pipeline: minimum federal safety standards • PHMSA 49 CFR 195: Transportation of hazardous liquids by pipeline	Important codes and standards • ASME B31.12: Hydrogen piping and pipelines

- USCG 33 CFR 154: Facilities transferring oil or hazardous material in bulk	
Scenarios 3 and 4 – Road transport and Mobility and partially confined spaces: tunnels	
Regulations - PHMSA 49 CFR 172: Hazardous materials table, special provisions, hazardous materials communications, emergency response information, training requirements and security plans - PHMSA 49 CFR 173: Shippers – General requirements for shipments and packagings - PHMSA 49 CFR 177: Carriage by public highway	Important Codes and Standards: - CSA/ANSI HGV 2-2021: Compressed Hydrogen Gas Vehicle Fuel Containers - SAE J2578_201408: Recommended Practice for General Fuel Cell Vehicle Safety - SAE J2579_201806: Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles
Scenario 5 – Mobility and partially confined spaces: refuelling stations	
Regulations - OSHA 29 CFR 1910.103: hydrogen	- ASME B31.12: Hydrogen piping and pipelines - NFPA 2: Hydrogen Technologies Code - SAE J2600_201510: Compressed Hydrogen Surface Vehicle Fuelling Connection Devices - SAE J2601_202005 Fuelling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

Scenario 1 – Production

Regulations by OSHA are included in the Code of Federal Regulations and are therefore legally enforceable throughout the United States. On the other hand, standards such as those issued by the NFPA (National Fire Protection Association) are widely adopted by authority-having jurisdictions (such as state governments). When any standards are cited in legal documents issued by jurisdictions, they become legally enforceable. Different states can choose to adopt different standards which massively complicates the regulatory landscape.

Widely adopted standards, such as NFPA 2, are mostly coherent with federal regulations. This is the case with most of the standards that will be mentioned in this document. Usually, an OSHA regulation presents more general guidelines while a code or standard goes into greater depth.

Generally, in regard to hydrogen production, NFPA 2 is the most complete source for guidelines.

For ventilation, one of the following should be applied:

- in adherence to NFPA 2. 6.18 an exhaust point must be placed within 305 mm from the ceiling. Inlet air openings can also be installed below this threshold level. These inlets should be designed to prevent blockage or designed to detect and react to that blockage. Both inlets and exhausts should be designed so as to provide air movement across the room or area and prevent the accumulation of hydrogen, and
- the discharge should be terminating at a point outdoors not less than 9.1 m from opening line, 3 m from operable openings into buildings, 1.8 m from exterior walls and roofs, 9.1 m from combustible walls and operable openings into buildings that are in the direction of the discharge and 3 m above adjoining grade.

Or

- ventilation that ensures average hydrogen levels below 25% LFL (based on the maximum anticipated hydrogen leak as determined by the manufacturer’s installation instructions).

A hydrogen detection system to initiate ventilation at 10% LFL should also be in place.

An explanatory NFPA 2 annex for informational purposes suggests that a gas detector should be mounted a foot or more below the ceiling because of the elevated temperatures at the ceiling. It should face the potential release point but also give consideration to the effect that ventilation would have on air flow. They should not be located in any structural entrapments. At least annual tests of gas detector systems should take place. Also, records for maintenance, inspection, calibration and testing should be kept for 3 years.

For indoor systems of less than 141.6 Nm^3 in a ventilated area, there should be:

- a minimum distance of 7.6 m from sources of ignition
- a minimum distance of 15 m from intakes of ventilation, air conditioning equipment and air compressors, and
- a minimum distance of 15 m from other flammable gas storage (NFPA, 2020[96]).[153]

More than one system of 141.6 Nm^3 or less can be installed in the same room or area, provided that the systems are separated by at least 15 m or a full-height fire-resistive partition with a minimum fire resistance rating of 2 hrs. If oxygen is released inside the room or area, there should be sufficient ventilation to prevent oxygen atmospheres exceeding 23.5%. Distances for compressed outdoor hydrogen systems (of less than 141.6 Nm^3) are presented below (NFPA, 2020[96]):[154]

Table 10.30. Distances for compressed outdoor hydrogen systems (of less than 141.6 Nm3)

Maximum amount per storage area (m^3 approx. *[converted from ft^3]*)	Minimum distance between storage areas (m)	Minimum distance to public streets, public alleys, or public ways, lot lines of property that can be built upon (m)
0-1 287	1.5	1.5
1 288-6 439	3	3
6 440-15 453	3	4.5
15 453-25 755	3	6
25 756-60 960	6	7.6

NFPA 2 also lists safety distances from outdoor bulk compressed hydrogen systems (larger than 141.6 Nm^3) for three separate groups of exposures:

- Group 1: lot lines, air intakes (HVAC, compressors et al.), openings in buildings and structures, ignition sources;
- Group 2: exposed persons and parked cars, and
- Group 3: buildings (of combustible or non-combustible construction), flammable gas, or hazardous materials storage systems, combustible solids, unopenable openings, Encroachment by overhead utilities, piping containing other hazardous materials, flammable gas metering and regulating stations.

The American Society of Mechanical Engineers provides standards for piping. B31.12 is the standard addressing hydrogen piping. It includes general requirements (for materials, welding, brazing etc.), standards for piping (requirements for components, design, erection etc.) and standards for pipelines (components, design, installation, and testing) (ASME, 2020[97]). Mechanical exhaust or fixed natural ventilation should be provided at a rate of not less than 0.0051 m^3/sec.

NFPA requires an emergency shutdown system for both gaseous and liquefied hydrogen systems.

All fuel cell equipment, compressors, hydrogen generators, electrical distribution equipment and similar appliances must be separated from GH2 storage areas within the hydrogen equipment enclosure by a one-hour rated barrier that also has to be capable of preventing gas transmission (NFPA, 2020[96]).[155]

There are parts of NFPA 2 that are currently reserved for new requirements or a future revision of the standard. This is the case for chapter 9, which deals with explosion protection (NFPA, 2020[98]).[156]

Scenario 2 – Transport pipelines

At the federal level, the Pipeline and Hazardous Materials Safety Administration (PHMSA) sets minimum safety requirements for pipeline facilities and the transportation of gas. PHMSA is the legal authority enforcing requirements for pipelines throughout US territory (via its Office of Pipeline Safety, OPS).

The pipelines' oversight includes inspections. Intrastate pipelines are regulated through either the state agencies or the OPS via an agreement with the state. A database named National Pipeline Mapping System (NPMS) includes locations and information regarding gas transmission under the jurisdiction of the PHMSA. The data is used by PHMSA for emergency response and pipeline inspections (NPMS, n.d.[99]).[157]

49 CFR 171 to 179 regulate the transport of hazardous materials in commerce. 49 CFR 192, which regulates the transport of flammable gas in pipelines, is used for regulating hydrogen pipelines in the US. The agency can delegate authority over to state regulators for those sections of interstate pipelines within their boundaries.

The agency has published protocols, regulatory orders, and guidance manuals and relies on a range of enforcement actions, including corrective action orders and civil penalties. However, the primary focus of most of these regulations is natural gas, so certain characteristics of hydrogen were not fully contemplated in their design.

PHMSA is currently conducting research to determine the effect of hydrogen on steel pipelines, since corrosion is one of the areas of concern regarding the use of the already existing natural gas pipeline infrastructure.

The PHMSA set areas of *high consequence* based on their "class location unit": the class location unit is an onshore area that extends 220 yards (200 m) on either side of the centreline of any continuous 1-mile (1.6 km) length of pipeline. Notably classes 3 and 4 are considered to be of "high consequence".

- Class 1:
- An offshore area; or
- any class location unit that has 10 or fewer buildings intended for human occupancy.
- Class 2: any class location unit that has more than 10 but fewer than 46 buildings intended for human occupancy.
- Class 3:
  - Any class location unit that has 46 or more buildings intended for human occupancy; or
  - An area where the pipeline lies within 100 yards (91 m) of either a building or a small, well-defined outside area (such as a playground, recreation area, outdoor theatre, or other place of public assembly) that is occupied by 20 or more persons on at least 5 days a week for 10 weeks in any 12-month period. (The days and weeks need not be consecutive.)
- Class 4: any class location unit where buildings with four or more stories above ground are prevalent.

Areas categorised in classes 3 or 4 should be subject to leakage surveys of the transmission line, conducted at intervals not exceeding 15 months, but at least once each calendar year. Buried transmission line must be installed with a minimum cover as follows:

Table 10.31. A minimum cover for buried transmission line

Location	Normal soil (mm)	Consolidated rock (mm)
Class 1	762	457
Class 2, 3, or 4	914	610
Drainage ditches of public roads and railroad crossings	914	610

Each buried main line must be installed with at least 610 mm of cover.

PHMSA regulation demands from operators to take additional measures beyond those required by Part 192 to prevent a pipeline from failing and to mitigate the consequences of a pipeline failure.

Such additional measures include:

- installing Automatic Shut-off Valves or Remote-Control Valves,
- installing computerised monitoring and leak detection systems,
- replacing pipe segments with pipe of heavier wall thickness,
- providing additional training to personnel on response procedures,
- conducting drills with local emergency responders and implementing additional inspection and maintenance programmes.

Combustible gases in the distribution line must contain natural odorants or be odorised so that at a concentration in air of one-fifth of the lower explosive limit, the gas can be readily detectable. This is not necessary if the hydrogen is intended for use as a feedstock in a manufacturing process.

The American Society of Mechanical Engineers also provides standards for piping and transportation pipelines.

B31.12 is the standard governing hydrogen piping. It includes general requirements (for materials, welding, brazing et al.), standards for piping (requirements for components, design, erection et al.) and standards for pipelines (components, design, installation, and testing) (ASME, 2020[100]).[158]

ASME B31.12 requires a full weld joint penetration for stub-on and stub-in branches. The code also prohibits the use of piping joints associated with materials not permitted by B31.12 such as caulked, soldered, bell and gland and plastic joints.

The code also guides to avoid the use of nickel-based alloys.

An 80ºC (175ºF) preheat is mandatory for carbon steel for any thickness.

B31.12 also requires that a radiography or ultrasonic testing be performed after post-weld heat treatment for low alloy steels (Kumar Dey, 2021[101]).[159]

Almost all existing hydrogen pipelines in the United States are associated with industrial facilities such as oil refineries or chemical plants. They operate at constant, relatively low pressure, 500-1200 psi (3.4-8.27 MPa). Transmission pipelines within the U.S. natural gas system typically operate at pressures of 200–1500 psi (1.37-10.34 MPa) (U.S. Department of Energy, 2013[102]).[160]

The ASME B31.12 code considers pressures up to 15 000 psi (103.4 MPa) for many piping materials although the code's maximum allowable hydrogen pipeline pressure is currently only 3 000 psi (20.68 MPa) (according to its 2015 edition) (Penev, Zuboy and Hunter, 2019[103]). It is noted that each pipeline must have pressure relieving or pressure limiting devices.

Scenario 3 – Road transport

Standards related to the transportation of hazardous materials include PHMSA 49 CFR 172, which lists hazardous materials and prescribes requirements for shipping papers, package marking, labeling and transport vehicles placarding applicable for their transportation. T75 and TP5 codes in 49 CFR Part 172 are applicable to portable tanks and fill rate of liquid hydrogen tankers. 49 CFR Part 173 includes specific requirements for the use of insulated cargo tanks for cryogenic hydrogen transportation and bulk cylinders for compressed, non-cryogenic hydrogen. Additionally, 49 CFR Part 177 lists loading and unloading practices. 49 CFR Part 178 includes details on the design and approval of shipping containers including cylinders and tanks.

The National Highway Traffic Safety Administration issues Federal Motor Vehicle Safety Standards (FMVSS). These are U.S. federal regulations for the design, construction and safety performance of motor vehicles. FMVSS No. 305 “Electric-powered vehicles” was amended in 2017 to include requirements related to new technologies, including hydrogen FCEVs.

CSA/ANSI HGV 2-2021 contains requirements for the material, design, manufacture, marking and testing of serially produced, refillable containers intended only for the storage of compressed hydrogen gas for vehicle operation.

According to the standard, these containers have to be permanently attached to the vehicle, have up to 1 000 litre water capacity and a nominal working pressure that does not exceed 70 MPa (Kelechava, 2021[104]).[161]

Self-contained portable fuel cell power systems have to be designed and tested according to CSA/ANSI F38 or IEC 62282-5-1.

SAE (the Society of Automotive engineers) has more standards that apply to hydrogen vehicles:

- J2578 is the standard for General Fuel Cell Vehicle Safety: It describes a Recommended Practice that identifies requirements relating to the safe integration of the fuel cell system, the hydrogen fuel storage and handling systems (as defined and specified in SAE J2579) and high voltage electrical systems into the fuel cell vehicle. It may also be applied to hydrogen vehicles with internal combustion engines.
- J2579 is the Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles. Its purpose is to define design, operational, and maintenance requirements for hydrogen fuel storage and handling systems in vehicles.
- J1766 lays out the recommended practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing.

Scenario 4 – Mobility and partially confined space: tunnels

No hydrogen-specific regulations related to tunnels have been found. NFPA 502, “Standard for Road Tunnels, Bridges and Other Limited Access Highways”, provides safety requirements and lists hazard mitigation measures such as ventilation, installation of detectors and labelling of alternate fuel vehicles.

Scenario 5 – Mobility and partially confined spaces: refuelling stations

The OSHA standard 29 CFR 1910.103 governs hydrogen systems. It sets safety distances (see Table 10.32) and requirements for inlet and outlet openings (1 ft^2 per 1 000 ft^3 of room volume).[162]

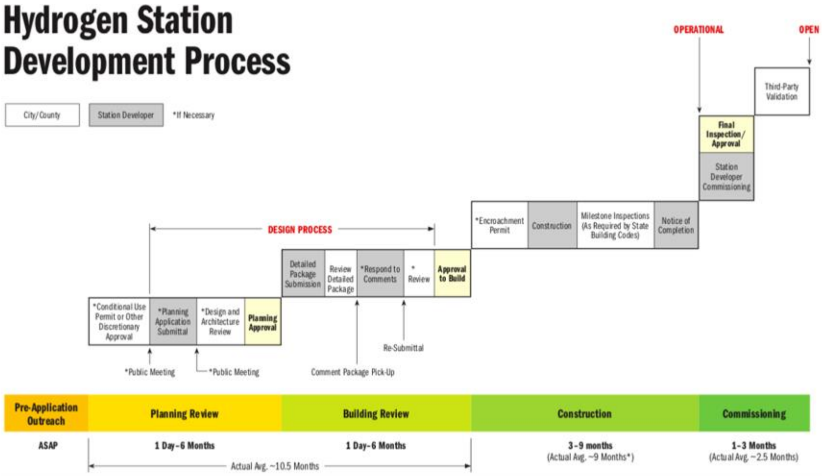
Table 10.32. Safety distances according to size of H2 system

Type of outdoor exposure		Size of H2 System in m^3		
		Less than 3 000 CF (c. 85 m^3)	3 000-15 000 CF (85-425 m^3)	More than 15 000 CF (425 m^3)
Building/structure	Wood frame construction	3	7.5	15
	Heavy timber, non-combustible or ordinary construction	0	3	7.5
Wall openings	Not above the system	3	3	3
	Above the system	7.5	7.5	7.5
Flammable liquids above ground	0 to 3 785 lt (1 000 gallons)	3	7.5	7.5
	In excess of 3 785 lt	7.5	15	15
Flammable liquids below ground (0 to 3785 lt)	Tank	3	3	3
	Vent or fill opening	7.5	7.5	7.5
Flammable liquids below ground (more than 3785 lt)	Tank	6	6	6
	Vent or fill opening	7.5	7.5	7.5
Flammable gas storage	0 to 425 m^3	3	7.5	7.5
	More than 425 m^3	7.5	15	15
Fast burning solids		15	15	15
Slow burning solids		7.5	7.5	7.5
Open flames and other sources of ignition		7.5	7.5	7.5
Air compressor intakes or inlets to ventilating or air-conditioning equipment		15	15	15
Concentration of people		7.5	15	15

There should be an explosion venting area on the exterior walls or roof only (1 ft^2 per 30 ft^3 of room volume). Safety relief devices should discharge upward to the open air, unobstructed and should be designed or located in such a way as to prevent moisture from collecting.

For the development of a hydrogen refuelling station a number of permits are required. The state of California, which is the state with the largest hydrogen refuelling system in the country, has released a hydrogen fuelling station permitting guidebook, which includes a diagram Figure 10.3 with the processes involved along with estimated timelines (California Governor's Office of Business and Economic Development, 2020[105]).[163]

Figure 10.3. Hydrogen station development process



The most comprehensive set of rules for hydrogen refuelling stations can be found in the ((n.a.), 2022[106]).[164] The Code includes requirements for dispensing systems, approved equipment (cylinder, containers, tanks, pressure relief devices, including pressure valves, hydrogen vaporisers, pressure regulators, hoses, hose connections, compressors, hydrogen generators, dispensers, detection systems and electrical equipment). Other requirements are as follows:

- Dispensing systems shall be equipped with an overpressure protection device set at 140 percent of the service pressure of the fuelling nozzle it supplies.
- The vehicle shall be fuelled on non-coated concrete or other *approved* paving material having a resistance not exceeding 1 megohm.
- Fuel-dispensing areas under canopies shall be equipped with an approved automatic sprinkler system. Operation of the automatic sprinkler system shall activate an automatic emergency discharge system, which will discharge the hydrogen gas from the equipment on the canopy top through the vent pipe system. Operation of the automatic sprinkler system shall activate an emergency shutdown control.
- A manual emergency shutoff valve shall be provided to shut down the flow of gas from the hydrogen supply to the piping system. In addition, a remotely located, manually activated emergency shutdown control shall be provided. This shall be located within 75 feet (22.86 m) of, but not less than 25 feet (7.62 m) from, dispensers and hydrogen generators. Activation of the emergency shutdown control shall automatically shut off the power supply to all hydrogen storage, compression, and dispensing equipment, shut off natural gas or other fuel supply to the hydrogen generator, and close valves between the main supply and the compressor and between the storage containers and dispensing equipment.

A documented procedure that explains the logic sequence for defueling or discharging shall be maintained on site and provided to a fire code official upon request. The procedure shall list the actions that the operator is required to take in the event of a low-pressure or high-pressure hydrogen release during discharging.

Other key codes and standards concerning the development and operation of a hydrogen refuelling station are:

- ASME B31 Pressure Piping and ASME Boiler & Pressure Vessel Code are the standards for high pressure equipment and hydrogen storage tanks
- SAE J2600 applies to fuelling connection devices (connectors, dispenser nozzles and receptacles
- SAE J2601 provides fuelling protocols for Light Duty Gaseous Hydrogen Surface Vehicles. They establish protocols for light duty vehicle fuelling applicable for two pressure classes (35 MPa, for vehicles with storage capacity from 2.4 to 6 kg, and 70 MPa, for vehicles with storage capacity from 2 to 10 kg) and three fuel delivery temperatures (-40 °C, -30 °C, -20 °C).

SAE J2601 allows for refuelling using either a look-up table approach, or a formula-based approach, with or without wireless communications between the FCEV and the hydrogen station. The table-based protocol provides a fixed end-of-fill pressure target (based on ambient temperature and initial fuel pressure), whereas the formula-based one calculates the end-of-fill pressure target continuously.

The standard also establishes safety limits for maximum fuel temperature at the dispenser nozzle, maximum fuel flow rate and maximum rate of pressure increase (SAE, 2020[107]).[165]

NFPA 2 chapter 10 is specific to gaseous hydrogen vehicle fueling facilities and includes requirements regarding the fuel dispenser.

In addition, NFPA 2 distances for outdoor bulk hydrogen distances (see above) are used to calculate separation distances from a hydrogen refuelling station.

Scenario 6 – Domestic use

There are no regulations specifically targeting the domestic use of hydrogen in the United States. Such use is however not prohibited as can be seen by the existence of small-scale pilot projects such as Hydrogen House. The design and completion of Hydrogen House, a solar-hydrogen residence in New Jersey, was accepted by local residential building regulations. The House, which is still in operation, is outfitted with modern equipment including high pressure hydrogen gas tanks and a high-pressure electrolyser (2 000-6 000 psi).

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Yoon, J. (2019), *Ulsan Ministry of Land, Infrastructure, and Hydrogen Demonstration City, Ministry of Industry Hydrogen Convergence Complex Demonstration Project*, http://www.electimes.com/news/articleView.html?idxno=192199. [87]

Zhao, F. et al. (2020), "Hydrogen fuel cell vehicle development in China: An industry chain perspective", *Energy Technology*, Vol. 8/11, p. 2000179. [8]

Notes

[1] The NGL applies in the ACT, NSW, the NT, Queensland, SA, Tasmania and Victoria. A modified version of the NGL applies in WA, with WA only adopting the economic regulation of pipeline provisions. The WA Bulletin Board and GSOO are established under Gas Services Information Rules made under the Gas Services Information Act 2012 (WA) and Gas Services Information Regulations 2012 (WA), while the regulated retail markets are established under the Energy Coordination Act 1994 (WA).

[2] The customer protection framework as it relates to natural gas is set out in local legislation in Tasmania, Victoria and WA. In the NT, the gas reticulation and retail sale sectors are very small, and there is no specific regulation of the retail sale and supply of natural gas in the NT.

[3] "Australia's first green hydrogen/gas power plant", 2021, retrieved from: https://www.nsw.gov.au/media-releases/australias-first-green-hydrogen-and-gas-power-plant.

[4] 'Hydrogen Fuel Cell Partnership, hydrogen stations', 2022, retrieved from: HYDROGEN STATIONS | H2 Station Maps

[5] 'AGID launches domestic hydrogen appliance in Victoria', 2022, retrieved from: https://www.pipeliner.com.au/2022/07/04/agig-launches-domestic-hydrogen-appliance-in-victoria/.

[6] In Chinese, available at: http://www.gov.cn/premier/2019-03/16/content_5374314.htm.

[7] Handling: manufacturing, distribution by commerce, transportation, storage, use & disposal.

[8] Where hydrogen and fuel cell technnology was assigned as one of the major tasks

[9] Buildings or facilities that supply hydrogen but do not produce hydrogen itself, for example a hydrogen refuelling station which does not have onsite hydrogen producing facilities.

[10] Hydrogen concentration not specified in this standard.

[11] For abnormal input & output pressure, abnormal temperature & pressure of the cooling system.

[12] Hydrogen production, purification, compression, or storage facilities, releasing pipes etc. Horizontal distance of 4.5m from rooms containing (a). A vertical distance of 7.5 m for outdoor production & storage facilities

[13] The number of times that the total air volume in a room or space is completely removed and replaced in an hour.

[14] If the room is less than 100m2 in size, then only one exit (leading to the outside) is required.

[15] A compression test should be performed for tubes transporting gasses such as hydrogen or natural gas. Compression should not cause any cracks.

[16] Average per 3s. Spontaneous concentration should always be less than 8%.

[17] Based on ISO 19880-1 Gaseous Hydrogen-Fuelling Stations: Part 1: General Requirements; SAE J 2601 Fuelling protocols for Light Duty Gaseous Hydrogen Surface Vehicles and Chinese standards such as GB/T 31138-2014 Compressed Hydrogen Dispenser for Vehicles.

[18] Installation Classified for the Protection of the Environment.

[19] https://www.ecologie.gouv.fr/nicolas-hulot-annonce-plan-deploiement-lhydrogene-transition-energetique (see Plan de Déploiement de l'Hydrogène France 2018).

[20] https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000043148001.

[21] Article L. 131-3, 5° of the Environmental Code.

[22] https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000043148001/.

[23] https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000042369361/.

[24] On the one hand, the commercial criterion, an installation whose production will not be marketed could not fall under this heading, for example an installation intended to produce. This is the case, for example, for an installation intended to produce hydrogen for its owner's own needs. On the other hand, the environmental criterion, a small-scale installation producing limited quantities of hydrogen by electrolysis limited quantities of hydrogen by electrolysis and having a minimal impact on the environment and its environment and its resources (water) could, even if the use of the production is commercial, be excluded.

[25] https://aida.ineris.fr/reglementation/4715-hydrogene-numero-cas-133-74-0/.

[26] https://www.legifrance.gouv.fr/codes/section_lc/LEGITEXT000006074220/LEGISCTA000006176596/2021-08-01/.

[27] https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000020879393/2013-01-01/.

[28] https://aida.ineris.fr/reglementation/4715-hydrogene-numero-cas-133-74-0/.

[29] https://www.legifrance.gouv.fr/loda/id/JORFTEXT000020796240/.

[30] https://www.legifrance.gouv.fr/codes/section_lc/LEGITEXT000006072050/LEGISCTA000006160776/#LEGISCTA000006160776/.

[31] Order of 12 February 1998 on the requirements for installations classified for the protection of the environment subject to declaration under heading no. 4715 (https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000571176/).

[32] UNECE, Agreement Concerning the Adoption of Uniform Technical Prescriptions for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of these Prescriptions, 2015 https://unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2015/R134e.pdf.

[33] The Directive was adopted by the European Union in 2014 to streamline processes for improving alternative fuel infrastructure and refuelling. Anchored in this directive, Germany has declared hydrogen as an alternative fuel.

[34] States (a state is "Land") in German are referred to as Länder.

[35] https://www.gesetze-im-internet.de/bbaug/.

[36] https://www.gesetze-im-internet.de/baunvo/.

[37] https://www.umweltbundesamt.de/en/immission-control-law#undefined.

[38] HyLAW online database: https://www.hylaw.eu/.

[39] For instance, TÜV SÜD enables stakeholders to furnish proof that hydrogen produced from regenerative sources has significantly lower levels of greenhouse-gas emissions than conventional hydrogen or fossil fuels. A certificate for generation of green hydrogen can be issued if the hydrogen produced has a greenhouse-gas reduction potential of at least 60 per cent compared to fossil fuels. Going further, green hydrogen produced by electrolysis must have a GHG reduction potential of 75 per cent. The comparison is based on the current reference values set forth in the Renewable Energy Directive II (RED II).

[40] https://www.gesetze-im-internet.de/betrsichv_2015/. The Ordinance is broad in its scope and covers all employers who operate hazardous and high-pressure equipment.

[41] More information on tunnel categorisation can be found here: https://adrbook.com/en/2019/ADR/1.9.5.

[42] https://elaws.e-gov.go.jp/document?lawid=326AC0000000204.

[43] https://elaws.e-gov.go.jp/document?lawid=341M50000400053.

[44] Exemplified Standards are those Circular Notices (Internal Rules) summarised as standards for each ordinance or piece of equipment and provide concrete examples of technical details that satisfy the technical standards specified by each Ministerial Ordinance. Related Exemplified Standards indicate the examples that comply with the technical standard specified by an Ordinance of the ministry, and therefore do not necessitate absolute conformity, but appropriateness judged by the prefectural governor having authority of the permission. The provisions are available (in Japanese) at: https://www.meti.go.jp/policy/safety_security/industrial_safety/sangyo/hipregas/files/20210315_hg_16.pdf.

[45] GHPGSO, Article 2 (xv).

[46] GHPGSO, Article 6 (1)(xxv).

[47] GHPGSO, Article 6 (1)(ix).

[48] GHPGSO, Article 6 (1)(xxxi).

[49] GHPGSO, Article 6 (1)(xxvi).

[50] Exemplified Standards, Article 6.

[51] Regarding the definition of allowable operating pressure, the following response was given by METI on May 22, 2006, and is used as a reference for application. "There is no definition of allowable operating pressure, however, if the normal pressure is not less than the allowable operating, the safety valve will operate, therefore, the allowable operating pressure should not less than the normal pressure."

[52] GHPGSO, Article 6 (1) (xi).

[53] GHPGSO Article 6 (1) (xii).

[54] GHPGSO Article 6 (1) (xiii).

[55] The gauge pressure (where such pressure fluctuates, the highest pressure in the fluctuating range) acting on the equipment concerned under normal conditions of use.

[56] Normal pressure: 82 MPa or less, Normal temperature: -253°C to 120°C or less.

[57] Normal pressure: 82 MPa or less, Normal temperature: -253°C to 120°C or less. Exemplified Standards, Article 9.

[58] HPGSA, Article 5, Enforcement Order of the High-Pressure Gas Safety Law, Article 3.

[59] HPGSA, Article 16 (1), Enforcement Order of the High-Pressure Gas Safety Law, Article 5.

[60] GHPGSO, Article 6 (1).

[61] https://www.khk.or.jp/Portals/0/resources/english/dl/overview_general_hpg_ordinance.pdf, p. 6.

[62] https://www.khk.or.jp/Portals/0/resources/english/dl/overview_general_hpg_ordinance.pdf, p. 6.

[63] Schools, hospitals, theatres, cinemas, department stores, hotels, inns, and other buildings intended to accommodate an unspecified large number of people (General High Pressure Gas Safety Regulations, Article 2 (1) (v)).

[64] Buildings other than Class 1 Protected Properties that are used for residential purposes.

[65] GHPGSO, Article 2 (1)(xix).

[66] Eguchi area, Shunan City (Yamaguchi), Shunan City Local Wholesale Market and Roadside station Sorene Shunan ((Yamaguchi)), Higashida area, Yahatahigashi ward, Kitakyushu City (Fukuoka).

[67] Higashida area, Yahatahigashi ward, Kitakyushu City (Fukuoka).

[68] HPGSA, Article 2.i - See Appendix 2.3.2.

[69] To prevent corrosion due to rainwater splash.

[70] Ibid.

[71] Exemplified Standards, Article 38.

[72] Exemplified Standards, Article 38.

[73] Exemplified Standards, Article 37 (3) iii-ii.

[74] Article 168 of the Enforcement Regulations of the Gas Business Law.

[75] Gas Business Act Enforcement Regulations, Article 1 (2) (iii).

[76] Gas Business Act Enforcement Regulations, Article 1 (2) (ii).

[77] See Scenario 1.

[78] The Ministry of Land, Infrastructure, Transport and Tourism Notice on Traffic Regulation of Vehicles Transporting Hydrogen-fuelled Vehicles on 31 March 2005 (Traffic Regulations of vehicles carrying dangerous goods in accordance with Article 46(3) of the Road Act. (https://www.jehdra.go.jp/pdf/kiken/kiken6_14.pdf).

[79] http://www.cev-pc.or.jp/suiso_station/

[80] Normal pressure: 40 MPa or less.

[81] Normal pressure: 82 MPa or less, Normal temperature: -253°C to 120°C or less.

[82] Normal pressure: 82 MPa or less, Normal temperature: -253°C to 120°C or less.

[83] Normal pressure: 25 MPa or less, Normal temperature: -40°C to 100°C or less. Exemplified Standards, Article 9.

[84] GHPGSO, Article 7-3.

[85] GHPGSO, Article 7-3 (2)(xxiv).

[86] Exemplified Standards, Article 6.

[87] GHPGSO, Article 7-3 (2)(xviii).

[88] GHPGSO, Article 6(1)(vii), Exemplified Standards, Article 5.

[89] Fixed devices capable of sprinkling water by means of perforated pipes or pipes with sprinkler nozzles.

[90] GHPGSO, Article 6 (1) (xxxii).

[91] GHPGSO, Article 7-3 (2)(xix).

[92] GHPGSO, Article 7-3 (2)(xii).

[93] GHPGSO, Article 7-3 (2)(x).

[94] GHPGSO, Article 6 (1)(xix).

[95] GHPGSO, Article 7-3 (2)(xxii).

[96] GHPGSO, Article 7-3 (2)(vi).

[97] Exemplified Standards, Article 58.

[98] Exemplified Standards, Article 22.

[99] Ministry of Economy, Trade and Industry of Japan, https://www.meti.go.jp/policy/safety_security/industrial_safety/sangyo/hipregas/hourei/20210518_hg_01.pdf, p45.

[100] GHPGSO, Article 8-2 (1)(iii).

[101] The Fire Prevention Ordinance of the Fire Service Act, Article 8-3.

[102] The Electricity Business Law, Article 39, Ministerial Ordinance Establishing Technical Standards for Electrical Equipment.

[103] The Electricity Business Law, Article 42.

[104] The Electricity Business Law, Article 43.

[105] The Electricity Business Law, Article 48.

[106] t: Minimum thickness of pipe (unit: mm), D: Outer diameter of the pipe (unit: mm), P: Design pressure (pressure designed as the maximum pressure at which the pipe can be used) (unit: MPa) (unit: MPa), a: Permissible tensile stress of the material, n: Welding efficiency.

[107] Ibid.

[108] Exemplified Standards, Article 7.

[109] https://www.acm.nl/nl/publicaties/acm-stelt-kader-op-om-pilotprojecten-met-waterstof-mogelijk-te-maken.

[110] https://www.sodm.nl/actueel/nieuws/2022/11/01/nieuwe-taak-voor-sodm-toezicht-op-de-veiligheid-bij-experimenten-distributie-waterstof-naar-woningen.

[111] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:subsidiarity.

[112] https://www.navigator.nl/thema/1102/omgevingsdiensten.

[113] http://www.inspectieszw.nl/inspectie-szw

[114] https://www.rijksoverheid.nl/onderwerpen/veiligheidsregios-en-crisisbeheersing/veiligheidsregios.

[115] https://nick.groenen.me/notes/safety-regions-in-the-nederlands/.

[116] https://www.nen.nl/nen-en-17124-2020-ontw-en-276582.

[117] Delpierre, Mathieu et al. "Assessing The Environmental Impacts Of Wind-Based Hydrogen Production In The Netherlands Using Ex-Ante LCA And Scenarios Analysis". Journal Of Cleaner Production, vol 299, 2021, p. 126866. Elsevier BV, https://doi.org/10.1016/j.jclepro.2021.126866.

[118] Prolonged processes.

[119] https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/netherlands.

[120] https://www.iso.org/obp/ui/#iso:std:iso:23876:dis:ed-1:v1:en.

[121] https://unece.org/about-adr.

[122] However, it should be noted that all hydrogen vehicles must meet the *UN GTR No. 13 – Global Technical Regulation concerning the hydrogen and fuel cell vehicles* requirements to get a license plate.

[123] Act of 27 June 2008 No. 71 relating to Planning and the Processing of Building Applications (the Planning and Building Act) (the Planning part).

[124] The Lloyd’s Register using the TNO Green Book for sourcing vulnerability criteria summarised a report for DSB (Norwegian Directorate for Civil Protection) to describe vulnerability criteria for various hazards. Vulnerability means the vulnerability of people to exposure to hazards like cryogenic loads, toxicity, flames, radiation, explosion pressures and impact from failing structures’ projectiles.

[125] https://ec.europa.eu/growth/sectors/mechanical-engineering/equipment-potentially-explosive-atmospheres-atex_en#modal.

[126] Regulation of road transportation of dangerous goods, 1. July 2009.

[127] The national regulation of 2009 has been revised and includes, implements the requirements of the ADR/RID Directive. However, ADR and RID do not apply to a) transport of dangerous goods that solely takes place within a restricted area, b) transport of dangerous substances on mobile vehicles in cases where the substance is used by the mobile vehicle, c) military, police, and customs authorities' transport of certain dangerous substances, for certain specified purposes.

[128] This document, issued by the Directorate for Civil Protection (DSB) spells out the ADR/RID Directive in detail in Norwegian language, and includes guidelines on the practical implications.

[129] The Korean Ministry of Trade, Industry and Economy (MOTIE) published its Hydrogen Economy Roadmap on 17 January 2019. Korea's vision in the roadmap is to become a leading country in the new global hydrogen economy with the support of two pillars: fuel cell electric vehicles (FCEVs) and fuel cells.

[130] It should be mentioned that there are other legislative acts, which mention hydrogen, (e.g. the act on the promotion of the development use, and diffusion of new and renewable energy) however, no direct link to safety matters of 6 scenarios were detected for now.

[131] https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=54651&type=lawname&key=hydrogen.

[132] https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=53854&type=sogan&key=13.

[133] https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=53855&type=sogan&key=13.

[134] http://english.motie.go.kr/www/main.do.

[135] https://www.korea-certification.com/en/glossary/korea-gas-safety-corporation-kgs/.

[136] "As Korea's large-scale renewable energy complexes are less advanced than those of developed countries, the development, demonstration, and commercialisation of water electrolysis technologies has been delayed."

[137] Guideline applies to gaseous hydrogen storage containers with a capacity of 10 Nm^3 or more and its ancillary facilities. However, if several facilities are installed with an interval of less than 1.5 m, it can be applied when the total capacity is 10 Nm^3 or more, but this guideline does not apply to mobile hydrogen transport facilities and gaseous hydrogen manufacturing processes.

[138] Killed carbon/killed steels are characterised by a high degree of chemical homogeneity and freedom from porosity (from Handbook of Valves and Actuators, 2007).

[139] A basic study on the hazard of hydrogen fuel cell vehicles in road tunnels: https://www.koreascience.or.kr/article/JAKO202106960485604.kr&sa=U.

[140] Code for Facilities, Technology, and Inspection for Fuel Vehicles Refuelling by Type of On-Site Hydrogen Production (KGS FP216 2021) and Code for Facilities, Technology and Inspection for Vehicles Refuelling by Type of Compressed Hydrogen Delivery (KGS FP217 2021).

[141] Para 2.6.3 of KGS Code FP217 2021.

[142] Para 2.6.3.5 of KGS Code FP217 2021.

[143] http://www.electimes.com/news/articleView.html?idxno=192199.

[144] http://www.electimes.com/news/articleView.html?idxno=192199.

[145] H2FCSUPERGEN, 2020, "Opportunities for hydrogen and fuel cell technologies to contribute to clean growth in the UK" retrieved from: http://www.h2fcsupergen.com/wp-content/uploads/2020/04/2020_04_H2FC_Supergen_Hydrogen_Fuel_Cells_P_Dodds_DIGITAL_W_COVER_v05.pdf.

[146] Ten Point Plan for a Green Industrial Revolution retrieved from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf.

[147] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf.

[148] Hydrogen law and regulation in the United Kingdom | CMS Expert Guides.

[149] The Directives that underpin ATEX regulations were created by the European Union. Although not laws in their own right, they do become law when adopted by an EU member state. This is the case for the UK where European ATEX legislation was implemented through two Regulations under the Health & Safety at Work Act 1974. These are DSEAR (Dangerous Substances and Explosion Atmospheres Regulations 2002) implementing the requirements of EU Directive 99/92/EC and EPS (The Equipment and Protective Systems Intended for use in Potentially Explosive Atmospheres Regulations 1996) implementing the requirements of EU Directive 94/9/EC (latterly replaced by 2014/34/EU). Brexit doesn't affect the implementation of those regulations as they have already become part of the UK law. The UK Department for Business, Energy and Industrial Strategy (BEIS) has policy responsibility for the regulations and the Health and Safety Executive (HSE) enforces them.

[150] InsHyde Project Deliverable D113. Initial guidance for using hydrogen in confined spaces – Results from InsHyde. https://www.hysafe.org/inshyde.

[151] HSE. A guide to the Gas Safety (Management) Regulations 1996. 2007; 2nd [p.49]. Available from: https://www.hse.gov.uk/pUbns/priced/l80.pdf.

[152] ISO Policy, National Examples: United States of America, https://policy.iso.org/usa.html accessed 02.05.2022.

[153] NFPA 2, 7.2.2.2.2.

[154] NFPA 2, 7.2.2.3.2.

[155] NFPA 2, 7.1.22.11.2.

[156] NFPA 2, 9.

[157] https://www.npms.phmsa.dot.gov/About.aspx.

[158] https://www.asme.org/codes-standards/find-codes-standards/b31-12-hydrogen-piping-pipelines, accessed 02 May 2022.

[159] https://whatispiping.com/hydrogen-piping-and-pipeline-systems/, accessed 17 June 2022.

[160] Hydrogen Delivery Technical Team Roadmap U.S. Department of Energy, Washington, DC (2013).

[161] CSA stands for Canadian Standards Association. CSA/ANSI codes were published as a National Standard of Canada by CSA Group and was later also approved by the American National Standards Institute (ANSI) as an American National Standard. https://blog.ansi.org/csa-ansi-hgv-2-2021-hydrogen-gas-fuel-containers/#gref, accessed 03 May 2022.

[162] 0.3 m^2 per 304.83 m^3 of room volume.

[163] California Governor's Office of Business and Economic Development, Hydrogen Station Permitting Guidebook https://static.business.ca.gov/wp-content/uploads/2019/12/GO-Biz_Hydrogen-Station-Permitting-Guidebook_Sept-2020.pdf.

[164] California Fire Code 2309.

[165] https://www.sae.org/standards/content/j2601_202005/, accessed 03 May 2022, https://www.greencarcongress.com/2014/07/20140716-j2601.html,%20accessed%2003.05.2022.

Part III Review of international experience with hydrogen pilot projects

11

Hydrogen pilot projects around the world

This chapter discusses the international experience with hydrogen pilot projects, including data on hydrogen deployment and insights from a mapping exercise.

The present review aims to consolidate and shed light on international practices with respect to hydrogen related projects as well as incidents. It also details the processes through which several mid to large scale hydrogen projects have been rolled out. The extensive review of publicly disclosed projects intends to help identify the operational risks (when disclosed) associated with hydrogen-based technologies. For local authorities, the project in general and this output are expected to help clarify the risks and uncertainties associated with hydrogen-based applications for more efficient licensing and permitting processes and for promoting hydrogen centric initiatives.

