SEANERGY

the Sustainability EducationAl programme for greeNER fuels and enerGY on ports

This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement number 101075710. This visual support reflects only the author's view; the Commission is not responsible for any use that may be made of the information it contains.

Module #2 Energy transition in ports:

Part 3:
Risks and mitigation strategies/tool for hydrogen applications (synergetic)

Course coordinator:

Dirk Fischer

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Dipl.-Ing. (FH)

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ARGO ANLEG Advanced Hydrogen Technologies

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Learning objectives of the course

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On completion of this course, the participants will be able to:

- **Assess and manage risks:** Gain awareness of the risks associated with hydrogen use and learn effective strategies for risk management and mitigation.

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3.1 Hydrogen safety and risk perception

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- **Addressing myths and misconceptions**

(introduction)

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3.1 Hydrogen safety and risk perception

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- Addressing myths and misconceptions

Hydrogen is no more or less dangerous than other currently used combustible fuels such as gasoline or natural gas. It has a unique set of characteristics that distinguish it from other fuels.

Some of its properties even provide safety advantages over other fuels used to date. But hydrogen, like all combustible fuels, must be handled responsibly. Like gasoline and natural gas, hydrogen is flammable and can create hazards under certain conditions.

Understanding the properties of hydrogen and knowing its applications will therefore lead to the safe implementation of the gas as a new fuel.

Source: [Ses Hydrogen]

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3.1 Hydrogen safety and risk perception

- Addressing myths and misconceptions

The expected growth of the hydrogen economy raises many questions about the safety of hydrogen production, transportation, storage, and end-use.

These **questions are answered by Hydrogen Safety Engineering**, which can be defined as the application of scientific and engineering principles to protect life, property, and the environment from the adverse effects of incidents and emergencies involving hydrogen.

Source: Ses Hydrogen

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3.1 Hydrogen safety and risk perception

- Historical perspective on hydrogen safety

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The **Latin name for hydrogen is hydrogenium**. However, the original name of the gas comes from the Greek words hydōr (water) and gignomai (creation, formation). As a unique gas, it was discovered by Henry Cavendish in 1766. Just seven years later, Antoine Lavoisier gave it the name “forming water,” thus proving that water is composed of two basic elements – hydrogen and oxygen.

…

The wider use of hydrogen technologies will require the creation of a new culture, innovative safety strategies, and specific engineering solutions.

To achieve this, engineers, designers, operations personnel, plant users, etc., should be aware of all the specific risks associated with the handling and use of H_2 systems. **Interestingly, most of the risks associated with hydrogen stem directly from its properties. Therefore, it is important to have access to knowledge about its physical and chemical properties including flammability and explosivity.**

Source: Ses Hydrogen

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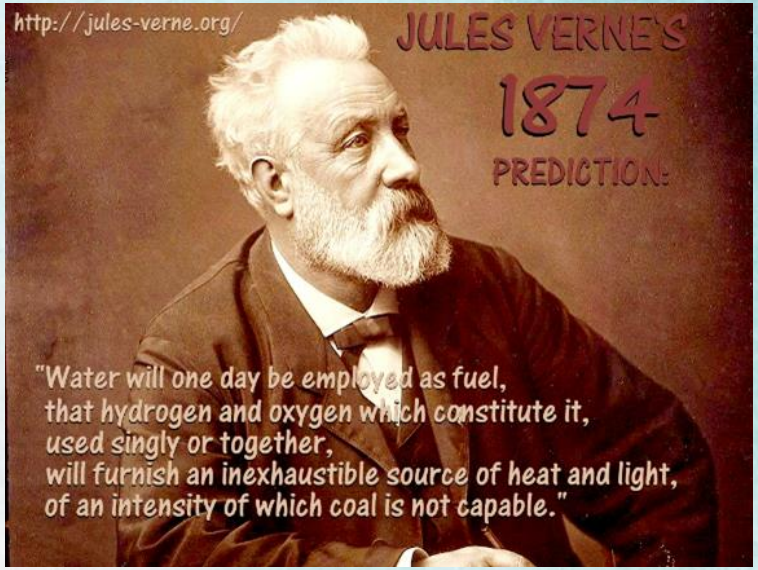
3.1 Hydrogen safety and risk perception

- Historical perspective on hydrogen safety



Source: www.elizabethqueenseaswann.com/

Hydrogen is **extremely flammable**, **but it doesn't burn without the presence of oxygen**. If you were to place a lit match into a container of pure hydrogen, the match would simply go out, not cause an explosion. Now, if it was a mixture of hydrogen and air, the gas would ignite!

Source: www.thoughtco.com

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3.1 Hydrogen safety and risk perception

- Historical perspective on hydrogen safety

Myth 1. **Hydrogen is too explosive** and dangerous to be widely used

Myth 2. **Hydrogen is a green and renewable fuel**

Myth 3. **The production** of renewable hydrogen **requires too much energy and financial input** to call it an efficient and attractive fuel

Myth 4. **Hydrogen vehicles are not competitive with electric vehicles** and there is no future for them

Myth 5. **Production of green hydrogen will be complicated and expensive**

Myth 6: Green hydrogen production **technology is immature**

Myth 7: Green hydrogen **will only find application in the industrial sector**

Source: [(h2euro.org)](h2euro.org)

Note:

comments to the above „Myth‘s will be find here:

Source: seshydrogen.com/de/3-hydrogen-myths-that-raise-strong-market-concerns/

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3.1 Hydrogen safety and risk perception

- Historical perspective on hydrogen safety

The "Bad Image" and Myths?

- The Hindenburg phenomena is one of the best-known Myth!

(As a matter of fact, Myths stay stable over a long period. At least endless!)