The pilot projects selected and reviewed in this output are from 9 countries (China, France, Germany, Japan, Norway, Russia, South Korea, the United Kingdom and the United States). Globally, these countries are leading the transition to renewable energy. For instance, renewable electricity counts for 20.8% in Russia and 98.4% in Norway.[1] Further, out of the 14 governments that have already adopted hydrogen strategies (IEA, 2019[1]) the countries selected in this report were the first countries to operate pilot projects and investigate the associated risks as well as socio-economic benefits and costs. The pilot projects were retrieved from websites, reports and technical papers along with information and guidance from experts from the field and the support of the International Energy Agency (IEA).

For each country, the pilot projects are presented first, followed by a detailed analysis of incidents reported in the country. For each country, reported accidents were highlighted in a separate table with causes and safety concerns analysed in detail. It is, however, worth mentioning that many minor incidents and near-misses go unreported. Underreporting of these types of incidents is a big challenge for safety and reliability in general, and especially for new technologies. Information on the status of the project, being under development or completed, is also provided.

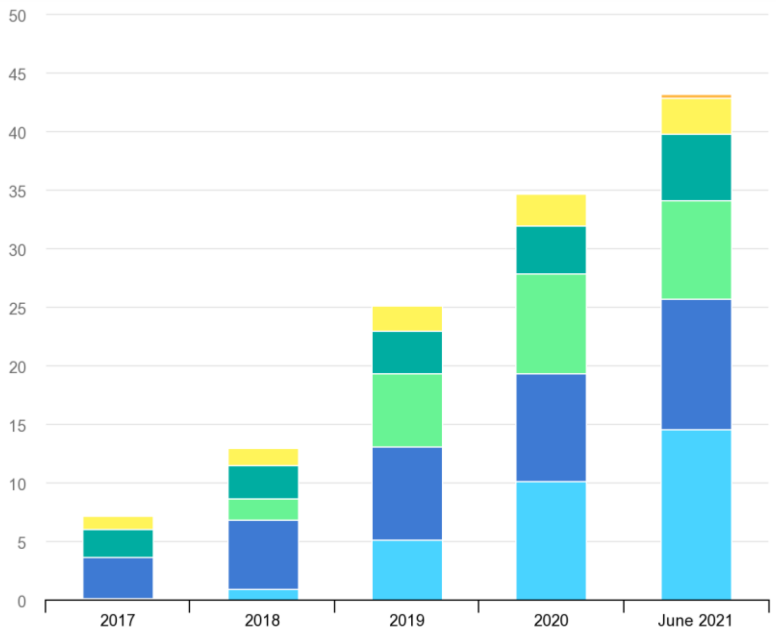
Data on hydrogen deployment

The International Energy Agency (IEA) presents, on the IEA databases, all the projects that they are aware of that are at different stages of development around the world. Currently only for hydrogen production, the agency is preparing other databases that will be released with the next edition of the Global H2 Review.

Among other useful information, the IEA has, in their global hydrogen review, also compiled data that showcase the increasing global stock of fuel cell electric vehicles (FCEVs) over the past five years (from 2017 to June 2021). The 2017-2020 data were obtained by the AFC TCP, while 2021 data were obtained by IPHE Country Surveys, the Korean Ministry of Trade, Industry and Energy, and the California Fuel Cell Partnership (Figure 11.1).

Besides information on FCEVs, the IEA have also tracked the global production of hydrogen by electrolysis per region, as calculated through their tracking of hydrogen projects worldwide. Through this review, an increase in the water electrolysis capacity was observed over six consecutive years, from 2015 to 2020 (IEA, 2021[2]).

Figure 11.1. Fuel cell electric vehicle stock per country between 2017 and June 2021



Source: IEA, Fuel cell electric vehicle stock by region, (from bottom to top, in all columns: Korea, USA, People's Republic of China, Japan, Europe, Rest of the world) 2017-2020, IEA, Paris https://www.iea.org/data-and-statistics/charts/fuel-cell-electric-vehicle-stock-by-region-2017-2020.

Despite the fact that China is a relatively late starter, the scale and the effort the Chinese government made to promote environmental innovations in the field of renewable energy make Chinese hydrogen policy an interesting object to study. France has been chosen since it is a major European country committed to investing large amounts of funding to deploy its hydrogen strategy. Germany has initiated several projects in the areas of hydrogen refuelling stations, urban mobility including cars, buses and tube-trailers, pipeline networks and even indoor heating in residential areas. This makes Germany an interesting case study on how hydrogen-related risks have been assessed while selecting projects for commercial and large-scale use of hydrogen.

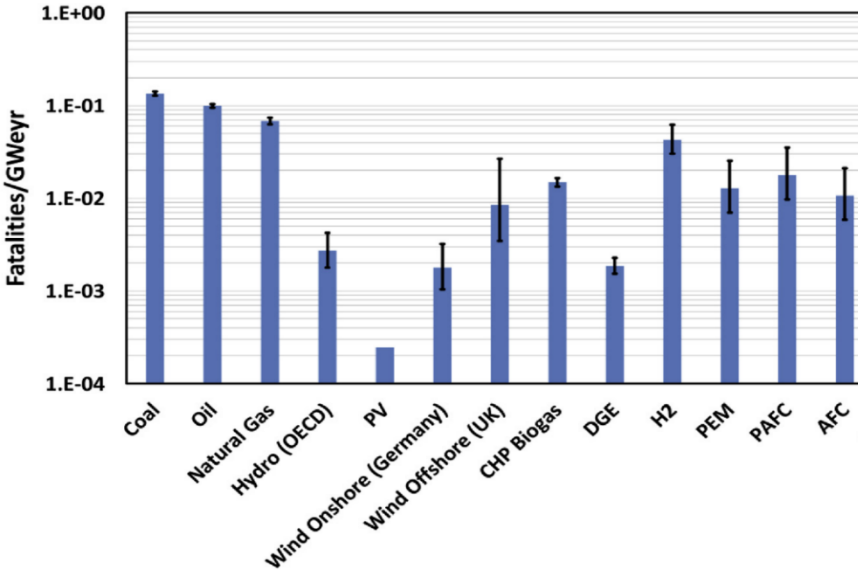
Japan, for its part, represents a highly advanced country in hydrogen use and at the forefront of research and development in this field. Japan also had the greatest number of hydrogen fuel stations worldwide as of the end of 2020, with 137 operational stations (IEA, 2021[2]). Japan's position as the leading provider of hydrogen automotive fuel is somewhat expected as Japanese automotive industries have been investing in hydrogen commercial cars since 2015. Norway's energy transition to hydrogen, while relatively slow compared to German or US counterparts, is still relevant: much of Norway's focus has been on large-scale use of hydrogen, for instance in maritime and industrial use. New research for small and mid-scale safe use of hydrogen is currently underway. Russia aims to seize the opportunity of producing and exporting hydrogen by building up on its own infrastructure, the capabilities of its state Natural Gas companies and the extensive knowledge on hydrogen developed during years of research for military and space use.

South Korea aims to promote a hydrogen-based economy that focuses on the transportation sector, decarbonising industry and buildings, and managing the production and distribution of hydrogen. The United Kingdom is investing significantly in building its hydrogen economy by incentivising several projects that span all the scenarios in analysis. The most innovative project aims at supplying hydrogen for domestic use. For the United States hydrogen is key in the plan to accelerate breakthroughs in clean energy solutions. Large-scale hydrogen projects are currently in the works throughout the country.

Insights from the mapping exercise

Work by (Spada, Burgherr and Boutinard Rouelle, 2018[3]) estimated an overall lower normalised risk for hydrogen as compared to other hydrocarbon fuels based on historical data (Figure 11.2), confirming hydrogen's potential as a fuel to replace oil and natural gas that are widely used today. Normalised risk is defined a measure of risk created by mathematically adjusting a value in order to permit comparisons.

Figure 11.2. Fatality rates for fossil fuels, hydropower, new renewables, hydrogen and selected hydrogen fuel cells (PEM, PAFC, AFC, MCFC)



Source: (Spada, Burgherr and Boutinard Rouelle, 2018[3]).

The mapping exercise provides a summary of pilot projects that have taken place, or that are currently underway, in 9 countries (China, France, Germany, Japan, Norway, Russia, South Korea, the United Kingdom and the United States). that were among the first to investigate the risks associated with hydrogen use, hydrogen safety and potential risks. This information can be used to support the growth of hydrogen activities in the Netherlands.

The main findings of the scoping exercise are summarised below:

- China listed hydrogen as a form of energy in its energy portfolio in 2020 and more than 30 cities have their hydrogen plans.
- With 12 renewable hydrogen production sites (IEA, 2021), 99 refuelling stations (H2stations.org) and more than 600 hydrogen buses[2] in operation, there are only 4 hydrogen-related accidents reported in the last 5 years in China. Two of the accidents happened at refuelling stations hence within the scope of the current study.
- Several projects in France aimed at deploying hydrogen ecosystems (dedicated not only to land but also sea mobility) and the country is working on projects to install hydrogen production sites using water electrolysis.
- France aims to optimise the integration of several solar photovoltaic farms supplying the electrolyser to minimise energy losses, to increase industrial safety thanks to the use of 3D digital models for each component of the installation.

- The German Federal government is assessing the viability of current gas networks, especially liquid gas networks for transporting hydrogen. It also plans to upgrade the regulatory framework presently applicable for natural gas for making hydrogen transportation safer.
- Germany also plans to improve its refuelling infrastructure to allow for greater introduction of cars, buses, agricultural vehicles and other heavy vehicles. The plan is to promote greater hydrogen-based mobility while also improving infrastructure simultaneously.
- Most initiatives in Japan aimed to promote the construction of hydrogen stations with the objective to contribute to their efficient operation and to commercialise scale fuelling ability (also promoting reduction in costs by reviewing regulations and standardising equipment).
- Norway is investing significantly to improve the regulatory as well as scientific understanding of hydrogen for use in several different areas including maritime, public and private transport, refuelling stations and usage in armed forces installations and equipment such as submarines.
- Russia aims at maximising the opportunities of its wide transport infrastructure and leading role as energy supplier by boosting the production of hydrogen and exporting it to two key markets Japan and Europe. It is doing so by targeting specific regions(oblast) where pilot projects are being deployed. It is also focusing on the use of hydrogen for transportation and industrial production, while there is no evidence of the use for domestic heating and cooking.
- South Korea's hydrogen strategy, in the short term, mainly focuses on the scale-up of hydrogen production from fossil fuel and on the development of the necessary infrastructure for hydrogen delivery. Additionally, a large-scale expansion of the hydrogen refuelling infrastructure is currently underway, to accommodate the Korean aim to become a leading producer and deployer of fuel cell electric vehicles.
- The UK is investing massively in hydrogen projects aimed at building an industrial and business economy around this energy carrier. By using its internal infrastructural networks, mainly in the north eastern side of the country, it aims at being the frontrunner of the domestic use of hydrogen.
- The United States is investing massively in projects to facilitate hydrogen production through electrolysis as well as hydrogen and natural gas blending into the existing natural gas infrastructure. There is emphasis placed on safety systems for gas and fire detection and comprehensive ventilation regimes.

References

IEA (2021), *Global Hydrogen Review 2021*, OECD Publishing, Paris, https://doi.org/10.1787/39351842-en. [2]

IEA (2019), *The Future of Hydrogen: Seizing today's opportunities*, OECD, Paris Cedex 16, https://doi.org/10.1787/1e0514c4-en. [1]

Spada, M., P. Burgherr and P. Boutinard Rouelle (2018), "Comparative risk assessment with focus on hydrogen and selected fuel cells: Application to Europe", *International Journal of Hydrogen Energy*, Vol. 43/19, pp. 9470-9481, https://doi.org/10.1016/J.IJHYDENE.2018.04.004. [3]

Notes

[1] Enerdata (2020) "Share of renewables in electricity production" https://yearbook.enerdata.net/renewables/renewable-in-electricity-production-share.html (accessed 16 May 2023).

[2] From different resources, see section 2.1 Scenario 4, selected pilots on hydrogen city bus for detail.

12

Pilot projects by country

This chapter summarises the pilot projects both underway or completed in each of the selected nine countries. A short description of each project and source references are provided to facilitate future investigation. Where research has uncovered information about incidents and accidents which have occurred involving hydrogen, these too have been recorded either against the relevant scenario or at the end of each country's summary.

China

Scenarios

Scenario 1: Production: Leakage from the pipe connected to electrolyser

Due to the country's dependency on imported natural gas and abundant availability of renewable resources, hydrogen production from electrolysis is of significant interest (IEA, 2019[1]). In 2022, it was estimated (Bloomberg, 2022[2]) that China accounts for 62-66% of global electrolyser installations. This includes 2 refuelling stations with on-site electrolysing facilities (Meng et al., 2021[3]) . In recent years, no accidents were reported for renewable hydrogen production. None-the-less, two accidents associated with fossil fuel-based hydrogen production were reported (discussed in detail in Section 2.1.1).

S. No	Year	Project description	Source
1	2021, April (Completed)	"National Demonstration project on Solar Energy Water Electrolysis for Hydrogen Production" -Location: NingXia, West of China -Electricity generation power: 2GW -Hydrogen production rate: 20,000 Nm^3/h -Cost of production: € 0.19 (1.34 CNY) /m^3	(2021, April 20) BaoFeng Solar energy water electrolysis project officially in production, *Chinese Chemical Industry Press*, Retrieved 14/03/2022 From: http://www.ccin.com.cn/detail/284767 Liu,X. (2020, December 18) NingXia BaoFeng Group: Extends green energy industry chain to reduce carbon footprint, *XinHua News Agency* Retrieved 22/02/2022 From: http://www.xinhuanet.com/2020-12/18/c_1126879207.htm

Scenario 2: Pipeline transport: Leakage from high pressure pipeline

Hydrogen transportation in China mainly relies on tube trailers (Beijing Hydrogen Industry Development Plan, 2021[4]) and therefore information/pilot projects on pipelines are limited. The company Sinopec had by 2020 completed at least 3 hydrogen pipelines with the longest being 43 km. Hydrogen is transported between 0.1 MPa to 4 MPa. No accidents have been reported.

S. No	Year	Project description	Source
2	2014 (Completed)	"Balingyi – Changling" Hydrogen pipeline - Length: 43km 18.8km underground, 24.2 km overground - Newly build - Hydrogen purity: >=99.5% - Yearly operation: 8000h/ 333 days - Pressure: ca. 2.6MPa	Final Environmental Impact Report "Balingyi – Changling" Hydrogen purification and transportation (2015), Retrieved 22/02/2022 http://sthjt.hunan.gov.cn/uploadfiles/201511/20151106152901331.pdf
3	2015 (Completed)	"Jiyuan-Luoyang'' Hydrogen pipelines -Length: 25km -Pipe width: 508mm -Pipe thickness: 11.1mm- Pressure: 4Mpa -Capacity: 100.4 kt/year	*Sinopec Release* (2015), Retrieved 22/02/2022 http://www.cnpc.com.cn/cnpc/trqxgdt/201511/0d99b30f7dfb43eebfb12583c1aa106b.shtml
4	2019 (Completed)	Short pipeline connecting a chemical company and *Sinopec* - Length: 3.2 km, overground - Hydrogen purity: >= 99.5% - Pressure: Atmospheric pressure - Capacity: 5 000m^3/h	Final Environmental Impact Report on Hydrogen Transportation, JinCheng Chemicals(2019), Retrieved 22/02/2022 http://www.kamtian.com/Public/userfiles/files/report181101.pd

Scenario 3: Road transport: H2 leakage in a confined space/ built environment

Despite manufactured more than 5 000 hydrogen vehicles (Beijing Government Plan on Fuel Cell Vehicles,, 2020[5]) by the end of 2019 and undertaking hydrogen transportation from production to refuelling stations mainly rely on road transportation (Hydrogen pipe trailers at 20 MPa (Beijing Hydrogen Industry Development Plan, 2021[4]),. There have been no hydrogen-related accidents associated with transportation.

Scenario 4: Mobility and a partially confined space: a hydrogen city bus driving in a tunnel is involved in a traffic accidents

More than Over 30 cities in the country have their own hydrogen projects which normally involve hydrogen city buses. Apart from one demonstration project started in Beijing in 2004, all other hydrogen buses start to operate in/after 2018. Although it is unclear whether risk assessment related to Scenario 4 was performed, there were no accidents reported regarding hydrogen bus operation.

Selected pilots projects on hydrogen city bus:

S. No.	Year	Project Description	Source
6	2005 (Completed)	Beijing (3)	Xinhua News Agency (2005), Retrieved 22/02/2022 www.gov.cn/jrzg/2005-11/23/content_107446.htm
7	2019	Datong (50)	Shanxi Government(2019), Retrieved 22/02/2022

	(Completed)		http://www.shanxi.gov.cn/yw/zwlb/gsdt/201904/t20190417_527867_ewm.shtml
8	2020 (Completed)	Shanghai (6) 285 additional Hydrogen fuel cell vehicles operating in the city	Xinhua News Agency (2019), Retrieved 22/02/2022 http://www.gov.cn/xinwen/2019-06/11/content_5399067.htm
9	2020-2021 (Completed)	Zhangjiakou (304)	Hebei daily (2021), Retrieved 22/02/2022 http://jtt.hebei.gov.cn/jtyst/wap/zt/dah/mtjj/101630318221594.html
10	2021 (Completed)	Shanghai (6)	LINGANG Group (2021),Retrieved 22/02/2022 https://www.shlingang.com/lg1/lingangjituan/xwzx/focusnewarea/202112/t20211207_23747.shtml
11	2021 (Completed)	Shenzhen (5)	Shenzhen Transportation Bureau (2021), Retrieved 22/02/2022 http://jtys.sz.gov.cn/zwgk/jtzx/cxtx/content/post_9280522.html
12	2021 (Completed)	Nanjing (11)	Xinhua News Agency (2021), Retrieved 22/02/2022 http://www.js.xinhuanet.com/2021-05/01/c_1127402127.htm
13	2021-2022 (Completed)	Beijing (212)	Xinhua News Agency (2022),Retrieved 22/02/2022 http://bj.news.cn/2022-01/18/c_1128272686_2.htm

Scenario 5: Mobility and partially confined space: accidents at a hydrogen fuel station

With the first immobile hydrogen fuel station started its operation in 2007, the country currently has 61 refuelling stations in operation (Meng et al., 2021[3]) with most of them started operation in the last 5 years. Only one accident was reported at a hydrogen fuel station – the rupture of a connecting soft pipe causing local fire but no injury. Another accident with the same root event was reported (Section 2.1.1).

S. No	Year	Project description	Source
14	2007 (Completed)	Shanghai -Hydrogen Storage: Increased gradually from 200 to 800kg -Hydrogen Source: Road Transport(8 tubes with volume of 2.3m^3 at 20MPa) -Total Refuelling: 142.346Tons/33697 times -Refuelling Pressure: 35MPa Safety measures: 1) 24h manned 2) Trained staff member for operation 3) Regular checks for Pressured components	Li, Z., Pan, X., & Ma, J. (2010). Quantitative risk assessment on a gaseous hydrogen refuelling station in Shanghai. *International Journal of Hydrogen Energy*, 35(13), 6822-6829. Pan, X(2021) Safety Analysis on Shanghai's first Hydrogen Refuelling station, *Shunhua New Energy Cooperation*
15	2019 (Completed)	Dalian -Location: Northeast China -Hydrogen Storage: 200kg -Hydrogen Source: On-site water electrolysis -Refuelling Pressure: 35/70MPa -Daily Supply: 500kg	Pan, X., Li, Z., Zhang, C., Lv, H., Liu, S., & Ma, J. (2016). Safety study of a wind–solar hybrid renewable hydrogen refuelling station in China.*International Journal of Hydrogen Energy*,*41*(30), 13315-13321.
16	2020 (Completed)	Beijing Largest hydrogen refuelling station in the world -3 minutes for one 9 kg hydrogen refuelling, which is sufficient for 350 km operation. -The station is expected to serve 800-1000 lorries on a daily basis. -Hydrogen Source: Pipeline -Refuelling Pressure: 35/70MPa -Daily supply: 4 000 kg	*People's Daily* (2021) Retrieved 22/02/2022 http://society.people.com.cn/n1/2021/0518/c1008-32106311.html

Scenario 6: Residential use: Safety of hydrogen in buildings with focus on hydrogen cooking stoves and boilers

Research (Haeseldonckx and D'Haeseleer, 2007[6]) suggested the current natural gas pipeline is feasible to transport hydrogen should the volume ratio be below 17%.

17	2019 (Completed)	-Hydrogen produced by water electrolysis is then mixed with natural gas at 10% for transportation. -The gas mixture can then be used for	State Power Investment Corporation (2021) Retrieved 22/02/2022 https://h2.in-en.com/html/h2-2408939.shtml *Xinhua News Agency* (2019), Retrieved 22/02/2022

		cooking upon delivery -Location: Chaoyang City, Northeast of China -Safe operation for more than 1 year.	http://m.xinhuanet.com/ln/2019-11/13/c_1125224994.htm
Other projects worth mentioning:			
18	2020 (Completed)	Hydrogen Tram -Location: Foshan, Guangdong Province -First of its kind in the world -6.57km, 10 stations -Daily passenger 1101 (2020), 578 (2021) -Cost: ca. € 153.2 million (1070 million CNY)	Gaoming District modern light railway demonstration line (2021) *Wikipedia,* Retrieved 22ed Feb, 2022 From https://zh.wikipedia.org/wiki/???????????

Incidents

No.	Scenario-related	Description	Analysis
1	5	Fire caused by the rupture of tube trailer's flexible hose connection during refuelling (20MPa) at a chemical plants producing propene, hydrogen *etc.* -Damage at ca. € 3 117 (21 760 CNY), no injury reported. - 1h18min passed between pipe rupture and fire suppression.	The accident was initiated by the rupture of a flexible hose that is used for hydrogen refuelling. The flexible hose in question were faulty and ruptured at pressures below that of the designed maximum pressure. The hose failure happened at 7.5MPa for accidents 1 and 17.7 MPa for accidents 2. The flexible hose connection in question was purchased in April, 2020 and the accident happened in July 2020. Flexible hose connections should be thoroughly pressure tested before use, and potentially changed regularly. Regulation on the design of hydrogen refuelling stations (GB50177-2005) does not specify the safety distance between tube trailers or between tube trailers and a hydrogen supplying facility.
2	N/A	Long-term corrosion led to the rupture of a connecting pipe, which resulted in the leakage and explosion of a Naphtha/Hydrogen mixture. No injuries reported The accident can be classified to be “with H2 by chance” instead of “because of H2”. Therefore, no H2 specific action is required.	The direct cause for this accident was the corrosion of a connection pipe. According to national regulation, pipelines operating under pressure should be tested regularly and the integrity data analysed. Despite the fact that data from 2020 were available, it is uncertain if the pipeline which ruptured was inspected. In addition, no analysis of the integrity of the pipeline from the inspection data was performed.
3	N/A	Fire involving hydrogen at a petrochemical production facility in Yunnan - It took 2h40min to extinguish the fire. - 4 personnel were slightly injured	A detailed report not yet available.

Source: (IchemSafe, 2020[7]) (China Corrosion and Protection Network, n.d.[8]) (CCTV News, 2021[9])

Concluding remarks: China

For the first time, China listed hydrogen as a form of energy in its energy portfolio in 2020, and only thereafter would hydrogen be included in the energy statistics released by the National bureau of statistics. As a result, a large proportion of the country's hydrogen pilot projects started in 2020 or later.

Being the largest country by population, China currently owns the largest water-electrolysis (2 GW) facilities (hydrogen production at 20 000 Nm^3/h) in the world (Pilot Project 1) and there are plans to build an even larger facility (Xinhua News Agency, 2021[10]) for large-scale hydrogen production powered by renewable electricity. More than 30 cities have their own hydrogen plans and most of these plans involve hydrogen city bus operations. Besides the usual safety measures involving hydrogen use, our research suggests that most of the country's hydrogen vehicles are buses or larger vehicles for cargo transportation, reducing potential risks, given the fact that the drivers are trained acts as an extra safety measure.

With most of its pilot projects, as well as other hydrogen-related industries, operating without accidents, there were 4 hydrogen related accidents reported in the last 5 years: 2 at petrochemical production sites and 2 at refuelling facilities. While the former 2 are not within the scope of the current study the later 2 accidents were led by the same initiating event: Rupture of flexible hose connection. These hoses connect pressured hydrogen tubes to the refuelling facility and are crucial for the refuelling process. We therefore suggest that flexible hose connections should be thoroughly pressure tested before use, and potentially changed regularly.

Status of project: China

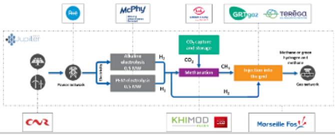
China	Status
National Demonstration project on Solar Energy Water Electrolysis for Hydrogen Production In operation since 2021	Completed
“Balingyi – Changling” Hydrogen pipeline In operation since 2014	Completed
“Jiyuan-Luoyang’’ Hydrogen pipelines In operation since 2019	Completed
Shanghai Anting refuelling station In operation since 2007	Completed
Dalian station First renewable hydrogen refuelling station in China. In operation since 2019	Completed
Beijing Daxing refuelling station In operation since 2020	Completed
Foshan hydrogen tram In operation since 2019	Completed
Hydrogen city buses (more than 600 in operation)	Under development
Chaoyang hydrogen blending project	Under development

France

Scenarios

Scenario 1: Production: Leakage from the pipe connected to electrolyser

S. No	Project Name	Project description	Source
1	Jupiter 1000 (financed jointly by the European Union (ERDF), the French State (investments in future, entrusted to	This project is the first industrial demonstration of Power to Gas with a power rating of 1 MWe for electrolysis and a methanation process with carbon capture. The objective is to produce green hydrogen using two electrolysers involving different technologies, from 100% renewable	https://www.jupiter1000.eu/english

	the ADEME) and the Provence-Alpes-Côte d'Azur Region of France) 2014-2023 (under development)	energy. The installation of the methanation process will be based on an innovative methanation technology and CO_2 will be captured on a nearby industrial site. 	
2	Masshylia project (Total and Engie) 2021-2024 (under development)	It is France's largest renewable hydrogen production site at Châteauneuf-les-Martigues in the Provence-Alpes-Côte d'Azur South region. Located at the heart of Total's La Mède biorefinery and powered by solar farms with a total capacity of more than 100 MW, the 40 MW electrolyser will produce 5 tonnes of green hydrogen per day to meet the needs of the biofuel production process at Total's La Mède biorefinery, avoiding 15 000 tonnes of CO2 emissions per year. The project thus integrates the implementation of 5 innovations that prefigure the industry's decarbonation solutions, which is unprecedented without any precedent in Europe: • A digital piloting system for the continuous supply of hydrogen with real-time management of solar electricity production, • Optimising the integration of several photovoltaic farms supplying the electrolyser to minimise energy losses and limit grid congestion, • Large-scale hydrogen storage to balance intermittent electricity production and continuous hydrogen consumption, • A direct current connection between a photovoltaic farm and the electrolyser to improve the energy balance, • Enhanced industrial safety thanks to the use of 3D digital models for each component of the installation	https://totalenergies.com/media/news/press-releases/total-and-engie-to-develop-france-s-largest-site-of-green-hydrogen

Scenario 1: Production: Leakage from the pipe connected to electrolyser
Scenario 3: Road Transport: H2 leakage in a confined space/ built environment
Scenario 5: Mobility and partially confined spaces: accidents at a hydrogen fuel station
Projects listed below are related to 3 Scenarios

3	VHyGO project (Grand Ouest Hydrogen Valley) (Completed)	TIn VHyGO project is set up in a three-phase approach that takes account of each partner's specific project timeframe. The completion dates for these phases are December 2020, March 2021 and September 2021. Phase 1 of the VHyGO project includes: Three new green hydrogen production sites using electrolysis. Three new refuelling stations. These will be located as close as possible to points of use. From an initial capacity of (1 900 kg a day in total), these stations will be scalable to accompany the ramp-up planned over the different project phases. Twenty-three 12-metre hydrogen buses, seven hydrogen-powered domestic refuse collectors, one retro-fitted hydrogen powered heavy goods vehicle, ten light commercial vehicles and thirty	https://www.lhyfe.com/press/whygo-project/

		18-metre hydrogen buses (funding for the latter will be requested in September).	
Scenario 1: Production: Leakage from the pipes connected to electrolysers Scenario 5: Accidents at a hydrogen fuel station Projects listed below are related to 2 Scenarios			
4	MONANhySSA project 2021-2024 (under development)	The MONANhySSA project plans the installation in Nice of a hydrogen production station using electrolysis and a distribution station in Nice.	https://www.banquedesterritoires.fr/la-commission-europeenne-et-la-banque-des-territoires-soutiennent-le-projet-monanhyssa-au-sein-de
5	HyGreen Provence 2021-2028 (under development)	Production and massive storage of green hydrogen in saline cavities. The HyGreen Provence project will participate in the construction of a local renewable electricity of local renewable electricity, based on solar resource (sites located in the Provence-Alpes-Côte d'Azur région) among the most competitive in France, and selling the electricity produced produced either directly to energy buyers energy buyers, or in a chain of production of green hydrogen stored on a massive scale and intends for local use.	https://www.capenergies.fr/portfolio_page/hygreen-provence/
Scenario 3: Road Transport: H2leakage in a confined space/ built environment			
6	Hynomed, a new accelerator for hydrogen mobility 2020 - 2022 (under development)	SAS Hynomed has as objective to to deploy a hydrogen ecosystem dedicated to land and sea mobility in the southern region. The Brégaillon port site, to the west of Toulon, is an important maritime, land and rail transport hub and is the proposed location for the first station. Expected to be operational by the end of 2022, the station will be able to power 7 to 10 hydrogen-powered buses in the city, around 50 light commercial vehicles and an innovative maritime shuttle with a capacity of 250 passengers.	https://www.engie-solutions.com/en/news/sas-hynomed
Scenario 6: Residential use: Safety of hydrogen in buildings with focus on hydrogen cooking stoves and space heating boilers			
7	The GRHYD demonstration project, coordinated by ENGIE in association with 10 other partners, supported by the government as part of the Future Investment Program operated by ADEME and labeled by the Tenerrdis competitiveness cluster. (completed)	The project was launched to inject hydrogen into the territory's natural gas distribution network in order to meet the heating, hot water and cooking needs of the residents of the new neighborhood of Cappelle-la-Grand in terms of heating, hot water and cooking.	https://www.engie.com/en/businesses/gas/hydrogen/power-to-gas/the-grhyd-demonstration-project

Incidents – none reported in France.

Concluding remarks: France

Seven pilot projects were reviewed in France. Several projects aimed at deploying hydrogen ecosystems (dedicated not only to land but also sea mobility) were investigated. France is working on projects to install hydrogen production sites using water electrolysis but also intends to increase the number of hydrogen refuelling stations and hydrogen vehicles. It also seems to aim, specifically in one pilot, to optimise the integration of several solar photovoltaic farms supplying the electrolyser to minimise energy losses, limit grid congestion and enhance industrial safety thanks to the use of 3D digital models for each component of the installation. Moreover, a project with the first industrial demonstrator of power to gas with a power rating of 1 MWe for electrolysis and a methanation process with carbon capture was reported. In addition, another project attempting to inject hydrogen into the territory's natural gas distribution network was launched via another project.

The projects seem to have run smoothly until now, since no accidents were reported.

Status of project: France

France	Status
GRHYD demonstration project 2014-2021	Completed
Jupiter 1000: 2014-2023	Under development
Hynomed, a new accelerator for hydrogen mobility 2020-2022	Under development
Masshylia project (Total and Engie) 2021-2024	Under development
MONANhySSA project 2021-2024	Under development
HyGreen Provence 2021-2028	Under development

Germany

Scenarios

Scenario 2: Pipeline transport: Leakage from high pressure pipeline			
S. No.	Project name	Project description	Source
1	H2HoWi 2020-2023 (first phase) (under development)	In the state of North Rhine-Westphalia, an existing public gas pipeline is being converted to convey pure hydrogen for the first time in Germany. Continuous scientific monitoring is being performed to confirm the impact of hydrogen on the structure of the pipe material and the suitability of the existing infrastructure. Current technical standards limit the addition of hydrogen to the natural gas network to 10%. individual projects are testing higher concentrations. H2HoWi is testing pure hydrogen to determine the feasibility of upgrading the existing gas pipeline infrastructure. An existing medium-pressure pipeline is first disconnected from the natural gas network and then connected to a hydrogen storage facility receiving a supply of hydrogen to service four commercial entities. The required space heating is to be generated by hydrogen. In addition to changing the line, adjustments to the existing customer installations were required and hydrogen compatible condensing boilers have been installed.	https://fuelcellsworks.com/news/unique-project-in-germany-existing-natural-gas-pipeline-will-be-converted-to-100-percent-hydrogen/
2	H2 Starnetz 2030 2020- ~ (under development)	World's largest gas pipeline grid being planned by pipeline operators which is designed to cover 1 200 km. Consumption centres in North Rhine Westphalia and Lower Saxony will be linked to hydrogen production centres in the North. The completely new energy grid would emerge from existing gas grids giving large industries the opportunity to become climate neutral. 1100 km will be from existing gas grids while the remaining will be built new.	https://www.rechargenews.com/transition/german-pipeline-operators-present-plan-for-world-s-largest-hydrogen-grid/2-1-810731
Scenario 3: Road Transport: Hydrogen leakage in confined spaces/ built environments			
S. No.	Project Name	Project Description	Source
3	Karlsruhe Institute of Technology (KIT) Hydrogen Shuttle Bus Service/ 2013	Fuel cell buses and refuelling stations were introduced in Karlsruhe university campus for shuttle operations between various KIT premises. The fuel station originally supplied 80 kgs of hydrogen per day, enough to fuel three buses. The capacity was one of the highest in south Germany. Refuelling takes about 20 minutes and the bus transports employees and students at no additional costs. An estimated 80,000 passengers per year	https://www.kit.edu/kit/english/pi_2013_13080.php

	(completed)	is guaranteeing permanent high usage for the fuel station.	
4	H2 City Gold 23.12.2021 (first phase completed)	Electrification of bus fleet- initiative by moBiel, public transport operator in Bielefeld. Four low floor buses fitted with Toyota fuel cell stack and 44KWh battery pack and offering a driving range of 400 kms. Capacity to carry 76 passengers. Buses have a home base at the new Sennestadt Lilienthalstrasse depot. A second working level has been installed for easy and safe access to the components installed on the roof of the bus. Hydrogen fuelling station is undergoing completion. Refuelling time is estimated at 9 minutes.	https://caetanobus.pt/en/caetanobus-e-rampini-anunciam-acordo-comercial-para-alargar-o-seu-portefolio-de-produtos-2-2-2-2/
5	E-Farm Project 17.06.2020 (under devlopment)	Project launched by renewable energy solutions provider GP Joule GmbH. Wind power from older turbines converted to H2. Waste heat is used to heat buildings in the local area. Fuel is transported to two filling stations in Husum and Niebül where fuel cell powered buses, trucks and cars can fill up. Two fuel cell buses were purchased to demonstrate the project. Funded partly by the Federal Ministry of Transport and Digital Infrastructure.	https://www.german-energy-solutions.de/GES/Redaktion/EN/News/2020/20200617-e-mobility-farm.html
6	National Hydrogen and Fuel Cell Technology Innovation Program (NIP) (completed)	Launched in 2007 to accelerate market preparation for hydrogen technology in Germany. NIP is divided into three program areas: Transport and Hydrogen Infrastructure; Stationary Energy Supply and Special Markets. Autostack Industrie initiative announced in 2017 aims to ensure the preconditions exist for commercial introduction of fuel cell vehicles by 2020. Competitive series production of fuel cells to be established rather than importing. The Bodensee project (2009) was started to capture mass markets through NIP's Special Markets program. It focused on onboard power supply of camping vehicles (camper vans, mobile homes) and the power drive of leisure vehicles (boats, light vehicles) using fuel cell systems. The goal was increased publicity.	https://juser.fz-juelich.de/record/135833/files/78_11.pdf
7	Zero Regio (2004-2010) (completed)	Five Mercedes Benz F-Cell vehicles including one with 700 bar storage tested in Frankfurt through real-life cycles over a period of three years. Findings: Breakaway coupling activated on two occasions presumably because of third party damage. Better monitoring procedures should be used for critical components such as breakaway coupling. A car collided with a conventional vehicle and the hydrogen dispenser was damaged but did not leak. Dispensers should be robustly designed to withstand foreseeable impact damage.	https://trid.trb.org/view/1255324
Scenario 6: Residential use: Safety of hydrogen in buildings with focus on hydrogen use in cooking stoves and boilers			
8	Callux (Lighthouse project under NIP) Since 2008 (several phases completed)	Project intended to test fuel cell-based combined heat and power systems in residential applications for mass. Installation and operation of up to 800 fuel cell heating systems is the largest field trial for fuel cells in homes. 1,046 units in real customer homes with more than 5.5 million hours of reliable operation generating in excess of 4.5 GWh of electricity. Safety: FC CHP (Fuel Cell Combined Heat and Power) are used which are gas appliances running on gas from the grid. In FC CHP only very small amounts of H2 are present (less than 1 litre between reformer and stack) All safety requirements like any other tested gas appliance are met for use of FC CHP.	https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cd85bc7c&appId=PPGMS https://enefield.eu/category/about/

Incidents

S. No.	Scenario	Description	Analysis
1	3	In 2001, a lorry crashed at a considerable speed into a hydrogen tube trailer on the A1 highway near Köln. The lorry driver was killed. The fire brigade let the gas burn and cooled the undamaged tanks. Other vehicles or persons were not involved. The evidence of a catastrophic accident involving HFCV is low. A few accidents involving HFCVs did not suffer hydrogen leakage.	Hydrogen gas escaped from tubes and valves to three of the nine tanks, and ignited.
2	3	In 2001, a hydrogen powered boat caught fire due to fault in the battery (and not in the hydrogen system). The fuel cell and hydrogen were not affected by the fire because of the design safety.	

Note: Hydrogen Incidents and Accidents Database (HIAD 2.0) requires special permission and is accessible at https://odin.jrc.ec.europa.eu/giada/.

Concluding remarks: Germany

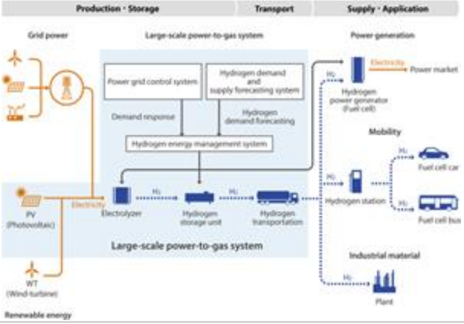
Germany has plans of investing significant financial and research time into hydrogen transition. The next steps are aiming at producing and distributing green hydrogen. There are plans to establish 5 GW of generation capacity including offshore and onshore energy generation facilities by 2040 at the latest. However, since this covers only 1/7th of Germany's projected energy demand for 2030, the gaps for energy demand are to be closed through import of hydrogen. Structural and infrastructure improvements through public-private partnerships and projects are also seeing a rise. At present, Germany has 90 hydrogen refuelling stations of which 45 (as of 2017) are publicly accessible. Plans are already in place for setting up a 1 200 km of pipeline network for hydrogen using existing natural gas pipelines- once again one of the largest pipeline networks in the world. However, publicly available data on safety studies and risk-assessment from pilot projects are scant and would require more research.