The **Hindenburg** disaster at Lakehurst, New Jersey on May 6, 1937 brought an end to the age of the rigid airship.
The disaster killed 35 persons on the airship, and one member of the ground crew, but miraculously 62 of the 97 passengers and crew **survived**.
After more than 30 years of passenger travel on commercial zeppelins — in which tens of thousands of passengers flew over a million miles, on more than 2,000 flights, without a single injury — the era of the passenger airship came to an end in a few fiery minutes.

https://www.airships.net/hindenburg/disaster/

Source:
Risks and mitigation strategies for hydrogen applications, Dirk Fischer & Ria Papst, Argo-Anleg GmbH, 09 November 2023, SYNERGETICS | Synergies for Green Transformation of Inland and Coastal Shipping

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3.1 Hydrogen safety and risk perception

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- Historical perspective on hydrogen safety

Review of hydrogen-related accidents - Using statistics „to learn“

Statistic of accident cases

There are **two types of activities**:

1. Those in which **hydrogen is produced or used**:

Chemical, refinery, transportation, packaging, industry.nuclear power.

2. Those in which hydrogen is produced accidentally: metallurgy and metal processing, wastewater disposal, waste treatment waste disposal, recovery. The main activities concerned the following table shows the main sectors concerned by accidents involving hydrogen. **With regard to the causes of accidents involving hydrogen, their analysis shows that in over 70% of cases, the "organizational and human factor"** plays a predominant role in the root causes of these accidents.

Ongoing vigilance is therefore required within the company, at all hierarchical levels - management, supervisors, field operatives, subcontractors - bearing in mind that in the presence of hydrogen, the risk of ignition is permanent.

Source: www.aria.developpement-durable.gouv.fr

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3.1 Hydrogen safety and risk perception

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- Historical perspective on hydrogen safety

Review of hydrogen-related accidents - Using statistics „to learn“

Activités	Sur échantillon de 215 cas	
	Nombre de cas	%
Chimie	84	39
Raffinage / pétrochimie*	47	22
Transport, conditionnement et stockage	35	16
Métallurgie / travail des métaux	17	7,9
Traitement des déchets / récupération	8	3,7
Industrie nucléaire	5	2,3

* hors transport, conditionnement et stockage

61+16=**77%**

Source: www.aria.developpement-durable.gouv.fr

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3.1 Hydrogen safety and risk perception

- Historical perspective on hydrogen safety

Review of hydrogen-related accidents – technology point of view

Example "LH2":

Hydrogen in liquid form LH_2 has a higher energy density than in gaseous form GH_2, so it would make more sense to store it in liquid form. A vehicle tank that uses liquid hydrogen holds up to 120 liters (8 kg) of liquid hydrogen at around 5 bar, which enables a range of up to 300 kilometers.
However, the LH_2 tank did not catch on due to its high cost and the evaporation losses that occur, and 700-bar pressure tanks were increasingly used.

Boil-off rate

Due to the low but uniform heat supply, low evaporation losses occur (a certain percentage of the liquid hydrogen evaporates inside). As the gas has a larger volume than the liquid, the pressure in the container increases. To compensate for this, a safety valve opens at a certain pressure and gas is released (blow-off or boil-off), which leads to a loss of vaporization.

Source: https://www.uni-augsburg.de.../lh2/

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3.1 Hydrogen safety and risk perception

- Historical perspective on hydrogen safety

Review of hydrogen-related accidents – technology point of view

Example "LH2":

Daimler liquid #hopium-fueled truck- image credit, Daimler Truck

Source: www.linkedin.com/pulse/why-liquid-hydrogen-dumbass-paul-martin-vhbfc/

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3.1 Hydrogen safety and risk perception

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- Historical perspective on hydrogen safety

Review of hydrogen-related accidents – technology point of view

Nevertheless, it is not yet possible to completely eliminate evaporation losses, which is why almost all car manufacturers rely on 700-bar storage technology.

Note: Currently, 350 bar technology is also being used.

Safety

The insulation not only serves to protect against heat input, but also to protect against contact with the environment, as otherwise there is a risk of injury when touching cryogenic components.

Atmospheric oxygen liquefies at temperatures below 90 K, which leads to an undesirable accumulation of oxygen and thus to an increased risk of fire.

Source: https://www.uni-augsburg.de.../lh2/

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3.1 Hydrogen safety and risk perception

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- Historical perspective on hydrogen safety

Review of hydrogen-related accidents – technology point of view

Advantages
Liquid hydrogen has a high energy density.
LH_2 is particularly suitable for large volumes.

Disadvantages
Kyrogen tanks are expensive to manufacture and weigh a lot.
Boil-off rate has not yet been eliminated.

Source: https://www.uni-augsburg.de.../lh2/

Outlook:
LH2 storage in bulk storage tanks is common. LH2 is a **relative "new technology" if it comes to mobility.**
Compared to CHG its refilling procedure is much more complex and safety requirements for refill as well operating vehicles differ to CHG.

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3.1 Hydrogen safety and risk perception

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- Historical perspective on hydrogen safety

Review of hydrogen-related accidents Using **hydrogen as a ship fuel** is a relatively new concept, so it is **important to learn from other industries' experiences with H2 safety**.

The European Hydrogen Safety Panel (EHSP), as part of the Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU), **put together a working group to analyse over 700 incidents in the HIAD 2.0 database.**
The result from this work is presented in the report
"Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database", **published in September 2019** (X. Wen, et al., 2019).
The **following sections will summarize the findings from this repor**t and input from other studies on the topic.
The HIAD 2.0 database includes accidents and events from the following sources:

- The French database ARIA
- The EU database eMARS
- The database IChemE
- The Japanese database RISCAD
- US CSB, NTSB and OHSA
- Other public databases
- Scientific articles
- Online news from local and technological newspapers.

Source: www.emsa.europa.eu/

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3.1 Hydrogen safety and risk perception

- Historical perspective on hydrogen safety

Review of hydrogen-related accidents - Using statistics „to learn“

Figure 5-1: Number of events categorised by cause (many events had multiple causes, providing a total of more than 100%). Based on 575 events from the HIAD 2.0 Database (X. Wen, et al., 2019).

Source: www.emsa.europa.eu/

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3.1 Hydrogen safety and risk perception

SEANERGY

- Historical perspective on hydrogen safety

Review of hydrogen-related accidents

Using statistics „to learn“

Main causes

From the 575 accidents analysed in the HIAD 2.0 database, the **leading causes of hydrogen-related accidents fall into two categories: system design failure and human error.**

A combination of both was also a cause of accidents with severe consequences.

Figure 5-1 shows that **the cause was related to technical issues in 422 events and human error in 532 events**.

The **largest number of cases were linked to safety management system factors (49%).**

The **second largest cause** was errors **in material or manufacturing (35%).**

The **same figure also shows that** many of the **incidents were caused by individual human errors (29%)** and **system design errors (27%).**

Source: www.emsa.europa.eu/ (X. Wen, et al., 2019).

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3.1 Hydrogen safety and risk perception

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- Historical perspective on hydrogen safety

Review of hydrogen-related accidents

Consequences – **Lesson learned?**

Of all the events recorded in the HIAD 2.0 database, **79% involved ignited hydrogen**, and **of these 48% led to explosion** and **31% resulted in fire**.

15% of the events resulted in leakage with no ignition, and 6% were near misses.

The **learning from the events resulting** in leakage but no ignition and near misses **is that early detection and quick mitigation of a potentially larger release of hydrogen can potentially avoid escalation to fire and explosion.**

Source: EMSA/OP/21/2023 Date: 24/06/2024 Authors: Marius Leisner (DNV), Linda Sigrid Hammer (DNV), Ingeranne Strøm Nakstad (DNV), Hans Jørgen Johnsrud (DNV).

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3.1 Hydrogen safety and risk perception

- Historical perspective on hydrogen safety

Review of hydrogen-related accidents

Consequences – **Lesson learned?**

Lessons learned and recommendations To prevent future accidents, safety issues need to be identified and considered at the earliest stage possible, preferably in the design stage, but it is important to have a safety focus throughout the lifetime of the system.

It was found that different events analysed in the HIAD 2.0 database had the same or similar causes, which proves that lessons learned from earlier accidents can help improve safety if applied.

The lessons learned from the events in the HIAD 2.0 database are divided into four main categories:
(1) system design,
(2) system manufacturing, installation, and modification,
(3) human factors, and
(4) emergency response.

Source: EMSA/OP/21/2023 Date: 24/06/2024 Authors: Marius Leisner (DNV), Linda Sigrid Hammer (DNV), Ingeranne Strøm Nakstad (DNV), Hans Jørgen Johnsrud (DNV).

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3.2 Material properties and risk assessment

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3.2 Material properties and risk assessment

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- Properties of hydrogen relevant to safety

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3.2 Material properties and risk assessment

- Properties of hydrogen relevant to safety

Source: [Eye opening hydrogen safety field trip to DNV's full scale Research and Testing facility Spadeadam]

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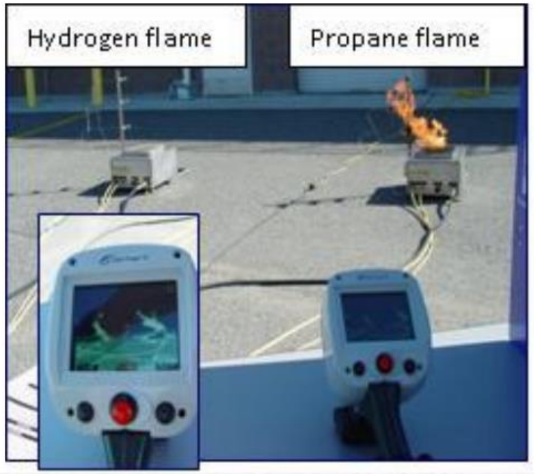
3.2 Material properties and risk assessment

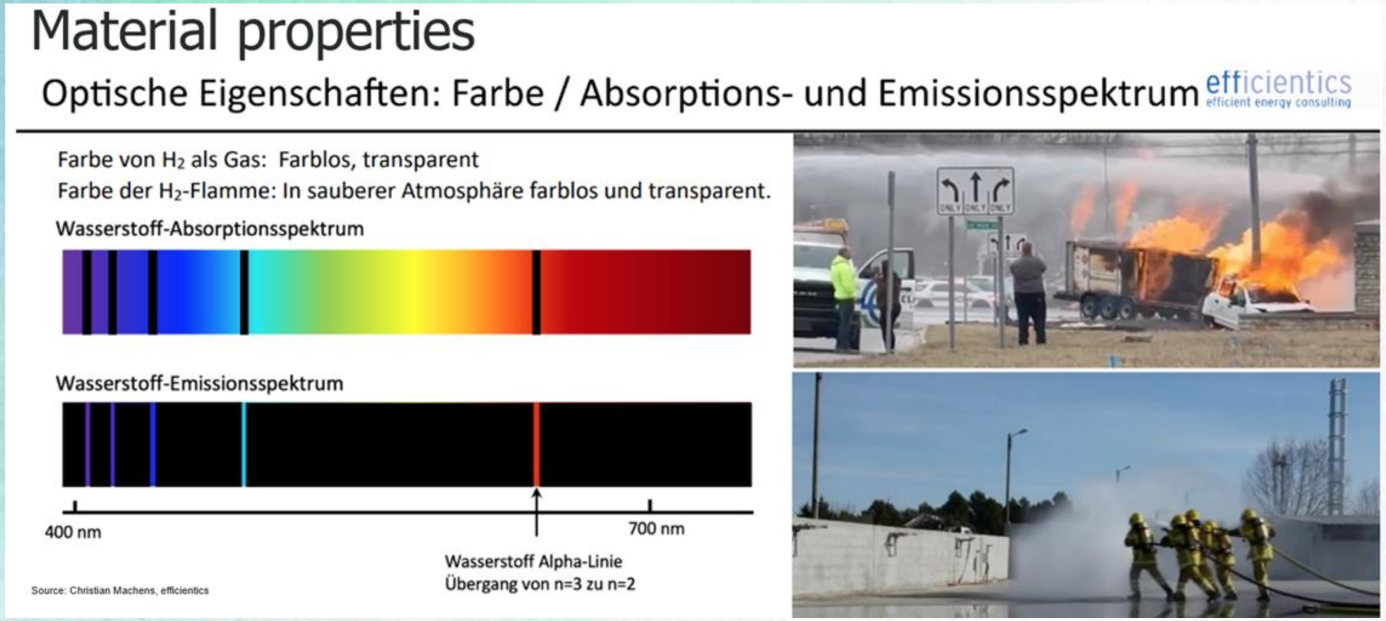
- Properties of hydrogen relevant to safety