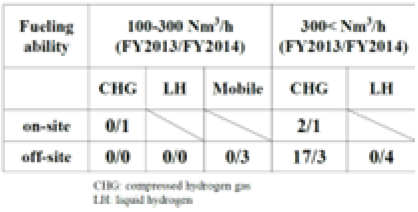
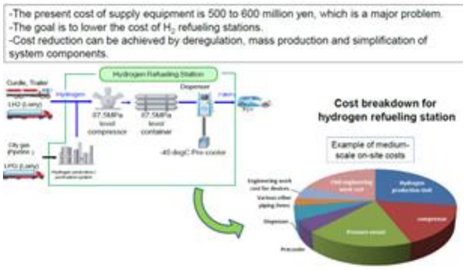
Status of project: Germany

Germany	Status
Karlsruhe Institute of Technology (KIT) Hydrogen Shuttle Bus Service/ 2013	Completed
National Hydrogen and Fuel Cell Technology Innovation Program (NIP)	Completed
Zero Regio 2004-2010	Completed
H2 City Gold 2021 - ~	First phase completed
Callux (Lighthouse project under NIP) 2008 - ~	Several phases completed
H2HoWi 2020-2023 (first phase)	Under development
H2 Starnetz 2030 2020 - ~	Under development
E-Farm Project 2020 - ~	Under development

Japan

Scenarios

<table>
<tr><td colspan="4">Scenario 1: Production: Leakage from the pipe connected to electrolyser
Scenario 2: Pipeline transport: leakage from high pressure pipeline</td></tr>
<tr><th>S. No</th><th>Project name/</th><th>Project description</th><th>Source</th></tr>
<tr><td>1</td><td>Hydrogen Energy Supply Chain (HECS) Pilot Program
2018 - 2022
(under development)</td><td>Plt produces hydrogen from coal in Latrobe Valley in Australia and transports it in liquid as liquid hydrogen form to Japan onboard the world’s first liquefied hydrogen carrier. This project recently started the Australian arm of its operations and is expected to begin shipments in the first half of 2022.</td><td>https://www.hydrogenenergysupplychain.com/about-hesc/</td></tr>
<tr><td colspan="4">Scenario 1: Production: Leakage from the pipe connected to electrolyser
Scenario 2: Pipeline transport: leakage from high pressure pipeline
Scenario 3: Road Transport: H2 leakage in a confined space/ built environment</td></tr>
<tr><td>2</td><td>Global Hydrogen Supply Chain Demonstration Project (Chiyoda Corporation, together with Mitsubishi Corporation, Mitsui & Co. Ltd. and NYK Line, the other members of the Advanced Hydrogen Energy chain Association for technology Development (AHEAD))
2015 - 2020
(completed)</td><td>Some Japanese companies completed the world’s first global hydrogen supply chain system on 25 December 2020. The project was conducted by AHEAD and subsidised by the New Energy and Industrial Technology Development Organization (NEDO).</td><td>https://www.chiyodacorp.com/en/service/spera-hydrogen/</td></tr>
<tr><td>3</td><td>Fukushima Hydrogen Energy Research Field (FH2R - developed by NEDO, Toshiba ESS, Tohoku Electric Power and Iwatani Corporation)
2018 - 2020
(completed)</td><td>FH2R uses 20 MW of solar power generation facilities on a 180 000 m2 site along with power from the grid to conduct electrolysis of water in a renewable energy-powered 10 MW-class hydrogen production unit., The largest in the world. It has the capacity to produce, store, and supply up to 1 200 Nm3 of hydrogen per hour (rated power operation).
It uses a 10 MW electrolyser to convert renewable power from a 20 MW solar power unit.
 </td><td>https://www.toshiba-energy.com/en/info/info2020_0307.htm</td></tr>
<tr><td>4</td><td>Japan H2 Mobility, LLC (abbreviation: JHyM)
Participating companies: Toyota Motor, Nissan Motor, Honda Motor, JXTG Nippon Oil & Energy, Idemitsu Kosan, Iwatani Corporation, Tokyo Gas, Toho Gas, Air Liquide Japan, Nemoto Tsusho, Seiryu Power Energy, Toyota Tsusho, Development Bank of Japan, JA Mitsui Leasing, Sompo Japan Nipponkoa Insurance, Sumitomo Mitsui Finance and Leasing Company, NEC Capital Solutions, Mirai Creation Fund</td><td>A Japan-wide initiative to promote construction of hydrogen stations is created in 2018
1. Strategic deployment of hydrogen stations - 80 hydrogen stations nationwide by year 2021 - Deploy strategically hydrogen stations compatible with maximisation of both FCV demand and user convenience 2. Contribution to efficient operation of hydrogen stations (1) Improvement of convenience for FCV users - Better coordination of operating days and time between neighbouring stations (2) Promotion of sustainability of hydrogen stations business - Cost reduction and regulation review through collaboration with other related organisations 3. Positive information provider to convince the public of hydrogen society realisation</td><td>PPT presentation
Accelerating the Construction of Hydrogen Stations to Promote Widespread Use of Fuel Cell Vehicles Toward the Creation of a Hydrogen-based Society
Sep. 11, 2018 Tomonari Komiyama Japan H2 Mobility, LLC</td></tr>
</table>

<table>
<tr><td></td><td>2018 - 2021
(completed)</td><td>Contribution to efficient operation of hydrogen stations</td><td></td></tr>
<tr><td colspan="4">Scenario 5: Mobility and partially confined spaces: accidents at a hydrogen fuel station</td></tr>
<tr><td>5</td><td>New Energy and Industrial Technology Development Organization(NEDO)
2011 - 2015
(completed)</td><td>System of FCEV/Hydrogen Infrastructure Projects in Japan ~HRS with commercial scale fuelling ability
Promotion of HRS Installation ~HRSs in Japan~
Prior to the market introduction of FCEVs (2015), 100 HRSs will be installed in 4-major-populated-areas (Tokyo, Aichi, Osaka, Fukuoka) METI will subsidise about 50% of the HRS’ installation cost (2014FY 7.2 billion JPY)
Summary of the approved HRSs by type

<table>
<tr><td>Fueling ability</td><td colspan="3">100-300 Nm^3/h (FY2013/FY2014)</td><td colspan="2">300< Nm^3/h (FY2013/FY2014)</td></tr>
<tr><td></td><td>CHG</td><td>LH</td><td>Mobile</td><td>CHG</td><td>LH</td></tr>
<tr><td>on-site</td><td>0/1</td><td></td><td></td><td>2/1</td><td></td></tr>
<tr><td>off-site</td><td>0/0</td><td>0/0</td><td>0/3</td><td>17/3</td><td>0/4</td></tr>
</table>
CHG: compressed hydrogen gas
LH: liquid hydrogen
Research and development on low-cost equipment for HRS

-The present cost of supply equipment is 500 to 600 million yen, which is a major problem.
-The goal is to lower the cost of H_2 refueling stations.
-Cost reduction can be achieved by deregulation, mass production and simplification of system components.
 </td><td>PPT presentation
Hydrogen Infrastructure in Japan
2014 AMR June 19, 2014
Washington Marriott Wardman Park Hotel Washington, USA Shigenobu Watanabe New Energy and Industrial Technology Development Organization (NEDO)
2014 AMR June 19, 2014
Washington Marriott Wardman Park Hotel , Washington, United States</td></tr>
</table>

Concluding remarks: Japan

Five pilot projects were reviewed in Japan. Country-wide initiatives to promote the construction of hydrogen stations were found, with the aim to contribute to the efficient operation of hydrogen stations and to commercialise scale fuelling ability (also promoting reduction in costs by reviewing regulations and standardising equipment). Japanese companies were also found to complete the world’s first global existing hydrogen supply chain system. This move also marks the first consumption of foreign-produced hydrogen for power generation. In addition, the world-first hydrogen energy supply Chain Project aims to safely produce and transport clean liquid hydrogen from Australia to Japan. A key objective of the pilot project is to demonstrate an end-to-end supply chain between both countries. A Japanese consortium launched a renewable energy-powered 10 MW-class hydrogen production unit, the largest-class in the world.

The projects seem to have run smoothly until now, since no accidents were reported, making us assume that safety strategies followed were sufficient and effective.

Status of project: Japan

Japan	Status
New Energy and Industrial Technology Development Organization (NEDO); 2011-2015	Completed
Global Hydrogen Supply Chain Demonstration Project; 2015-2020	Completed
Fukushima Hydrogen Energy Research Field (FH2R); 2018-2020	Completed
Japan H2 Mobility, LLC (abbreviation: JHyM); 2018-2021	Completed
Hydrogen Energy Supply Chain (HECS) Pilot Program; 2018-2022	Under development

Norway

Scenarios

Scenario 1: Production: Leakage from the pipe connected to electrolyser			
S. No.	Project name	Project description	Source
1	Electrolyser 2030-Cell and Stack (under development)	1. Pilot focusing on techno-economic analysis of large scale PEM electrolysers. 2. Costs of electrolysers need to be reduced to make green hydrogen competitive with natural gas. 3. Better understanding of materials and components lifetime, optimal electrolyser cell and stack design 4. In-depth analysis at levels of electrolysis ranging from single cells to stack level.	Source: Research Council of Norway Organisation: Institute-Technical Sectors, SINTEF AS, Trondheim https://prosjektbanken.forskningsradet.no/ Past study can be accessed at: https://www.sintef.no/contentassets/f8060684df6f459da532cb3aec6b8c02/d.1.1-cost-benefit-analysis-and-cost-and-performance-target-for-large-scale-pem-electrolyser-stack.pdf
Scenario 2: Pipeline transport: Leakage from high pressure pipeline			
S. No.	Project Name	Project Description	Source
	Safe Pipelines for Hydrogen Transport (under development)	Comprehensive materials screening program of four vintage pipelines and one new steel pipeline carried out in 2020 (subsea transportation of hydrogen). Mechanical test results clearly show degradation of the old pipelines due to hydrogen. Further studies are being performed on two X65 pipeline steels for analysis of microchemical properties, fatigue and fracture resistance.	Source: Research Council of Norway Organisation: Technical-Industrial Institutes, SINTEF AS, NTNU, Kyushu University Japan; Trondheim https://www.sintef.no/globalassets/projectweb/greenh2webinars/20210324-green-h2-webinar---sintef-hydrogen-pipelines.pdf
Scenario 3: Road Transport: H2 leakage in confined space/ built-up areas **Scenario 4: Mobility and partially confined space: a hydrogen city bus driving in a tunnel is involved in a traffic accident** **Scenario 5: Mobility and partially confined space: accidents at a hydrogen fuel station**			
3	Infrastructure for Materials Research for Transporting Hydrogen (SMART-H) (under development)	Study to tackle hydrogen embrittlement. SMART-H is a research infrastructure consisting of 4 labs to analyse hydrogen in metals, macro-scale mechanical testing in high pressure hydrogen, nano and micro-scale mechanical testing in hydrogen and materials informatics lac for consolidating experimental works. Research Issues: How much and how fast hydrogen enters and diffuses in various materials. Primary mechanisms that govern distribution of hydrogen in the structure of the material and the related material degradation. Effect of hydrogen gas pressure and temperature on material properties, strength, fracture and fatigue resistance.	Source: Research council of Norway Organisation: Norway's Technical Natural Science University, Trondheim https://prosjektbanken.forskningsradet.no/
4	H2Moves Scandinavia 2010-2012 (completed)	The Scandinavian hydrogen highway partnership (SHHP) road-tested a fleet of hydrogen-fuelled cars and a state of the art refuelling station in Oslo. Project goal was to create a hydrogen-fuelled network of 15 main and 30 satellite refuelling stations along with a fleet of 100 buses, 500 cars and 500 specialty vehicles by 2015. The Oslo refuelling station which opened in 2011 has a capacity of 200 kg/day and refuelling of 20 kg/hour. The refuelling is as per SAE standards. Hydrogen is produced onsite as well as through truck delivery.	https://cordis.europa.eu/article/id/90044-hydrogen-fuelled-transport-infrastructure
5	Risk assessments of hydrogen refuelling station concepts based on onsite production (2003) (completed)	Study commissioned under then EC funded research project European Integrated Hydrogen Project 2 (EIHP2) Analysis performed of both compressed gas and liquified systems. Some risk reducing measures suggested are as follows: i) Transportation of refrigerated ammonia (in case of ammonia splitting) should be considered.	http://www.eihp.org/public/Reports/Final_Report/Sub-Task_Reports/ST5.2/RISK%20ASSESSMENTS%20OF%20H2-REFUELLING%20STATION_Onsite_%20CONCEPTS.pdf

		ii) Area should be cordoned off during ammonia unloading iii) Filling hose design to withstand external impact iv) Regular checks of rupture valves v) Driver should be present during refuelling In addition to this several other suggestions have been made including continuous measurement of H2 in O2, gas detection and emergency ventilation, appropriate material selection etc. Safety Distances: in addition to strict inspections and quality preconditions, sabotage should also be factored in. Walls and fences around the fuelling station should be designed in a way that allows for leaking hydrogen to escape upwards. Ignition Sources (forbidden): Prominently placed notices for smoking, open fire and mobile phone use should be placed.	
6	Hydrogen powered fuel cell forklifts, field demonstration and durability studies (HyLift-DEMO) (several phases completed)	Large scale demonstration of hydrogen powered FC material handling vehicles, which enables a following deployment and commercial market introduction. 30 material handling vehicles and corresponding hydrogen refuelling infrastructure demonstrated. Project contributed to the establishment of appropriate regulations, codes and standards (RCS) framework.	Source: Research council of Norway Organisation: SINTEF (for work package related to demonstration monitoring and target validation) https://cordis.europa.eu/project/id/256862/reporting HyLift-DEMO Final Report: https://cordis.europa.eu/docs/results/256/256862/final1-hylift-demo-final-report-v08.pdf

Incidents

S. No.	Scenario	Description	Analysis
1	5	In 2012, hydrogen was found leaking from a HRS due to a defect in the high pressure dispenser hose. The leak was extremely small and the gas was directed upward. Secondly, all safety equipment worked as per design and the system automatically shut down.	Possible reason for the defect was due to extreme temperature swings of -15º and -18º Celsius
2	5	In 2019, 1.5 to 3 kg of hydrogen leaked from high pressure storage due to human error as the two bolts securing the gaskets were not tightened well.	Human error was identified as the cause of the accident. The bolts which were to be tightened manually had not been done optimally. Stricter outer perimeter requirements to shield public, and stronger protocols from manufacturers and double witnesses at maintenance activities are some of the measures to mitigate risk.

Concluding remarks: Norway

Studies from Norway suggest that while steps are being taken towards energy transition to hydrogen, much of the focus is on the large-scale use of hydrogen, for instance in maritime and industrial use. This is not to say that no efforts have been made for small scale use of hydrogen. The country has ambitious plans of ramping up its hydrogen infrastructure and is in partnership with other Scandinavian nations concerning this. Several projects funded by ENOVA and the Research Council of Norway under the National Strategy are studying the risks and potential benefits emerging from hydrogen use in urban mobility, pipeline infrastructure, material selection etc. Results from these projects will be ready in the coming years. Evidence of results from previous studies is still low suggesting that much of the information may still not be publicly available.

Three incidents involving hydrogen leaks from HRSs have been recorded in Norway. The latest, in 2019, resulted in the leakage of 1.5 to 3 kg of hydrogen from high pressure storage due to human error. Another incident in 2012 was due to a defect in a dispenser hose, caused likely by the very low temperatures.

Stricter outer perimeter requirements to shield public, stronger protocols from manufacturers and double witnesses at maintenance activities are some of the suggested mitigation measures to make HRSs safer.

Status of project: Norway

Norway	Status
H2Moves Scandinavia 2010-2012	Completed
Risk assessments of hydrogen refuelling station concepts based on onsite production 2003	Completed
Hydrogen powered fuel cell forklifts, field demonstration and durability studies (HyLift-DEMO)	Several phases completed
Electrolyser 2030- Cell and Stack	Under development
Safe Pipelines for Hydrogen Transport	Under development
Infrastructure for Materials Research for Transporting Hydrogen (SMART-H)	Under development

Russia

Scenarios

S. No	Project name	Project description	Source
Scenario 1: Production: Leakage from the pipe connected to electrolyser			
1	Hydrogen Clusters - Obasts (Under Development) Organizations: Rosatom, Federal Ministry for the Development of Far East and the Artic	Creation of three unique regional hydrogen clusters in Russia: in the Far East (Sakhalin), the northwest (St. Petersburg) and the Arctic. In April 2021, Rosatom, the Sakhalin Government and Russia's Federal Ministry for the Development of the Far East and the Arctic signed an official cooperation agreement on the creation and development of this cluster. Production of hydrogen to be exported to Japan and other asian countries. Production of hydrogen to be used in hay-duty mining equipment and passenger transport. The northwestern cluster will be located in St. Petersbourg and will focus on the production of hydrogen through electrolysis at the Leningradskaya power plant to be exported and used in the industrial process(Steel industry, cement production) and transportation. The Arctic cluster will focus on the use of hydrogen for energy storage in remote and isolated areas to ease the gap of remote areas not connected to the national grid.	O.E. Aksyutin et al. The contribution of the gas industry to the formation of an energy model based on hydrogen. / Vesti gas science - scientific and technical collection. Environmental protection, energy saving and labor protection in the oil and gas complex. Special edition - 2017, p. 12 https://www.swp-berlin.org/10.18449/2021C34/ https://energy.skolkovo.ru/downloads/documents/SEneC/Research/SKOLKOVO_EneC_Hydrogen-economy_Eng.pdf
2	Snezhinka zero-carbon international Arctic research station - (Under Development) planned to open in 2023	A pilot project using hydrogen-based solutions for energy storage and transportation.	https://arctic-mipt.com/en
3	NLMK site (Under Development) Organizations: NLMK, Air liquide	Cooperation between the leading steel producer in Russia NLMK and Air Liquide (France) in developing its hydrogen assets and reducing the carbon footprint of its steel. Air Liquide will invest around 100 million euros in the flagship site of NLMK in Lipetsk	https://www.airliquide.com/group/press-releases-news/2020-07-16/air-liquide-signs-new-long-term-contract-leading-steel-producer-nlmk-russia
4	Gazprom Vodorod (Hydrogen) (Under Development)	Gazprom announced in December 2021 the creation of a newco to develop its own technologies aimed at producing methane-hydrogen mixtures and hydrogen from methane without carbon dioxide emissions. The company also wants to build the infrastructure necessary for the product transportation aiming at involving the Nordstream2 project	http://www.gazpromexport.ru/files/BLUE_FUEL_48326.pdf

S. No	Project name	Project description	Source
		in the wider plan.	
5	Rusnano - Enel Russia Wind based Green Hydrogen power plant in Murmansk - 2021 (Under Development) Due 2024	Rusnano and Enel Russia agreed to implement Russia's first project on green hydrogen production at a wind power plant in the Murmansk region. The project is planned to produce 12 thousand tonnes of hydrogen per year and to export it to the EU; Estimated investment $320 million.	https://www.enelrussia.ru/en/media/news/d2021-6/08062021 https://www.h2bulletin.com/enel-russia-rusnano-green-hydrogen/
6	Kolskaya NPP - 2020 (Completed)	A pilot project to construct infrastructure for the development of hydrogen energy technologies and electrolysis production is to be implemented at Kolskaya NPP in the Murmansk region.	https://hydrogenru.com/en/investment-projects/#:~:text=Rusnano%20and%20Enel%20Russia%20intend,is%20estimated%20at%20%24320%20million.
Scenario 2: Pipeline Transport: Leakage from high pressure: Leakage from high pressure pipeline			
7	Russian-Japan agreement 2020-2021 (agreement signed. Supply yet to start)	In september 2019 Rusatom Overseas, the subsidiary of the state company Rosatom, signed an agreement with the Agency for Natural Resources and Energy of the Ministry of Economy, Trade and Industry of Japan to start a feasibility study of a pilot project for the hydrogen export from Russia to Japan. A pilot export project considers the possibility of producing hydrogen for the Japanese market by electrolysis. The ambition is to supply up to 40% of Japan's demand by 2030, and potentially to other Asian Pacific countries.	https://hydrogenru.com/en/investment-projects/#:~:text=Rusnano%20and%20Enel%20Russia%20intend,is%20estimated%20at%20%24320%20million.
Scenario 3: Road Transport: H_2 leakage in a confined space/ built environment			
8	Liquefied Hydrogen for the national Space Programme. (Completed)	Scientific and experimental developments in the field of liquefying and transporting hydrogen in a liquefied state were carried out by the NPO Geliymash94 for the space programme of Russia and by PJSC Cryogenmash The creation of cryogenic complexes for hydrogen liquefaction, its long-term storage and transportation by railroads and highways began in the 1960s, primarily in connection with the widespread use of liquid hydrogen as a fuel for rocket and space systems.	http://geliymash.ru/production/vodorodnye-ozhizhiteli/ https://www.cryogenmash.ru/catalog/vodorodnoe-oborudovanie/
Scenario 4: Mobility and partially confined space: a hydrogen city bus driving in a tunnel is involved in a traffic accidents			
9	Vtek project Yekaterinburg - 2015 (Completed)	In 2015 a pilot project of a hydrogen transportation and energy complex (vtek) was launched in the city of Yekaterinburg on the bus route of the railway station and airport "koltsovo".	https://www.isjaee.com/jour/article/view/188/191 http://h2org.ru/images/stories/rauvtek2015.pdf
10	Sakhalin H2 Train - 2019 (Completed) Organizations: Rosatom, RZD, Sakhalin Oblast Government	In 2019 a cooperation between Rosatom, Russian Railways (RZD), Transmashholding and the Sakhalin Oblast regional government signed an agreement to develop the first project on the use of hydrogen in rail transport. This will see the launch by 2025 of seven suburban hydrogen trains with 13 more by 2030.	https://hydrogenru.com/en/investment-projects/#:~:text=Rusnano%20and%20Enel%20Russia%20intend,is%20estimated%20at%20%24320%20million.
11	St. Petersburg retrofitted single-section LM-68M2 hydrogen-powered tram - 2019 (Completed) Organizations: City council, Central Research Institute of Electrical & Marine Technology.	On November 1 2019 the city of St. Petersburg operated the testing of a hydrogen fuel cell retrofitted single-section LM-68M2 tram created jointly by the operator Gorelektrotrans and the Central Research Institute of Electrical & Marine Technology.	https://fuelcellsworks.com/news/russia-hydrogen-fuel-cell-tram-tested-in-st-petersburg/
12	Hydrogen buses - 2020 (Under Development) Organizations: InEnergy, KAMAZ	The fast growing startup InEnergy is partnered with Russia's truck making giant, KAMAZ which recently included hydrogen-powered buses and trucks in its R&D programme for 2021, to develop hydrogen bus prototypes, with expected presentation this year.	https://www.swp-berlin.org/10.18449/2021C34/

S. No	Project name	Project description	Source
Scenario 5: Mobility and partially confined space: accidents at a hydrogen fuel station			
13	Refuelling stations - National Hydrogen strategy 2030 (Under development) Organizations: Federal Government	Currently Russia has only one refuelling station in Chernogolovka. The country's hydrogen strategy projects the build-up of 100 refuelling stations by 2025. And to reach 300 in 2028 and 200 hydrogen refuelling sites — in each of 2029 and 2030.	https://tass.com/economy/1329193
Scenario 6: Residential use: Safety of Hydrogen in buildings with focus on hydrogen cooking stoves and boilers			
No examples found of pilot projects under this scenario			

Concluding remarks: Russia

Russia is one of the major energy producers with major companies such as Gazprom, Rusatom and Novatek leading at global level. With export of gas accounting for a great share of its economy, the country is focusing on seizing its opportunity on hydrogen by exploiting its advanced gas transportation infrastructure and its longstanding hydrogen production history for military and space exploration purposes. On this note the hydrogen strategy of the country is rounded up on three main pillars: Development of pilot projects for hydrogen exports, development of hydrogen clusters in the domestic market and development of fundamental and applied research on hydrogen.

The three main pillars support the production side with a focus on technologies for producing "grey" hydrogen in Russia. They are deployed at oil and gas processing plants (methane conversion) and power plants (electrolysis). All hydrogen produced is used onsite - for example, to improve the quality of hydrocarbon processing or in the cooling systems of power generators. Russia is focusing on projects to export hydrogen to targeted markets such as Japan and Germany/Europe.

Concerning the other 5 scenarios, few projects are in place, based mostly on three main production clusters to support key industries, all mostly based on the initiative by private companies.

The mobility sector is set to become the first hydrogen technology niche in Russia for a number of reasons: there are emerging Russian technology providers, concrete pilot projects (such as the Sakhalin hydro-gen train), and an interest on the part of investors. This is supported by the project of building several refuelling stations beyond the only one present in the country. An exception to the relatively new interest in hydrogen is provided by the state's Space Program that has been experimenting on the use - as fuel for its rocket since the 1960s - of liquified hydrogen transported via road by tanks.

There is no evidence of projects concerning the residential use of hydrogen for domestic heating and cooking.

Status of project: Russia

Russia	Status
Liquefied Hydrogen for the national Space Programme.	Completed
Vtek project Yekaterinburg - 2015	Completed
Sakhalin H2 Train - 2019	Completed
St. Petersburg retrofitted single-section LM-68M2 hydrogen-powered tram - 2019	Completed
Kolskaya NPP - 2020	Completed
Hydrogen Clusters - Obasts	Under development
Snezhinka zero-carbon international Arctic research station - planned to open in 2023	Under development
NLMK site	Under development
Gazprom Vodorod (Hydrogen)	Under development

Russia	Status
Rusnano - Enel Russia Wind based Green Hydrogen power plant in Murmansk - 2021-2024	Under development
Russian-Japan agreement 2020-2021 (agreement signed. Supply yet to start)	Under development
Hydrogen buses - 2020	Under development
Refuelling stations - National Hydrogen strategy 2030	Under development

South Korea

Scenarios

S. No	Project Name	Project description	Source
1	Hydrogen pilot cities, 2019 (under development)	In 2019, the Korean government identified three cities that will serve as "hydrogen pilot cities". These cities are Ulsan, Ansan, and Wanju. As part of the hydrogen pilot city program, the necessary infrastructure will be built for hydrogen production and distribution, so that the produced hydrogen will be used for heating, cooling, transport and electricity supply. The pilot cities will launch demonstration projects and begin testing the application of hydrogen in transportation, industry, and space heating in 2022. The cities will obtain their hydrogen from different sources. Ulsan seeks to produce hydrogen from local petrochemical complexes to power buildings and to refuel FCEVs and ships. Ansan, while still getting most of its hydrogen supply from natural gas reforming, also plans to supply green hydrogen from the Sihwa Lake Tidal Power Station (254 MW). Wanju will also serve as a hydrogen production site, while the nearby city of Jeonju will act as a demand centre.	South Korea's hydrogen strategy and industrial perspectives (Kan, 2018[11]).
Scenario 1: Production: Leakage from the pipe connected to electrolyser			
2	Green hydrogen floater, (2021-2030) (under development)	South Korea is researching a scheme to develop an offshore green hydrogen plant based on a floating production, storage and offloading vessel using offshore wind power to produce the hydrogen. A consortium was established to spearhead initial engineering of a newbuild hydrogen FPSO (Floating production storage and offloading), which will later be rolled into a pilot project. The consortium, led by Korea Maritime & Ocean University (KMOU), aims to produce a 1 MW pilot plant in 2022 before developing and demonstrating a gigawatt-class plant in 2030. KMOU will carry out the research, development and demonstration of the H-FPSO using the university's patented floating technology from a previous project in which it built a floating nuclear power system.	https://www.upstreamonline.com/energy-transition/south-korea-makes-splash-with-green-hydrogen-floater-plan/2-1-1055407
3	Donghae offshore wind plant and green hydrogen plant (2021-2025) (under development)	The Korea National Oil Corporation (KNOC) and the Korean power company Korea East-West Power (EWP) plan to develop Korea's first large-scale floating offshore wind farm with a preliminary feasibility study, conducted by the Korea Development Institute (KDI), completed in 2021. This wind farm, if completed as proposed, will be the largest in the world. The project will commence construction in 2022 with the aim of generating power by 2024. Along the 200 MW wind farm, a 100 MW hydrogen plant will be built in the East Sea with the aim of generating green hydrogen. Hydrogen will be produced from seawater using the electricity generated from the wind farm.	https://www.maritime-executive.com/article/korea-adds-hydrogen-plant-as-it-approves-giant-floating-wind-farm-plan
4	P2G demonstration project and hydrogen tank	A government-funded, three-year demonstration project about electricity generation from hydrogen took place at Gangwon Technopark. As part of this project, electricity generated by photovoltaic arrays was used to generate hydrogen using a water	HIAD 2.0 hydrogen incident and accident database

S. No	Project Name	Project description	Source
	explosion at Gangwon Technopark, in Gangneung (2016 - 2019) (interrupted)	electrolyser. During the final year of the project, (May 2019) a hydrogen tank exploded, leaving two people dead and six injured. Three hydrogen storage tanks with a capacity of 400 m^3 each (operating pressure of 1 MPa) were destroyed in the explosion. There was no secondary fire and the damage was caused merely by the detonation pressure. The equivalent TNT of the explosion was estimated to be of about 50 Kg based on the damage nearby. Within a 15 m distance from the hydrogen tank, the structure beam of the building was damaged and most of the windows of a 5-story building about 100 m away were crushed. A preliminary investigation concluded that the hydrogen and buffer tanks exploded due to a static spark in the hydrogen buffer tank, with oxygen concentration exceeding 6%, which is the explosion threshold. The presence of oxygen in the hydrogen stream was due to the wrong operation of the water electrolyser. The system had to be operated above 98 kWh, however, due to the characteristics of the solar panels providing the power, the system often operated below this threshold. The investigation has also identified contributing causes: An oxygen removing component was not used in the final design, as well as a static spark remover in the hydrogen buffer tank. This was probably done to reduce costs. When oxygen concentrations higher than 3% were detected, it was decided to continue operation to achieve the 1000 hrs of operation necessary to validate the tests. The hydrogen quality was not tested daily as required. This accident would not have happened if the appropriate operating procedures had been followed and if the required safety measures had been put into place. Lessons learnt The following corrective actions are required: Investigation into the relationship between the gas permeability of the electrolyser membrane and dynamic operation range caused by the variability of renewable power sources Improvement of standardised performance and safety tests, aiming at defining more realistic testing requirements and conditions at partial/low load cycles. Further mitigation measures should be put into place, e.g. an in-situ diagnostic system able to trigger emergency stops of the hydrogen production system and an automatic isolation of the storage.	
Scenario 4: Mobility and partially confined space: a hydrogen city bus driving in a tunnel is involved in a traffic accident			
5	Hydrogen buses (2022) (under development)	The South Korean government has announced its intention to subsidise the purchase of 624 hydrogen buses that will operate in the southern provinces of the country by the end of 2025. Local private bus companies in Busan, Ulsan and Gyeongnam province will therefore only pay 320 million won (235 000 euros) per hydrogen bus to replace the diesel and compressed natural gas buses that are currently in operation. It is intended that hydrogen buses will begin operating in pilot projects in the three provinces in the first half of 2022.	https://fuelcellsworks.com/news/south-korean-authorities-to-spend-157m-subsidising-worlds-largest-ever-order-for-hydrogen-buses/
Scenario 5: Mobility and partially confined spaces: accidents at a hydrogen fuel station			
6	Hydrogen Energy Network (HyNet), (2019-2029) (under development)	Hydrogen Energy Network (HyNet) was established as a joint venture between 13 leading industrial companies in South Korea, with the aim of expanding the nation's hydrogen refuelling infrastructure by installing 100 stations by 2022 and operating them until 2029.[1] As of January 2022, South Korea has 112 hydrogen refuelling stations (HRSs). The government's intention is to roll out at least 2000 HRSs by 2050.[2] As of 2019, Korean regulation dictates that only trained	(Stangarone, 2021[12]) https://www.iphe.net/republic-of-korea, (Keller, Hamilton and Harris, 2019[13])

S. No	Project Name	Project description	Source
		personnel are allowed to do the hydrogen fuelling.[3]	
7	Mobile liquid hydrogen refuelling station (2018) (completed)	The world's first mobile liquid hydrogen refuelling station was launched in Korea by Hylium Industries. The station is a five-tonne truck carrying fuelling equipment, consisting of a liquid H_2 pump, a vaporiser, and a dispenser. It has a capacity of 7,500 litres of low-pressure (3 bar) liquid H_2 and can provide fuel for up to 100 H_2-powered cars per day. The liquid H_2 used has a high purity of over 99.995%. The main advantage of the refuelling station is that it uses a 900 bar liquid H2 pump system. As a result, it eliminates the need for a compressor and cooling system, significantly reducing equipment and driving costs.	http://www.ihfca.org.cn/index.php?m=content&c=index&a=show&catid=8&id=121
Other projects			
8	Hyosung pilot project (2021-2022) (under development)	The company Hyosung has launched a demonstration project that will generate electricity from the hydrogen byproduct produced at its Hyosung Chemical Yongyeon Plant facility. The plant produces propylene through propane de-hydrogenation and up to 13 000 tons of hydrogen byproduct are generated annually during this process. The demonstration project will result in a reduction in Hyosung's carbon emissions, while at the same time providing electricity for the facilities' operations. Hyosung selected INNIO Jenbacher hydrogen engine technology for their demonstration project, in what is South Korea's first demonstration project using an engine fueled by hydrogen to produce electricity.	https://www.innio.com/en/news-media/magazine/article/hyosung-s-hydrogen-to-help-power-its-business-in-south-korea
9	Shinhincheon Bitdream Centre (2017-2021) (Completed)	The Shinincheon Bitdream Fuel Cell Power Plant in Incheon is a power plant with a total capacity of 78 MW constructed at the Shinincheon Bitdream headquarters of Korea Southern Power by using fuel cells supplied by POSCO Energy and Doosan Fuel Cell. It is the world's largest fuel cell power plant currently in operation, capable of supplying electricity to 250.000 households annually. The expected benefits from its operation are: a) the provision of clean air to local residents by purifying fine dust emitted from the LNG (liquefied natural gas) thermal power plant at the Shinincheon Bitdream headquarters, b) the production of hot water for heating for 44 000 households and c) the supply of inexpensive heat through local heating companies.	https://www.devdiscourse.com/article/international/1784161-worlds-largest-hydrogen-fuel-cell-power-plant-was-built-in-korea
10	Bloom Energy and SK Engineering & Construction Co Ltd pilot plant (2020) (under development)	Bloom Energy and SK Engineering & Construction Co Ltd have deployed in South Korea 100 kW of solid-oxide fuel cells (SOFC) that are powered by hydrogen, as part of a demonstration project announced in July 2020. The SOFCs will use the hydrogen byproduct generated by SK Advanced to produce electricity. A 1-MW unit of Bloom Energy's Energy Server fuel cell-based distributed power generation system will be installed by 2022. In 2022, Bloom Energy will also ship solid-oxide electrolyser cells (SOEC) to South Korea for the production of green hydrogen, which will be used to power the SOFC.	https://renewablesnow.com/news/bloom-energy-finalises-100-kw-fuel-cell-pilot-project-in-korea-739407/
11	Hyundai Oilbank blue hydrogen ecosystem (2021-2025) (under development)	Hyundai Oilbank will establish by 2025 a "blue hydrogen ecosystem" that will produce 100,000 metric tons of blue hydrogen annually. The carbon byproducts generated by the production process will be used in commercial products such as dry ice. Hyundai Oilbank will collaborate with Air Products and use its blue hydrogen technologies for the blue hydrogen ecosystem, aiming to later on expand the partnership to the generation of green hydrogen.	http://www.koreaherald.com/view.php?ud=20210531000636

Concluding remarks: South Korea

In 2019, South Korea published a roadmap for the promotion of a hydrogen-based economy focusing mainly on the use of hydrogen in the transportation sector, on decarbonising industry and buildings, and on the building of the necessary infrastructure for the production and distribution of hydrogen. With the eventual aim of powering 10% of the country with hydrogen by 2030, the Korean government identified three cities as "hydrogen pilot cities" (Ulsan, Ansan, and Wanju). These pilot cities will begin testing the application of hydrogen in transportation, industry, and space heating in 2022. A Hydrogen Law was put into place to lay the legal foundations for the government's promotion of hydrogen and the implementation of safety standards for facilities. This law went into effect in 2021 and stipulates several important industrial strategy elements, such as supporting hydrogen-focused companies through research and development (R&D) subsidies, loans, and tax exemptions.

South Korea's hydrogen strategy is very ambitious, but it is mainly focusing on the scale up of the production of carbon-intensive hydrogen generated by petrochemical plants or by natural gas reforming. As such, this strategy is not as climate-friendly as that of other countries', since there are no immediate plans in place to decarbonise the industry sector.

A lot of South Korea's R&D efforts revolve around liquefied hydrogen storage technology and the reduction of transportation costs. Additionally, the government's long-term aim is to build a hydrogen pipeline network across the country, with the development of the appropriate infrastructure beginning in 2022. The Korean government has also committed $2.34 billion (2.14 billion euros) to the establishment of a public-private hydrogen vehicle industry by 2022.

A major accident took place in Gangneung, Korea in 2019, during a demonstration project involving electricity generation from hydrogen. The accident caused the deaths of two people and injured six. Hydrogen and buffer tanks in the facility exploded due to a static spark in the hydrogen buffer tank. Oxygen was present in the hydrogen tank due to wrong operation of a water electrolyser, which was coupled to solar panels. The accident could have been prevented if the proper operating and safety procedures had been followed. To prevent future incidents, investigation is required into the proper operating conditions for the electrolyser. The standardised performance and safety tests should also be improved, and further mitigation measures should be put into place, such as, e.g., an in-situ diagnostic system able to trigger emergency stops of the hydrogen production system and an automatic isolation of the storage.

Status of project: South Korea

South Korea	Status
P2G demonstration project at Gangwon Technopark, Gangneung – 2016-2019	Interrupted
Shinhincheon Bitdream Centre – 2017-2021	Completed
Mobile liquid hydrogen refuelling station – 2018	Completed
Hydrogen pilot cities – 2019-~	Under development
Green hydrogen floater – 2021-2030	Under development
Donghae offshore wind plant and green hydrogen plant – 2021-2025	Under development
Hydrogen buses – 2022-	Under development
Hydrogen Energy Network (HyNet) – 2019-2029	Under development
Hyosung pilot project – 2021-2022	Under development
Bloom Energy and SK Engineering & Construction Co Ltd pilot plant – 2020 -	Under development
Hyundai Oilbank blue hydrogen ecosystem – 2021-2025	Under development

United Kingdom

Scenarios

S. No	Project Name	Project description	Source
Scenario 1: Production: Leakage from the pipe connected to electrolyser			
1	Trafford Green Hydrogen - 2021 (Under development)	H2 Electrolyser (10 MWe – 200 Mwe) Carlton Power’s Trafford Green Hydrogen is developing a 10 MWe hydrogen electrolyser plant at Carrington in Greater Manchester. The project will use onsite and offsite renewable energy to produce green hydrogen fuel for transport and heating.	https://www.traffordgreenhydrogen.co.uk/theproject
2	HyGreen Teesside project - 2025 (Under development)	60 MWe of ‘green’ hydrogen production by 2025? strengthening Teesside role as UK’s leading hydrogen hub to decarbonize industry ?and heavy transport The two projects combined will potentially deliver 30% of the UK’s ??2030 target for hydrogen production?.	https://www.bp.com/en/global/corporate/what-we-do/gas-and-low-carbon-energy/h2teesside.html https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/news-and-insights/press-releases/bp-plans-major-green-hydrogen-project-in-teesside.pdf
3	HyNet North West - 2025 (Under development)	The focus of the project is to produce, store and distribute low carbon hydrogen as well as capture and lock up carbon dioxide emissions from industry. It will develop a 100 000 Nm^3 per hour clean hydrogen production facility for deployment as part of the HyNet Cluster By the year 2030 it will cut carbon emissions by 10 million tonnes every year – the equivalent of taking 4 m cars off the road	https://hynet.co.uk/
4	Gigastack (Under development)	Developing electrolyser technology to produce renewable hydrogen at large-scale the project is also aimed at developing a system that uses electricity from Orsted’s Hornsea. Two offshore wind farm to generate renewable hydrogen for the Phillips 66 Humber Refinery	https://gigastack.co.uk/
5	Acorn Hydrogen Project (Under development)	The project will reuse 420 km of existing offshore pipeline through the National Transmission System to transport hydrogen into homes, offices and factories across the UK	https://theacornproject.uk/ https://theacornproject.uk/documents/
Scenario 3: Road Transport: H2 leakage in a confined space/ built environment			
6	NPROXX type 4 vessels. (Completed)	NPROXX developed the first certified Type 4 pressure vessel for hydrogen storage infrastructure, refuelling stations and hydrogen-powered vehicles with a working pressure of 350 bar, 500 bar and 700 bar. The 500 bar pressure vessels offer a usable H2 capacity of 6.2kg	https://www.nproxx.com/capabilities/type-4-pressure-vessels/
7	Project Hystor (Completed)	High-Pressure storage hydrogen tank was developed by a consortium of UK aimed for use in large good vehicles (HGV), bus and off highway applications.	https://www.boconline.co.uk/en/products-and-supply/hydrogen-energy-solutions/hydrogen-distribution-storage.html
Scenario 4: Mobility and partially confined space: a hydrogen city bus driving in a tunnel is involved in a traffic accidents			
8	Hydrogen Transport Programme (HTP) - 2017 (Under development)	The HTP program is an umbrella funding program aimed at the deployment of 5 new hydrogen refuelling stations, 73 fuel cell electric vehicles and 33 fuel cell electric buses. The winning projects are dispersed across the UK with activities in Northern Ireland (Belfast), Scotland (Aberdeen), Wales (Monmouthshire) and England (Crawley, St. Helens, Middlesbrough and Stockton on Tees).	https://ee.ricardo.com/htpgrants#:~:text=The%20Hydrogen%20for%20Transport%20Programme,the%20deployment%20of%20new%20vehicles.
9	UK H2Mobility (Under development)	It is a consortium partnership of leading UK industrial players with an interest in hydrogen mobility, working with the Government to develop hydrogen-fuelled transport.	
10	Air Products Go-Ahead Hydrogen bus supply - June 2022	The project aims at decarbonising the UK's transport sector with the partnership between Air Products and Go-Ahead to provide a fleet of 20 hydrogen fuel cell buses that will be deployed in Crawley, Horley, and the Gatwick Airport areas of	https://newsroom.go-ahead.com/news/go-ahead-selects-air-products-as-partner-for-pioneering-hydrogen-bus-fleet#:~:text=Go%2DAhead%20selects%20Air%20Products%20as%20partner%20for

S. No	Project Name	Project description	Source
	(Under development)	the United Kingdom.	%20pioneering%20hydrogen%20bus%20fleet,-Air%20Products%20to&text=The%20Go%2DAhead%20Group%20has,Airport%2C%20Crawley%20and%20Horley%20area.
11	Tees Valley multi-modal hydrogen transport hub - 2025 (Under development)	Tees Valley to become home to the UK's first-ever hydrogen transport hub Pop-up trials could see local shops, supermarkets and transport benefitting from cutting-edge hydrogen tech to power transport and move goods The hub could be fully operational by 2025 The UK government is funding several projects to accelerate the use of hydrogen transport in the Tees Valley region, including diesel buses retrofitted with hydrogen fuel cells, supermarket chains benefiting from hydrogen delivery vans, and the police and National Health Service using hydrogen vehicles.	https://www.gov.uk/government/news/uks-first-ever-hydrogen-transport-hub-kick-started-by-3-million-government-investment
12	Hydroflex (Hydrogen train) trial - 2020 (Completed)	After two years of development the HydroFLEX train went out on trial on UK's mainline travelling for 40 km through Warwickshire and Worcestershire. The ground-breaking technology behind the trains will also be available by 2023 to retrofit current in-service trains to hydrogen.	https://www.bbc.com/news/av/business-54350046 https://www.porterbrook.co.uk/hydroflex-cop#:~:text=HydroFLEX%20offers%20zero%2Demission%20rail,'tri%2Dmode'%20train.
13	Alstom - Eversholt Rail agreement to build hydrogen train fleet (Under development)	The two companies agreed to design, build, commission and support a fleet of 10 three-car hydrogen multiple units (HMUs)	https://www.alstom.com/press-releases-news/2021/11/alstom-and-eversholt-rail-sign-agreement-uks-first-ever-brand-new
14	The FlyZero project - 2021 (Under development)	The FlyZero project, led by the ATI and funded by the UK government, has developed a concept for a midsize aircraft powered by liquid hydrogen. It is capable of flying 279 passengers halfway around the world without a stop or anywhere in the world with just one stop to refuel.	https://www.ati.org.uk/flyzero/ https://www.gov.uk/government/news/government-backed-liquid-hydrogen-plane-paves-way-for-zero-emission-flight
Scenario 5: Mobility and partially confined space: accidents at a hydrogen fuel station			
15	Kittybrewster, Aberdeen - 2015 (Completed)	Aberdeen City Council partnered with BOC to deliver a commercially viable hydrogen refuelling station using proven technology to power one of Europe's largest fleets of hydrogen buses. Fast refuelling – 10 minutes for a bus, 5 minutes for a car opened in 2015 to refuel single-deck buses. Scaled up in 2018 for cars and vans, and in 2019 double decker buses.	https://www.boconline.co.uk/en/images/Case%20study%20Kittybrewster%20Aberdeen%20hydrogen%20refuelling%20station_tcm410-563229.pdf
16	Element 2 Ways2H project (Under development)	Partnership between Element 2 and Ways2H to deliver 40 waste-to-hydrogen (facilities that convert waste into hydrogen gas) refuelling stations in the UK as part of Element 2's plans to deploy over 800 hydrogen pumps in the UK by 2027, and 2 000 by 2030.	https://www.element-2.co.uk/news/new-partnership-from-ways2h-and-element-2-brings-40-waste-to-hydrogen-refuelling-stations-to-the-uk-beginning-in-scotland#:~:text=Under%20the%20partnership%2C%20Ways2H%20will,day%20of%20renewable%20hydrogen%20fuel.
17	Hydrogen stations (Completed)	11 hydrogen stations are open and active in the United Kingdom.	http://www.ukh2mobility.co.uk/stations/ https://www.drivingelectric.com/hydrogen/1363/where-can-i-buy-hydrogen-and-where-is-my-nearest-hydrogen-filling-station
Scenario 6: Residential use: Safety of Hydrogen in buildings with focus on hydrogen cooking stoves and boilers			
18	H21 Hydrogen for Leeds (Under development)	The project aims at supplying the population 760,000 of leeds hydrogen for heating and cooking over the next fifteen years. It will repurpose the existing gas infrastructure by redesigning the gas network to establish a high pressure (17 bar) outer city ring main transporting methane (CH4) to steam methane reforming (SMR) plants for distribution into the network (below	https://www.kiwa.com/4a3d51/globalassets/uk/pages/hydrogen/h21-report-interactive-pdf-july-2016.compressed.pdf https://h21.green/about/

S. No	Project Name	Project description	Source
		7 bar).	

Concluding remarks: United Kingdom

The UK envisages hydrogen as a new low carbon solution which can help the UK to achieve net zero by 2050, and its Sixth Carbon Budget target by 2035. The main focus is to capture the economic benefits of growing the UK hydrogen economy, supporting innovation and stimulating investment to develop the supply chains and skills needed and create jobs and export opportunities for the UK. On this note the government is directly investing in hydrogen pilot projects working with industry to achieve a 5 GW of low carbon hydrogen production capacity by 2030 as set out in the 10 point plan for a green industrial revolution.