- Pure hydrogen burns with a pale-blue flame invisible in a daylight. On burning with air it forms water.
- Hydrogen produces low radiant heat upon combustion.



Source: H2BestPractices.

Source: (hyresponder.eu)



Source: Christian Machens efficientics

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3.2 Material properties and risk assessment

SEANERGY

- Properties of hydrogen relevant to safety

…to having a low ignition energy, hydrogen also has a wide flammability range. Volume fractions from 4% to 75% can combust in air; for reference, methane has flammability limits of 5%–15%, propane 2%–9%, and gasoline 1%–7% with respect to safety, the upper flammability limit (75% for hydrogen) is not as important as the lower flammability limit (4% for hydrogen). The **lower flammability limit** (or some factor thereof**) is used to define safety distances, usually the distance between a potential flammable gas leak and potential ignition sources**, and this distance will be further from the gas leak than the upper flammability limit.
The lack of soot and low radiant fraction does mean that hydrogen flames can be hard to see and sense, Hydrogen flames are detectible by infrared and ultraviolet sensors, which are typically employed where hydrogen is used as a fuel.

FIG. 16.2 Laboratory diffusion flame of cryogenic hydrogen flowing through a 1 mm equivalent diameter nozzle with some ambient light (left) and in a dark room (right).

Source: R.W. Schefer, W.D. Kulatilaka, B.D. Patterson, T.B. Settersten, Visible emission of hydrogen flames, Combust. Flame 156 (6) (2009) 1234–1241

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3.2 Material properties and risk assessment

- Properties of hydrogen relevant to safety

Delayed ignition, deflagration, and detonation
If a mixture of air and fuel is ignited, there will be a volume change as the hot products are formed, and pressure can be generated as
the flame-front expands during the combustion process. The flame-front in mixtures of fuel and air can move at subsonic velocities or
supersonic velocities. If the flame-front is moving at a subsonic velocity, this combustion processes is termed deflagration, and typically,
only modest overpressures are generated. If the flame-front moves at supersonic speeds, this combustion process is termed detonation,
and shock waves can generate large overpressures.

Source: R.W. Schefer, W.D. Kulatilaka, B.D. Patterson, T.B. Settersten, Visible emission of hydrogen flames, Combust. Flame 156 (6) (2009) 1234–1241

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3.2 Material properties and risk assessment

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- Properties of hydrogen relevant to safety

Hydrogen embrittlement
The term ‘hydrogen embrittlement’ is a generic term used to describe numerous phenomena related to the influence of hydrogen on mechanical properties of materials.
However, the response of materials in the presence of gaseous hydrogen is more nuanced than the term ‘embrittlement’ suggests.

Few, if any, low- to medium-strength structural metals truly become brittle in high-pressure gaseous hydrogen.

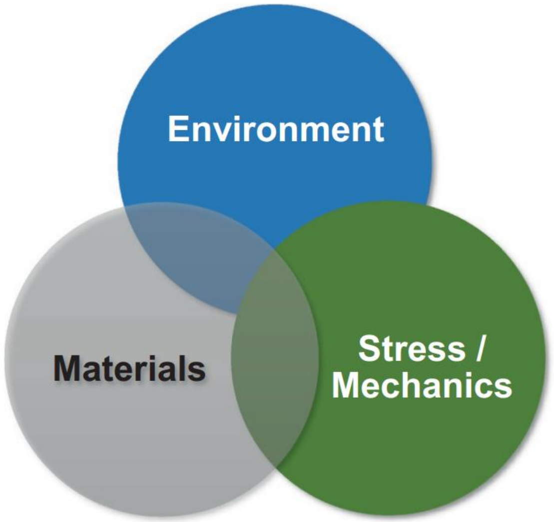

FIG. 16.3 Hydrogen embrittlement occurs at the intersection of materials, environmental and mechanical variables.

Source: R.W. Schefer, W.D. Kulatilaka, B.D. Patterson, T.B. Settersten, Visible emission of hydrogen flames, Combust. Flame 156 (6) (2009) 1234–1241

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3.2 Material properties and risk assessment

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- **Key risks associated with hydrogen use**

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3.2 Material properties and risk assessment

- Key risks associated with hydrogen use

Hydrogen is very easily ignited. Ignition sources include examples such as mechanical sparks from rapidly closing valves, electrostatic discharge, sparks from electrical equipment, catalyst particles, heating equipment, atmospheric discharge near a vent stack, etc. **Therefore, ignition sources should be properly eliminated or isolated.**

The standard auto-ignition temperature of hydrogen in air is from 584.85°C [according to ISO/TR 15916:2015(E)]. It is relatively high compared to long molecule hydrocarbons. Compared to hydrocarbon combustion, hydrogen flames also emit much less heat. Thus, the human physical sensation of this heat does not occur until there is direct contact with the flame.

A hydrogen fire can go undetected and will spread despite direct human monitoring in areas where hydrogen can leak, spill, or accumulate and form potentially flammable mixtures.