The government released its Hydrogen strategy in August 2021, outlining a comprehensive roadmap for the development of the wider hydrogen economy over the 2020s to deliver its 2030 5 GW ambition.

The strategy is centred around the production side and the use of the existing national infrastructure in the North Sea to further deploy hydrogen through the pipeline system. The major innovative push towards hydrogen for heating and cooking in domestic homes started with a blended mix of up to 20% v/v of hydrogen with natural gas. There is an aim to build a new set of refuelling stations, thus strengthening the recharging infrastructure services. Several private sector actors are running pilot projects on hydrogen use, often cooperating with universities and local governments participating in tenders and competitions for government funding.No major accidents are reported concerning the projects described.

Status of project: United Kingdom

United Kingdom	Status
NPROXX type 4 vessels.	Completed
Project Hystor	Completed
Hydroflex (Hydrogen train)trial – 2020	Completed
Kittybrewster, Aberdeen – 2015	Completed
Hydrogen stations	Completed
Trafford Green Hydrogen – 2021	Under development
HyGreen Teesside project – 2025	Under development
HyNet North West – 2025	Under development
Gigastack	Under development
Acorn Hydrogen Project	Under development
Hydrogen Transport Programme (HTP) – 2017	Under development
UK H2Mobility	Under development
Air Products Go-Ahead Hydrogen bus supply – June 2022	Under development
Tees Valley multi-modal hydrogen transport hub – 2025	Under development
Alstom - Eversholt Rail agreement to build hydrogen train fleet	Under development
The FlyZero project – 2021	Under development
Element 2 Ways2H project	Under development

United States

Scenarios

Scenario 1: Production: Leakage from the pipe connected to electrolyser

Electrolysis is a leading hydrogen production pathway to achieve the goal of the U.S. Department of Energy's "Hydrogen Earthshot": reducing the cost of clean hydrogen by 80% to €0.91($1) per 1 kilogram in 1 decade ("1 1 1"). On November 15th, 2021, the bipartisan Infrastructure Bill was signed into law, further solidifying the US roadmap and strategy for hydrogen: €7.27 ($8) bn were allocated for large-scale regional clean hydrogen hubs, €0.91($1) bn for clean hydrogen electrolysis research and development and €454 ($500) M in funds for clean hydrogen manufacturing and recycling. Some planned large-scale hydrogen projects are: a 5 MW electrolyzer project in Washington State, a 20 MW electrolyzer plant set to produce hydrogen from solar power in Florida, hydrogen production, storage, and end use in turbines through the €0.91($1) billion Advanced Clean Energy Storage project in Utah and a number of nuclear-to-hydrogen projects in multiple states. The following table lists projects for which safety information was readily available.

S. No	Project name	Project description	Source
1.	ACES Delta (2022) (under development)	A facility combining 220 megawatts of alkaline electrolysis with barrel salt caverns to store clean hydrogen	https://www.energy.gov/lpo/advanced-clean-energy-storage
2.	ARIES/ Flatirons Facility (2021) (under development)	A hydrogen infrastructure including a research-ready-megawatt-scale electrolyser with hydrogen compression, storage system and megawatt-scale fuel cell generator. The system will be used to provide a testbed to demonstrate systems integration, grid services and innovative use applications.	https://www.hydrogen.energy.gov/pdfs/review22/ta048_leighton_2022_o.pdf
3.	Hawaii Natural Energy Institute Hydrogen Station (2020) (under development)	A 65 kg/day hydrogen production and dispensing station. The objective of the project is to evaluate the technical and financial performance, and durability of the equipment, and support a fleet of three hydrogen Fuel Cell Electric Buses operated by the County of Hawai?i Mass Transit Agency. **Safety systems:** Gas detection: gas detection probes connected to a monitoring panel. The monitoring panel reads hydrogen measurements from each probe and triggers an alarm if a threshold is crossed. The alarm outputs are connected in series with the emergency stop device circuitry. Fire detection: composed of thermal probes and a hydrogen flame detection sensor. All thermal probes are connected in series with the Emergency Shutdown circuitry. The hydrogen flame detectors are focused on the hydrogen dispenser and tube trailer connection posts. If a flame detector or any thermal probe is triggered, the station's control air is shut down, causing all air-actuated valves to revert to a fail-safe state and become inoperable. The control system deactivates all station functions, including dispensing and compression, and prevents the flow of hydrogen from the storage vessels. In the event of a high pressure incident, each storage system is equipped with a pressure relief valve set at 6,960 psig (480 bar). The hydrogen compressor is equipped with pressure relief valves to protect the compressor from an overpressure event at the suction inlet and discharge outlet. These pressure relief valves have a pressure switch in the relief vent stack which alerts the PLC if there is an overpressure event. All vent stacks direct vented gas upward and away from any personnel. The hydrogen compressor room includes ventilation fans, to mitigate any leaks. The ventilation fans run continuously at a nominal speed to allow for a minimum of 1 cfm per square foot of floor area. If the control system detects a hydrogen leak in the vicinity, the appropriate fan is run at a higher speed to help disperse the leak. Dispenser purge:the dispenser is able to use non-rated electrical equipment in an area classified as hazardous, by housing this equipment in a partially sealed cabinet and using a purge fan to continuously purge and pressurise the cabinet. If the purged air is lost (e.g. due to the cabinet being opened), a pressure switch is triggered, which sends an alarm signal to the control system. If the control	HNEI NELHA Hydrogen Production and Fuelling Station Visitor Briefing, Retrieved 15.03.2022 http://records.hawaiicounty.gov/Weblink/1/edoc/97017/181126%20NELHA%20Visitor%20Briefing.pdf (Vrijil et al., 2020`[14])

		system detects a loss of purge, the dispenser power supply is interrupted immediately, and the control system deactivates all station functions. When the cabinet is re-pressurised, there is a 10-minute delay before the dispenser power is re-enabled, to allow time for at least four complete purges of the electrical cabinet. All electrical circuitry that cannot be designed as intrinsically safe, and must be located in an area classified as hazardous, is housed in explosion-proof cabinets.	
4.	Wind2H2 project (2008–2009) (completed)	A project developed by the U.S. National Renewable Energy Laboratory (NREL) as a part of research at the National Wind Technology Centre in Boulder, Colorado. The main goals of project were to reduce capital costs of electrolysis through improved designs and lower cost materials and to develop low-cost hydrogen production from electrolysis through integration with renewable electricity sources Safety measures taken: The balance of the plant included a glycol cooling loop that utilised a fluid pump, heat exchanger, and cooling fan. Nitrogen gas was required by the alkaline electrolyzer for startup- and shutdown-purging cycles. Ultraviolet/infrared (UV/IR) cameras monitored for hydrogen-flare conditions. The building was continuously purged by a ventilation fan that was monitored by a differential pressure switch.	(Harrison, Ramsden and Kramer, 2009[15]) (Ramsden, Harrison and Steward, 2009[16])
5.	Wind-to-Hydrogen Energy Pilot Project: Basin Electric Power Cooperative (2004-2008) (completed)	A hydrogen production system consisting of: • Hydrogen production system • Gas control panel • Hydrogen storage assembly • Hydrogen-fuelling dispenser • Procurement and operation of end-use hydrogen vehicles. A feasibility report, completed in 2005, found that the proposed hydrogen production system would produce between 8 000 and 20 000 kg of hydrogen annually depending on the mode of operation (scaled wind, scaled wind with off-peak, full wind and full wind with off-peak). Safety features included: general ventilation air and roof exhaust, glycol cooling system, waste oil/water collection system, O2 roof vent, H2 vent to station stack, emergency shutdown (ESD). Risk assessment for most serious accidents and mitigation measures 3/8 in. 316ss seamless tube creak, break or loose fitting leading to major leak or a fire: can be prevented through thorough testing, maintenance, infrequent use, limited hydrogen flow, installation by a certified installer. In case of fire there can be a fire detection system to shut down operations and initiate a call to the fire department Failure of Valve/pressure control which regulates the pressure of nitrogen supply to the fuel generator allows nitrogen above pressure to flow to the fuel generator. Prevention: robust equipment designed exclusively for this purpose, maintenance, system master control panel able to communicate fault conditions Failure of the valve in the gas control panel leads to hydrogen fire. Prevention: tests during manufacture/installation, maintenance, installation by a certified installer. In case of fire there can be a fire detection system to shut operations and initiate a call to the fire department. system master control panel able to communicate fault conditions Gas control panel allows H_2 to flow to storage or dispenser. Prevention: robust equipment, thorough testing, maintenance, installation by a certified installer, fails safe in closed position Faulty plug fitting leading to hydrogen release: can be avoided through testing, maintenance, installation by a certified installer, limiting the rate of hydrogen Dispenser-unit continues to flow fuel to full cylinder – overfilled:	(Rebenitsch, Boushee and Woeste, 2009[17])

		prevention: testing, maintenance, installation by a certified installer, fails safe in closed position, attended fuelling with trained vehicle operators Leaks from storage may lead to fire: H_2 should rise and disperse rapidly. Pressure relief devices present over-pressure conditions. In case of fire, a flame detection system shuts down all systems,	
6.	Hawaii Hydrogen Center for Development and Deployment of Distributed Energy Systems (2003-2008) (completed)	Goals and objectives • Demonstrate an integrated hydrogen power park comprised of: an electrolyzer powered by a renewable energy source, hydrogen storage and distribution system, PEM fuel cell connected to the grid and building, optional hydrogen-fueled vehicle dispensing system • Demonstrate hydrogen as an energy carrier • Investigate interface issues with the grid and buildings • Identify codes and standards required to site a power park • Identify barriers to hydrogen infrastructure Safety control components: • Hydrogen fire sensor, a hydrogen sensor, and an oxygen concentration sensor for controlling hydrogen purity. • Three emergency-stop buttons at different locations on the site. • Many essential measurement sensors were duplicated in order to ensure that gas leaks or component failure would be detected. • A brick firewall was built surrounding the hydrogen storage area. • In order to avoid hazardous situations, the interface was designed as a fail-safe system, meaning that in such unattended events, the system stops safely: 1) all components are disconnected, 2) the gas storage is isolated, and 3) the gas lines are depressurised. • The design was subjected to a safety analysis based on Fault Tree Analysis methodology.	https://www.hnei.hawaii.edu/wp-content/files/Hawaii%20Hydrogen%20Center%20Final%20Report.pdf
7.	Stone Edge Farm Microgrid, California, United States, (2013) (ongoing)	The MicroGrid's solar energy powers the farm and also splits water into oxygen and hydrogen in an electrolyzer. An on-site hydrogen filling station powers three fuel-cell electric cars. The Stone Edge Farm microgrid in California was not able to export excess renewable power to the California Independent System Operator (CAISO) market in an economically viable way. The microgrid developer is now using hydrogen to export its power. It has set up a bank of onsite electrolysers, which converts the excess electricity into hydrogen. When required, the hydrogen is also used to produce power using fuel cells.	https://sefmicrogrid.com/#

Scenario 2: Pipeline transport: Leakage from high-pressure pipelines

The U.S. Office of Fossil Energy invests in projects to address design and materials requirements for blending hydrogen into the existing natural gas infrastructure. Specific R&D activities coordinated with DOE's Office of Energy Efficiency and Renewable Energy and other offices include the following:

- Develop new configurations, and sensor technologies combined with artificial intelligence for real time monitoring and early fault detection for the safe transport of hydrogen.
- Identify and prioritise materials performance gaps to avoid leakage within pipeline elements, such as joints, valve and flange connections and compressors

Some planned projects are:

- Pipeline transmission and distribution as part of the Center Point Energy Inc., Minneapolis project announced 08/2020.
- Dominion Energy, Salt Lake City, announced Q3 2020: pipeline transmission and distribution. Four-phase pilot project aiming for 5% hydrogen blending capability in Utah distribution system by 2030.

Scenario 3: Road transport

- In 2013, a Multi-State Zero Emission Vehicle action plan was formed, when the governors of eight states—California, Connecticut, Maryland, Massachusetts, New York, Oregon, Rhode Island and Vermont—signed a Memorandum of Understanding committing to coordinated action to support successful implementation of state Zero-Emission Vehicle programs. The state of California issued a Zero-Emission Vehicle Action Plan in 2018 with the aim of boosting the supply of Zero-Emission Vehicles and increasing the provision of charging and refuelling stations. Due to the state's strong climate policies California's zero-emission vehicle (ZEV) market now represents about half of the United States' ZEV market.

		• On May 4, 2021, Clean Transit for America Plan was unveiled. which provides USD 73 billion to aid the transition of the country's public transit systems to zero-emission fleets. • (Cummins Inc., 2020[18]) opened the Hydrogen Fuel Cell Powertrain Integration Center in West Sacramento, California. At the West Sacramento facility, the focus is PEM fuel cells, which are considered a good solution for high-power transportation applications, like heavy-duty, long-haul trucks. The site is designed specifically for hydrogen innovation, including safety features, and will house fuel cell integration and fuel cell powertrain development and testing, controls and electrical engineering. • The San Bernardino County Transit Authority is set to launch a hydrogen-powered train. FLIRT H2, starting operations in California in 2024.	
8.	National Fuel Cell Bus Program, 2005 (ongoing)	A cooperative initiative between the US government and the private sector to advance the commercialisation of fuel cell technology in US transit buses. The main goals of the Program include: Facilitating the development of commercially viable fuel cell buses Improving fuel cell bus efficiency	Federal Transit Administration. (2018), National Fuel Cell Bus Program, 2005-2018
9.	Hydrogen Buses – California (ongoing)	There are 76 Fuel cell buses in operation in California Programmes: • AC Transit (more than 20 fuel cell electric buses and two hydrogen stations) • SunLine Transit (16 Hydrogen FCVs) • Orange County Transit (10 Hydrogen FCVs) Challenges include: • Fuel cell system issues—Agencies report that the fuel cell stacks continue to prove robust and that fuel cell system issues involve components in the balance of the plant. Air blowers, compressors, sensors, and sometimes plumbing leaks have resulted in downtime for the buses.	Buses & Trucks | California Fuel Cell Partnership
10.	Hydrogen Buses - Hawaii (ongoing)	Hele-On 29-Passenger Fuel Cell Electric Bus: Onboard hydrogen is stored in composite carbon fibre cylinders located under the bus with a capacity of 20 kg. The fuel cell power system is integrated with two 11 kWh A123 Lithium-ion battery packs to provide motive power to a 200 kW electric drive system. US Hybrid also replaced batteries with the new technology A123 batteries using U.S. Hybrid internal funding. At cruising speed, the fuel cell maintains the battery state of charge within a range that supports the long-term health of the battery. Hele-On 19-Passenger Fuel Cell Electric Buses: Two 19-passenger FCEBs were converted by U.S. Hybrid. Onboard hydrogen capacity is 10 kg giving a projected range of 100 miles.	
Scenario 5: Mobility and partially confined spaces: accidents at a hydrogen fuelling station			
11.	H2FIRST (Hydrogen Fuelling Infrastructure Research and Station Technology) (2014) (ongoing)	A project jointly led by Sandia National Laboratories and the National Renewable Energy Laboratory (NREL). Scope includes development and physical testing of components and systems, technology validation and systems and station architecture design. Under the H2FIRST project, Sandia and NREL, along with Powertech Labs developed and built the Hydrogen Station Equipment Performance (HyStEP) Device, in order to help reduce the time to commission a hydrogen station.	https://h2tools.org/h2first
12.	Refuelling stations (ongoing)	California has one of the largest hydrogen refuelling station networks in the world. As of March 2022 there are 47 open retail hydrogen fuelling stations in the state. There is also one hydrogen refuelling station in Hawaii. These hydrogen stations are designed to be self-service and operate similarly to fuelling with compressed natural gas. Safety parameters: • Fuel cell cars and hydrogen fuelling stations are designed to prevent hydrogen from leaking and have systems that shut down the flow of hydrogen automatically if a leak is detected. Example safety systems include: • Both the dispenser and the fuel cell car have leak detecting sensors and will shut-off the flow of hydrogen if a leak is detected. • The hydrogen fuelling nozzle connects to the fuel cell car with a	https://afdc.energy.gov/stations/states https://h2tools.org/sites/default/files/4997_20_CHS_Fuelling_Flyer_NoCrops.pdf

		tight seal and stays locked as long as there's hydrogen fuel pressure in the hose. - Fuel cell cars have a protective device that prevents the vehicle from being driven while the fill hose is attached, thus preventing "drive-offs" and damage to the hydrogen dispenser.	
Scenario 6: Residential use: Safety of Hydrogen in buildings with focus on hydrogen cooking stoves and boilers			
13.	Hydrogen House (2006) (ongoing)	Hydrogen House is the first solar-hydrogen residence in North America. System versatility provides power for multiple applications: appliances, electric vehicles, fuel cell, etc. This house, which is still operating, is outfitted with modern equipment including high pressure hydrogen gas tanks, high pressure electrolyzer (2 000-6 000 psi) and higher efficiency inverters.	https://www.hydrogenhouseproject.org/the-first-consumer-hydrogen-house.html Hydrogen House Project - Home | Facebook

Concluding remarks: United States

The United States is investing massively in clean hydrogen production and in projects to facilitate hydrogen and natural gas blending into the existing infrastructure. Attempts have been made to create fully functional hydrogen-powered systems with the production of green hydrogen through electrolysis and its use to support transportation systems. There is emphasis placed on safety systems for gas and fire detection, comprehensive ventilation regimes etc.

In many states, there are plans to boost the supply of hydrogen vehicles and increase the provision of charging and refuelling stations. This is particularly the case for California, which has an operating fleet of 76 fuel cell buses. There are also currently 47 open retail hydrogen fuelling stations in the state. There are a number of reported accidents due to hydrogen leaks in refuelling stations- these are reported in Part IV of this report. In all accident cases, the role of the systems that shut down the flow of hydrogen in case of a leak had been vital and prevented further escalation and greater damage.

Status of project: United States

United States	Status
Hawaii Natural Energy Institute Hydrogen Station: 2020 - ~	Under development
ACES Delta 2021	Under development
Aries/ Flatirons Facility 2021	Under development
Wind2H2 project: 2008-2009	Completed
Wind-to-Hydrogen Energy Pilot Project: Basin Electric Power Cooperative: 2004-2008	Completed
Hawaii Hydrogen Center for Development and Deployment of Distributed Energy Systems: 2003-2008	Completed
Stone Edge Farm Microgrid, California, United States: 2013 - ~	Under development
National Fuel Cell Bus Program: 2005 - ~	Under development
Hydrogen Buses – California	Under development
Hydrogen Buses – Hawaii	Under development
H2FIRST (Hydrogen Fuelling Infrastructure Research and Station Technology): 2014 - ~	Under development
US Network of Refuelling stations	Under development
Hydrogen House: 2006 - ~	Under development

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Part IV Review on incident database and lessons learnt

13 Scenario-based accident data review and analysis

This chapter provides an overview of scenario-based data of two hydrogen incident and accident databases to generate insights into the nature of potential safety consequences.

Hydrogen as an energy carrier provides a feasible solution to reduce greenhouse gas emissions, and hence achieve the goal of controlling global average temperature rise to no more than two degrees Celsius according to the *Paris agreement*. Successful transition to a hydrogen economy can provide a link between the generation of renewable electricity and sectors where carbon emissions are hard to abate (International Renewable Energy Agency, 2018[1]).

However, as a new energy form, most countries do not yet have a defined hydrogen strategy nor have hydrogen included in their regulatory policy frameworks. This report develops and presents a detailed, scenario-based review of two hydrogen incident & accident databases, HIAD 2.0 and H2tools, to provide more insights into the nature of potential safety consequences from the following scenarios indicated as of particular interest by the Dutch Ministry of Economy and Climate Policy:

- **Scenario 1 –** Production: Leakage from pipes connected to electrolysers
- **Scenario 2 –** Transport pipelines: Leakage from high-pressure pipeline
- **Scenario 3 –** Road Transport: Hydrogen leakage in confined spaces/ built environments
- **Scenario 5 –** Mobility and partially confined spaces: accidents at a hydrogen refuelling stations

An additional section on storage is also included, as it potentially relates to Scenarios 1, 3 or 5.

The report does not map Scenario 4 (Mobility and partially confined spaces: e.g., a hydrogen city bus driving in a tunnel involved in a collision and Scenario 6 (Domestic use: safety of hydrogen in buildings with focus on hydrogen boilers), as there are no recorded accidents related to these scenarios.

The analyses in this report are performed in a scenario-specific manner, allowing us to draw scenario-specific conclusions about the risks involved with each technology. This goes a step further than more general hydrogen accident analyses available in the literature. Furthermore, normalised accident rates are calculated for each scenario, which are then compared to accident rates in similar hydrocarbon-based industries, in order to determine whether hydrogen is more hazardous than currently used fuels. The following comparisons are made:

- **Scenario 1 –** Normalised fatality rates caused by hydrogen production compared to fatality rates caused by energy production from other sources, such as coal, oil and natural gas
- **Scenario 2 –** Leakage rate from hydrogen pipelines compared to natural gas pipelines
- **Scenario 3 –** Hydrogen leakage rates from hydrogen-powered vehicles compared to liquefied petroleum gas (LPG) vehicles
- **Scenario 5 –** Accident rates at hydrogen refuelling stations compared to LPG refuelling stations

In general, the reported hydrogen accidents are typical of the types and range of accidents occurring in conventional hydrocarbon-based industry sectors. The calculated normalised accident rates suggest that the use of hydrogen in each of the four scenarios is as safe, and even safer, than the fuel currently used in comparable industries, when the proper precautions are taken. As the accident causes are the same or broadly similar it can be concluded that: (a) Existing knowledge and good practices and safety measures can be applied to the technology deployed in the four scenarios analysed and (b) No new or special solutions are required to make the use of hydrogen sufficiently safe for the intended use.

HIAD and H2tools

The report reviews 2 incident databases, the *Hydrogen Incidents and Accidents Database* (HIAD) and H2tools. The incidents recorded in both HIAD 2.0 and the H2Tools database are hydrogen-related incidents that either resulted in, or had the potential to result in hydrogen leakage.

The Hydrogen Incidents and Accidents Database (HIAD) was initially created as part of the HySafe project (2004-09), a research project supported by the European Commission, and was populated by the members of the HySafe network. The network consisted of 25 partners across 12 countries who shared their respective expertise in the automotive, chemical, gas and oil and nuclear fields with the aim of developing mitigation methods that facilitate the safe and efficient introduction of hydrogen technologies (HySafe, 2007[2]). Since the end of the project, HIAD has been populated by the Joint Research Centre of the European Commission (EC-JRC). It is an open communication platform that compiles publicly available data on international hydrogen-related incidents and accidents. A new, more streamlined, version of the database, HIAD 2.0, has been in development since 2016. This new version is more focused on identifying and sharing lessons learnt from hydrogen-related incidents, as well as other useful information about hydrogen system safety. HIAD 2.0 contains 628 entries as of December 2021. The entries are largely compiled from 10 smaller incident databases.[1]

The H2Tools database was created with the support of the US Department of Energy, with the aim of assisting in the spread of important information and lessons from incidents during the use of hydrogen (H2Tools, n.d.[3]). The database is a hydrogen incident reporting tool which any individual can use to provide information on incidents or near-misses involving hydrogen. The events are anonymised to encourage the reporting of any incidents. As of May 2022, the database contains 221 entries, 67 of the most relevant are examined for this report.

Chapter 14 – *Results and discussion* presents an overview of the databases in terms of the number of accidents recorded and human & social consequences in terms of the number of injuries & deaths. The following subsections provide in-depth analysis of the recorded accidents mapped to 4 key scenarios – Scenarios 1, 2, 3 and 5.

In addition to the scenarios, a separate subsection on hydrogen storage is presented, since the safe storage of hydrogen is an important consideration in many applications. Hydrogen storage can be potentially linked to Scenarios 1, 3 and 5, since in most instances storage is required during its production, transportation and at hydrogen refuelling stations before dispensing. Finally, the knowledge drawn from the database review is summarised and scenario-specific analyses to evaluate the risk and consequences associated with the use of hydrogen are presented.

Key takeaways

A total of **266 incidents and near-misses**, reported in HIAD 2.0 and the H2tools database, were studied for the purpose of this report, as they were relevant to applications of interest. These accidents were sorted out based on their relevance to scenarios 1, 2, 3 and 5 out of the six scenarios of interest, with no relevant accidents having been reported for scenarios 4 and 6. **Normalised incident rates** were calculated for the different scenarios which were then compared to incident rates in similar hydrocarbon-based industries. Through this comparison, it was determined that, based on the information provided by the databases, the incident rate caused by the use of hydrogen in scenarios 1, 2 and 5 is **lower** than in the cases where a comparable hydrocarbon fuel is used. In the case of scenario 3, data suggests that LPG vehicles are currently safer than hydrogen-powered vehicles, likely due to the difference in the maturity of the two technologies. However, most of the recorded incidents involving hydrogen vehicles were traffic accidents caused by external factors and therefore there were no novel causes that resulted in these incidents.

The hydrogen incidents were further analysed based on their **physical consequences**, as well as their reported **root causes**. For the majority of the incidents, there were multiple interconnected contributing causes. For example, equipment failure was frequently caused by inadequate maintenance and/or deficiency in procedure. In such cases, only the main cause of the incident was considered. Overall, 153 of the accidents studied (58%) were more severe, resulting in a fire or explosion, while the other 113 incidents (42%) resulted in unignited hydrogen release or no hydrogen release at all. It may be worth noting that especially in the case of voluntary self-reporting, severe hydrogen specific incidents may be over represented.

The decline in the number of casualties and injuries caused by hydrogen accidents in recent years demonstrates that the production and use of hydrogen is relatively safer than before, although there is more room for improvement.

Scenario 1

- In accidents connected to hydrogen production (scenario 1), the hydrogen **compressor** was identified as the most risky component.
- Most accidents are related to ***equipment failure***, it is therefore recommended to evaluate guidance on the design life of critical components.

Scenario 2

The use of high-pressure pipelines for hydrogen transport (scenario 2) is **not yet wide-spread**, a fact that is reflected by the small number of hydrogen incidents involving hydrogen pipelines. Furthermore, small hydrogen leaks from pipes might not be detected and thus not reported.

It is important that hydrogen pipelines are maintained by competent personnel who are aware of the proper maintenance procedures.

Warning labels at regular space intervals to indicate the presence of underground hydrogen pipelines is highly recommended to avoid excavation works that could lead to pipe damage.

Scenario 3

- Most accidents related to scenario 3 are **traffic accidents** involving either vehicles transporting hydrogen or vehicles powered by hydrogen. As vehicles powered by hydrogen are not yet very common, most accidents relate to hydrogen transportation.
- The high number of traffic accidents highlights the importance of proper training for the drivers. It also highlights how necessary it is that the drivers are always alert and in good physical conditions.

Scenario 5

- Most incidents at hydrogen refuelling stations (scenario 5) involved equipment failure, with the most common being **dispenser & compressor** failure.
- The compressors as well as stand-by machines should be maintained regularly. Specifically, a research piece on the common faults of hydrogen compressors (Han et al., 2020[4]) suggests regular checks & cleaning of the lubricating oil system, air valves, cylinder blocks and crankshafts (ranked by fault frequency).

Storage:

- Accidents involving hydrogen storage **have become less common** in recent years, as the safety regulations have become stricter, however, accidents can still occur if the proper safety procedures are not enforced.
- Ensuring that the correct protocols for hydrogen storage and handling are followed is vital, as well as ensuring that all relevant personnel are suitably trained.

The main causes of process safety loss of containment incidents in the chemical industry are a combination of technical, organisational and human failures which are well-documented and understood and taken into account when designing new process equipment and installations (COMAH competent authority, 2011[5]), (HSE, 2017[6]), (Lisbona, 2022[7]), (Wishart, Chowdhury and Ayeni, 2022[8]). As this report has shown, the causes of the hydrogen accidents recorded in the databases are typical of the types and range of accidents, which occur in the conventional hydrocarbon-based industry sectors. In other words, there are no novel hydrogen accidents when it comes to causation. Based on this observation we can conclude that hydrogen installations and equipment will suffer from the same types of failure and at similar frequencies as has been previously observed in the industry. The consequences of the accidents may vary slightly but not significantly.

As such, it can be concluded that existing knowledge and good practice to safeguards that is currently in place can be applied to the technology deployed in the four example scenarios and no new or uncommon solutions are required to make the use of hydrogen sufficiently safe for the intended use.

The primary databases used as major sources of data for HIAD 2.0

HIAD 2.0 is a database collecting systematic data on hydrogen-related incidents, accidents or near misses. The database combines information on accidents from a range of sources that collect data at the national or regional level (Table 13.1).

Table 13.1. Databases used a source of data for HIAD 2.0: Database and related organisations

	Description	Link
ARIA French Ministry of Environment / Bureau for Analysis of Industrial Risks and Pollutions	French database that records incidents, accidents and near misses of all kinds which affect human health, public safety or the environment. It spans several decade and covers international incidents, but most entries are about French incidents.	https://www.aria.developpement-durable.gouv.fr/?s=
eMARS European Commission / Joint Research Centre	Database of chemical accidents and near misses reported to the Major Accidents Hazards Bureau (MAHB) of the European Commission's Joint Research Centre (JRC).	https://emars.jrc.ec.europa.eu/en/emars/Content/
ICHEME Institution of Chemical Engineers	Closed database that was active between 1997 and 2000. It contains summaries of worldwide industrial chemical accidents with a focus on UK-related accidents.	https://www.icheme.org/knowledge/safety-centre/resources/accident-data/
ASN Autorité de sûreté nucléaire	Public list the French nuclear authority which records all its investigations of accidents.	https://www.asn.fr/
OSHA US Occupational Safety and Health Administration	Repository containing OSHA investigation summaries, including incident description and causes of US-based fatalities or catastrophes.	https://www.osha.gov/pls/imis/accidentsearch.html
CBS US Chemical Hazard Investigation Board	Repository of CBS investigations of specific, 'big' US-based accidents.	https://www.csb.gov/investigations/completed-investigations/?Type=2
NTSB US National Transportation Safety Board	NTSB database of US-based civil aviation accidents and significant accidents involving other modes of transportation, such as railroad, highway, marine and pipeline.	https://www.ntsb.gov/investigations/AccidentReports/Pages/AccidentReports.aspx
NRC US Nuclear Reactors Commission	US-based public list of all NRC investigations of accidents involving nuclear power plants and materials.	https://www.nrc.gov/reactors.html
RISCAD Relational Information System for Chemical Accidents Database Japanese Institute for Advanced Industrial Science and technology	Offline Japanese chemical industry accidents database containing brief summaries of the accidents.	https://sanpo.aist-riss.jp/riscad/

	Description	Link
ADRC Accident and Disaster Information Center	Japanese repository of all kinds of accidents that occurred in Asia. The repository owner and their objectives are unclear.	https://www.adrc.asia/adrc/

Source: (HIAD 2.0, 2018[9]).

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Note

[1] HySafe (28 June 2018), "HIAD 2.0- free access to the renewed hydrogen incident and accident database" https://hysafe.info/hiad-2-0-free-access-to-the-renewed-hydrogen-incident-and-accident-database/ (accessed on 16th May 2023).

14

Results and discussion

The study of the databases HIAD 2.0 and H2tools, allows us to observe the trends on hydrogen accidents. Four different accident scenarios are examined, namely production, transport pipelines, road transport and mobility and partially confined spaces.

Despite the limitation related to comprehensiveness of data, the present report relied on the HIAD and H2tools database to prepare this Part of the report. This is because, amongst publicly available data, this is the most reliable. The authors also acknowledge that for such incident databases, relatively more data exists in the early phases of the database creation as more information is sought at that stage. For both HIAD 2.0 and H2tools, a steady increase in the number of recorded accidents from 1970 to 2009 is observed, followed by a decrease in the next decade Figure 14.1. Nonetheless, one should bear in mind that there is also a steady increase in global hydrogen demand Figure 14.2 since 1975 (IEA, 2019[1]). To address both points, the normalised risk, defined by the number of accidents per million ton (Mt) of hydrogen demand, was calculated (orange curve, Figure 14.1) and plotted.

The lack of sufficient safety measures is likely to be the cause for the initial increase in normalised risk between 1970-2009, during which global hydrogen demand increased from 18.2 Mt to 62.4 Mt (IEA, 2019[1]) Figure 14.3. The later decrease in normalised risk indicates the impact of regulation implementation, codes and standards regarding the H_2 industry, as well as increased learning regarding hydrogen safety from past accidents.

Figure 14.1. Number of incidents over time in HIAD 2.0 (pink) and H2tools (green) and the corresponding normalised risk in terms of number of incidents per Mt of hydrogen produced

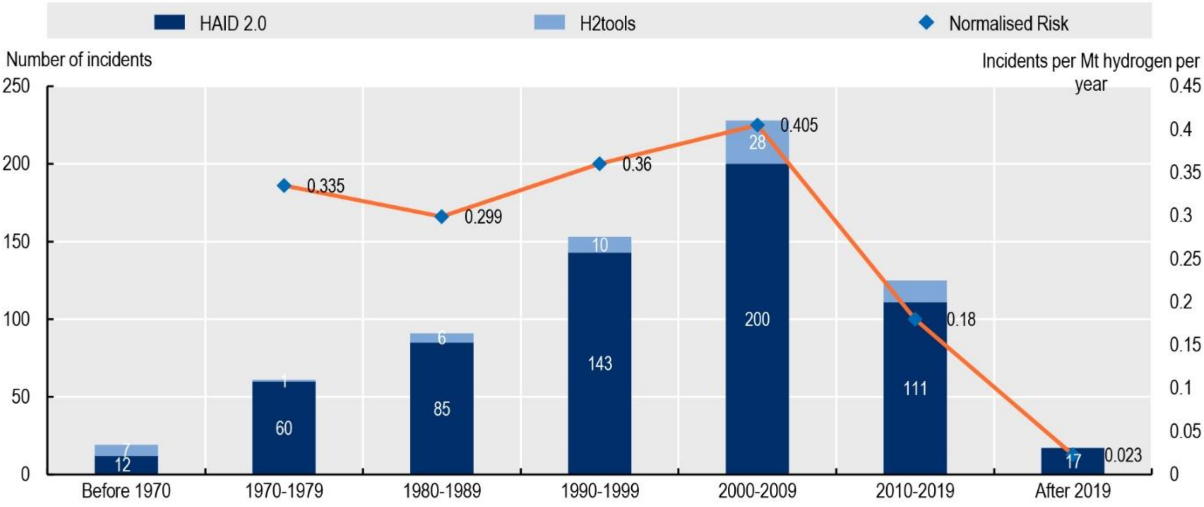
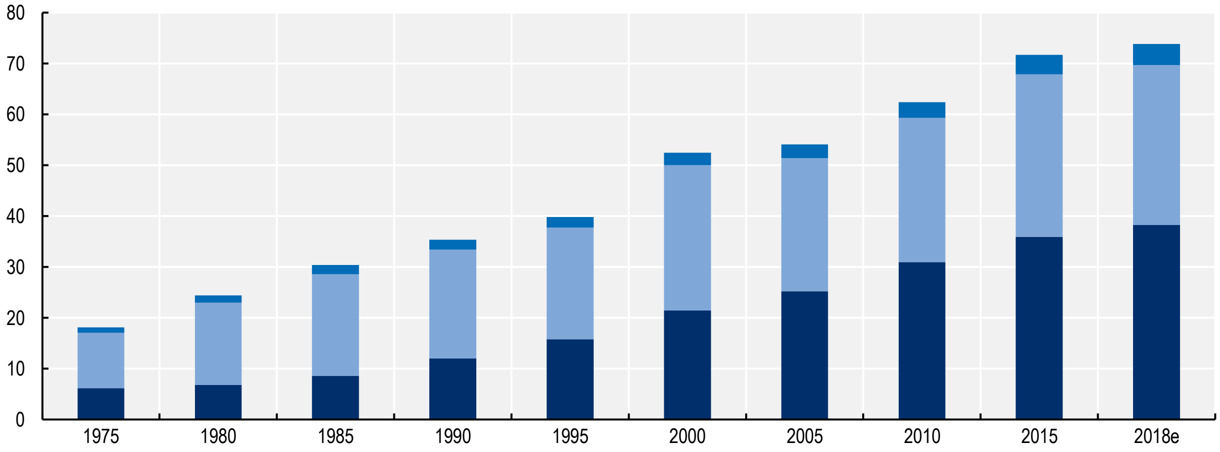


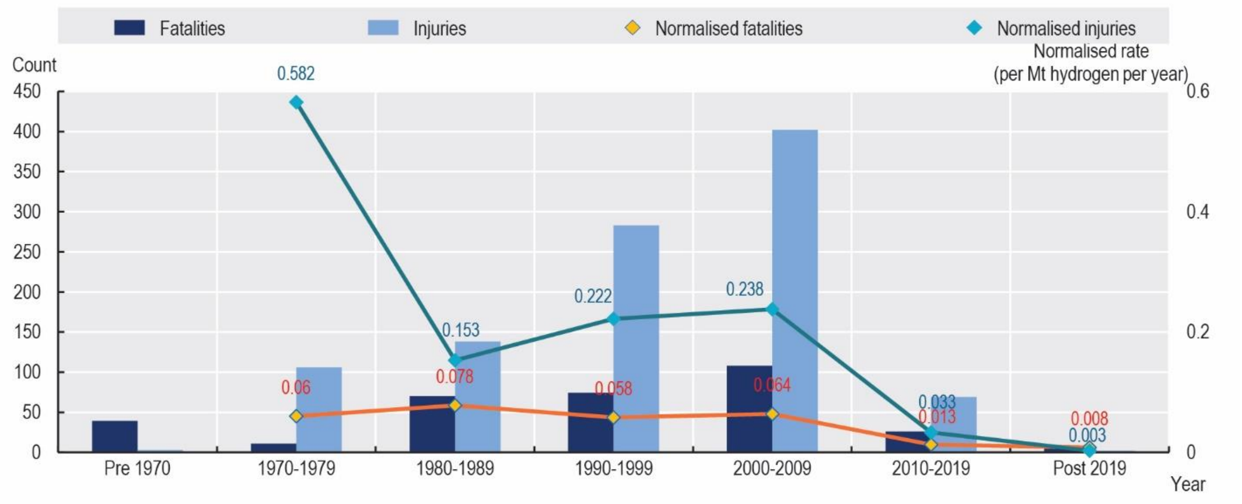
Figure 14.2. Global demand for pure hydrogen, 1975-2018



Source: (IEA, 2022[2]).