Source: Ses Hydrogen

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3.2 Material properties and risk assessment

- Key risks associated with hydrogen use

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Although hydrogen is **non-corrosive and non-reactive under standard conditions**, it is capable of reducing the mechanical strength of some materials through a series of processes and interactions commonly referred to as **hydrogen embrittlement.**

Gaseous hydrogen – properties, characteristics

At standard temperature and pressure, hydrogen is a colorless, odorless, and tasteless gas.
There is a **high risk associated with these properties, as leaks from the system are difficult to detect with the human senses.** The **low weight and small particle size** of hydrogen also **contribute to the high diffusivity of hydrogen gas and its tendency to leak through fittings, flanges, threads, gaskets, porous materials**, etc.

It is the lightest of all known gases. Hydrogen gas (GH2) is 14 times lighter than air, which means **it will float and diffuse quickly when released** from a plant in an open environment. **This is a major advantage of hydrogen from a safety standpoint because it will float and diffuse quickly if released.**

Source: Ses Hydrogen

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3.3 Preventative measures and risk mitigation

- Health, safety, and environment (HSE) regulations

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3.3 Preventative measures and risk mitigation

- Health, safety, and environment (HSE) regulations

Prevent accidents!

Documentation and processes:

- HSE (health-Safety-Environment) regulations
- Use SDS (safety data sheets)
- Define quality processes (FMEA, HAZOP, risk-analysis etc.)
- Order consulting support (consulting engineers, notified bodies, experts…)
- Skill operators and responsible persons.
- Communicate with authorities, fire-departments, local authorities, hospitals
- Mark (signs…) hydrogen “areas”
- Frequent assessments, audits and re-qualifications

Further Action:

Inhouse/external trainings in different skill levels, for different person groups

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3.3 Preventative measures and risk mitigation

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- **Safety data sheets** and quality processes (FMEA, HAZOP)

Save handling, risk mitigation possible?!

ISO 15869

Testbezeichnung	Typ1	Typ2	Typ3	Typ4
Materialtest (Metall)	x	x	x	
Materialtest (Polymer)				x
Harzeigenschaften		x	x	x
Druckwechsel (20°C)	x	x	x	x
Leckage vor Bersten	x	x	x	x
Beflammungstest	x	x	x	x
Beschusstest mit 7,62mm	x	x	x	x
Chemikalieneinwirkung		x	x	x
Fehlertoleranzen		x	x	x
Beschleunigter Stresstest		x	x	x
Druckwechsel (+85/-40°C)		x	x	x
Falltest (1,8m)			x	x
Permeationstest				x
Flaschenhalstorsion				x
H_2 Zyklisierung				x

SDS (Safety data sheet) – risks and properties of gaseous H2

Sichere Lagerung und Handhabung von Druckgasflaschen

Im Sicherheitsdatenblatt (SDB) sind enthalten:

- Eigenschaften von H_2
- Erste Hilfe
- Hinweise zur Brandbekämpfung
- Arbeitsschutzempfehlungen
- Transportvorschriften

Link: www.dguv.de

Source: www.dguv.de

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3.3 Preventative measures and risk mitigation

- **Safety data sheets** and quality processes (FMEA, HAZOP)

EXPLOSIONSDATEN

Untere Explosionsgrenze:
4,0 Vol.-%
3,4 g/m³
Obere Explosionsgrenze:
77 Vol.-%
65 g/m³
Grenzspaltweite: 0,29 mm
Explosionsgruppe: IIC
Maximaler Explosionsdruck:
8,3 bar

GEFÄHRLICHES REAKTIONSVERHALTEN

Gefährliche chemische Reaktionen:

Explosionsgefahr bei Kontakt mit:
Brom
Chlor
Fluor
Oxidationsmitteln
Sauerstoff
Acetylen/Ethylen; Bromtrifluorid; Chlordioxid; Chlortrifluorid; Dichloroxid; Disauerstoffdifluorid/Funken; Distickstofftetroxid; Dioxan + Raney-Nickel; Fluorperchlorat; oxidierende Gase; Hitze; Katalysatoren/Luft; Iodheptafluorid/Funken; Kalium/Wärme; Katalysatoren/Öle; Kohlenmonoxid/Sauerstoff; Kupferoxid; Luft; Magnesium + Calciumcarbonat; Nitrylfluorid (Wärme); Ozon; Palladiumpulver; 1-Pentol/Hitze; Perchlorsäure; Platinpulver/Luft; Raney Nickel; Sauerstoffverbindungen; Stickstofftrifluorid; Wasserstoffperoxid/Katalysator

Der Stoff kann in gefährlicher Weise reagieren mit:
Iod
Lithium
Barium; Bleifluorid; Bromfluorid; Calcium/Wärme; Palladiumoxid; Xenonhexafluorid

Source: www.dguv.de

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3.3 Preventative measures and risk mitigation

SEANERGY

- **Safety data sheets** and quality processes (FMEA, HAZOP)

SDS (Safety data sheet) – risks and properties of gaseous H2

MASSNAHMEN BEI BRÄNDEN

Brandklasse:
C gasförmige, auch unter Druck stehende Stoffe

C Brände von Gasen
z.B. Acetylen, Methan, Propan, Butan, Erdgas, Wasserstoff

Geeignete Löschmittel:
Wasser (Sprühstrahl - keinen Vollstrahl einsetzen)
Trockenlöschpulver

Ungeeignete Löschmittel:
Kohlendioxid

Die Reaktion verläuft nach folgendem Prinzip:
$CO_2+2H_2 \longrightarrow C+2H_2O, \Delta H0=-90{,}1$ kJ/mol
Kohlenstoffdioxid reagiert mit Wasserstoff zu Kohlenstoff und Wasser, wobei Energie frei wird

Verhaltensmaßregeln:
Im Brandfall Feuerwehr auf das Vorhandensein von Druckbehältern aufmerksam machen.
Gefährdete Druckbehälter mit Wassersprühstrahl aus geschützter Position kühlen.
Behälter wenn möglich aus der Gefahrenzone bringen.
Drucksteigerung, Berst- und Explosionsgefahr beim Erhitzen.
Zündquellen beseitigen.
Nur löschen, wenn der Gasstrom zu unterbrechen ist.