The overall trend in the number of hydrogen accidents is also reflected by the number of fatalities and injuries caused by these accidents, with these numbers reaching a maximum in the 2000’s. There is a noticeable decrease in the number of both fatalities and injuries after that, implying that, despite the increased global hydrogen demand and the new hydrogen applications and technologies, the number of serious hydrogen accidents is lower Figure 14.3. Part of the effect might also stem from a decrease in participation to the database, after the initial effort at their creation in the late 2000s would have subsided, although incidents resulting in personal injury and death, being notable, might be the less affected by such a trend. Normalising the number of fatalities and injuries caused by hydrogen accidents against the global hydrogen demand showed that the normalised annual fatality rate decreased from 0.064 fatalities per Mt hydrogen per year in the decade from 2000 to 2009, to 0.013 fatalities per Mt hydrogen per year in the following decade. Similarly, the normalised injury rate from hydrogen incidents also decreased, from 0.238 in the 2000s to 0.033. This observation (or trend) can again be attributed to increased learning about hydrogen safety, insights from lessons learned from past H_2 incidents & accidents as well as implementation of H_2 safety codes and standards.

Figure 14.3. Number of fatalities and injuries over time caused by incidents reported in H2tools and HIAD 2.0 and the corresponding normalised rates per Mt hydrogen per year



Nevertheless, one should remember that since certain industrial sectors are bound to investigate and report accidents while others are not, the reported numbers may be inaccurate. However, the numbers reported still enabled us to observe a trend of improved safety in hydrogen technology over the years.

Scenario 1 – Production: Leakage from pipes connected to electrolysers

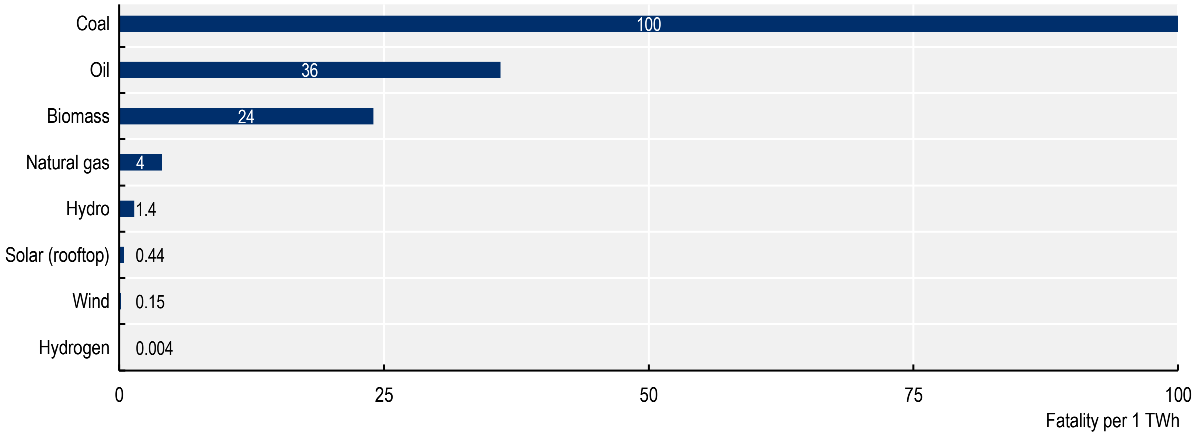
Out of the 695 accidents reported in the two databases, **131 accidents** (19%) are related to Scenario 1 Table 14.1. In HIAD 2.0, *Chemical & Petrochemical Production* is classified as an application stage. We reasoned that hydrogen applications at this stage are related to Scenario 1 since **water electrolysis, hydrogen compression, pipework transportation** as well as **storage** are all covered at this application stage.

Table 14.1. Accidents related to Scenario 1

	HIAD – chemical/petrochemical	HIAD – H_2 production	H2tools	**Total**
No. of incidents	103	16	12	131

Hydrogen production is associated with a lower normalised fatality risk[1] as compared to other conventional energy sources based on historical data Figure 14.4, confirming its potential as a fuel to replace oil and natural gas that are widely used today.

Figure 14.4. Normalised fatality rate: Number of fatalities per TWh for coal, oil, biomass, natural gas, hydro, solar, wind and hydrogen



Note: Terawatt-hour. 1 Terawatt-hour = 1 012 watt hours.
Source: Adapted from (Brook et al., 2014[3]).

In addition, work by (Spada, Burgherr and Boutinard Rouelle, 2018[4]) based European data until 2012 yielded a fatality per Terawatt-hour at ca. 0.03.[2] These two works suggest that the use of hydrogen does not present an elevated risk to the safety of people when compared to current energy sources.[3]

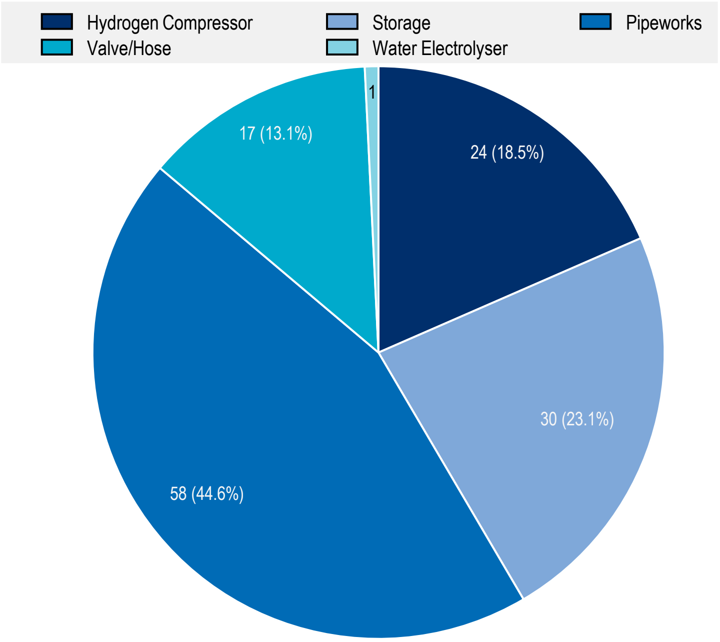
In order to study which component at water electrolysis facility is the major risk contributor, we summarised the number of accidents arising in 5 key components of an installation Table 14.2. These components are commonly used in all types of water electrolysis facilities. In agreement with scientific literature (Pan et al., 2016[5]), (Skjold et al., 2017[6]) and previous review on electrolysers (FCH 2 JU, 2020[7]), hydrogen **compressors are the major risk contributor, while water electrolysers are considered to be a very safe technology**. The hydrogen compressor is associated with the highest Death/Accident ratio, which is 3-5 times higher than the ratios for other components. On the contrary, there is only one accident recorded from a water electrolyser itself and a fatality did not result from that accident.

Table 14.2. Number of accidents and death classified by component failure

Component	Water Electrolyser	Pipeworks	**Hydrogen Compressor**	Storage	Valve/Hose
No. of incidents	1	58	**8**	30	17
No. of deaths	0	4	**24**	3	1
Death/Accident ratio	0	0.07	**0.33**	0.1	0.06

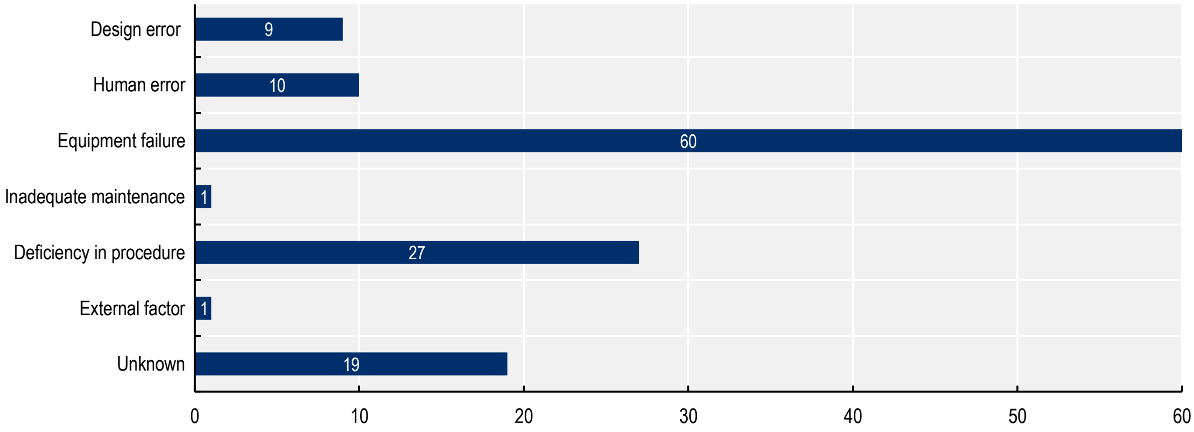
Figure 14.5 summarises the information in Table 14.2 in a pie chart using colours to label risk level (number of deaths per accident). The component that is most prone to failure is hydrogen pipework, which made up 44.6% of the total accidents that are related to Scenario 1. This is followed by storage (23.1%) and hydrogen compressor (18.5%).

Figure 14.5. Component failure in percentage ranked by risk levels (number of deaths per accident)



Furthermore, the root causes of the reported accidents are analysed and presented in Figure 14.6. The majority of accidents were caused by equipment failure, followed by deficiency in procedure and unknown. Equipment failure relates to failures that are unexpected and cannot be eliminated by minor changes in procedure. An example of such accidents is HIAD ID 660: the failure of a 400 mm pipe at 1.7 MPa caused release and ignition took 10 seconds. It is therefore recommended to evaluate guidance on the expected lifespan of critical components.

Figure 14.6. Statistics related to the cause of accidents related to Scenario 1



Scenario 2 – Pipeline transport: leakage from high pressure pipeline

The transport of hydrogen through high pressure pipelines is not yet widespread (most hydrogen pipelines that are currently operating are located in industrial sites), a fact that is reflected by the low number of reported incidents that are related to hydrogen pipelines. Only **9** such incidents have been recorded in the HIAD 2.0 database, while no incidents are recorded in the H2Tools database. Although these incidents are related to hydrogen pipelines, the operating pressure of these pipelines, as well as information about the pipe components and physical dimensions, is not reported to enable a more thorough analysis.

Globally, there are currently approximately 4 500 km of pipelines globally dedicated to hydrogen transport (Shell, 2017[8]) which is much less than the several million km of pipelines used for natural gas transport (Placek, 2021[9]). Nevertheless, a comparison between the normalised leakage incident rate from natural gas pipelines and hydrogen pipelines in recent years (2015-19) shows that the calculated normalised incident rate for hydrogen pipelines is 0.09 incidents per 1 000 km of pipeline per year, which is slightly lower than the leakage incident rate for natural gas pipelines, which is reported to range from 0.13 to 0.16 incidents per 1 000 km of pipeline per year Table 14.3. However, the hydrogen pipeline leakage incident rate will most likely change in the future, once the usage of pipelines for hydrogen transport becomes more widespread. Please refer to the section on Normalisation calculations: Scenario 2 - Pipeline transport: leakage from high pressure pipeline for more details on the normalised leakage incident rate calculations.

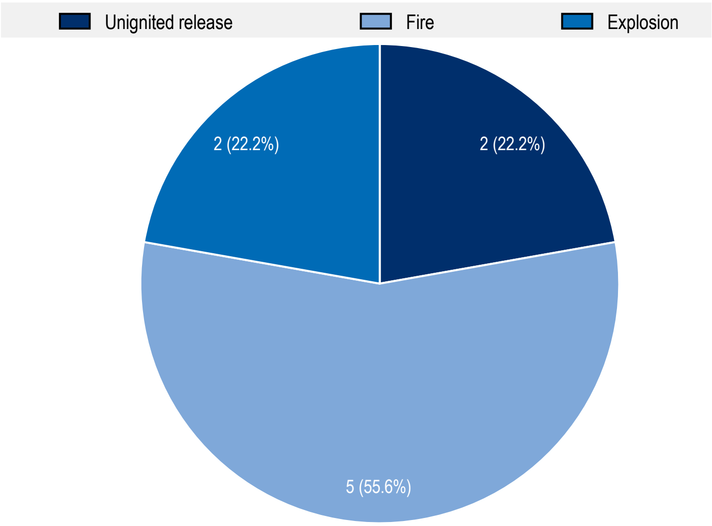
Table 14.3. Normalised leakage incident rate per 1 000 km of pipeline per year for hydrogen and natural gas pipelines

	Number of incidents per 1 000 km pipeline per year (2015-19)
Hydrogen	0.09
Natural gas	0.16 (United States), 0.13 (Europe)

Source: (PHMSA, 2022[10]), (EGIG, 2020[11]), (Shell, 2017[8]).

Further investigation into the 9 reported incidents found in the HIAD 2.0 database revealed that 2 of the incidents did not involve hydrogen ignition, while 5 incidents resulted in hydrogen fires. The remaining 2 incidents were found to have resulted in an explosion Figure 14.20.

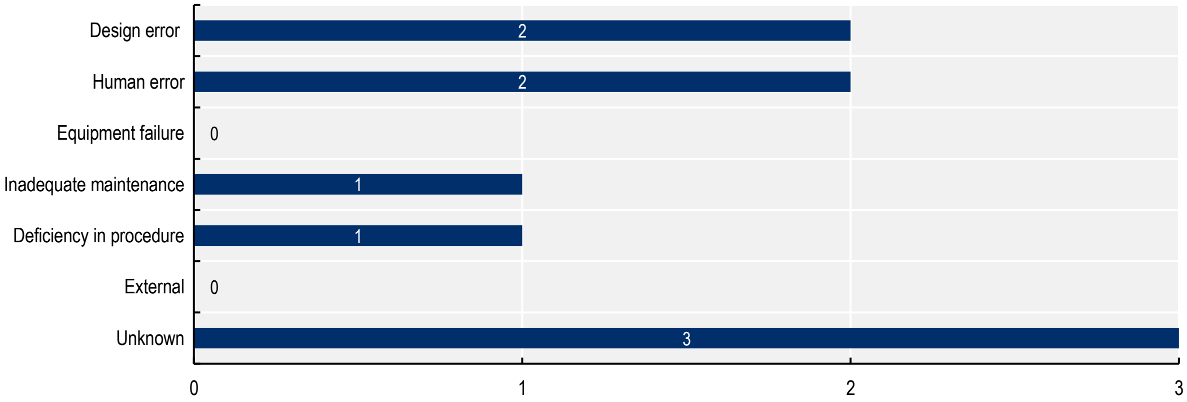
Figure 14.7. Physical consequences of accidents related to Scenario 2



The root causes behind the reported incidents were also studied. While for 3 incidents the root cause was unknown/unreported, for the other 6 incidents the causes were error in the design of the pipelines, human error, inadequate maintenance of the pipeline, as well as deficiency in procedure Figure 14.8. A characteristic example of an incident caused by human error is the leakage of hydrogen due to improper depressurisation of the pipeline during maintenance, as reported for event No. 345 in the HIAD 2.0 database. The incident that was caused by deficiency in procedure was the damage of a hydrogen pipeline by an excavator during excavation works, due to the fact that the company was not notified about the presence of the pipeline at that location.

These types of incidents are typical of those, which occur in any major hazard pipeline carrying hazardous substances such as flammable gas (methane) or liquid hydrocarbons. Therefore, the same causative risk profile can be assumed for hydrogen as well.

Figure 14.8. The main causes of accidents related to Scenario 2



Normalisation calculations: Scenario 2 - Pipeline transport: leakage from high pressure pipeline

We normalised the number of incidents against the length of pipelines used for gas transportation per year for hydrogen and natural gas. Only incidents between 2015 and 2019 were considered, as they are more relevant to the current state of things than older incidents.

Hydrogen

Data published by Shell (Shell, 2017[8])showed that the total length of hydrogen pipelines globally was 4 542 km as of 2017. Only two incidents involving hydrogen pipelines were recorded between 2015 and 2019, so these were normalised against the pipeline length.

Natural gas

Data on natural gas leakage incidents from pipelines in the United States were obtained from the PHMSA incident database. Information about the length of natural gas pipelines in the United States over the years was obtained from Statista (Placek, 2021[9]).

Table 14.4. Incidents per 1 000 km pipeline per year = Number of incidents per year/(Pipeline length/1 000 km)

	Natural gas	Hydrogen
No. of incidents (2015-19)	3 281	2
Incidents per year	656.2	0.4
Pipeline length / km	4 095 798	4 542
Incidents per 1 000 km pipeline per year	**0.16**	**0.09**

Already normalised data on the number of natural gas leakage incidents per 1 000 km of pipeline per year for European pipelines was obtained from the 11th EGIG report (EGIG, 2020[11]).

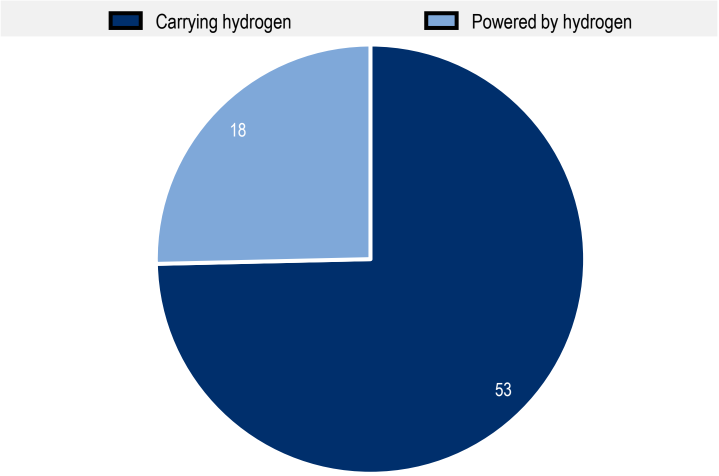
Scenario 3 – Road transport: Hydrogen leakage in a confined space/ built environment

For this scenario, incidents that involved vehicles transporting hydrogen, as well as incidents involving vehicles powered by hydrogen were considered. A total of **71** such incidents were reported, with 67 of the incidents being reported in HIAD 2.0, 2 incidents reported in H2tools and another 2 incidents reported in both databases Table 14.5.[4] Of these incidents, 53 involved vehicles transporting hydrogen and 18 involved vehicles powered by hydrogen Figure 14.9.

Table 14.5. Incidents related to Scenario 3

Data Source	HIAD	H2tools	Both	**Total**
No. of incidents	67	2	2	**71**

Figure 14.9. Division of the incidents related to Scenario 3 based on the type of vehicle involved



In terms of the physical consequences of these events, most of them (26 in number, 37%) did not result in hydrogen release, 20 of them involved hydrogen release but no ignition, while 16 resulted in fire and 9 of them (13%) resulted in a hydrogen explosion Figure 14.10.

Figure 14.10. Physical consequences for accidents related to Scenario 3

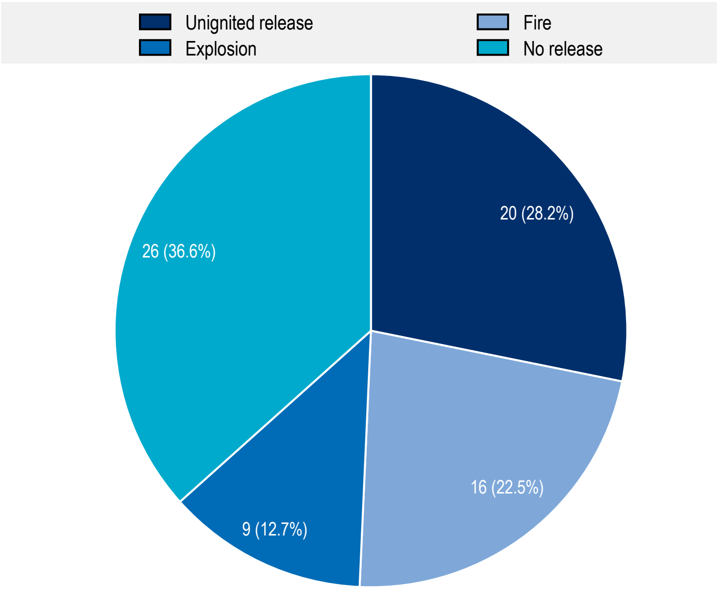


Table 14.6 shows a comparison between liquefied petroleum gas (LPG) vehicle incidents recorded in the Japanese High Pressure Gas Act Incident Database[5] and hydrogen vehicle incident data.

Table 14.6. Normalised incident rate (incidents per vehicle per year) 2010-2021

	Incident rate when used as fuel
Hydrogen	2.6×10^{-5}
LPG	3.0×10^{-6}

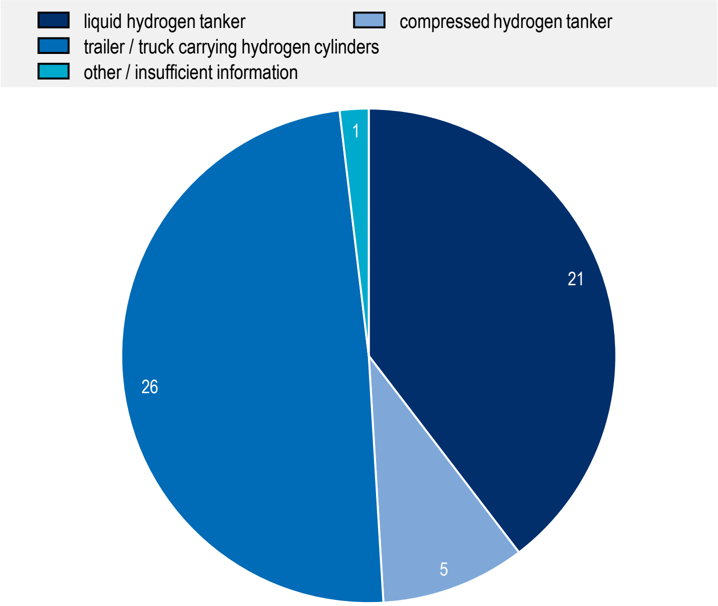
Normalised incident rate suggests LPG vehicles are ca. one order of magnitude safer than hydrogen vehicles. LPG being a more mature technology certainly contributes to this observation. Nonetheless, most of the hydrogen accidents observed were traffic accidents and again, there were no novel hydrogen accidents when it comes to causation. We can therefore consider that hydrogen is not much more dangerous than LPG which is widely transported by vehicles and used as a fuel today.

For vehicles transporting hydrogen, the majority of accidents recorded were substance leaks due to collisions or traffic accidents and there were no novel hydrogen accidents when it comes to causation.

When the incidents are further divided into incidents that involve vehicles transporting hydrogen or incidents that involve vehicles powered by hydrogen, a difference in incident severity is observed.

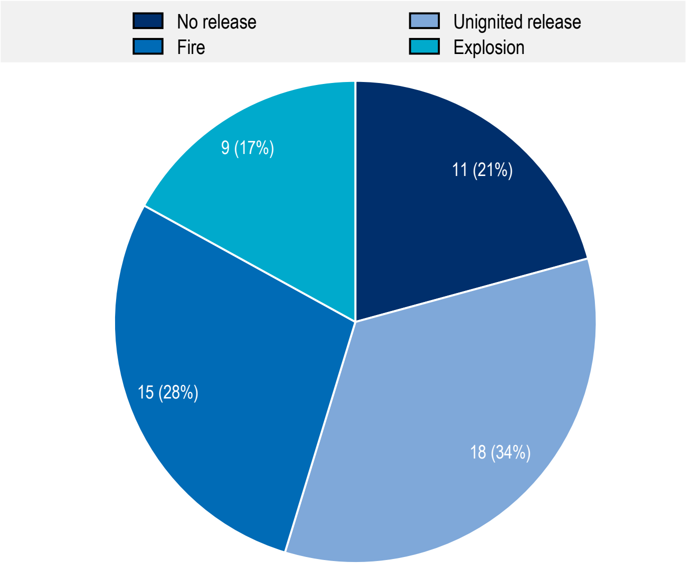
When referring to vehicles transporting hydrogen, these are divided mainly into liquid hydrogen and compressed hydrogen tankers (involved in 26 of the incidents) and into trailers / trucks carrying hydrogen cylinders (involved in 26 of the incidents) Figure 14.11.

Figure 14.11. Types of hydrogen transportation vehicles involved in the studied incidents



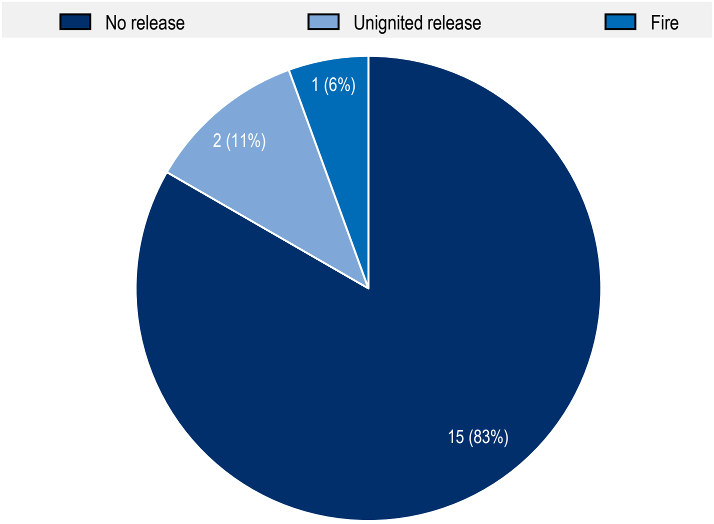
In terms of incident severity, 11 incidents resulted in no hydrogen release whatsoever and 18 incidents resulted in unignited hydrogen release, while 15 of the incidents involving hydrogen transport resulted in fires and 9 resulted in hydrogen explosions Figure 14.12. It should be noted that because of the relatively small number of incidents these ratios may change over time as the use of hydrogen increases.

Figure 14.12. Physical consequences for incidents involving vehicles transporting hydrogen



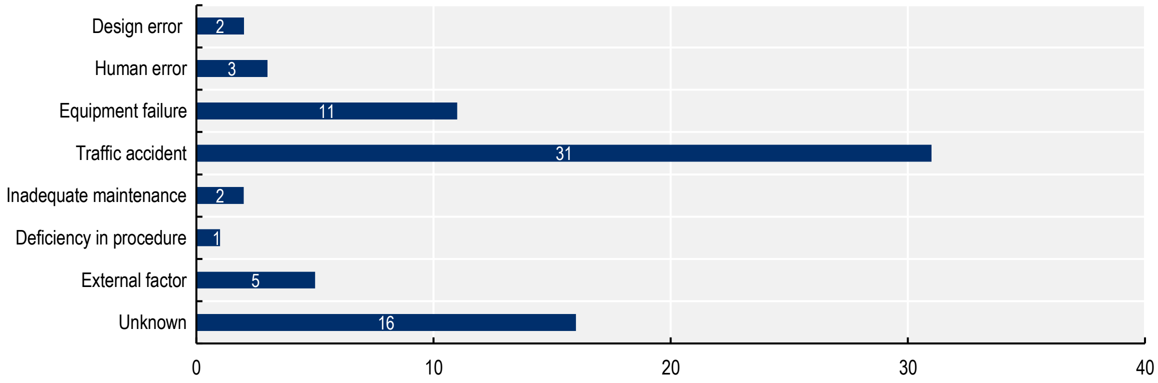
In contrast, the 18 incidents which involved vehicles powered by hydrogen exclusively concerned fuel cell buses. These incidents occurred mainly during pilot projects such as the CHIC project (Müller, K. et al., 2017[12]), where the vehicle operation was more closely monitored and therefore minor incidents were reported that might not have been reported otherwise. This is reflected by the high number of reported incidents that resulted in no hydrogen release (15 incidents), with only two incidents resulting in unignited hydrogen release and one incident resulting in a hydrogen fire Figure 14.13.

Figure 14.13. Physical consequences for incidents involving vehicles powered by hydrogen



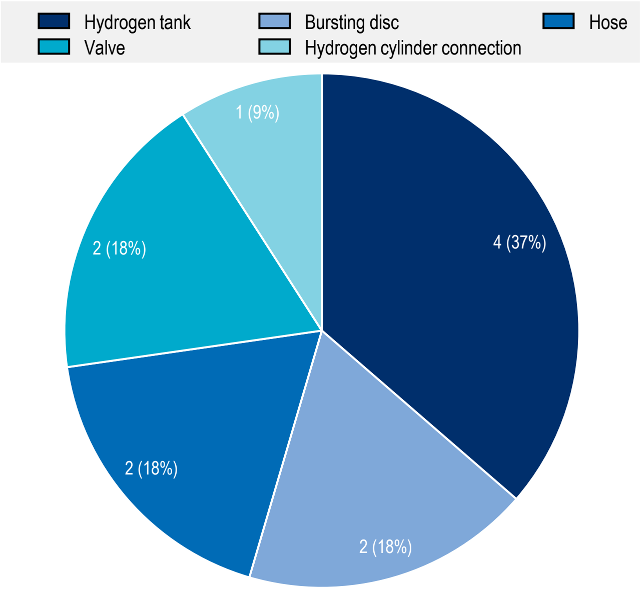
The main root cause of all the reported incidents that are relevant to Scenario 3, was vehicles involved in a **traffic accident**, which accounted for 31 of the incidents (44%). Other significant incident causes were equipment failure, human error, as well as other external factors Figure 14.14.

Figure 14.14. The main causes of incidents related to Scenario 3



Of the 11 incidents related to equipment failure, most involved **flaws in the hydrogen tanks** themselves, but there were also incidents that involved the failure of other components such as pressure relief bursting discs, hoses, valves and connections between hydrogen cylinders Figure 14.15.

Figure 14.15. Components whose failure resulted in incidents related to Scenario 3



Normalisation calculations: Scenario 3 – Road transport: Hydrogen leakage in a confined space/ built environment

We normalised the number of accidents against *per registered vehicle per year* for hydrogen and LPG. We considered only accidents between 2010 and 2021 as we believe they are more relevant to older accidents.

Hydrogen

An article published by jupyter research (Jupyter Research, 2022[13]) estimated the number of hydrogen vehicles on road to be ca. 60 000 in 2022. We only considered registered accidents in the databases (HIAD 2.0 and H2tools) between 2010 and 2021 as we consider older accidents to be less relevant.

Table 14.7. Accidents per vehicle per year = Accident per year/ No. hydrogen vehicles

	hydrogen vehicles
No. accidents (2010-2021)	17
Accident per year	1.54
Accidents per vehicle per year	**2.58×10^{-5}**

LPG

We were able to find detailed Japanese LPG data in their High Pressure Gas Act Database. A report by World LPG Association (World LPG Association, 2019[14]) reported the number of registered LPG vehicles in Japan to be 182 000 in 2018.

Table 14.8. Accidents per vehicle per year = Accident per year/ No. LPG vehicles

	LPG vehicles
No. accidents (2010-2021)	6
Accident per year	0.54
Accidents per vehicle per year	**3.00 x 10^{-6}**

Scenario 5 – Mobility and partially confined spaces: accidents at a hydrogen refuelling station

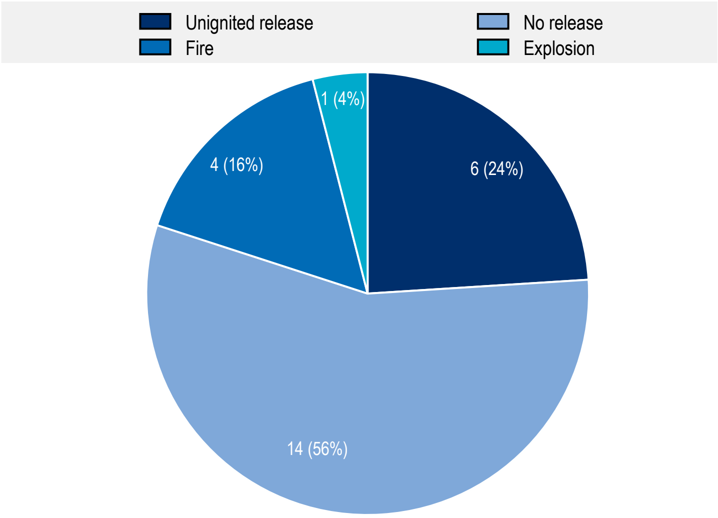
We identified 25 accidents that are related to Scenario 5: of which 9 accidents were reported in HIAD 2.0 and an additional 16 reported in H2tools. In contrast with most hydrogen-related accidents, the majority of Scenario 5 related accidents (15) are caused by the mal-function of the compressor or dispenser, and result in no hydrogen leak (Figure 14.16 and Figure 14.17). This is in agreement with an earlier study (Sakamoto *et al*, 2016) focused on Scenario 5 related accidents in Japan and the United States,[6] which are not yet covered by either HIAD 2.0 or H2tools.[7]

The accident rate is normalised to be 1.19 x 10^{-7} accidents per refuelling (Appendix 5.2.3). As a comparison, we also calculated the (normalised) accident rate for LPG stations, which is at 2.52 x 10^{-7} accidents per refuelling. The numbers suggest that hydrogen refuelling stations, in their current states, can be considered slightly safer than LPG stations (see Table 14.9).

Table 14.9. Normalised accident rate in refuelling stations

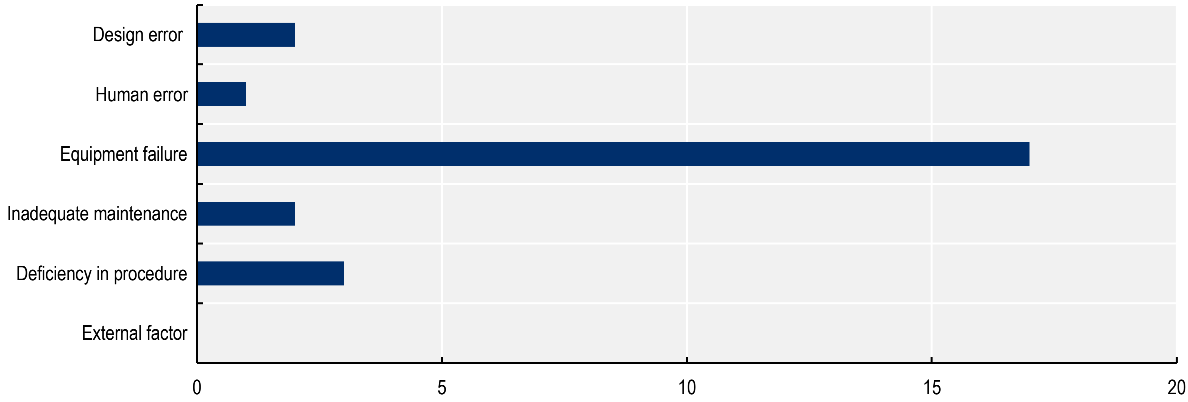
	Number of accidents per refuelling
H2 stations	1.19 x 10^{-7}
LPG stations	2.52 x 10^{-7}

Figure 14.16. Physical consequences for accidents related to Scenario 5



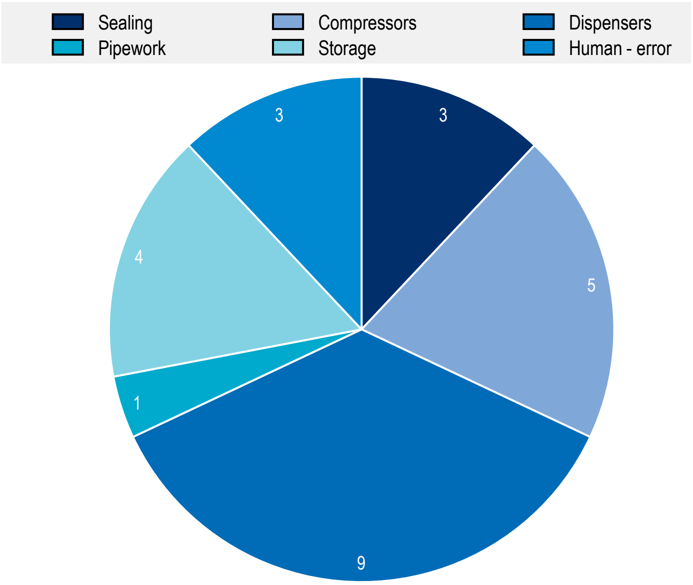
As expected, the majority of the accidents are caused by *equipment failure* Figure 14.17, which is dominated by **dispenser and compressor failure**. Other equipment failures are related to *storage facilities* and *sealings* Figure 14.18.

Figure 14.17. Statistics related to the cause of accidents related to Scenario 5



In specific, dispenser-related accidents are dominated by flexible hose failures (4), and the majority of *human error* was caused by fuel cell vehicles (FCV) users. The above-mentioned Japanese study (Sakamoto et al., 2016[15]) highlights that no user-induced accidents were reported in Japan due to the regulations prohibiting self-serviced hydrogen fuelling stations.[8] Nonetheless, even self-serviced petrol stations were once prohibited in many countries based on state fire codes (National Association of Convenience Stores (NACS), 2022[16]). Therefore it is still necessary to provide safety measures for the prevention of FCV-user induced accidents as like petrol stations, we expect FCV-users would eventually be able to perform self-fuelling, even in Japan. The same Japanese study also mentions that the majority of leakages in Japan are caused by screw joints. Since joints are mainly welded in the United States, there is a reduced proportion of joints-related leakages from 81% (Japan) to 45% (United States). This example suggests a relatively small change in design can in some cases significantly reduce the risk associated with a certain component.[9]

Figure 14.18. Component failure ranked by frequency



Normalisation calculations: Scenario 5 – Mobility and partially confined spaces: accidents at a hydrogen refuelling station

We normalised the number of accidents against p*er refuelling* for hydrogen and LPG.

Hydrogen

A presentation by the National Renewable Energy Laboratory reported a number of refuelling per station per hour at 3.1. Based on this, we estimated a number of refuelling per day per station at 49.6 assuming hydrogen stations operate between 7:00-23:00. For accidents registered in the databases, we only considered those after 2004 as there is only one recorded accident before 2004 (1991) and it may be less relevant.

Table 14.10. Accidents per refuelling =Accident per year/ No. refuelings per year worldwide

No. refuellings per station per day	49.6
No. refuelling stations worldwide (Source: h2tools.org)	685
No. refuellings per day worldwide	33 976
No. refuellings per year worldwide	12 401 240
No. hydrogen accidents (2004-2020)	25
No. hydrogen accidents per year	1.47
No. accidents per refuelling	**1.19×10^{-7}**

LPG (Japan)

For LPG vehicles we once again relied on the Japanese High Pressure Gas Act Database. In addition, the (World LPG Association, 2019[14]) reported an average estimated number of registered LPG cars at around 2.2×10^{5} and an average LPG consumption at 1.28×10^{6} metric tons for the period 2004-2018. Since LPG tank sizes range between 20 and 140 litres, we used the median (80.25 L) to estimate the number of refuelling. A conversion factor of 1.96L/kg is used to convert this volume (80.25L) to weight (42.09 kg).

Table 14.11. No.accident per refuelling (Japan) = No. accidents per year / No. refuellings

Japanese LPG Consumption (2004-2018 average)/ kg	1.28x109
Fuel weight per fuelling / kg	42.09
No. of fuellings (Japan)	3.04x107
No. of accidents in Japan (2004-2018)	14
No. of accidents per year	0.93
No. of accidents per fuelling per year (Japan)	3.06 x 10-8

Note that there were no recorded LPG station accidents in Japan after 2012. If we consider only the period between 2004 and 2011, then the number of accidents per fuelling per year would be 5.75×10^{-8}.

LPG (Korea)

Work by (Park et al., 2006[17]) provided the total number of LPG accidents between 1992 and 2003. In addition, Korea Energy Economics Institute[10] published LPG consumption data.

Table 14.12. Total number of LPG accidents (1992-2003)

Total No. of accidents (1992-2003)	41
Accidents per year	3.73
LPG Consumption (2001) / kg	3.316×10^7
No. of refuellings per year (Korea)	7.88×10^6
No. of accidents per fuelling per year (Korea)	**4.73×10^{-7}**

LPG - Accident rate summary

Table 14.13. LPG - Accident rate summary

	No. of accidents per fuelling per year
Japan	3.06×10^{-8}
Korea	4.73×10^{-7}
Average	2.52×10^{-7}

Storage

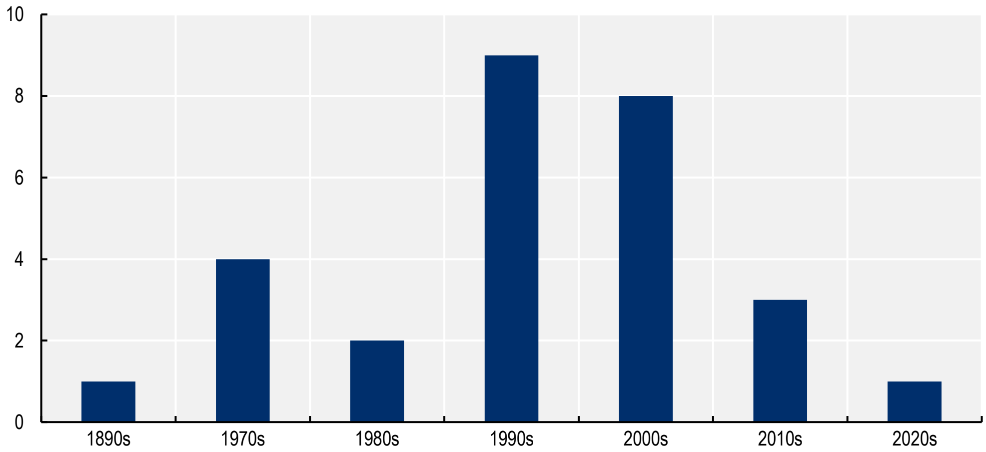
Besides the incidents that have been analysed in previous sections, which are related to specific scenarios, a number of incidents were identified which involve the storage. Since hydrogen storage can be related to scenario 1, 3 and 5, these incidents are analysed here separately.

In total, **28** incidents related to hydrogen storage were reported, with 22 of the incidents being reported in HIAD 2.0, 4 incidents reported in H2tools and another 2 incidents being reported in both databases Table 14.14. Notably **most of the incidents took place before 2010**, with only 4 of the incidents taking place after 2010 Figure 14.19. This could be an indication of the success of the stricter regulations and safety requirements regarding the storage of hydrogen.

Table 14.14. Incidents related to hydrogen storage

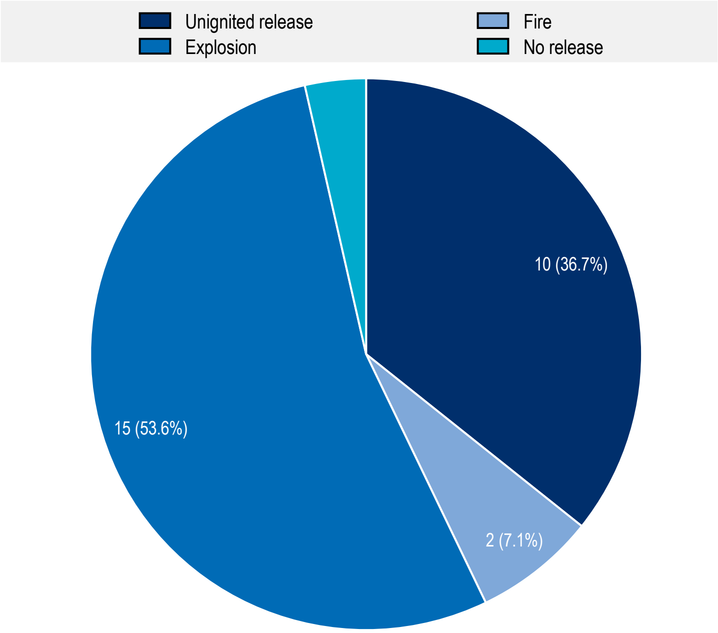
Data source	HIAD	H2tools	Both	**Total**
No. of incidents	22	4	2	**28**

Figure 14.19. Incidents related to hydrogen storage over time



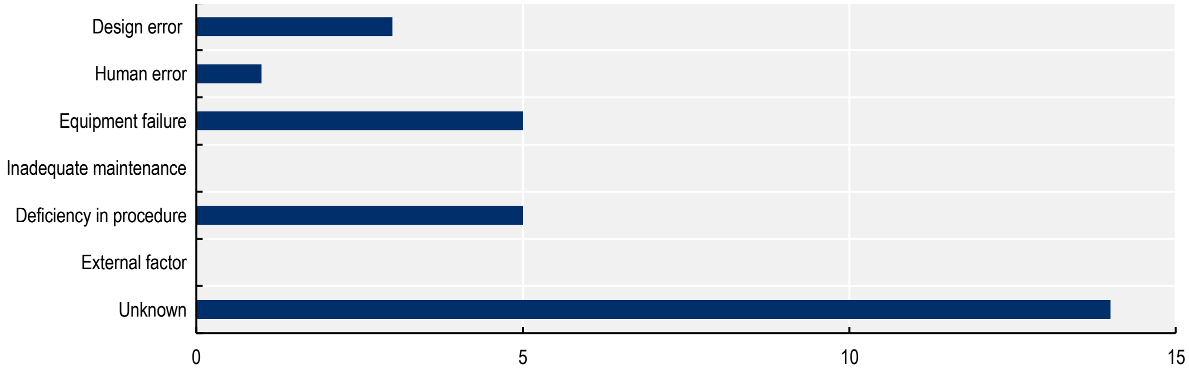
Incidents that involve hydrogen storage have the potential to be severe due to the high pressure of the stored hydrogen and its large mass. In terms of incident severity, 15 of the reported incidents resulted in hydrogen explosions, 2 resulted in fires, while 10 incidents resulted in unignited hydrogen release and 1 incident involved no hydrogen release whatsoever Figure 14.20.

Figure 14.20. Physical consequences of incidents involving hydrogen storage



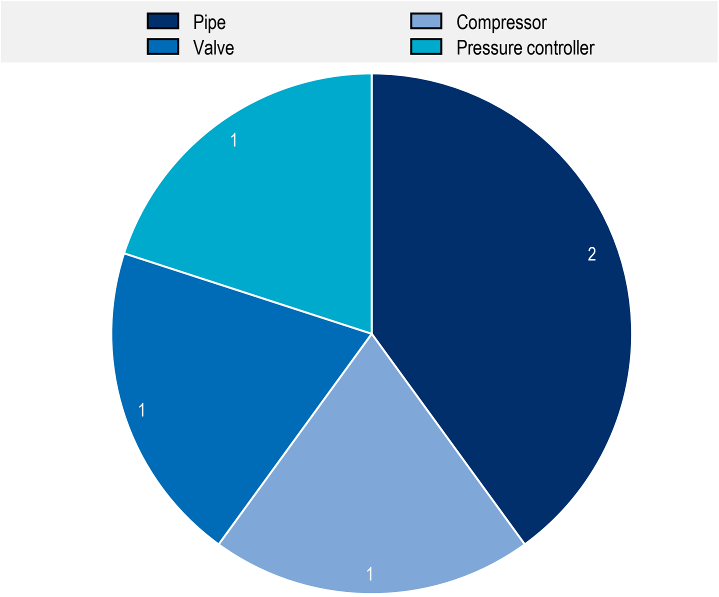
Since most of the incidents occurred before 2000, in many cases the available **information is limited** and the causes of the incidents were unclear or unreported. Overall, the main causes of accidents involving hydrogen storage are the failure of the storage equipment, errors in the design of the hydrogen storage or deficiencies in the hydrogen handling procedure Figure 14.21. An example of deficiency in procedure observed in a recent incident is the release and ignition of hydrogen at the gas storage station of a nuclear power plant in France. The accident took place because, when a pallet of empty hydrogen cylinders was being replaced, the pallet was not disconnected from the gas supply line. The hose connecting it to the pressure relief system was then accidentally torn off during the pallet removal by a forklift. This incident revealed that the safety procedures had not been properly adapted to the specific storage conditions. Issues were discovered which could be contributing causes to the incident, such as uncontrolled access to the storage area, lack of respect of the ATEX[11] distance for welding work and the abnormally high frequency by which the gas pallets were being replaced.

Figure 14.21. The root causes of incidents that involve hydrogen storage



In terms of component failure, only 5 incidents that were caused by failed components were identified. The components involved in these incidents were pipes, a compressor, a high-pressure valve and a pressure controller Figure 14.22.

Figure 14.22. Failed components that lead to incidents related to hydrogen storage



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Notes

[1] Normalised risk: A measure of risk created by mathematically adjusting a value in order to permit comparisons.

[2] A similar figure plotted by (Spada, Burgherr and Boutinard Rouelle, 2018[4]) is presented in Output 2.

[3] In addition to these figures, comparative data with normalised number of road accidents and / or fatality rates among hydrogen-powered vehicles and other types of vehicles have been requested by the Japanese authorities.

[4] An additional accident involving liquid hydrogen release from a rail tanker was reported in HIAD 2.0, however as rail transport of hydrogen was determined to be beyond the scope of this review, this was not included in this report.

[5] High Pressure Gas Act Incident Database, 2021, the High Pressure Gas Safety Institute of Japan (KHK).

[6] Recorded in the Japanese High Pressure Gas Safety Act Database (in Japanese) for period 2005-2014 and US HIRD (hydrogen incident reporting database) database for period 2004-2012.

[7] While H2tools and HIAD 2.0 cover a broad range of hydrogen accidents from across the world, they rely on the gradual collation of information from smaller hydrogen databases and user reports, so such gaps in coverage are not unexpected.

[8] The *Self-Serviced Hydrogen Station Guidelines* (JPEC-TD 0004, in Japanese) released by the Japan Petroleum Energy Center (JPuEC) in 2018 allows driver-performed hydrogen fuelling provided they have gone through required safety training.

[9] Nonetheless, the complex layouts of hydrogen refuelling stations can make welding operations difficult and there was limited data on material strength of welded parts in high-pressure hydrogen environments when the study was published (2016).

[10] http://www.keei.re.kr/main.nsf/index_en.html?open&p=%2Fweb_keei%2Fen_Issues01.nsf%2F0%2FFBCEC343E68337DF49256E2900483FB5&s=%3FOpenDocument, accessed 20/07/2022.

[11] ATEX is the name given to European Directives 99/92/EC and 2014/34/EU which define the minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres, as well as directing the laws of Members States concerning equipment and protective systems used in potentially explosive atmospheres.

Part V Hazard and consequences analysis

15

Bow tie barrier analysis

This chapter presents ideas on expected minimum safety control and mitigation measure, which should be in place for each set of technology. These safety controls can be viewed as safeguards which prevent a loss of containment (a leak) of hydrogen gas from the technology set out in each scenario.

A Bow Tie analysis is an ideal way to assess the risks associated with technology or activities as it is used to identify potential hazards and to understand the adverse consequences the hazards may cause, if not effectively controlled (CCPS; Energy Institute, 2018[1]). A Bow Tie diagramme is a visualisation of the path a hazard may take to cause a severe consequence and a description of the combination of preventative and mitigative barriers required to reduce the process safety risk to an acceptable level.

Simple Bow Tie Diagrams are shown in Figure 15.1 and Figure 15.2. The circumstances which may give rise to a loss of control are displayed as blue boxes on the left-hand side of the diagramme. These "initiating events" are derived from hazard analysis identified in the literature review, supplemented by professional experience of the author in dealing with major hazards in order to understand and describe how a component or system may fail.

Figure 15.1. Simple bow tie diagrammes

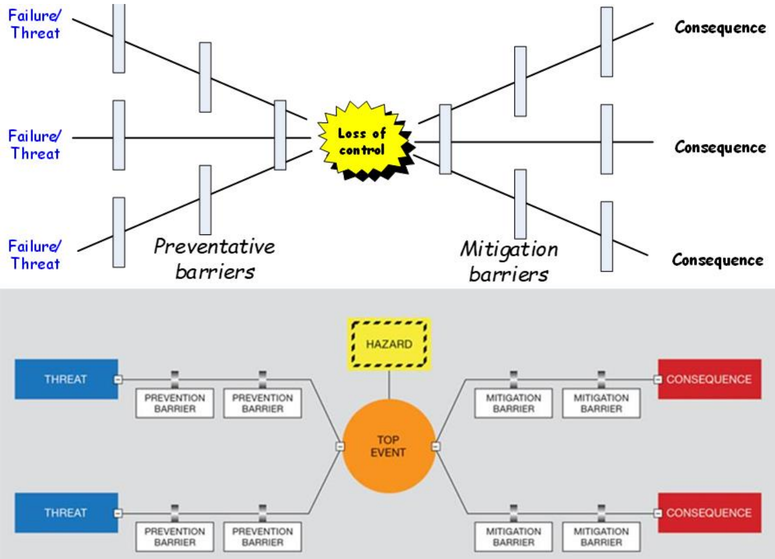
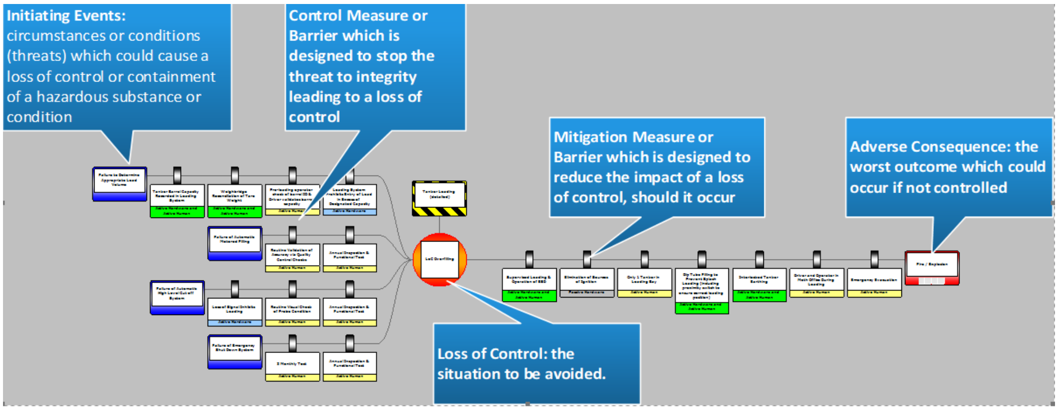


Figure 15.2. Components of a bow tie diagramme



The control measures, or barriers, are the safeguards which are in place to prevent a threat from causing a loss of control or containment of a hazardous substance. Ideally, they should be independent of each other to avoid any common mode of failure. The barriers can be categorised by their function, which makes it easier to decide whether they are sufficiently reliable to prevent a threat from causing harm.

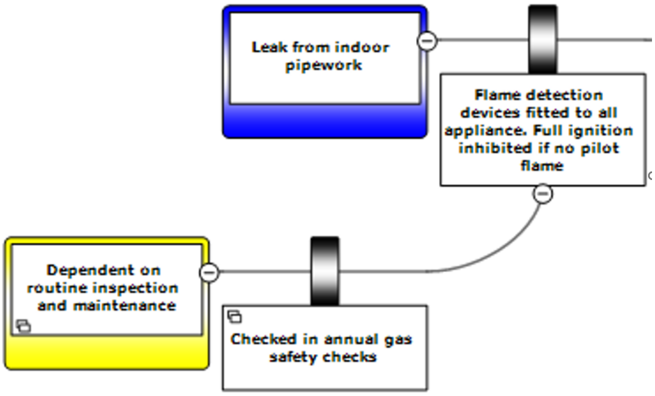
In the centre of the Bow Tie, the knot, describes the condition which represents a loss of control of the hazard, such as loss of containment of a hazardous substance. The right-hand side of the Bow Tie shows the mitigation measures or barriers which serve to reduce the final impact of the loss of control. Examples include, emergency shut-down systems, elimination of sources of ignition (ATEX Equipment) which reduces the chance of ignition if a flammable substance is released, and the emergency response actions required.

The red boxes to the extreme right-hand side describe the outcome or consequences which could occur following a loss of control. These should represent the "worst-case" outcome which could happen.

The visual nature of the Bow Tie means that it is easy to see the number and range of controls available to safeguard against a major incident and to decide whether the number and type of safeguards in place are sufficient to reduce risk to an acceptable level. Well-constructed Bow Tie diagrams quickly show the "basis of safety" (what is being relied upon to keep process conditions safe) for individual activities and processes. Bow Tie diagrams are also very useful for training people in the hazards and risks associated with their activities and for incident investigation as it is relatively straightforward to see which control measures should have been in place and to identify which barriers failed leading up to and during the incident.

The effective functioning of some control and mitigation measures are dependent on a secondary set of actions or controls. These are call "barrier dependencies" and are show as yellow boxes in the Bow Tie diagram, as shown in Figure 15.3. For example the effective functioning of a flame detection device in a heating appliance may deteriorate over time and require routine inspection and maintenance actions to sustain its function.

Figure 15.3. Barrier dependencies



Barrier classification

Classifying control and mitigation measure by their type and function helps us to make judgements about the value and robustness of the measures which can be applied to the technology or situation which could give rise to a major incident. Ideally all control measures will be robust and will function as desired when called upon to provide protection. However, in practice no protection measure can be perfect and the circumstances of how and why they may fail are important considerations when designing and implementing safety systems.

Basic mode of operation

The initial classification used in this assessment is by basic mode of operation of the barrier. This helps us to understand if the control was part of the original safety design of the installation and therefore will be fixed for the lifetime of that system. A further consideration is whether it is an active control measure or is a task undertaken by people and whether it should appear in a maintenance program. Five categories are used for this purpose:

- Design
- Automated
- Semi-automation
- Maintenance
- Procedure

Design: These barriers are determined during the initial design of the safety system and tend to be fixed for the duration of the use of the technology. Once installed and operational it is usually difficult to change the design without a major modification of the installation or system.

Automated: Automated controls operate without human intervention. These controls operate when safety is compromised, and action is needed quickly to prevent an incident. Automated controls are usually reliant on routine maintenance to keep them functioning in an optimal condition.

Semi-automated systems: These controls relay partly on technology and then human intervention to bring the situation back into safety. An alarm followed by corrective action is an example of this type of control. In an emergency the right action requires a pre-determined response.

Maintenance: These are the controls which keep safety systems functioning and delivering the desired safety outcomes. As with all human tasks maintenance can be prone to error and mistakes which may remain undetected until a safety system is called upon in an emergency.

Procedure: These are tasks performed by people and normally the correct action is set out in a safe operating procedure. People tend to have more failure modes than technology and when an error may happen is very difficult to predict.

Criticality

Not all barriers or control / mitigation measures are of equal value in protecting against a major incident, so it is helpful to differentiate them. The two types of classification are criticality or “importance” in the prevention of a major accident (safety criticality) and the second is ‘reliability’ (or vulnerability to failure on demand). They are quite separate and distinct features that are generally independent of each other.

Adopting this classification helps an organisation focus on the most important issues with complex process safety management systems. It helps to concentrate efforts aimed at assuring that weak control measures continue to function and deliver the desired outcome against a constant tendency for control measures to deteriorate over time.

Consider the safety criticality of a barrier as a function of its contribution to the prevention of a major accident. Applying guide words such as ‘essential’ and ‘vital’ or ‘incidental’ or ‘marginal’ to the prevention of a major incident can help as a starting point. It is more helpful to also consider which failure mechanism the barrier helps to prevent and how significant that failure mechanism is compared to alternative routes to failure e.g. does it lie on one of the most significant major hazard scenarios for the facility. A further factor to consider is whether the control measure or barrier is involved in the maintenance of a process condition within prescribed boundaries such as pressure, temperature or level, where an excursion outside such boundaries could lead to a loss of containment?

The following questions help assess criticality (Travers and McCulloch, 2018[2]):

- Does the barrier lie on the critical path to a major accident e.g. is this a major hazard initiator should it fail?
- Does the control measure / barrier directly relate to controlling process conditions e.g. temperature, pressure, flow, level which could directly lead to a loss of containment?
- Does the control measure / barrier guard against another important loss of containment failure mechanism, e.g. corrosion, stress, impact?
- How essential is the control or mitigation measure in preventing a loss of containment e.g.
  - Essential?
  - Important?
  - Moderately relevant?
  - Marginal?
  - Supplementary / adjunct to a more important control measure?

Three categories of criticality are used:

- High criticality
- Medium criticality
- Low criticality

Vulnerability (to failure)

The next classification to be applied to the barriers relates to the reliability of the control measure to work and deliver the correct control and outcome when it is needed. The term vulnerability is used to help focus on the weakest elements of the system and vulnerability should be viewed as the inverse of reliability. This is based on the characteristic of the barrier function. This is illustrated in Table 15.1 which identifies five main characteristic types which fulfill the stages of "Detect, Decide and Act" from the CCPS and Energy Institute Guidance: Bow Ties in Risk Management (CCPS; Energy Institute, 2018[1]).

Table 15.1. Barrier types and vulnerability based on function

	Barrier type	Attributes	Function			Vulnerability
1	Passive Hardware	The control works by virtue of its presence			Act	**Low**
2	Active Hardware	All elements in the control are executed by technology	Detect	Decide	Act	**Low** **Low / medium**
3	Active Hardware & Human	Control is by combination of human behavioural and technological execution	Technology detects & alarms	Human decide	Human initiates response	**Medium** **Medium / High**
4	Active Human	The control consists of human actions, often interacting with technology	Human observation	Human evaluation	Human acts (including acting via technology)	**High**
5	Continuous	The control is always operating			Always active	**Low** **Low / medium**

Type 1. Passive Hardware – this type of control operates without human intervention. For example, a storage tank containment bund falls into this category as it can contain a spillage without any prior detection of a leak. It is simply a physical protective measure. Generally considered as of "low vulnerability".

Type 2. Active Hardware – this type of control fulfills its function automatically once a set of conditions are encountered. The system detects the condition, decides whether it is acceptable and if not takes action to bring the situation back into its controlled state. An automatic gas detector linked to an emergency shut down valve fulfills this action as the flammable gas is detected and the system then automatically closes the pipe inlet valve without any human intervention. Generally considered as of 'low vulnerability' as a main barrier but the inspection, maintenance, and calibration activities upon which its performance relies upon can be considered as 'medium' or 'high vulnerability'.

Type 3. Active Hardware and Human – this type of control is partially automated but then relies on human intervention to decide if the situation is unacceptable and to initiate a corrective action. The action to be taken on the initiation of a high-pressure alarm is an active hardware / human control as the hardware gives information from the sensor about a rise above a pressure threshold, or even sounds an alarm at a set pressure but then it is the operator who decides whether the system should be shut down. Generally considered as 'medium vulnerability'.

Type 4. Human Active – this is a control where a person or several people undertake the whole of the control or mitigation measure. Generally considered as "high vulnerability" because of the opportunity for human error. This value can be further assessed using human reliability analysis on such critical tasks to gauge the likelihood of an error occurring or the opportunity for recovery should an error be made.

Type 5. Continuous – this type of control is active continuously regardless of the situation or condition of the plant or process. For example, a ventilation fan which is constantly running in a confined or indoor space is an example of a continuous measure. Generally considered as "medium" or "low vulnerability" depending on the thoroughness of periodic checks and tests of its function.

Findings

Hazards are always generic, and risks are always context-based. So, hydrogen gas is always flammable (the hazard) but the degree of exposure to potential harm to people and assets (the risk) varies based on the context in which hydrogen is deployed. When hazards are present there can never be zero risk, instead it is important to determine what is an acceptable level of risk associated with the deployment, throughout society, of hydrogen as a fuel source, rather than it being a specialised industrial commodity confined to specific industrial locations.

This bow tie analysis provides an initial and slightly crude risk assessment based on limited information available about the exact nature and configuration of the technology within which it is deployed (McCulloch, 2017[3]).

The control and mitigation measures determined for each scenario are set out in Bow Tie Diagrammes as summarised in the tables below. These are not meant to be definitive or absolute but rather to help industry and regulators consider and debate what needs to be in place to reduce the likelihood of a major incident to as low as is reasonably practical.

Special attention needs to be paid to controls which are classified as both high criticality and high vulnerability as these are really important controls, but which cannot be considered as highly reliable.

The best control measures are associated with intrinsically safe systems, that is systems with high levels of automation and few failure modes. However, given the range of technologies involved in the hydrogen fuel transition it will not always be possible to adopt intrinsically safe solutions for every technology.

In-situ electrolytic H2 generation

BowTie Group: Hydrogen Safety	
Hazard	**1. In-situ electrolytic H2 generation**
Top event	**Loss of Containment of Hydrogen**

Mechanical failure of Compressor				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Specific design codes for H2 compressors	High Criticality	Low Vulnerability	Design	Passive Hardware
Design to eliminate vibration via mountings and connection couplings	High Criticality	Low Vulnerability	Design	Passive Hardware
Site in open air or in well ventilated building (see specific ventilation standards)	High Criticality	Low Vulnerability	Design	Passive Hardware
Compressor protected from impact - within cage or behind barriers	High Criticality	Low Vulnerability	Design	Passive Hardware
Equipment earth bonded	High Criticality	Medium Vulnerability	Design	Continuous Hardware
Routine visual inspections (at least weekly)	Medium Criticality	High Vulnerability	Procedure	Active Human
Routine service and maintenance	High Criticality	Medium Vulnerability	Maintenance	Active Human
Critical spares kept on site	Medium Criticality	High Vulnerability	Maintenance	Active Human

Mechanical failure of pipework connecting generator to compressor or compressor to delivery line				
Barrier & escalation factors	Crit.	Vun.	Barrier Category	Barrier type
Specific design codes for pipework to resist H2 attack / embrittlement and corrosion	High Criticality	Low Vulnerability	Design	Passive Hardware
Seam welded joints avoiding flange connections	High Criticality	Low Vulnerability	Design	Passive Hardware
Automatic isolation valves fitted to pipeline before and after each item of equipment	High Criticality	High Vulnerability	Automated	Active Hardware
Pipework provided with adequate supports	High Criticality	Low Vulnerability	Design	Passive Hardware
Routine visual inspections (at least weekly)	Medium Criticality	High Vulnerability	Procedure	Active Human

Mechanical Failure of Electrolyser				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Specific design codes for electrolyser	High Criticality	Low Vulnerability	Design	Passive Hardware
Site in open air or in well ventilated building (see specific ventilation standards)	High Criticality	Low Vulnerability	Design	Continuous Hardware
Reaction condition sensor and alarm linked to automatic shutdown system	High Criticality	Medium Vulnerability	Automated	Active Hardware

Over pressurisation				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Designated maximum pressure rating	High Criticality	Medium Vulnerability	Design	Passive Hardware
Designated safe operating pressure parameters for system	High Criticality	Medium Vulnerability	Design	Active Hardware
Pressure sensor and alarm	Medium Criticality	Medium Vulnerability	Semi-automated	Active Hardware / Active Human
Routine inspection under Pressure Systems Regulations	High Criticality	Medium Vulnerability	Maintenance	Active Human
Pressure relief valve located to direct H2 upwards in the event of a release	High Criticality	Medium Vulnerability	Automated	Active Hardware

Corrosion

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Material of construction resistant to corrosion	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipework routed above ground	Medium Criticality	Medium Vulnerability	Design	Passive Hardware
Metallic pipework coated or painted to protect against corrosion (unless intrinsically corrosion resistant)	Medium Criticality	Medium Vulnerability	Design	Passive Hardware
Pipework earth bonded (if metal)	High Criticality	Medium Vulnerability	Automated	Active Hardware
Routine visual inspections (at least weekly)	Medium Criticality	High Vulnerability	Procedure	Active Human

Impact

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Restricted access to equipment area. :locked enclosure and authorised access only	High Criticality	High Vulnerability	Procedure	Passive Hardware
Equipment protected from impact by barriers	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipework routed above ground and at high level or protected from impact damage	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipelines marked as conveying H2	Medium Criticality	Low Vulnerability	Design	Passive Hardware
Pipework routes recorded on site layout plans	Medium Criticality	Low Vulnerability	Design	Passive Hardware

Fire / Explosion

Barrier & Escalation Factors	**Crit.**	**Vun.**	**Barrier Category**	**Barrier type**
Local emergency stop buttons	High Criticality	Medium Vulnerability	Semi-automated	Active Hardware / Active Human
Automated shut down systems in the event of gas detection or high temperature reading from IR sensor	High Criticality	Medium Vulnerability	Automated	Active Hardware
Infra red temperature sensors to compressor and high temperature alarm	Medium Criticality	Medium Vulnerability	Semi-automated	Active Hardware / Active Human
Warning signs prohibiting ignition sources	Medium Criticality	High Vulnerability	Design	Passive Hardware
Elimination of sources of ignition including ATEX compliant equipment	High Criticality	High Vulnerability	Design	Passive Hardware
Ventilation if equipment is located inside building or enclosure	High Criticality	Low Vulnerability	Design	Passive Hardware
Fire wall between electrolyser / compressor and “at risk” population	Medium Criticality	Low Vulnerability	Design	Passive Hardware
Gas leak detection, alarm and automated shut down system	High Criticality	High Vulnerability	Automated	Passive Hardware
2m separation distance between electrolysers	High Criticality	Low Vulnerability	Design	Continuous Hardware
6m separation distance between compressors and 'at risk' population	High Criticality	Low Vulnerability	Design	Passive Hardware
Emergency plan detailing fire response and evacuation arrangements and safety cordons	High Criticality	High Vulnerability	Procedure	Active Human

Unignited release

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Local emergency stop buttons	High Criticality	Medium Vulnerability	Semi-automated	Active Hardware / Active Human

Automated shut down systems in the event of gas detection or high temperature reading from IR sensor	High Criticality	Medium Vulnerability	Automated	Active Hardware
Infra red temperature sensors to compressor and high temperature alarm	Medium Criticality	Medium Vulnerability	Semi-automated	Active Hardware / Active Human
Warning signs prohibiting ignition sources	Medium Criticality	High Vulnerability	Design	Passive Hardware
Elimination of sources of ignition including ATEX compliant equipment	High Criticality	High Vulnerability	Design	Passive Hardware
Ventilation if equipment is located inside building or enclosure	High Criticality	Low Vulnerability	Design	Passive Hardware
Fire wall between electrolyser / compressor and "at risk" population	Medium Criticality	Low Vulnerability	Design	Passive Hardware
Gas leak detection, alarm and automated shut down system	High Criticality	High Vulnerability	Automated	Passive Hardware
2m separation distance between electrolysers	High Criticality	Low Vulnerability	Design	Continuous Hardware
6m separation distance between compressors and "at risk" population	High Criticality	Low Vulnerability	Design	Passive Hardware
Emergency plan detailing response and evacuation arrangements and safety cordons	High Criticality	High Vulnerability	Procedure	Active Human

H2 transport by high pressure pipeline

BowTie Group: Hydrogen Safety	
Hazard	**2. H2 transport by high pressure pipeline**
Top event	**Loss of Containment of Hydrogen**

Physical damage to pipeline by unauthorized 3rd party damage				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Pipelines routed below ground wherever possible	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipeline material of construction and thickness resistant to impact	High Criticality	Low Vulnerability	Design	Passive Hardware
Route selection to avoid high populations and land designated for development	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipeline buried to a suitable depth to avoid incidental excavation	High Criticality	Low Vulnerability	Design	Passive Hardware
Communication information sent to property owners, landlords, tenants and contractors	High Criticality	Medium Vulnerability	Procedure	Active Human
Pipeline route markers posts and information placards	High Criticality	High Vulnerability	Design	Passive Hardware
Pipeline route information available to utilities and highways agencies with authorisation required before planned excavations	High Criticality	Medium Vulnerability	Procedure	Active Human
Publish pipeline routing and contact details on a national search enquiry system	High Criticality	Medium Vulnerability	Procedure	Active Human
Routine aerial surveys to detect unauthorized excavations	High Criticality	High Vulnerability	Procedure	Active Human

Sabotage / trespass (above ground assets)				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Route marking posts and emergency help line contact	High Criticality	High Vulnerability	Design	Passive Hardware
Above ground valves and connections within protected enclosure / fencing	High Criticality	Medium Vulnerability	Design	Passive Hardware
Routine security checks	Medium Criticality	High Vulnerability	Procedure	Active Human

Overpressurisation

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Pipeline design and material of construction suitable for maximum possible pressure from supply compressors	High Criticality	Low Vulnerability	Design	Passive Hardware
All welded seams as far as possible avoiding flanged jointing	Medium Criticality	Low Vulnerability	Design	Passive Hardware
Designated safe operating pressure for pipeline	High Criticality	Low Vulnerability	Design	Passive Hardware
Control over change in operating pressure via regulatory control	High Criticality	Medium Vulnerability	Procedure	Active Human
Pipeline fitted with pressure relief valves	High Criticality	Medium Vulnerability	Automated	Active Hardware
Pipeline isolation valves at set distances and pipeline junctions	Medium Criticality	Low Vulnerability	Design	Active Hardware

Corrosion

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Metallic pipeline earth bonded & provided with cathodic protection	High Criticality	Low Vulnerability	Design	Continuous Hardware
Pipeline material of construction resistant to corrosion	High Criticality	Low Vulnerability	Design	Passive Hardware
Metallic pipework coated with water resistant cover	High Criticality	Medium Vulnerability	Design	Passive Hardware
Routine NDT testing / intelligent pigging	High Criticality	High Vulnerability	Maintenance	Active Human

Unstable geology

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Route survey and route planning to identify geological challenges and to select a stable route free from ground movement or erosion	High Criticality	Medium Vulnerability	Design	Active Human
Seismic monitoring	Medium Criticality	High Vulnerability	Automated	Active Hardware / Active Human
Routine NDT testing / intelligent pigging	High Criticality	High Vulnerability	Maintenance	Active Human

Inappropriate routing

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Route design to avoid dense or vulnerable populations	High Criticality	Medium Vulnerability	Design	Passive Hardware
Route planning to avoid river bed crossing using pipe bridges instead	High Criticality	Medium Vulnerability	Design	Passive Hardware
Route planning to avoid major highways or train lines to reduce degradation from ground vibration	High Criticality	Medium Vulnerability	Design	Passive Hardware
Routine aerial surveys to check for encroachment	High Criticality	High Vulnerability	Procedure	Active Human
Legislative spacial planning control to avoid development encroachment	High Criticality	High Vulnerability	Procedure	Active Human
Routine NDT testing / intelligent pigging	High Criticality	High Vulnerability	Maintenance	Active Human

Mechanical damage during maintenance

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Maintenance by authorised contractors competent for work on H2 systems	High Criticality	Medium Vulnerability	Maintenance	Active Human
Safe systems of work and method statements for maintenance activities	High Criticality	High Vulnerability	Procedure	Active Human
Re-instatement protocols and hand back procedures	High Criticality	High Vulnerability	Procedure	Active Human

Fire / explosion leading to personal injury / asset / building damage				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Pipeline Emergency Plan	High Criticality	High Vulnerability	Procedure	Active Human
Leak warning automatic calling to nearby residents	Medium Criticality	High Vulnerability	Procedure	Active Human
Suitable separation distance between high pressure pipeline and "at risk" populations	High Criticality	Low Vulnerability	Design	Passive Hardware
Pressure drop monitoring, alarms and automatic section valve isolation	High Criticality	Medium Vulnerability	Automated	Active Hardware
Routine emergency exercises with emergency responders	High Criticality	Medium Vulnerability	Procedure	Active Human
Prohibition of sources of ignition near to above ground installations	High Criticality	High Vulnerability	Procedure	Active Human

Un-ignited release				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Pipeline Emergency Plan	High Criticality	High Vulnerability	Procedure	Active Human
Leak warning automatic calling to nearby residents	Medium Criticality	High Vulnerability	Procedure	Active Human
Suitable separation distance between high pressure pipeline and "at risk" populations	High Criticality	Low Vulnerability	Design	Passive Hardware
Pressure drop monitoring, alarms and automatic section valve isolation	High Criticality	Medium Vulnerability	Automated	Active Hardware
Routine emergency exercises with emergency responders	High Criticality	Medium Vulnerability	Procedure	Active Human
Prohibition of sources of ignition near to above ground installations	High Criticality	High Vulnerability	Procedure	Active Human

H2 in road transport

BowTie Group: Hydrogen Safety	
Hazard	**3. H2 in Road Transport**
Top event	**Loss of containment of H2 in confined space**

Failure of HFCV - tank leakage				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Design codes and standards for road vehicles	High Criticality	Low Vulnerability	Design	Passive Hardware
ADR Compliant vehicle	High Criticality	Medium Vulnerability	Design	Passive Hardware
Type III hydrogen tank (seamless metallic liner)	High Criticality	Low Vulnerability	Design	Passive Hardware
Specific ADR training for drives of H2 commercial vehicles	Medium Criticality	High Vulnerability	Procedure	Active Human
Frequent safety checks on vehicle condition by independent authorised engineer	High Criticality	High Vulnerability	Procedure	Active Human

Failure of HFCV - leakage during purging				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Design codes and standards for road vehicles	High Criticality	Low Vulnerability	Design	Passive Hardware
ADR Compliant vehicle	High Criticality	Medium Vulnerability	Design	Passive Hardware

Redesign of HFCV purging system by improving H2 utilisation rate via H2 recirculation pump & optimising air compressor control strategy	High Criticality	Medium Vulnerability	Design	Passive Hardware
Specific ADR training for drives of H2 commercial vehicles	Medium Criticality	High Vulnerability	Procedure	Active Human
Frequent safety checks on vehicle condition by independent authorised engineer	High Criticality	High Vulnerability	Procedure	Active Human

Fire / Explosion leading to personal injury / property damage					
Barrier & Escalation Factors		Crit.	Vun.	Barrier Category	Barrier type
H2 gas detectors linked to alarms located above source of potential release in confined space		High Criticality	High Vulnerability	Semi-automated	Active Hardware / Active Human
Dependent on routine maintenance	Routine sensor calibration checks	High Criticality	High Vulnerability	Maintenance	Active Human
Dependent on effectiveness of responders	Responders trained and practiced in the appropriate response to gas detection alarm	High Criticality	High Vulnerability	Procedure	Active Human
	Control center staffed at all times confined spaces used for H2 vehicles	High Criticality	High Vulnerability	Procedure	Active Human
Porous diffusion boundaries between adjacent compartments in HFCV		Medium Criticality	Medium Vulnerability	Design	Passive Hardware
Mechanical ventilation in confined spaces - horizontal (transverse rectangular) ventilation openings to achieve 10 ACH		High Criticality	Medium Vulnerability	Automated	Continuous Hardware
Emergency responders wait for at least 2 minutes before approaching damaged vehicles following activation of TPRD		High Criticality	High Vulnerability	Procedure	Active Human
Public remains 100 m from vehicle if TPRD has not activated (no hissing sound) and 10 m if TPRD is activated.		High Criticality	High Vulnerability	Procedure	Active Human
Emergency responders remain 6m from vehicle if no signs of H2 leakage		High Criticality	High Vulnerability	Procedure	Active Human
Emergency responders deploy portable ground blowers with a diffuser to flush under vehicle		High Criticality	High Vulnerability	Procedure	Active Human
Vehicle purging in open air whenever possible		High Criticality	Medium Vulnerability	Procedure	Active Human
Purging indoors within well ventilated spaces		High Criticality	High Vulnerability	Procedure	Active Human
No sources of ignition and ATEX equipment in purging area		High Criticality	Medium Vulnerability	Design	Passive Hardware
Dependent on routine maintenance	Routine inspection of ATEX equipment	High Criticality	High Vulnerability	Maintenance	Active Human
H2 vehicles fitted with warning signs to alert emergency services approaching a defective / crashed vehicle		Medium Criticality	High Vulnerability	Design	Passive Hardware

Mobility and partially confined spaces: Hydrogen city bus driving in a tunnel involved in a collision accident

BowTie Group: Hydrogen Safety	
Hazard	4. Mobility & partially confined spaces: hydrogen city bus driving in a tunnel involved in a collision accident
Top event	LoC from bus in tunnel

Vehicle collision				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type

vehicle fitted with 'leak-no-burst' tank (composite overwrap melting a polymer liner)	High Criticality	Medium Vulnerability	Design	Passive Hardware
Design codes and standards for road vehicles	High Criticality	Low Vulnerability	Design	Passive Hardware
ADR Compliant vehicle	High Criticality	Medium Vulnerability	Design	Passive Hardware
Specific ADR training for drives of H2 commercial vehicles	Medium Criticality	High Vulnerability	Procedure	Active Human

Failure of HFCV - tank leakage				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Design codes and standards for road vehicles	High Criticality	Low Vulnerability	Design	Passive Hardware
ADR Compliant vehicle	High Criticality	Medium Vulnerability	Design	Passive Hardware
Type III hydrogen tank (seamless metallic liner)	High Criticality	Low Vulnerability	Design	Passive Hardware
Specific ADR training for drives of H2 commercial vehicles	Medium Criticality	High Vulnerability	Procedure	Active Human
Frequent safety checks on vehicle condition by independent authorised engineer	High Criticality	High Vulnerability	Procedure	Active Human

Failure of HFCV - leakage during purging				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Design codes and standards for road vehicles	High Criticality	Low Vulnerability	Design	Passive Hardware
ADR Compliant vehicle	High Criticality	Medium Vulnerability	Design	Passive Hardware
Redesign of HFCV purging system by improving H2 utilisation rate via H2 recirculation pump & optimising air compressor control strategy	High Criticality	Medium Vulnerability	Design	Passive Hardware
Specific ADR training for drives of H2 commercial vehicles	Medium Criticality	High Vulnerability	Procedure	Active Human
Frequent safety checks on vehicle condition by independent authorised engineer	High Criticality	High Vulnerability	Procedure	Active Human

Fire / Explosion leading to personal injury / property damage				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Possible pre-notification or registration to highway / tunnel operator of type and safety certificates of vehicles permitted to use tunnels	Medium Criticality	High Vulnerability	Procedure	Active Human
Porous diffusion boundaries between adjacent compartments in HFCV	Medium Criticality	Medium Vulnerability	Design	Passive Hardware
Mechanical ventilation in confined spaces - horizontal (transverse rectangular) ventilation openings to achieve 10 ACH	High Criticality	Medium Vulnerability	Automated	Continuous Hardware
Emergency responders wait for at least 2 minutes before approaching damaged vehicles following activation of TPRD	High Criticality	High Vulnerability	Procedure	Active Human
Pubic remains 100 m from vehicle if TPRD has not activated (no hissing sound) and 10 m if TPRD is activated.	High Criticality	High Vulnerability	Procedure	Active Human
Emergency responders remain 6m from vehicle if no signs of H2 leakage	High Criticality	High Vulnerability	Procedure	Active Human
Emergency responders deploy portable ground blowers with a diffuser to flush under vehicle	High Criticality	High Vulnerability	Procedure	Active Human
H2 vehicles fitted with warning signs to alert emergency services approaching a defective / crashed vehicle	Medium Criticality	High Vulnerability	Design	Passive Hardware