	Brand-klassen	A	B	C	D	F
Pulverlöscher mit Glutbrandpulver	PG	✓	✓	✓	✗	✗
Pulverlöscher mit Metallbrandpulver	PM	✗	✗	✗	✓	✗
Pulverlöscher	P	✗	✓	✓	✗	✗
Kohlendioxid-Löscher (CO_2)	K	✗	✓	✗	✗	✗
Wasserlöscher	W	✓	✗	✗	✗	✗
Schaumlöscher	S	✓	✓	✗	✗	✗
Fettbrandlöscher	F	✗	✗	✗	✗	✓

Explosionsgefahr durch Gasansammlung und Rückzündung.
Nur explosionsgeschützte Geräte verwenden.
Kann austretender Wasserstoff gefahrlos abbrennen und die Gaszufuhr nicht unterbrochen werden, sollte der Brand nicht gelöscht werden, um die Bildung von gefährlicher explosionsfähiger Atmosphäre nach dem Löschen zu vermeiden.

Source: www.dguv.de

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3.3 Preventative measures and risk mitigation

- Safety data sheets and **quality processes** (**FMEA, HAZOP**)

Established principles for mitigation and control Eliminating hazards is always the best option, but it may not always be possible. In such cases, **it's essential to implement a range of risk controls to reduce the risks to an acceptable level.**

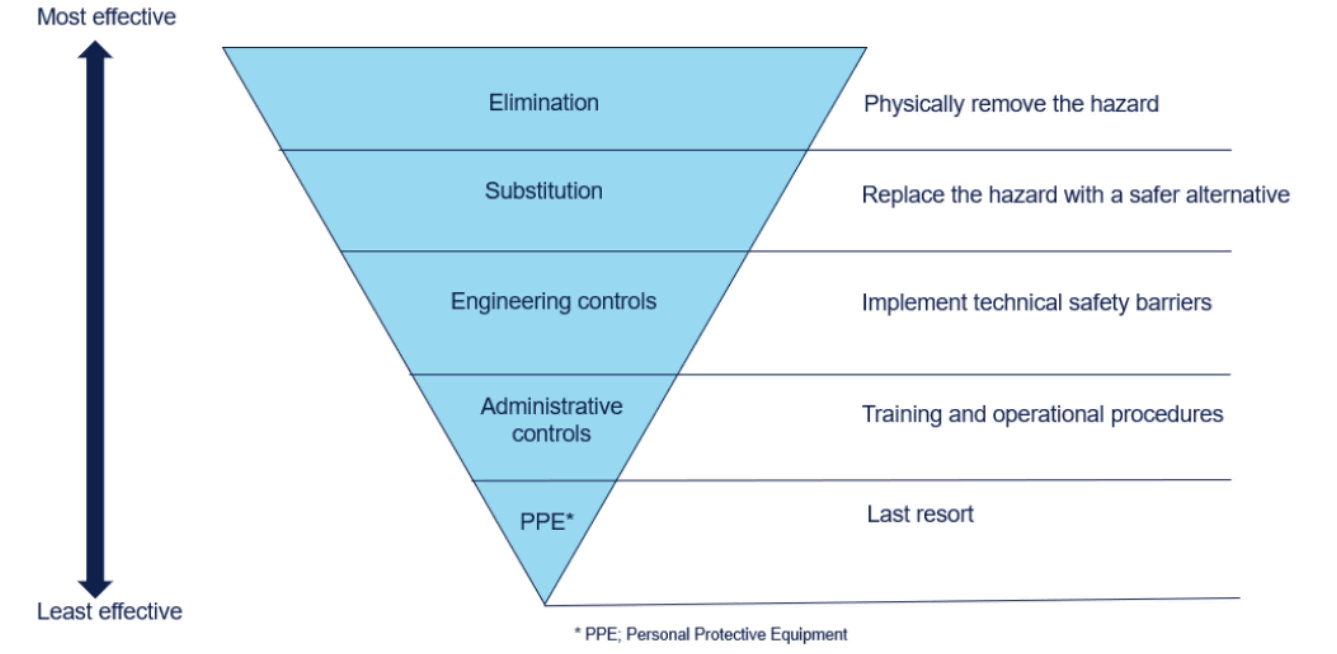

Figure 4-1 The Hierarchy of Risk Control Measures (Source: DNV).

Source: DNV

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3.3 Preventative measures and risk mitigation

SEANERGY

- Safety data sheets and **quality processes** (FMEA, HAZOP)

Risk assessment calculation methods
A fully detailed risk assessment can contain a huge amount of information and can give the most detailed and nuanced understanding of the overall risk.
A comprehensive quantitative risk assessment process would generally contain a list of possible scenarios, a numerical estimate for the likeliness of each
scenario, and a numerical estimate for the negative outcomes of each scenario.

One well-known and commonly used methodology is from the Dutch government publication **"Guidelines for quantitative risk assessment,"** also called the "Purple Book".
A basic overview of the risk assessment methodology is shown in Fig. 16.7.