Guidance to driver and occupants on action to take in the event of a H2 leakage, e.g. evacuate vehicle rapidly and move to a safe distance – display of safety cards?	High Criticality	High Vulnerability	Procedure	Active Human
H2 storage system designed to avoid simultaneous opening of all PRDs	High Criticality	Low Vulnerability	Design	Active Hardware
Downward facing TPRD orientated at 30-45deg.	High Criticality	Low Vulnerability	Design	Passive Hardware
Vehicle TPRD diameter of 0.5mm	High Criticality	Medium Vulnerability	Design	Passive Hardware
Design future road tunnels with a cross section which avoid H2 concentrations at a high level in the event of a leak.	Medium Criticality	Low Vulnerability	Design	Passive Hardware
Tunnel ventilation of at least 1-2m/s preferably via cross flow ventilation	High Criticality	Medium Vulnerability	Automated	Continuous Hardware

Mobility and partially confined spaces Accidents at a hydrogen refueling station

BowTie Group: Hydrogen Safety	
Hazard	5. Mobility & partially confined spaces: accidents at a hydrogen refueling station
Top event	LoC H2 at refuelling stations

Leakage from dispensers				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Routine thorough inspection and maintenance including joint leak testing	High Criticality	High Vulnerability	Maintenance	Active Human
Seam welded joints avoiding flange connections	High Criticality	Low Vulnerability	Design	Passive Hardware
Automatic isolation valves fitted to pipeline before and after each item of equipment	High Criticality	High Vulnerability	Automated	Active Hardware
Routine visual inspections (at least weekly)	Medium Criticality	High Vulnerability	Procedure	Active Human
Specific design codes for dispensers	High Criticality	Low Vulnerability	Design	Passive Hardware

Rupture of tube trailers				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Tube trailers parked in secure area and in outside area	High Criticality	Medium Vulnerability	Procedure	Active Human
Automatic isolation valves fitted to pipeline before and after each item of equipment	High Criticality	High Vulnerability	Automated	Active Hardware
Routine visual inspections (at least weekly)	Medium Criticality	High Vulnerability	Procedure	Active Human

Pipework failure				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Specific design codes for pipework to resist H2 attack / embrittlement and corrosion	High Criticality	Low Vulnerability	Design	Passive Hardware
Seam welded joints avoiding flange connections	High Criticality	Low Vulnerability	Design	Passive Hardware
Automatic isolation valves fitted to pipeline before and after each item of equipment	High Criticality	High Vulnerability	Automated	Active Hardware
Pipework provided with adequate supports	High Criticality	Low Vulnerability	Design	Passive Hardware
Routine visual inspections (at least weekly)	Medium Criticality	High Vulnerability	Procedure	Active Human

Mechanical failure of Compressor				

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Specific design codes for H2 compressors	High Criticality	Low Vulnerability	Design	Passive Hardware
Design to eliminate vibration via mountings and connection couplings	High Criticality	Low Vulnerability	Design	Passive Hardware
Site in open air or in well ventilated building (see specific ventilation standards)	High Criticality	Low Vulnerability	Design	Passive Hardware
Compressor protected from impact - within cage or behind barriers	High Criticality	Low Vulnerability	Design	Passive Hardware
Equipment earth bonded	High Criticality	Medium Vulnerability	Automated	Continuous Hardware
Routine visual inspections (at least weekly)	Medium Criticality	High Vulnerability	Procedure	Active Human
Critical spares kept on site	Medium Criticality	High Vulnerability	Maintenance	Active Human

Overpressurisation

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Designated maximum pressure rating	High Criticality	Medium Vulnerability	Design	Passive Hardware
Designated safe operating pressure parameters for system	High Criticality	Medium Vulnerability	Design	Active Hardware
Pressure sensor and alarm	Medium Criticality	Medium Vulnerability	Semi-automated	Active Hardware / Active Human
Routine inspection under Pressure Systems Regulations	High Criticality	Medium Vulnerability	Maintenance	Active Human
Pressure relief valve located to direct H2 upwards in the event of a release	High Criticality	Medium Vulnerability	Automated	Active Hardware

Corrosion

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Material of construction resistant to corrosion	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipework routed above ground	Medium Criticality	Medium Vulnerability	Design	Passive Hardware
Metallic pipework coated or painted to protect against corrosion (unless intrinsically corrosion resistant)	Medium Criticality	Medium Vulnerability	Design	Passive Hardware
Pipework earth bonded (if metal)	High Criticality	Medium Vulnerability	Automated	Active Hardware
Routine visual inspections (at least weekly)	Medium Criticality	High Vulnerability	Procedure	Active Human

Impact

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Restricted access to equipment area. :locked enclosure and authorised access only	High Criticality	High Vulnerability	Procedure	Passive Hardware
Equipment protected from impact by barriers	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipework routed above ground and at high level or protected from impact damage	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipelines marked as conveying H2	Medium Criticality	Low Vulnerability	Design	Passive Hardware
Pipework routes recorded on site layout plans	Medium Criticality	Low Vulnerability	Design	Passive Hardware

Mechanical Failure of Electrolyser

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type

Specific design codes for electrolyser	High Criticality	Low Vulnerability	Design	Passive Hardware
Site in open air or in well ventilated building (see specific ventilation standards)	High Criticality	Low Vulnerability	Design	Continuous Hardware
Reaction condition sensor and alarm linked to automatic shutdown system	High Criticality	Medium Vulnerability	Automated	Active Hardware

Fire / explosion / personal injury / property damage				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Fire protective wall and operation room at least 2m separation distance from H2 dispenser.	High Criticality	Low Vulnerability	Design	Passive Hardware
5m separation distance between H2 storage tank and H2 generation plant	High Criticality	Low Vulnerability	Design	Passive Hardware
Fire wall between electrolyser / compressor and 'at risk' population	Medium Criticality	Low Vulnerability	Design	Passive Hardware
Fire protection wall along boundary of fuel stations	Medium Criticality	Low Vulnerability	Design	Passive Hardware
Use LHRS not GHRS	High Criticality	Low Vulnerability	Design	Passive Hardware
H2 generation and storage system placed outside in well ventilated areas	High Criticality	Low Vulnerability	Design	Passive Hardware
Emergency response plan	High Criticality	High Vulnerability	Procedure	Passive Hardware
Local emergency stop buttons	High Criticality	Medium Vulnerability	Semi-automated	Active Hardware / Active Human
Automated shut down systems in the event of gas detection or high temperature reading from IR sensor	High Criticality	Medium Vulnerability	Automated	Active Hardware
Infra red temperature sensors to compressor and high temperature alarm	Medium Criticality	Medium Vulnerability	Semi-automated	Active Hardware / Active Human
Warning signs prohibiting ignition sources	Medium Criticality	High Vulnerability	Design	Passive Hardware
Elimination of sources of ignition including ATEX compliant equipment	High Criticality	High Vulnerability	Design	Passive Hardware
Ventilation if equipment is located inside building or enclosure	High Criticality	Low Vulnerability	Design	Passive Hardware
CCTV surveillance	Low Criticality	High Vulnerability	Procedure	Active Human
No self service and refueling undertaken by trained staff	Medium Criticality	Medium Vulnerability	Procedure	Active Human

Domestic use of H2 for cooking and heating

BowTie Group: Hydrogen Safety	
Hazard	**6. Domestic use of H2 for cooking & heating**
Top event	**LoC H2 in domestic premises**

Leak in incoming connection pipe				
Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Pipeline constructed from 100% polyethylene	High Criticality	Low Vulnerability	Design	Passive Hardware
Incoming pipework buried and only above ground at entry point to building	High Criticality	Medium Vulnerability	Design	Passive Hardware
Pipework routes marked on household safety file and with local municipal authority	Medium Criticality	High Vulnerability	Procedure	Active Human
Pipework protected in impact resistant conduit fitted with sensor detection strip to aid ground survey prior to excavation / maintenance work	High Criticality	Medium Vulnerability	Design	Passive Hardware
Installation undertaken by certified engineer and safety certificate issued prior to operation	High Criticality	High Vulnerability	Procedure	Active Human

All maintenance and repairs must be undertaken by a H2 certified engineer	High Criticality	High Vulnerability	Maintenance	Active Human

Leak from meter

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Design codes and standards for H2 meters and valves	High Criticality	Low Vulnerability	Design	Passive Hardware
Installation undertaken by certified engineer and safety certificate issued prior to operation	High Criticality	High Vulnerability	Procedure	Active Human
All maintenance and repairs must be undertaken by a H2 certified engineer	High Criticality	High Vulnerability	Maintenance	Active Human
Pressure relief valve fitted to incoming line at meter	High Criticality	Medium Vulnerability	Automated	Active Hardware
Dependent on routine inspection and maintenance Specified frequency or included in annual gas safe checks	High Criticality	High Vulnerability	Maintenance	Active Human
Annual gas safe inspections by competent engineers	High Criticality	High Vulnerability	Maintenance	Active Human

Leak from indoor pipework

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Design codes and standards for H2 pipework for use in buildings	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipeline constructed from 100% polyethylene	High Criticality	Low Vulnerability	Design	Passive Hardware
Pipe runs in protective ducting / conduit	High Criticality	Low Vulnerability	Design	Passive Hardware
Mechanical crimp fitting joints or seam welded(no flanged joints)	High Criticality	Low Vulnerability	Design	Passive Hardware
Flame detection devices fitted to all appliance. Full ignition inhibited if no pilot flame	High Criticality	Medium Vulnerability	Automated	Active Hardware
Dependent on routine inspection and maintenance Checked in annual gas safety checks	High Criticality	High Vulnerability	Maintenance	Active Human
Annual gas safe inspections by competent engineers	High Criticality	High Vulnerability	Maintenance	Active Human
Installation undertaken by certified engineer and safety certificate issued prior to operation	High Criticality	High Vulnerability	Procedure	Active Human
All maintenance and repairs must be undertaken by a H2 certified engineer	High Criticality	High Vulnerability	Maintenance	Active Human

Leak from boiler appliance

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Design codes and standards for H2 appliances	High Criticality	Low Vulnerability	Design	Passive Hardware
Annual gas safe inspections by competent engineers	High Criticality	High Vulnerability	Maintenance	Active Human
Installation undertaken by certified engineer and safety certificate issued prior to operation	High Criticality	High Vulnerability	Procedure	Active Human
All maintenance and repairs must be undertaken by a H2 certified engineer	High Criticality	High Vulnerability	Maintenance	Active Human

Leak from cooking appliance

Barrier & Escalation Factors	Crit.	Vun.	Barrier Category	Barrier type
Design codes and standards for H2 appliances	High Criticality	Low Vulnerability	Design	Passive Hardware
Annual gas safe inspections by competent engineers	High Criticality	High Vulnerability	Maintenance	Active Human

Installation undertaken by certified engineer and safety certificate issued prior to operation	High Criticality	High Vulnerability	Procedure	Active Human
All maintenance and repairs must be undertaken by a H2 certified engineer	High Criticality	High Vulnerability	Maintenance	Active Human

Fire / explosion / personal injury / building damage					
Barrier & Escalation Factors		Crit.	Vun.	Barrier Category	Barrier type
Cavity wall ventilation		High Criticality	Low Vulnerability	Design	Passive Hardware
Non-closeable ceiling vents ducted to external wall in room with H2 appliance		High Criticality	Medium Vulnerability	Design	Continuous Hardware
Odourisation of H2 with odourant		High Criticality	Low Vulnerability	Design	Continuous Hardware
Integrated excess flow valves automatically cut off supply in the event of excess flow		High Criticality	Medium Vulnerability	Automated	Active Hardware
Dependent on routine inspection and maintenance	Checked in annual gas safety checks	High Criticality	High Vulnerability	Maintenance	Active Human
Meter installed external to property in permanently ventilated cabinet		High Criticality	Low Vulnerability	Design	Passive Hardware
Gas detection fitted in properties and automatic shut off of inlet if gas detected		High Criticality	Medium Vulnerability	Automated	Active Hardware
Dependent on routine inspection and maintenance	Checked in annual gas safety checks	High Criticality	High Vulnerability	Maintenance	Active Human
Excess flow valves automatically cut off supply in the event of excess flow		High Criticality	Medium Vulnerability	Automated	Active Hardware
Dependent on routine inspection and maintenance	Checked in annual gas safety checks	High Criticality	High Vulnerability	Maintenance	Active Human
H2 appliances prohibited inside multi occupancy buildings above 18m or 5 floors		Medium Criticality	High Vulnerability	Design	Passive Hardware

References

CCPS; Energy Institute (2018), *Bow Ties in Risk Management: A Concept Book for Process Safety*, https://doi.org/10.1002/9781119490357. [1]

McCulloch, P. (2017), *Learning from Incidents- Linking incident analysis with BowTie based risk assessments*. [3]

Travers, I. and P. McCulloch (2018), *The Chemical Engineer*. [2]

Part VI Lessons learnt and preliminary findings regarding hydrogen safety elements

16

Hydrogen safety measures and their significance

A range of practical safety measures can be applied to hydrogen technologies. This chapter presents the approach to gathering lessons learnt and recommendations on key safety elements for hydrogen technologies that new or revised regulations could consider to achieve better outcomes.

The Paris Agreement on climate change and mitigation of greenhouse emissions has been ratified by all states worldwide with the exception of four states (Eritrea, Iran, Libya and Yemen) which have signed but not ratified the Agreement. The EU and all its member states are strongly committed to its implementation and in line with this commitment; the European Green Deal was approved in 2020 with the overarching aim of making Europe climate neutral by 2050. Similar long-term reduction plans to achieve net zero emissions by 2050 have been released by most countries outside EU, e.g. UK, Canada, Australia, Japan, South Korea, etc., while China aims to achieve net-zero emissions before 2060. The United States announced a commitment to reduce national greenhouse (GHG) emissions 50–52% by 2030 as part of the United States' "nationally determined contribution," or NDC and become carbon-neutral by 2050.

In this context, hydrogen can play a critical role to achieve the decarbonisation goals worldwide in several sectors, including hard-to-abate industries (steel and cement production) and heavy transport (truck, buses, trains, ships, and airplanes).

For hydrogen to take a prominent role in the energy sector, safe design of equipment and structures is required along with proper safety controls during their entire life cycle from design to decommissioning. Over-cautious regulatory restraints should be revised to ensure that they address tangible risks. Existing codes and standards for hydrogen equipment and processes can serve as guidelines for industry and governments. However, national regulations should be developed, or existing provisions amended to permit the safe use of hydrogen.

There is a range of practical safety measures which can be applied to hydrogen technologies, as set out in the individual sections covering each scenario. All installations require good standards of design and construction, combined with safe operational practices and maintenance. Fixed installations may also require safe separation distances from vulnerable populations and other high-risk installations.

If adequate safety measures are adopted for hydrogen technologies, the residual risks to safety associated with hydrogen is comparable to that associated with conventional fuels.

However, in many countries, there are no specific safety legislative frameworks for hydrogen technologies, although in many cases, existing safety legislation covering gas, energy, transport and heating sectors, can be applied to hydrogen. In some circumstances specific safety regulations on hydrogen might be required in where there are current safety gaps. Existing European and/or international safety regulations, such as the United Nations Global Technical Regulation No. 13 (GTR #13) (UNECE, 1998[1]) for hydrogen vehicle requirements can be used as a guide. Existing safety regulations might need revision to account for new technology advancements and innovations, while updated research findings could support less conservative measures to accelerate the deployment of hydrogen technologies and boost the hydrogen market.

In many places hydrogen deployment is very difficult if not impossible because of either complete ban or total uncertainty (there is no clear legal structure of responsible authorities and institutions)[1] or overly conservative safety distances in fixed installations.

Approach

This report provides the basis for a risk-based regulatory framework to facilitate the further use of hydrogen as a source of energy. It summarises the key findings from a literature review and a review of international experience with hydrogen pilot projects and provides recommendations for the safer use of hydrogen in six scenarios covering the entire hydrogen value chain that new/revised regulations should focus on.

The OECD carried out a literature review on hydrogen hazards and risks, as well as a review of international experience with hydrogen pilot projects to consolidate existing knowledge. The review provides information on the extent of the consequences in the event of hydrogen fire and explosion, as well as providing insights on the probability of hydrogen ignition. The overall conclusion was that, due to the many factors that could affect the outcome, is not possible to calculate a consistent value of ignition probability. Moreover, risk calculations have a strong dependence on the assumed technical, location and operational conditions. In the absence of exiting safety legislation, it is recommended that application and technology targeted risk assessments are developed for specific scenarios/applications.

This report presents lessons learned and recommendations on key safety elements for hydrogen technologies that new/revised regulations could consider in order to achieve better outcomes.[2] These recommendations are based on the OECD research findings[3] with the aim to support regulatory and permitting authorities dealing with authorization requests for hydrogen applications, sites. The recommended safety measures should be considered as a list of options to reduce the risks related to hydrogen technologies. The extent to which all or some of the measures will be applied should be evaluated by the responsible actors taking into account also other aspects, such as financial, societal and environmental targets and risks.[4] The recommendations are focused on six scenarios/applications that cover a wide spectrum of the hydrogen supply chain, including:

- Production: leakage in water electrolysis installations;
- Pipeline transport: leakage from high pressure;
- Road transport: a hydrogen transport truck driving in a built-up area experiences leakage;
- Mobility and partially confined space: a hydrogen city bus driving in a tunnel is involved in a traffic accident;
- Mobility and partially confined spaces: accident at a hydrogen fuel station, and
- Domestic use: safety of hydrogen in buildings with a focus on hydrogen use in cooking stoves and boilers.

The findings are presented in separate sections for each scenario with a synthesis of the review of findings from research data and relevant safety recommendations for that scenario.

Reference

UNECE (1998), *Global Technical Regulations (GTRs): 1998 Agreement on Global Technical Regulations (GTRs)*, https://unece.org/transport/standards/transport/vehicle-regulations-wp29/global-technical-regulations-gtrs. [1]

Notes

[1] In this OECD report, see Part II: Regulatory review, provides a review on existing regulations for hydrogen applications across several countries.

[2] In this OECD report, see Part II: Regulatory review, information about the ongoing regulatory developments in several countries can be found.

[3] In this OECD report: See Part I: Report on literature review, Part V: Bow tie barrier analysis, Part III: Review of international experience with hydrogen pilot projects, Part II: Regulatory review.

[4] Such analysis is beyond the scope of this report.

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Production: Leakage in water electrolysis installations

This section highlights the typical initiating events that could lead to a leak during hydrogen production via electrolysis (such as mechanical failure or over pressurisation). It also proposes recommendations on key safety elements for a water electrolysis site.

Hydrogen production by water electrolysis

Hydrogen production by water electrolysis is a technology that has been used for many years. Among the different types of electrolysers, an alkaline electrolyser is the more mature technology, with most large-scale plants (up to 165 MW) built in response to hydrogen demand for the production of ammonia (Krishnan et al., 2020[1]). Other technologies, including a proton exchange membrane (PEM) electrolyser, anion exchange membrane (AEM) electrolyser, and a solid oxide electrolyser cell (SOEC) are gaining market traction as they expect to be either more flexible or efficient and are more compact (IRENA, 2018[2]).

An electrolyser system comprises of an electrical power source, an electrolyser to split water molecules into H2 and O2 gases, gas collection and compression by a series of compressors and then either direct transmission for use in situ via pipework or storage within pressure cylinders for subsequent use either in situ or at another location.

Pressurised electrolysers are usually preferred due to the lower costs gained by avoiding or reducing the stages of mechanical compression of the generated hydrogen gas. Typically, hydrogen is delivered at 30 bar pressure. However, the pressure in storage systems and compressor are significantly higher (up to 1 000 bar).[1] Compressors and storage systems are the major source of a potential leak in hydrogen production plants.

Global decarbonisation goals and the increasing investments in green hydrogen production require large-scale water electrolysis systems, where limited operating experience exists. In principle, safety aspects for large-scale electrolysers are the same as in small-scale electrolysers. However, some risk components, e.g. failure modes and their frequency of occurrence, could differ in large scale plants and further research is needed to provide the relevant data.

Existing technical norms

ISO 22734:2019 has been developed to cover construction, safety and performance requirements for hydrogen gas generation appliances i.e. electrolysing water to produce hydrogen. The standard applies to electrolysers for industrial and commercial use, indoor and outdoor residential use in sheltered areas, such as garages, utility rooms and similar residential locations.

OSHA Standard 1910.103 of Occupational Safety and Health Administration (OSHA) (United States Department of Labor, 2023[3]) in the United States uses the maximum hydrogen storage inventory to determine the location of a hydrogen storage vessel. This has a control hierarchy ranging from an outdoor location to a separate building,[2] a special room[3] and inside buildings not in a special room and exposed to other occupancies. The OSHA standard provides the minimum distances of several specified outdoor exposures (e.g. buildings, oxygen storage, open flames, concentration of people in congested areas, such as offices, etc.) from the hydrogen storage system based on the volume (three groups of volume range are determined), as well as the fire-resistance rating of structures, operating and maintenance instructions. Based on this standard when there are no fire walls between the system and the exposure the maximum separation distance among all kinds of exposures and all groups of system's volume specified by the standard does not exceed 15.24 m.

Key safety / failure elements

The causes of hydrogen accidents in production site are similar to those of accidents which occur in the conventional hydrocarbon-based industry sectors.[4] Typical initiating events that could lead to a hydrogen leak are:

- mechanical failure of the components of the system, e.g. compressor, and of pipework that connects them
- over pressurisation in one or more components of the system,
- corrosion,
- damage due to impact, and
- human error (accidental opening of valves etc).

In general, the risk of harm associated with electrolysers is small compared to the risk of harm associated with compressors and pressurised storage.[5] Risk calculations (Matthijsen and Kooi, 2006[4]) estimated the individual fatality risk 10^{-6} per year contour to be 4.5 m for pipework in HRS with onsite hydrogen production via electrolysis.

Hydrogen incidents (involving fire/explosion and injuries) relating to pipework failure are reduced over the last decades because of modern valve design and implementation of safety regulations.[6] Based on historical data[7] for compressors, cylinders, hoses, joints, pipes and valves the connecting pipe leaking frequency falls within the acceptable range[8] set by the Purple book (Dutch Ministry of Transport and Water Management, 2005[5]) which are between $5 \cdot 10^{-7}$ - $5 \cdot 10^{-6}$ $m^{-1} \cdot y^{-1}$ for small leak (10 % of pipe diameter) dependent on the pipe nominal diameter and $1 \cdot 10^{-7}$ - $1 \cdot 10^{-6}$ $m^{-1} \cdot y^{-1}$ for rupture, suggesting a low risk of hydrogen leakage from the pipework connecting to the electrolyser.

In case of a hydrogen leak, the degree of confinement is a key parameter in the likely occurrence of an explosion. Deflagration of a free hydrogen-air gas cloud would lead to a maximum overpressure in the order of 10 kPa (Hysafe, 2023[6]) which is not considered a serious threat to life (7 kPa is the threshold to result people falling to the ground), while higher degrees of congestion can lead to increased probability of explosion. Another key factor in hydrogen safety is the presence or not of mechanical ventilation inside confined spaces that can affect the hydrogen distribution, and consequently, the maximum concentration levels that are achieved and the residence time of the flammable mixture inside the confinement.

Recommendations on key safety elements for a water electrolysis site for hydrogen production

- Site layout
    - The inventory of the on-site hydrogen storage should be limited to the smallest practical amount required to meet operational demands.
    - The electrolyser should be located outdoors. If this is not possible, then any building or room in which an electrolyser is situated should be adequately ventilated to quickly disperse any hydrogen concentrations.
    - Hydrogen storage tubes should be situated outdoors.
    - Compressors should be located outdoors, or where this is not possible, indoors within a well-ventilated room. Compressors should be protected from impact by being located behind barriers or within a cage.
    - Safety distances between the different components of the production site should be implemented. In siting and layout design a safety distance of 6 m between all components and the compressors, which are considered the major risk contributors along with storage system, whereas a minimum of a 2 m distance[9] between electrolysers should be considered. Electrolyser size is also a factor and should be considered while adjusting minimum distance. This is because the size of the electrolyser determines the hydrogen production rate.

  - Protective walls can reduce the safety distances, because they can act as a physical barriers protecting from the expansion of a potential explosion, provided that their endurable pressure is higher than the explosion pressure. The location of the protective walls relative to the facility should be carefully designed as in case of ignition protective walls can lead to increased overpressures in the area that they enclose. Furthermore, the reflected shock waves may cause secondary damage in front of the wall.
- Standards / materials
  - The installation of hydrogen generation systems should meet the requirements of relevant standards, like ISO 22734:2019 (construction, safety, and performance requirements for hydrogen gas generation appliances). Moreover, standards like the OSHA Standard 1910.103 can be considered as safety reference for separation distances between the storage system and certain types of exposures.
  - Protective walls, if installed, should be constructed of non-combustible materials.
  - All equipment which is located within a potential flammable zone should comply with the ATEX Directive (European Commission, 2014[7]).
  - Non-combustible materials should be used in compartments or locations containing hydrogen storage vessels or hydrogen pipelines.
- Safety devices
  - Pressure relief valves (PRV) should be fitted to all components that operate at high pressure. Relief valves should direct any vented hydrogen upward.
  - Flammable gas detectors and alarm systems should be provided. Alarms should be activated before a flammable gas concentration reaches 2 vol% (half LFL of 4 vol%), while automatic safety shutdown devices are recommended to shut of the hydrogen supply at 3 vol% concentration levels. The International Electrotechnical Commission standard, IEC 60079-29-1, specifies general requirements for construction, testing and performance, and describes the test methods that apply to portable, transportable and fixed equipment for the detection and measurement of flammable gas or vapour concentrations with air. ISO 26142:2010 – Hydrogen detection apparatus — Stationary applications[10] provides the performance requirements of hydrogen detection apparatus in stationary installations (ISO, 2023[8]). The provision in this International Standard covers the hydrogen detection apparatus used to achieve the single and/or multifaceted safety operations, such as nitrogen purging or ventilation combined with supply system shut-off according to a hydrogen leak concentration. Hydrogen detection apparatus certified under this Standard ensure functional performance requirements, such as reliability, response time, stability, measuring range, selectivity and contamination.
  - Automated shutdown systems and local emergency stop buttons should be fitted in the electrolyser, compressor and storage areas.
- Practices
  - The production site should be kept clean, free of combustible materials and potential ignition sources and without obstructions.
  - Proper and clear marking of the area with visible warning signs in the electrolyser room, the compressor site and in the storage facility to minimise the risk of ignition.
  - The number of flanged joints to pipework should be minimised, as flanged joints pose a greater risk of hydrogen leakage. Welded connections for joining pipework are preferred as they can reduce the generation of flammable atmospheres from small scale leakages.

  - Emergency arrangements should include specification of site evacuation arrangements and the provision of cooling to compressors and storage tanks in the event of a fire. During an incident an exclusion zone of at least 50 m to keep the public away from an accident scene should be provided.
- Controls
  - Regular visual inspections (at least weekly) and risk-based maintenance of the electrolyser, the compressor and the equipment components, including the pipework, is crucial. Incorrect operation of a water electrolyser can lead to oxygen ingression in the hydrogen stream, which may exceed the explosion threshold limit. Using two staff (two pairs of eyes) for maintenance activities can reduce the risk of human error.

References

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Notes

[1] In low pressure releases (at 30 bar) through small, free jets leaks (d<1 mm) the flammable mixture extends less than 2.1 m from the leak point. In higher pressure releases (at 350 bar) and small leaks (d<1 mm) the extent flammable mixture extends to 6.3 m, leading also to longer flame length in case of jet fires. However, the distance of concentrations of nearly-stoichiometric mixtures, which are the most hazardous due to the fast burning velocities, is limited to less than 1 m, even for 350 bar operational pressures. Flash fires caused by a rupture in a stationary high pressure hydrogen storage vessel can lead to long harm distances (harm criteria 1% fatality) in order of "tens" m.

[2] Made of light non-combustible construction on a substantial frame. Walls and roofs shall be lightly fastened and designed to relieve at a maximum internal pressure of 25 pounds per square foot. Windows shall be of shatterproof glass or plastic in metal frames. Doors shall be located in such a manner that they will be readily accessible to personnel in an emergency. Adequate ventilation to the outdoors. No sources of ignition. More details in https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.103.

[3] Floors, walls, and ceilings shall have a fire resistance rating of at least 2 hours. Walls or partitions shall be continuous from floor to ceiling and shall be securely anchored. At least one wall shall be an exterior wall. Openings to other parts of the building shall not be permitted. Windows and doors shall be in exterior walls and doors shall be located in such a manner that they will be accessible in an emergency. Windows shall be of shatterproof glass or plastic in metal frames. Adequate ventilation. No sources of ignition. Explosion venting shall be provided in exterior walls or roof only. More details in https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.103.

[4] Analysis, from three incident databases (ENSAD， HIAD 2.0 and H2tools) showed that the causes of hydrogen accidents are similar to those of accidents which occur in the conventional hydrocarbon-based industry sectors. ENSAD reported no hydrogen releases at production sites.

[5] Based on the HIAD2.0 and h2tools incident databases.

[6] H2tools database reported no accidents (involving fire/explosion and injuries) relating to pipework failure after 1990 - when modern valve design and safety regulations were implemented.

[7] Data coming from offshore oil industry.

[8] According to calculations performed by Sandia National Laboratory in the United States.

[9] As per Chinese standard, design code for hydrogen station GB50177-2005.

[10] See Directive 2014/34/EU on Equipment for explosive atmospheres (ATEX) (European Commission, 2014[7]).

18 Pipeline transport: leakage from high pressure pipeline

This chapter discusses the major safety issues that may be encountered during the transportation of hydrogen through pipelines, most notably unintentional leakage. Key safety elements and recommendations are also presented.

Hydrogen transmission pipelines

Transportation of compressed hydrogen gas over long distances through pipelines is more cost-effective and environmentally friendly option than other modes of transport like rail and road transport. More than 4 000 km of hydrogen pipelines are operated in several European countries, in the United Kingdom, in Canada and in the United States. The United States has the longest pipeline system of some 2 608 km in length (Statista Research Department, 2016[1]). Most pipelines are located within industrial sites, such as refineries and chemical plants, where hydrogen is used directly in production processes and as a feedstock.

Long-distance transmission pipelines normally operate at high pressures (up to 10 MPa). The pipeline diameter in European gas infrastructure ranges from 20 to 48 inches (Wang et al., 2020[2]). Hydrogen transmission pipelines are expected to have diameter also within this range, because the hydrogen infrastructure in Europe, The European Hydrogen backbone, will make use mainly of existing infrastructure, which will be properly converted.

Recently, the use of the existing natural gas pipeline infrastructure to transfer hydrogen has been a subject of extensive safety and practical research and has focused in overcoming technical concerns, such as hydrogen embrittlement of the steel pipelines and welds, and permeation leaks, etc. Blends with hydrogen up to 20 vol% require minimal changes in the existing infrastructure of natural gas network (Castek and Harkin, 2021[3]). In the short-term, such blends, instead of pure hydrogen, are recommended to obtain more evidence on the performance and durability of the pipelines and the required maintenance activities.

The Dutch Ministry of Infrastructure and Water Management and the Bilfinger Tebodin, a multidisciplinary consultancy and engineering company, has performed research on the technical aspects of using the existing gas pipelines for hydrogen transport. The findings of the research are published in the Tebodin report “Research into the Technical Aspects of Hydrogen in Existing Pipelines for the Energy Transition” (Dutch Ministry of Transport and Water Management and Bilfinger Tebodin Consultancy, 2019[4]) with the aim to provide guidance and considerations for repurposing of the natural gas pipelines to hydrogen gas applications and, on the other hand, to provide technical background for external safety research. Among the main conclusions of the research are the following:

- The design factors that have been applied throughout the years for high pressure natural gas pipelines are in line with the design factors used for new hydrogen pipelines. Thus, the wall thickness of the existing pipes, corresponding to the relevant pipe diameters, design pressures and steel grades, are suitable for the use of hydrogen at a similar design pressure.
- The damage mechanism that requires special attention for hydrogen applications under natural gas design conditions is cracks due to fatigue. For smaller pipes (≤ DN400) with lower steel quality there is no need for an extensive quantitative analysis when they are repurposed for hydrogen gas applications. For larger pipes (> DN400) with higher steel quality there is a real risk of fatigue rupture when larger pressure fluctuations are expected. In this case, a quantitative analysis will be required, which may result in operating restrictions through lower operating pressures and/or pressure fluctuations.
- For leak-sensitive pipe components such as valves and flange joints, it should be verified that they are sufficiently leak-proof for hydrogen gas applications. If this cannot be demonstrated, these components shall be replaced by hydrogen gas-appropriate components.

Existing transmission pipelines are mainly buried underground for a safer and more reliable supply because the pipeline is better protected against accidental damage and frost. Similarly, new hydrogen pipelines are expected to be routed underground. Underground pipelines need to be protected against accidental excavation, shifting due to unstable soil, back fill damage to the external surface of pipe or the coating, and aboveground imposed loads such as vehicles or equipment moving over the path of the pipeline (European Industrial Gases Association, 2004[5]).

Existing technical norms

Safety standards for hydrogen pipelines include their design and construction in accordance with relevant industry codes and standards. For instance, requirements for piping in gaseous and liquid hydrogen service and pipelines in gaseous hydrogen service can be found in ASME B31.12 Standard on Hydrogen Piping and Pipelines (ASME, 2019[6]). This standard covers the requirements for materials, brazing, welding, heat treating, forming, testing, inspection, examination, operating, and maintenance. This Code is applicable up to and including the joint connecting the pipework to any associated pressure vessels and equipment but not to the vessels and equipment themselves.

Standards and regulations applied for high pressure pipelines are the basis for hydrogen pipelines in several countries,[1] like for example in Japan. In the Netherlands, NEN 3650 series and NEN 3651 are the technical standards that cover the total life cycle of pipelines and provide safety requirements related to pipeline systems for transport of natural gas, oil and other gases and liquids.

Key safety / failure elements

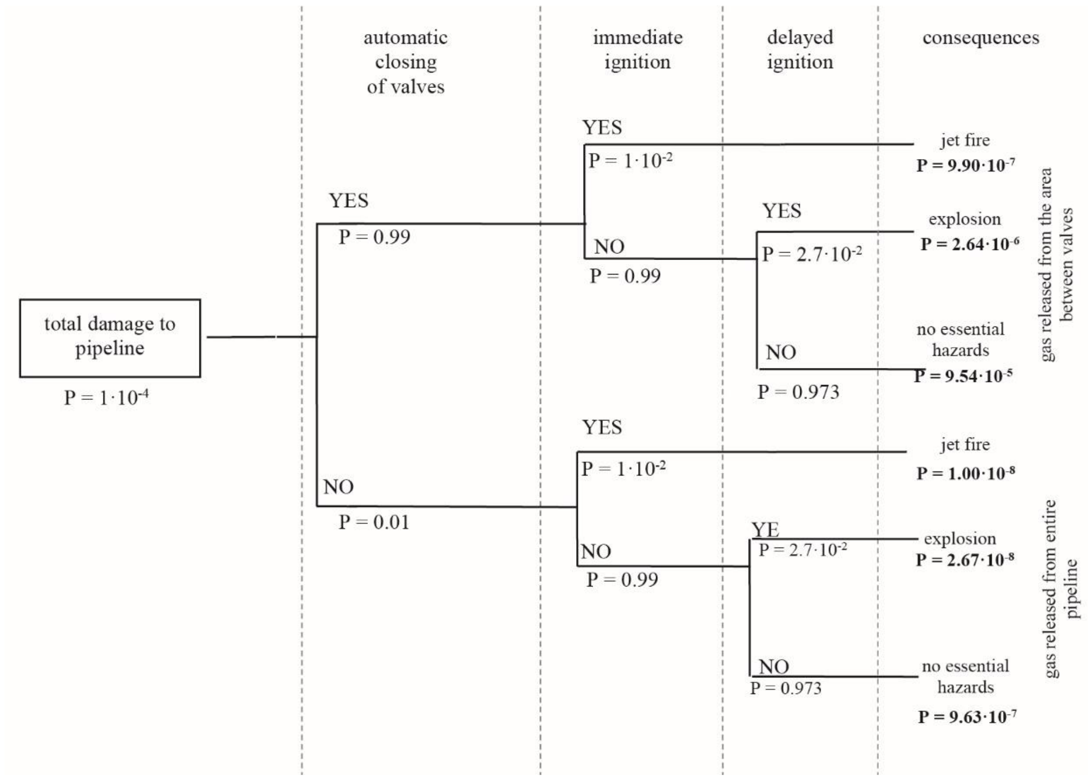
A major concern in transporting hydrogen through pipelines is unintentional leakage and consequential ignition. Leakage can occur either through pipe joints or due to pipe damage. In the onshore gas transmission network of 145 000 km in Western Europe gas network of Europe approximately 20 incidents of unintentional gas release were reported each year. From 2004 to 2013, 35% of these incidents were caused by third party (external aggressions), 24% by corrosion, 16% by material weakness, and 13% by ground movement (EGIG, 2015[7]).

The typical pipeline leak size is a 12 mm breach and the main cause of such leaks is corrosion. If the leak takes place in a buried section of the pipe a crater can be formed. The possibility of a crater formation at given pipe depth depends on the pressure, the release orientation and the soil properties. Based on relevant experiments (Houssin-Agbomso, G. and D., 2018[8]) in buried pipelines at 1 m it was found that in soil with low plasticity and cohesiveness, like sand, a crater is formed by displacement of soil by the leak pressure at pressures higher than 40 bar. At pressures between 17-40 bar, an uplift of the soil is observed allowing the evacuation of hydrogen, which then is easily dispersed at the ground surface. On the contrary in a clayed soil, no crater is formed, only uplifts. Ignited methane exhibited similar behaviour.

An uncontrollable hydrogen leakage would involve a pressure drop in the pipeline and should activate installed protection systems, i.e. the safety valves will close automatically, isolating the damaged section of the pipeline and limiting the quantity released. The magnitude of the consequences will depend on the successful operation of the safety system.

An event tree (see Figure 18.1) for damage to a hydrogen transport pipeline in (Witkowski et al., 2017[9]) suggests that the "no fire or explosion" event is more likely to occur, explosion follows and less likely is jet fire to occur. A probability of 0.01 for immediate ignition and of 0.027 for delayed ignition was applied in agreement with the proposed values from HYSAFE (Rodsaetre and Holmefjord, 2007[10]) and (Tchouvelev A.V., 2006[11]).

Figure 18.1. Event tree for damage to a hydrogen transport pipeline



Source: (Witkowski et al., 2017[9]).

Recommendations on key safety elements for hydrogen transmission pipelines

- Plan and design of pipeline system
  - For a new pipeline construction, perform route survey and planning to identify geological challenges and to select a stable route free from ground movement and erosion.
  - Use of buried pipelines. There is no “golden rule” for pipeline burial. Pipe diameter and length could be important factors to consider. Japanese regulation requires the pipelines to be buried at least 0.6 m below ground surface and in crossings of public roads, where vehicle traffic is particularly heavy, the depth shall be at least 1.2 m. However, larger depth might be necessary to avoid normal agricultural activities, surface water drainage works and imposed road loads. For the construction of new pipelines avoid populated and agricultural regions to reduce the likelihood of pipe damage due to external activities, like building construction, excavation, etc.
  - Appropriate separation distances between pipelines and nearby vulnerable populations. The methodologies used to determine separation distances vary across all the studies. To determine separation distances risk-based approaches should be used.
  - Pipe casings or load shields should be installed at railroad or road crossings or where unusual aboveground loading can occur.
  - Establish the quality of an existing pipe before it is used for hydrogen gas (or hydrogen blends) transport by conducting a quantitative risk analysis and deterministic analysis such as through Computational Fluid Dynamic Model (CFD) (Dutch Ministry of Transport and Water Management and Bilfinger Tebodin Consultancy, 2019[4]).[2]

- Standards/materials
  - Ensure that pipeline design and construction meets the requirements of relevant standards (e.g. NEN 3650 Requirements for pipeline systems – Part 1: General requirements, NEN 3651 Additional requirements for pipelines in or nearby important public works, ASME B31.12 Standard on Hydrogen Piping and Pipelines).
  - Limit joint flanges. Welded connections are preferred.
- Safety devices
  - When possible and practical, use a sudden loss of pressure automated shut down systems to isolate any damaged section of the pipeline and limit any loss of containment.
  - Implement an automatic leak warning that notifies nearby residents.
- Practices
  - Provide signs at regular space intervals (every 1 km) for underground hydrogen pipelines to advise against activities that can damage the pipes, like excavation and provide a contact number to report damage.
  - Land use planning policy and control development near the pipelines and to control development encroachment (e.g. in terms of safety distances from vulnerable populations and objects).
  - Give notification before starting any excavation activities to obtain information about pipelines (in the Netherlands this is called KLIC-notification)
- Controls
  - Inspection and maintenance interventions for both underground and aboveground pipelines. Routine, 5 yearly, Non-Destructive Testing (NDT) examination of the internal surface and thickness testing.

References

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Notes

[1] In this OECD report, see Part II: Regulatory review.

[2] The report brings together the main technical aspects involved in the application of hydrogen gas in existing pipelines.

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Road transport: A hydrogen leak from a hydrogen transport vehicle driving in a built-up area

This section discusses the accident scenario of leakage from a vehicle carrying hydrogen or from a hydrogen-powered vehicle. It also presents the key safety and failure elements and proposes specific safety recommendations.

Road transport

If hydrogen is to become a widely used green fuel then road transport should be considered as a crucial and effective mode of transport in the supply chain. This is a topic which at least in some countries raises serious concerns in terms of safety.

Hydrogen is frequently transported by road as compressed gas or as a cryogenic liquid. Pressurised tube or cylinder trailers typically are at 25 Mpa or higher based on the national transportation restrictions, while liquid hydrogen in cryogenic tank is at approximately 21 K. The storage conditions during road transport should be taken into account in risk management.

Existing technical norms

The Carriage of Dangerous Goods by Road (ADR) Regulation is a 1957 United Nations treaty governing national and transnational transport of dangerous or hazardous goods. ADR specifies packaging types, load security, the classification and labelling of dangerous goods and training of drivers. The Economic and Social Council (ECOSOC) Committee of Experts on the Transport of Dangerous Goods organised by the United Nations Economic Commission for Europe (UNECE) develops and updates safety provisions for the transport of hydrogen by all modes of transport, which are included in the UN Model Regulations on the Transport of Dangerous Goods.

Key safety / failure elements

Incidents in road transport and hydrogen mobility mostly involve either hydrogen containment leakage due to equipment failure or inadequate maintenance of components, tank rupture due to overpressurisation or release through a pressure relief device (PRD) caused by external factors, such as fire or impact. Small leaks can be caused by localised corrosion. A catastrophic failure of containment can also be caused by defects in construction particularly poor quality of seam welding. A hydrogen release will form a flammable vapour up to the point it is diluted or dispersed below its lower flammable limit.

Vehicles that transfer hydrogen and hydrogen powered vehicles are equipped with safety systems, like pressure relief devices that will be activated and vent hydrogen in case of pressure increase inside the storage vessels. Hydrogen venting with upwards orientation should be generally preferred due to the buoyant nature of hydrogen, as it would be easily dispersed and diluted provided that the release occurs in open environment. The size of the pressure relief device is another key element to safety. It should be designed as such as to reduce the formation of a flammable cloud, especially in confined spaces, taking into account also the fire resistance time of the storage vessels. Technology advancements in tanks can reduce the risks associated to tank rupture, which is one of the major safety concerns in road transport.

Most of the reported[1] hydrogen incidents related to hydrogen transport and hydrogen-powered vehicles were caused by traffic accidents. In 37% cases no release took place, in 31% there was an unignited release and in 32% a fire or an explosion occurred.

Recommendations on key safety elements for hydrogen road transport and hydrogen-powered vehicles

Recommendations focus mainly on road transport but include also few recommendations for hydrogen-powered vehicles on roads (more recommendations for hydrogen FCEVs can be found in Chapter 20).

- Design
  - Limit the maximum size of individual tube containers.
  - Limit the maximum pressure in tube trailers to not more than 25 Mpa. An exemption can be made taking into consideration the travelling distances and the routes to avoid transporting high pressure vessels close to populated areas and vulnerable areas, like hospitals and schools.
  - The package securing system in tube trailers should be designed with adequate safety margins to assure that hydrogen cylinder packing remains secured to the transport trailer under adverse conditions.
  - In hydrogen FCEVs consider the use of new technologies, like TPRD-less (leak-no-burst) tank that would not release hydrogen through TPRD in extreme conditions, like engulfing fire in hydrogen tank. However, the TPRD-less technology should be considered along with the fire resistance of the tank.
  - Hydrogen transport and hydrogen-powered vehicles should be fitted with warning signs to alert emergency services approaching defective / crashed vehicle.
- Safety devices
  - Pressure relief valves should be effectively connected to vent tubing to route hydrogen to the top of the truck to safely disperse in the atmosphere.
  - Systems involving more than one PRD should be designed to avoid simultaneous opening of all PRDs to limit the size of a flammable cloud in the event of an incident.
- Safety measures in confined spaces
  - Mechanical ventilation in confined spaces where hydrogen transport and/or hydrogen-powered vehicles are allowed. Ventilation in garages (Lach and Gaathaug, 2021[1]) should achieve at least 10 ACH (Air Changes per Hour).
- Practices
  - Train and educate drivers on the explosive characteristics of hydrogen. Haulage company's policies should require safe driving practices under all conditions (Hydrogen Tools, 2017[2]).
  - Train first responders to deal with all safety aspects for a range of hydrogen applications and design emergency plans based on hydrogen safety science and engineering.
    - In case of an accident involving hydrogen FCEVs, first responders would be able to approach the vehicle, conservatively, approximately two minutes after pressure relief valve activation (hearing the hissing sound). For the safety of the general public, a perimeter of 100 metres is suggested to be set in the accident scene if no hissing sound is heard. However, the perimeter can be reduced to 10 metres once the hissing sound of hydrogen release is observed. The first responders should remain 6 m from the vehicle if there are no signs of hydrogen leakage.
- Controls
  - Regular maintenance of the trailer, fastenings, manifolds and safety devices.

References

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Note

[1] Based on a recent review of the HIAD 2.0 and H2tools hydrogen incident databases 73 incidents related to hydrogen transport and hydrogen vehicles were reported (see Part IV: Review on incident database and lessons learnt).

20 Mobility and partially confined space: A hydrogen city bus driving in a tunnel

This section investigates a scenario in which there is a road accident involving hydrogen powered vehicle inside a tunnel. It presents the key safety concerns and proposed measures to avoid a worst-case scenario.

Hydrogen mobility

Limits to scaling of electric vehicles and also concerns (environmental and others) regarding batteries make hydrogen use in urban transport an attractive option. Hydrogen can be a key player in decarbonisation of transport sector with fuel cell heavy-duty vehicles, like buses and trucks. However, hydrogen mobility raises specific safety concerns that need to be addressed for its widespread use.

Existing technical norms

The United Nations Global Technical Regulation No. 13 (GTR #13) (UNECE, 1998[1]) for Hydrogen and Fuel Cell Vehicles, which occurred within the World Forum for Harmonization of Vehicle Regulations of the Inland Transport Committee (ITC) of UNECE, defines vehicle requirements for hydrogen FCEVs that can achieve equivalent (or higher) levels of safety as those for conventional gasoline powered vehicles. It includes specifications on the allowable hydrogen levels in vehicle enclosures during in-use and post-crash conditions and on the allowable hydrogen emissions levels in vehicle exhaust during certain modes of normal operation. GTR can be applied globally; however, the regulatory bodies in each country decide its incorporation into national regulations.

The use of hydrogen powered vehicles inside tunnels and other confined spaces is constrained by some national regulations. For instance, in Japan the passage of vehicles that transport hydrogen is prohibited or restricted in long tunnels (over 5 km long) and underwater/waterfront tunnels, while there are no specific restrictions for FCEV entering tunnels in several countries revealing the need to develop relevant regulations, standards, and codes.

Key safety / failure elements

As the number of hydrogen powered vehicles increases, their impact on various road infrastructures, such as tunnels and other confined spaces (e.g. garages and repair shops) must be considered. Associated risks from hydrogen vehicles driving inside tunnels are that in the event of accidental leak, hydrogen can be trapped and accumulated on the ceiling or other cavities at high concentration levels that could lead to a severe explosion. Compared with urban environments where blast waves decay quicker an overpressure can maintain its strength for long distances inside the tunnel due to the high level of confinement (Venetsanos et al., 2008[2]).

Scientific numerical studies (Venetsanos et al., 2008[2]), (Middha and Hansen, 2009[3]) suggest that the worst case scenario for a hydrogen powered bus incident inside a tunnel, i.e. release of the entire hydrogen volume, is the formation of nearly-stoichiometric mixture in air and ignition when the maximum flammable volume inside the tunnel is reached. This can lead to unacceptably high overpressures. When more realistic scenarios are considered, the explosion pressure is reduced to levels that correspond to the eardrum rupture threshold and moderate building damage, or even lower.

Recent experiments performed by CEA (Bouix et al., 2021[4]) with a 50L-tank hydrogen rupture of 4.7 Mpa inside a real scale horseshoe tunnel[1] showed that an overpressure of around 12.5 kPa was developed at the region close the explosion (threshold for people injured by flying glass and debris and moderate structural damage), which decays to about 6.6 kPa at 205 m from explosion.

The work of (Kim et al., 2021[5]) examined three Independent Protection Layers (IPLs) to reduce the risk from a release within a tunnel involving a hydrogen powered bus. These comprised of Temperature-Pressure relief device (TPRD) activation, ventilation and leak detection with safety shutdown. Three initiating events were considered: battery fire, bus fire, and hydrogen leak fire.[2] When applying these protection measures, a battery fire case with TPRD activation failure was considered as a non-negligible risk, with an outcome frequency in 10^{-5} events per year. The bus fire case with TPRD activation failure was considered as a moderate risk level with its frequency approaching 10^{-6} event per year and for the hydrogen leak fire case, all possible cases,[3] [4] resulted in the non-negligible risk range (i.e., outcome frequency > 10^{6} events per year).Therefore, additional IPLs in the current hydrogen-powered electric city bus design were recommended by (Kim et al., 2021[5]).

Another risk assessment (LaFleur et al., 2017[6]), (Ehrhart et al., 2019[7]) that focused on hydrogen vehicles incidents inside tunnels suggests that the most likely consequence of a crash is that there will be no additional hazard from the hydrogen fuel (98.1–99.9% probability). If the hydrogen does ignite, it is most likely to result in a jet flame from the pressure relief device released due to a hydrocarbon fire (0.03–1.8% probability).

Finally, based on the scientific findings of the HyTunnel-CS[5] project the TPRD size in vehicles should be as small as possible (<1 mm). TPRD orientation in buses could be on the top, while in cars an oblique orientation at 45^{o} degrees backwards is preferred.

Recommendations on key safety elements for a hydrogen city bus driving in a tunnel

- Design of vehicles
    - Design hydrogen vehicles based on United Nations Global Technical Regulation No. 13 (GTR #13).
    - Consider the use of new technologies, like TPRD-less (leak-no-burst) tank that would not release hydrogen through TPRD in extreme conditions, like engulfing fire in hydrogen tank. However, the TPRD-less technology should be considered along with the fire resistance of the tank.
    - Use multiple TPRDs to prevent the leak of the total mass of the tank in localized fires.
    - Hydrogen powered vehicles should be fitted with warning signs to alert emergency services.
- Design of tunnels[6]
    - Provide mechanical ventilation inside tunnels (1-2 m/s) to reduce the hydrogen vapour concentration in the event of a leakage.
    - Ensure sufficient distance of main tunnel and fittings and equipment, like dust collectors and exhaust fans that can trap hydrogen in flammable concentrations.
    - Avoid roof obstructions inside the tunnel, because they pose a potential risk in respect to possible fast deflagration or transition to detonation.
    - The design of future tunnels should include appropriate cross section design to avoid flammable mixture accumulating in the tunnel ceiling.
    - Set larger safety distances between vehicles when driving inside tunnels.
- Safety devices
    - The TPRD size should be reduced to avoid a flammable mixture at the tunnel ceiling in the event of a leak. The TPRD orientation in buses should be at the top of the vehicle.
    - Systems involving more than one PRDs should be designed to avoid simultaneous opening of all PRDs.
    - Additional protection could be provided by:
        - a battery fire suppression system within the battery pack,
        - a fire barrier between the battery pack area and the hydrogen tank,
        - increasing the tank integrity/fire resistance to thermal threats (minimum of 1 hour), and

    - a fire resisting deck to protect the upper deck area.
- Practices
  - Risk-based categorisation of tunnels to define which ones allow or not H2 powered vehicles to enter.
  - Emergency responders should receive training for reaction to incidents that involve hydrogen vehicles. Some key elements are presented below:
    - Emergency responders should remain at least 2 min before approaching damaged vehicles following activation of TPRD.
    - If there's no sign of hydrogen release, first responders should stand at least 6 m away from the vehicle.
- Controls
  - Perform frequent safety checks on vehicle integrity by an independent, competent engineer.

References

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Notes

[1] Tunnel du Mortier located in the commune of Autrans in the Vercors, France.

[2] It should be noted that for the initiating event frequencies related to some of the system components, such as battery, and for the conditional probabilities applied for the protection layers, data from industry were used.

[3] Case 1 – hydrogen leak occurs from the compressed hydrogen storage system and is detected followed by a safety shutdown procedure; Case 2 – hydrogen\leak occurs; however, detection and safety shutdown fails followed by ignition; therefore, a flame jet occurs but TPRD is activated successfully to omit any possible catastrophic tank explosion; Case 3 – hydrogen leak occurs and detection & safety shutdown fails followed by ignition; therefore, a flame jet occurs and TPRD fails to operate properly; Case 4 – hydrogen leak occurs and detection & safety shutdown fails; however, ignition does not occur resulting in safe release of hydrogen through venting.

[4] For this conclusion it was also assumed that TPRD activation may not occur due to the jet flames not being able to reach and heat up the TPRD. Thus, the Independent Protection Layer (IPL) offered by TPRD activation (case 2 and case 3 braches) was bypassed resulting in tank rupture with outcome frequency 2.9E-06 event per year. Multiplied by a factor of 2.5 to account for having 5 identical hydrogen tanks placed within a bus with 2 TPRDs for each tank the total outcome frequency was 7.25E-06 event per year.

[5] Hy-Tunnel-CS is an EU-funded project with pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces, https://hytunnel.net/.

[6] Proper design of vehicles is generally preferred over design of tunnels, as several recommendations for tunnel design can only be applied to newly built tunnels and not to existing infrastructure.

21 Mobility and partially confined spaces: Accident at a hydrogen fuel station

This section includes presents some of the main safety concerns surrounding the operation of hydrogen refuelling stations. It also provides recommendations on their appropriate design and safe operation

Hydrogen refueling stations (HRS)

To develop the hydrogen-powered vehicles market beyond the limitations of battery electric vehicles a well-structured network of refueling stations is needed at national and international level (across neighbouring countries). As of today H2 fuel stations are very constrained in many countries. In 2021, there were 492 operating hydrogen refuelling stations (HRS) worldwide (Statista, 2022[1]) with most of them (154) located in Japan.

Hydrogen refuelling stations can operate either with liquid hydrogen (LHRS) or with compressed hydrogen (GHRS) that can be produced onsite or be transported (mainly by road transport). Both types of refuelling stations raise specific safety concerns.

Existing technical norms

An international standard, ISO 19880-1:2020, covers the specifications for outdoor public and non-public fuelling stations that dispense gaseous hydrogen. This ISO standard defines the minimum safety design, installation, commissioning, operation, inspection and maintenance requirements, and, where appropriate, for the performance of GHRS.

In the United States, NFPA-2 code provides separation distances from certain group of exposures for GHRS and recent study by (Hecht and Ehrhart, 2021[2]) revised these distances for LHRS) (National Fire Protection Association, 2023[3]). For most systems the separation distances to most of the groups of exposures based on NFPA-2, were reduced in LHRS compared to GHRS. All separation distances were lower than 30 m.

Key safety / failure element

Most types of the reported incidents in Hydrogen Refuelling Station (HRS)[1] involve small leakages of hydrogen or no release at all. The 18.5 % of incidents led to serious consequences, such as fire and explosion. Most of the leakages occurred at the joint parts due to inadequate torque and inadequate sealing. Other causes include design error of the main bodies of apparatuses and human error.

The most severe leak scenario corresponds to a leak size equal to 100% of the pipe diameter connecting the components of the system. However, leaks equal to or less than 0.1% of the flow area of several components (compressors, cylinders, hoses, joints, pipes, valves) are estimated to represent 95% of the system leakage frequency (LaChance et al., 2009[4]). For a 0.1% diameter leak size, the system leakage frequency is $3 \cdot 10^{-2}$/year and $6 \cdot 10^{-2}$/year for 20.7 Mpa and 103.4 Mpa systems, respectively. What emerges from these values is that a 0.1% diameter leak would be anticipated during the lifetime of these facilities. Larger and less frequent leak sizes of at least 1% should be used as the basis for separation distances to reduce the likelihood of accidents.

A leak frequency analysis at HRS (Kodoth et al., 2020[5]) using Bayesian and frequentist methods estimated that the leak rate is 0.16/year, 0.20/year and 0.42/year based on the time-based, leak-hole-size, and non-parametric method, respectively. One of the possible solutions is to consider a conservative value for the design, in which case, the leak rate of 0.42/year can be used. The base value selected can be used in design to set performance standards for the availability and reliability in the operation and maintenance of HRSs.

A comparative risk assessment conducted by (Yoo et al., 2021[6]) indicated that the LHRS has a lower risk than the GHRS, but with small differences. Based on another quantified risk assessment, QRA performed by the National Institute for Public Health and the Environment in the Netherlands in 2016 the estimated distances[2] to 10^{-6} per year risk of a single fatality were:

- 30 m for the liquid hydrogen delivered via a tank and for the gaseous hydrogen dispensing system supplied by pipeline or local production, and
- 35 m for gaseous hydrogen delivering via tube or cylinder trailer.

For gaseous hydrogen with delivery via pipeline or tube trailer, the risk of single fatality beyond 50 metres was 10^{-9} per year. For liquid hydrogen supplied by a tanker a risk of single fatality of 10^{-9} per year was reached at 270 m. However, it should be noted that these distances were estimated with an overly conservative ignition probability of gaseous hydrogen equal to 1. Moreover, the risk contours can be further reduced by the use of proper safety measures.

For hydrogen refuelling stations with an onsite production facility risk studies show that water electrolysis presented lower individual, societal and environmental risk than methane reforming (Dash, Chakraborty and Elangovan, 2023[7]). This is because methane reforming involves other flammable gases such as methane, hydrogen and carbon monoxide. On the contrary, the major safety risk associate with water electrolyser is only the leakage related to the hydrogen produced. Another study (Pan et al., 2016[8]) indicated that compressor is the major risk contributor among HRS elements. Khalil 2017 showed that a small leakage from the compressor is associated with intolerable single death risk frequency, which exceeds both the acceptance criterion at $1.0 \cdot 10^{-4}$ /year and NFPA's guideline at $2.0 \cdot 10^{-5}$/year (Khalil, 2017[9]).

Recommendations on safe design and operation of hydrogen refuelling stations

- Design
  - For on-site hydrogen production, water electrolysis is the recommended production process as it presents lower risk than steam methane reforming.
  - Limit the inventory in the storage facility as low as practical based on the average daily number of fillings of the HRS.
  - Transportation of hydrogen through high-pressure pipelines allows station to dispense fuel without onsite compression and storage and reduce the risk. However, this system should additionally consider the risk of operating high-pressure pipelines in residential areas.
  - A QRA study indicated that liquid hydrogen refuelling stations entail less risk than compressed hydrogen refuelling stations, but the differences were small. Based on that the use of liquid hydrogen instead of compressed hydrogen could be recommended, but further research on that topic is highly advised.
- Site layout
  - Hydrogen processing systems, high pressure storage containers and generators should be sited outdoors in well ventilated areas.
  - Implementation of safety and separation distances:
    - Separation distances from exposures in GHRS can follow the NFPA-2 code.
    - Hydrogen storage tank (up to 40 Mpa) should be configured 5 m from the location of the hydrogen onsite production facility.
    - Safety distances can be reduced when installed safety systems are effective and can be quickly activated, by employing for instance a dispenser which operates in parallel with an emergency shutdown valve.

    - To determine safety distances for facility layout and under specific operating conditions it is recommended to perform quantified risk assessment targeted to the facility's specific parameters.
      - This requires a checklist of the HRS sub-systems and components and an extensive description of sub-systems, components, preventive and mitigation measures, configurations (including piping and instrumentation diagrams) and input parameters.
      - The estimated failure rate should be a function of number of fillings rather than based on survival time, as it is more reliable and realistic approach.
      - Establishing a national, independent review function for Quantitative Risk Assessments (QRAs) of HRSs is advisable (see Khalil, 2017). Such an entity would have the potential to become a centre of expertise that could collect existing and future QRAs of HRSs to monitor the latest developments and progress towards the consistent application of the approach as well as provide guidance to permitting authorities on how to apply the approach for HRSs.
  - Protective walls around the HRS can lead to reduced safety distance requirements if they are designed so that flammable concentrations will not reach outside these barriers. However, in case of ignition protective walls can act as obstacles and generate higher overpressures inside the facility. Therefore, their installation should be carefully examined and evaluated under the specific conditions of the facility.
  - Installation of a fire protection wall along station boundaries. This will also reduce the required safety distances.
  - A protective wall surrounding the production site and the storage tank can protect them from the impact from an explosion. Careful design of the protective wall is essential as its resistance to over pressure is another factor. A concrete wall without steel reinforcing bars can withstand a pressure of up to 0.2 bar. This limit may be exceeded under certain conditions if an explosion occurred, for example, in the dispenser. Thus, an additional distance of 2 m away from the dispenser is also recommended for the protective wall and the control room.[3]
- Standards / materials
  - Use of equipment in compliance with ATEX to eliminate ignition sources.
- Safety devices
  - Fit pressure relief valves to components that operate at high-pressure.
  - Provide hydrogen leak sensors and automatic shutdown systems as well as manual ESD buttons.
  - Use infra-red temperature sensors for compressor linked to a high temperature alarm.
- Safety measures
  - Use proper ventilation if hydrogen equipment is located indoors
- Practices
  - Install warning signs to prohibiting ignition sources at the HRS.
  - For physical security, install of CCTV surveillance system to act proactively in case of malicious actions.
  - Prohibit self-refilling. Refuelling should be undertaken by trained staff. Alternatively, similar to Japanese regulations, self-filling could be allowed if the driver receives safety education and training on how to mount and demount of the nozzle.

- Controls
    - If the leak rate based on historical data is estimated to be high, inspections activities shall be more frequent to limit the unrevealed leak time (evaluated from the estimated leak frequency) and increase the process of safety.
    - In densely populated areas, where large safety distances may be impossible to achieve, stricter requirements for quality, inspection and protection of refuelling stations against impact should be implemented.

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Notes

[1] Based on hydrogen incident databases (see OECD Report – Review on incident database, 2022).

[2] These distances should not be confused and compared directly with the values presented by (Hecht and Ehrhart, 2021[2]) (see Existing technical norms), because different assumptions on leak conditions were made in the two studies. Moreover, (Hecht and Ehrhart, 2021[2]) haven't calculated the distances based on risk contours, but based on the furthest distance to selective hazardous criteria of the exposure groups.

[3] Based on scientific work by (Kim et al., 2013[10]).

22

Domestic use: safety of hydrogen in buildings with focus on hydrogen use in cooking stoves and boilers

This section provides recommendations for hydrogen injection into the existing gas grid in terms of materials, devices, and practices. It also sets out some key safety elements and provides recommendations on design aspects and other safety measures.

Domestic use of hydrogen

The use of the existing infrastructure of natural gas pipelines to deliver hydrogen inside buildings will contribute to a faster energy transition. Several projects have investigated the effect of hydrogen blending on the infrastructure integrity and safety of existing pipelines, with the aim to eventually develop a 100% pure hydrogen network for heating and/or cooking purposes in houses and other residential and commercial buildings. Pilot and demonstrations projects worldwide (e.g. in the UK, Germany, France and China) have been launched, to assess the use of hydrogen up to certain composition in existing gas network. None of the pilots have reported any accidents.[1]

The infrastructure typically used for hydrogen use in residential areas consists of:[2]

- local hydrogen production via electrolyser (pressure at 10 – 40 barg) and/or local hydrogen storage in tube trailers (typical pressure at 200 barg – 300 barg);
- low distribution pressure systems, i.e. 4-8 bar, with a reduced to 100 mbar in pipework into houses for heating purposes;
- fiscal metering in gas cabinets, tubing, and H_2 heaters/boilers in domestic premises.

While this report focuses mainly on the safety concerns of the domestic use of hydrogen, it also provides recommendations regarding the use of the existing gas network for hydrogen blends and/or pure hydrogen.

Integrity issues of existing gas network

A primary concern with hydrogen in domestic use is the capability of the current gas distribution network to manage hydrogen/natural gas mixtures or pure hydrogen, as hydrogen can damage pipelines through embrittlement.[3] Another concern is the efficiency and appropriateness of the existing appliances that use natural gas. However, this is beyond the scope of this report.

Recommendations for hydrogen injection into the existing gas grid

- Materials
  - Use existing carbon steel transmission pipelines in medium to high pressure systems, as they can tolerate pressures between 55 to 210 bar and can withstand hydrogen concentrations up to 15% v/v without any significant impact (Capelle et al., 2008[1]), (Meng et al., 2017[2]) (Elaoud, Abdulhay and Hadj-Taie, 2014[3]), (Witkowski et al., 2018[4]).
  - Use plastic pipelines, which are commonly used in low-pressure systems, as they are generally unaffected by hydrogen injection up to 20 v/vand pose no danger in embrittlement. Generally speaking, up to 20% v/v blend of hydrogen with natural gas is still compatible with the existing infrastructure and heating appliances.
  - A phased transition to 100% polyethylene network is recommended, since most observed flammable gas leaks are caused by metallic network components. However, even with 100 % polyethylene pipelines for a 100 % hydrogen network additional mitigation measures should be implemented downstream of the gas meter to achieve fatality risk lower than the current network and as safe as the natural gas network.
- Devices
  - The existing domestic pressure regulators can be safely used with hydrogen, and it is therefore unnecessary to replace the regulators as part of the conversion to hydrogen.

- Practices
    - The seal tightness specifications in current pipelines should be stricter, ensuring that the maximum permissible leakage rate for hydrogen as 74% of that of natural gas.
    - Mechanical crimp fittings should be used in pipework instead of soldered joints, which are more prone to leakages. It can be considered safe to use the same materials and fittings for internal pipework for hydrogen as is currently used for methane, at least in the short term, in the context of a community trial.

Key safety/failure elements

A major concern when using hydrogen/natural gas blends or pure hydrogen either for heating or in cooking stoves in buildings relates to safety. Blending of hydrogen with natural gas up to 20 vol% concentration results in only a modest increase of developed overpressures and thus in a small increase in event severity of a leakage (a factor of about 1.2 greater overpressure for 20% hydrogen blend) compared to pure natural gas (Lowesmith et al., 2011[5]).

Experiments (Crewe, Johnson and Allason, 2020[6]) that assessed the potential for household electrical items (including white goods in new and used condition, plugs and switches, light fittings and extractor fans) to ignite hydrogen or methane mixtures with air showed that in 20 out of 43 tests, no ignition occurred with hydrogen. In two tests, ignition occurred with both hydrogen and methane. Very few domestic appliances caused hydrogen to ignite, but not methane. These included hair dryers, toasters, vacuum cleaners, tumble dryers and irons. Nearly all of these appliances can only be used with a human operator present, who would most likely be able to smell a gas release (provided that odorants are added as per the following recommendations, see below).

Based on relevant research even with pure hydrogen, for short-term, low-rate hydrogen releases inside properties flammable concentrations are unlikely to be formed even in scenarios with low air permeability rates.

Existing technical norms

Domestic use of hydrogen is still an application under development. Pilot and demonstration projects have been reported in several countries including Germany, France, the United Kingdom, the Netherlands and China, which inject hydrogen in the natural gas grid (up to 20% v/v) to supply houses in selected neighbourhoods for heating and/or cooking purposes.

As the domestic use of hydrogen is currently at the stage of piloting, there is no international standards that apply to this application and there is usually no or only limited regulation regarding the distribution and domestic use of hydrogen. However, China has published a group of standards for natural gas and hydrogen mixing stations and in Japan and South Korea the domestic use of hydrogen involves fuel cell systems, which are subject to regulations that apply to fuel cells in general.

Recommendations on key safety elements to ensure acceptable level of risk for domestic use of hydrogen

- Design[4]
    - The gas metre should be installed outside of the property, where possible, and comply with current best practice and BS6400-1:2016.

  - Provide sufficient ventilation and venting in any cavity should be mandatory, as specified by Building Regulations (i.e. an exemption should not be granted for hydrogen appliances). Such mitigation measures can reduce the maximum concentration of hydrogen and the risk of explosion.
  - Fit wall vents (non-closable) at the upper part of the room (no more than 50 cm from the ceiling) in all rooms with gas appliances or installed hydrogen-carrying pipes.
  - Fit vents to all the cupboards and other compartments (e.g. boilers) where hydrogen appliances are present should have vents.
    - Simple vent geometry, like rectangular vent area, should be promoted.
    - High aspect ratio (height/length) of the vent is also recommended as it provides more efficient ventilation.
    - Open ventilation grids can reduce to half the maximum concentration and up to 2 vol% (half of the LFL of 4 vol% hydrogen in air) for rates typical of leak through the piping connected to the gas meter. At such low concentration, ignition is unlikely to take place.
  - The use of airbricks in basements can be helpful, but current research studies have not reached conclusive results.
- Safety devices
  - Fit leak detection and alarm systems in the upper part of the rooms and inside cavities inside buildings, as hydrogen tends to accumulate in the ceiling and might be trapped inside cavities. The alarm should be activated as soon as hydrogen is detected at concentration above some fraction of the LFL.
  - Fit excess flow valves (EFV) to stop the flow of hydrogen in the service pipes when it reaches a certain level and emergency control valves (ECV) should be deployed to safely isolate a customer’s pipe from the network. The first EFV should be placed in the service pipe or immediately after the emergency control valve and the second one should be integrated in the hydrogen gas metre or added upstream of the metre.
  - Install flame failure devices (FFDs) to all hydrogen appliances.
- Practices
  - Odorise hydrogen supply gas for the early detection of hydrogen gas leaks. Odorant NB, which is a blend of 78% t-butyl mercaptan and 22% dimethyl sulphide and THT have also been tested and are found to be effective and compatible with network components and hydrogen appliances.
  - Provide a stronger flexible pipe at the rear of cookers to limit the likelihood of damage when the cooker is moved. Additionally, the cooker should be fixed to the wall using a chain and Rawl bolts to limit the loading on the flexible cooker connection.
- Controls
  - Inspection and maintenance in all equipment should be performed at a regular base by specialised personnel.

A more general recommendation for the domestic use of hydrogen is to aim at a smooth conversion of the system. In the short-term, a 20 vol% blend of hydrogen with natural gas for heating can be preferred, which would still be compatible with the existing infrastructure and household heating appliances and will not increase the risk (Khalil, 2019[7]).

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Notes

[1] In this OECD report, see Part III – Review of international experience with hydrogen pilot projects.

[2] Shared data by the Dutch counterparts in mail communications.

[3] Embrittlement is a significant decrease of ductility of a material, which makes the material brittle.

[4] The recommendations are mainly based on the conditions that apply in the United Kingdom, because most of the projects for domestic use of hydrogen reported in the OECD Output-Literature review, from which this report has been taken input, have been carried out in the United Kingdom. However, they can provide guidelines for other countries as well.

Part VII Quantitative risk assessment

23

Quantitative risk assessment: Hydrogen versus conventional fuel

This report consists of five quantitative risk assessments of hydrogen versus conventional fuel in five accident scenarios. The scenarios presented are: accident during production (electrolyser), leakage from a high-pressure pipeline, hydrogen leakage from a truck driving in a built-up area, traffic accident involving a hydrogen city bus driving in a tunnel and accident at a hydrogen fuel station.

Scenario 1 – Production-electrolyser

A semi-Quantitative Risk Assessment (sQRA) has been carried out for a theoretical electrolyser and hydrogen storage facility with the aim to establish an approximate level of risk and demonstrate the differing risks associated with a comparative system, namely a Liquefied Petroleum Gas (LPG) bulk store facility.

For the sQRA, consequence modelling was carried out on a selection of pre-defined scenarios with individual risk calculated for static receptors at intervals from the equipment. These scenarios are selected to demonstrate the worst-cases from perspectives of both consequence (typically lower frequency events) and frequency (typically lower consequence events).

The results showed that only results of the immediate ignition scenarios, resulting in a jet fire or localised explosion/fireball, were suitable for comparative analysis using the available software for the calculations. This is largely due to the uncertainty of ignition location for delayed ignition (i.e. flash fires and explosions) thus the large number of variables that would need to be considered to produce simple outputs.

The comparative analysis for the immediate ignition scenarios showed that the risk for LPG storage (including delivery and distribution) is clearly greater than the in-situ generation of hydrogen (including compression, bulk storage and distribution). It is proposed that this is not only due to the physical properties of the two materials, but the more rigorous incorporation of safety features assumed to be present in the hydrogen design.

However, a further high-level sensitivity analysis carried out to compare the above scenario to the import and use of natural gas from a pipeline (see Scenario 2) suggests that the assumed hydrogen facility still poses a greater risk to populations in the vicinity of releases from the equipment.

On this basis, the management of hydrogen risk to populations could more easily be controlled through simpler measures such as the separation of plant from buildings and equipment.

Scenario 2 – Pipeline transport (leakage from a high-pressure pipeline)

A comparative semi-Quantitative Risk Assessment (sQRA) has been carried out for high-pressure pipelines of hydrogen and methane with the aim to establish an approximate level of risk and demonstrate the differing risks associated with hydrogen and conventional fuels, methane in particular.

For the sQRA, consequence modelling was carried out on a selection of pre-defined scenarios with individual risk calculated for static receptors at intervals from the equipment. These scenarios are selected to demonstrate the worst-cases from perspectives of both consequence (typically lower frequency events) and frequency (typically lower consequence events).

The results showed that only results of the immediate ignition scenarios, resulting in a jet fire, were suitable for comparative analysis using the available software for the calculations. This is largely due to the uncertainty of ignition location for delayed ignition (i.e. flash fires and explosions) thus the large number of variables that would need to be considered to produce simple outputs. To a lesser extent, the simplistic nature of the modelling for deflagrations and inability for the software to model detonations, limits any meaningful interpretation of explosion results.

The comparative analysis for the immediate ignition scenario showed that the increase in risk for hydrogen is negligible compared to natural gas when the ignition probabilities proposed by Tchouvelev (Tchouvelev, Hay and Benard, 2008[1]) were used. However, when ignition probabilities based on RIVM MRCB methodologies (Rijksinstituut voor Volksgezondheid en Milieu (The Netherlands), 2020[2]) were applied there was a clear order of magnitude risk increase for hydrogen versus methane throughout most of the individual risk calculation intervals. In both instances, however, hydrogen risk tails off at further distance, where the model predicts a longer methane flame.

Scenario 3 – A hydrogen transport truck driving through a built-up area experiences a leak

This report studies the effects of leaks of various sizes experienced by a hydrogen delivery truck, from a small leak to a major outflow. In contrast with Scenario 4, the environment of Scenario 3 is not tightly confined.

This QRA utilises PHAST to model the phenomenon, in line with the expertise and time constraints of the contractors employed for the study. It quantifies risk in terms of location-specific individual risk (LSIR), which denotes the annual probability of injury or death in specific places, and allows expressing results in terms of iso-risk domains. The study models the effects of thermal radiation and the overpressure caused by explosions to quantify this LSIR.

The conditions of the blast are split between high or low ignition energy (e.g. an initial explosion vs a spark, respectively), then then further by obstruction level (high, low or none) and type (whether there are obstructions on at least 2 sides, or not). The model of explosion used is the analysis is the Boiling Liquid Expanding Vapour Explosion (BLEVE).

Individual risk is then estimated as the product of the event frequency, the occupancy (probability to be present at a certain location) and the vulnerability. Vulnerability is quantified for indoor and outdoor cases for various values of overpressure, as well as for a range of thermal radiation intensities. The large number of possible factors in such an accident (geometries of the affected area, traffic, etc.) forced to confine the study to a handful of well-determined cases.

The results show that in gas phase, hydrogen and methane have similar effects, with slightly larger danger distances for methane. In liquid phase, the results are also similar, with hydrogen exhibiting a slightly larger danger area. Catastrophic failure of the tank could yield a fireball of 56 metres in diameter for gaseous hydrogen and 81 metres for methane, while failure of the loading valve could cause an 8-metre hydrogen flame. With liquids, the values reach 116 metres in diameter for the hydrogen fireball. Finally, BLEVE-type explosions, where an external fire triggers evaporation of fuel within the tank and its eventual explosion, would yield a similar 116-metre fireball, compared to 129 metres for liquified natural gas. To illustrate the frequency of such accidents, in the last 30 years, three have occurred in France.

Scenario 4 – A hydrogen city bus driving in a tunnel is involved in a traffic accident

The modelling results of Scenario 4 – a hydrogen city bus driving in a tunnel is involved in a traffic accident (variations e.g.: small leakage/large tank rupture) are reported in this report.

A comparative QRA study is performed between a hydrogen and a methane city bus located in the center of a 1.2 km one-way tunnel. The comparative analysis has conducted both on the jet fire scenarios from TPRD (Thermal pressure relief device) and on the catastrophic tank rupture.

The QRA methodology combines event tree analysis for probabilistic analysis with engineering correlations (i.e., for hydrogen jet flames (Molkov and Saffers, 2013[3]) and for the blast wave decay in a tunnel from for consequence analysis (Molkov and Dery, 2020[4]).)

In the vicinity of the bus (20 m) higher IR values are calculated for jet fire scenarios than for catastrophic tank rupture, while the IR values of the tank rupture scenario are predominant for the whole tunnel.

For jet fire, the hazard distances from the bus are slightly higher for H2 than for methane. Furthermore, the frequency of jet fire events is higher for H2 than for methane.

For catastrophic tank rupture a similar profile is observed for both methane and H2, it can be seen that the overpressure decreases rapidly along the tunnel, especially within the first 50 m. For this scenario the individual risk is higher for hydrogen than for methane and correspondingly larger hazard distances are evaluated for hydrogen.

The results of the consequence modelling found that both the results of the immediate ignition scenario, resulting in a jet fire, and those of the catastrophic tank rupture scenario are suitable for comparative analysis without the use of more complex software (e.g. for modelling H2 release from TPRD and deflagration).

The comparative analysis for the immediate ignition scenario has showed that the frequency (events per year) is slightly higher for hydrogen than for methane, and slightly higher hazard distances are calculated for hydrogen than for methane. The results of the catastrophic tank rupture scenario showed that the individual risk is higher for hydrogen than for methane and correspondingly higher hazard distances are evaluated.

Scenario 5 – Accident at a hydrogen fuel station

A comparative QRA study between a hydrogen and a methane refuelling station is performed. The comparative analysis refers to two configurations of the refuelling station: one with discontinuous supply of H_2 by means of tube trailer mobile storage, and the other with continuous supply via pipeline. In addition, the analysis is performed for a hydrogen filling station with on-site H_2 production via electrolyser, comparable to that of the 2019 Norway incident.

The software used is HyRAM+ developed at Sandia National Laboratories. The HyRAM+ software toolkit provides a basis for conducting quantitative risk assessment and consequence modeling for hydrogen, methane, and propane systems.

The QRA results are reported in terms of Average Individual Risk (AIR), which expresses the average number of fatalities per exposed individual. It is based on the number of hours the average occupant spends at the facility (i.e., 2 000 exposed hours per occupant per year).

The analysis is performed considering the various sections of the hydrogen refuelling station at different pressures, specifically a high-pressure storage module with compressor at 90 MPa is assumed. For the other components of the hydrogen refuelling station (i.e., electrolyser, pipeline, tube trailer, and dispenser) the specific pressure is considered (i.e., 3 MPa, 10 MPa, 20 MPa, and 70 MPa respectively). For the CNG refuelling station a maximum pressure of 25 MPa is assumed for a conservative estimate.

The results of the comparative analysis show higher AIR values for CNG compared to the H_2 refuelling station in both configurations with pipeline gas supply and via tube trailer. For both gases, the refuelling station configuration with continuous gas supply via pipeline led to lower AIR values than the configuration with discontinuous supply via tube trailer.

In particular, for a hydrogen refuelling station the main components that contribute to the AIR are respectively the high-pressure storage module with compressor and the dispenser. Therefore, the lower AIR is for the configuration with onsite H_2 production via electrolyser where most of the H_2 is stored at 20 MPa. Decreasing the capacity of the hydrogen refuelling station to 500 kg/day results in a slight decrease in AIR.

It should be noted that the methane ignition probability used in HyRAM+ is verified to provide conservative estimate of AIR values.

The consequence analysis of the current HyRAM+ includes the hazard from hydrogen jet fires (for immediate ignition) and unconfined explosion (for delayed ignition). For a jet fire, hazard distances are higher for H_2 than for methane, due to the higher pressures encountered in the high-pressure storage module, compressor, and dispenser. Similarly, for an unconfined explosion the hazard distances are higher for H_2 than for methane, with possible escalation to detonation in case of high congestion.

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Risk-based Regulatory Design for the Safe Use of Hydrogen

Low-emission hydrogen is expected to play an important role in the energy transition to tackle the climate crisis. It can decarbonate "hard-to-abate" sectors still relying on fossil fuels, turn low-carbon electricity into a fuel that can be transported using pipelines and provide a green transport alternative, in particular for heavy-duty and long-distance transport. Given its potential to combat climate change, it can allow for a net reduction in societal risks if managed responsibly. However, while its potential is widely acknowledged, its application is not yet meeting ambitions. Regulation is crucial to facilitate its application and ensure its safety. This report analyses trends, risks, and regulation of hydrogen technologies across economies. It supports the use of low-emission hydrogen as part of the energy transition, by making recommendations for effective risk-based regulation, regulatory delivery and governance.

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