Source: P.A.M. Uijt de Haag, B.J.M. Ale, Guidelines for Quantitative Risk Assessment: Purple Book. Publication Series on Dangerous Substances (PGS 3), Ministerie van Volkshuisvesting en Ruimtelijke Ordening (VROM), 2005

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3.3 Preventative measures and risk mitigation

- Safety data sheets and **quality processes** (FMEA, HAZOP)

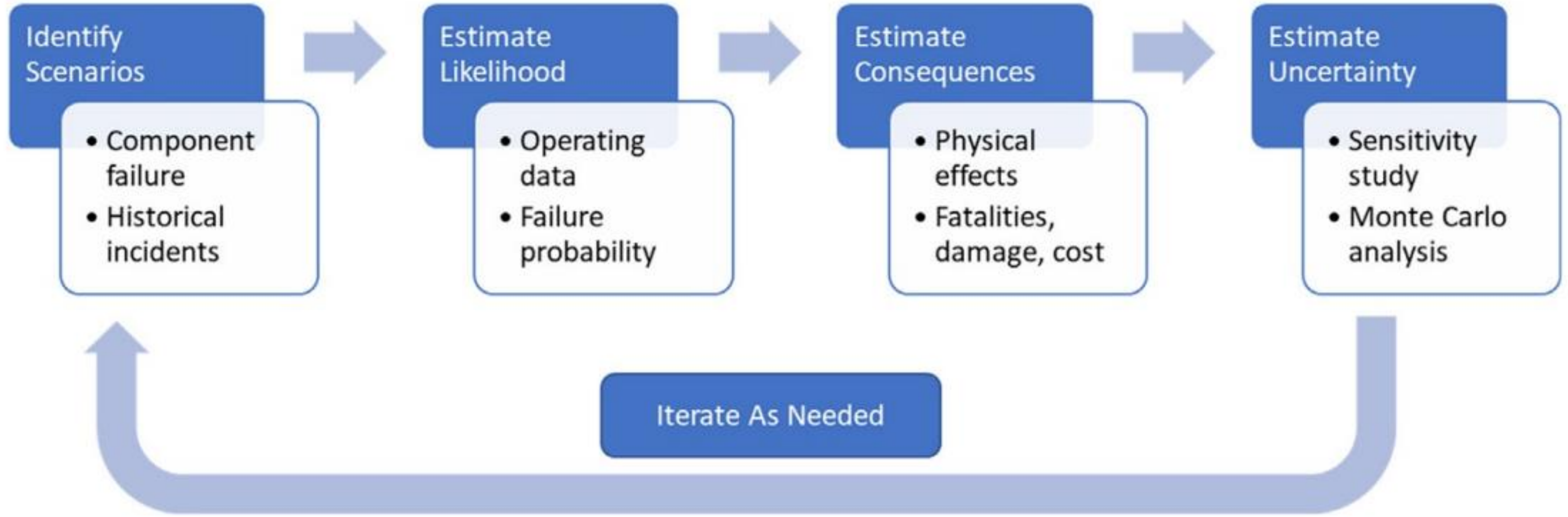

FIG. 16.7 General overview of risk assessment methodology, with examples for each of the major steps in the assessment.

Source: P.A.M. Uijt de Haag, B.J.M. Ale, Guidelines for Quantitative Risk Assessment: Purple Book. Publication Series on Dangerous Substances (PGS 3), Ministerie van Volkshuisvesting en Ruimtelijke Ordening (VROM), 2005

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3.3 Preventative measures and risk mitigation

- Safety data sheets and **quality processes** (FMEA, HAZOP)

Risk acceptability criteria

There are many ways to select criteria to determine if a risk may be acceptable or not. Different communities may be willing to accept different levels of risk for different activities, based on the perceived benefit of that activity. Some communities that are more comfortable with the concept of risk may have regulations that specify a specific level of risk that must be met. Others may not specify a specific risk level and instead may rely on inferred levels of acceptable risk.

In this case, risk might be compared to a similar activity that is already acceptable. For example, hydrogen fuel cell electric vehicles may be compared to existing hydrocarbon combustion engine vehicles;

Source: P.A.M. Uijt de Haag, B.J.M. Ale, Guidelines for Quantitative Risk Assessment: Purple Book. Publication Series on Dangerous Substances (PGS 3), Ministerie van Volkshuisvesting en Ruimtelijke Ordening (VROM), 2005

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3.3 Preventative measures and risk mitigation

- Safety data sheets and **quality processes** (FMEA, HAZOP)

Risk reduction through elimination, prevention, and mitigation
One benefit to risk assessments is that they can identify higher risk scenarios and events, which in turn can lead to design changes that can reduce the risk of these scenarios. This can be carried out through elimination of the risky scenario, prevention of the scenario from occurring, and mitigation of the outcomes should the scenario occur. Elimination of a risky scenario is the most straightforward approach, but it can also be the most difficult one. This involves a design change or substitution, which fully removes even the possibility of the undesirable scenario from occurring.

An example of prevention might also be more frequently scheduled preventative maintenance activities to prevent leaks of hydrogen. Hydrogen is still present and still may leak, but the maintenance activities may identify problem components and replace them before a leak occurs.

Source: P.A.M. Uijt de Haag, B.J.M. Ale, Guidelines for Quantitative Risk Assessment: Purple Book. Publication Series on Dangerous Substances (PGS 3), Ministerie van Volkshuisvesting en Ruimtelijke Ordening (VROM), 2005

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3.3 Preventative measures and risk mitigation

SEANERGY

- Safety data sheets and **quality processes** (FMEA, HAZOP)

Finally, mitigation is the reduction in the severity of the consequences of an event outcome. In this case, the undesirable event has occurred, and the mitigation makes the event outcomes less dangerous or damaging.
An example of mitigation might be to erect barrier walls around potential hydrogen leak points; this way, if a leak does occur and ignite, the resulting fire should not be as dangerous to nearby people or damaging to nearby equipment.

Hydrogen is still there and can still leak, and a barrier around a valve does not inherently prevent the valve from leaking, but the action can reduce the undesirable outcomes should a leak occur.

Source: P.A.M. Uijt de Haag, B.J.M. Ale, Guidelines for Quantitative Risk Assessment: Purple Book. Publication Series on Dangerous Substances (PGS 3), Ministerie van Volkshuisvesting en Ruimtelijke Ordening (VROM), 2005

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3.3 Preventative measures and risk mitigation

SEANERGY

- Safety data sheets and **quality processes** (FMEA, HAZOP)

Example safety distance estimation

A simple example of the applied use of a risk assessment is the determination of safety distances around a hydrogen system. Safety distances (also called setback distances or separation distances) can be a useful last line of defense to provide protection from an unintended release.

While it is almost always better to prevent or mitigate the leak directly, physical distance away from a potential hazard can provide additional levels of safety.

A quantitative risk assessment can be used to determine the safety distance, or it can be used to inform the basis of hazard- or physical effect-based distance.

Source: P.A.M. Uijt de Haag, B.J.M. Ale, Guidelines for Quantitative Risk Assessment: Purple Book. Publication Series on Dangerous Substances (PGS 3), Ministerie van Volkshuisvesting en Ruimtelijke Ordening (VROM), 2005

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3.3 Preventative measures and risk mitigation

- Safety data sheets and **quality processes** (FMEA, HAZOP)

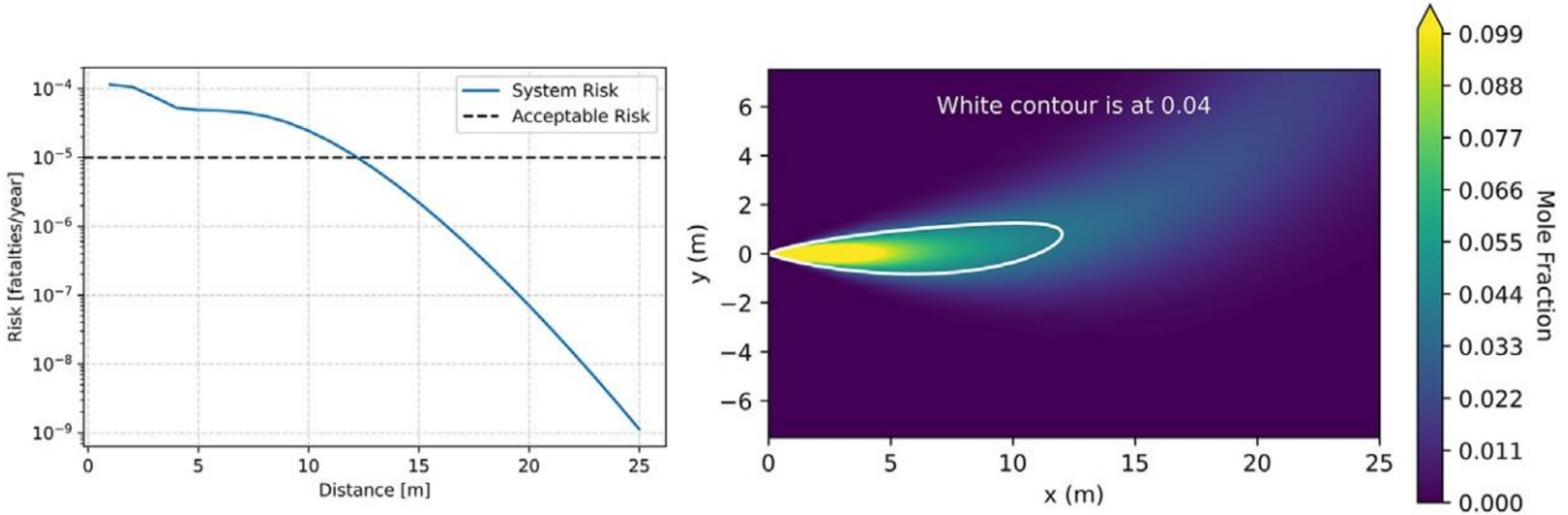

FIG. 16.9 Risk contour, for example, hydrogen system leading to a risk-based distance based on an acceptability criterion (left) and a concentration profile for a hydrogen leak leading to a consequence-based distance based on a harm acceptability criterion (right).

Source: P.A.M. Uijt de Haag, B.J.M. Ale, Guidelines for Quantitative Risk Assessment: Purple Book. Publication Series on Dangerous Substances (PGS 3), Ministerie van Volkshuisvesting en Ruimtelijke Ordening (VROM), 2005

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3.3 Preventative measures and risk mitigation

SEANERGY

- Safety data sheets and **quality processes** (FMEA, HAZOP)

Potential of Hydrogen as Fuel for Shipping

European Maritime Safety Agency

The HAZID study covers the following areas (as applicable):

- General arrangement of vessels
- H_2 fuel-storage arrangement and details
- H_2 fuel supply and vapour-handling system, from fuel storage to machinery spaces
- H_2 fuel arrangement in fuel handling room and engine room
- General arrangement of the fuel-handling and engine rooms, including their ventilation
- Main engine safety concepts and vessel integration
- Hazardous area classification plans
- Ventilation and vents for stored H_2 fuel, fuel-supply system, machinery space and hydrogen consumer
- H_2 fuel-bunkering arrangement
- Safety systems
- Gas detection and firefighting arrangement
- Arrangements to purge or make H_2 inert
- Cargo storage and its impact
- Bunkering
- Emergency Escape and Rescue

Source: EMSA/OP/21/2023 Date: 24/06/2024 Authors: Marius Leisner (DNV), Linda Sigrid Hammer (DNV), Ingeranne Strøm Nakstad (DNV), Hans Jørgen Johnsrud (DNV).
www.emsa.europa.eu/

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3.3 Preventative measures and risk mitigation

- Safety data sheets and **quality processes** (FMEA, HAZOP)

4.2.3 HAZID Workshop Methodology

A HAZID assessment is an extremely useful tool for performing high-level risk assessments of specific systems. ABS has used this approach in numerous risk-assessment projects, as a standalone analysis and to compare similar situations.

A HAZID workshop was held via video-conference. After the workshop, a brief review was conducted with the participants. A flow diagram for the overall HAZID process is shown in Figure 27 below.

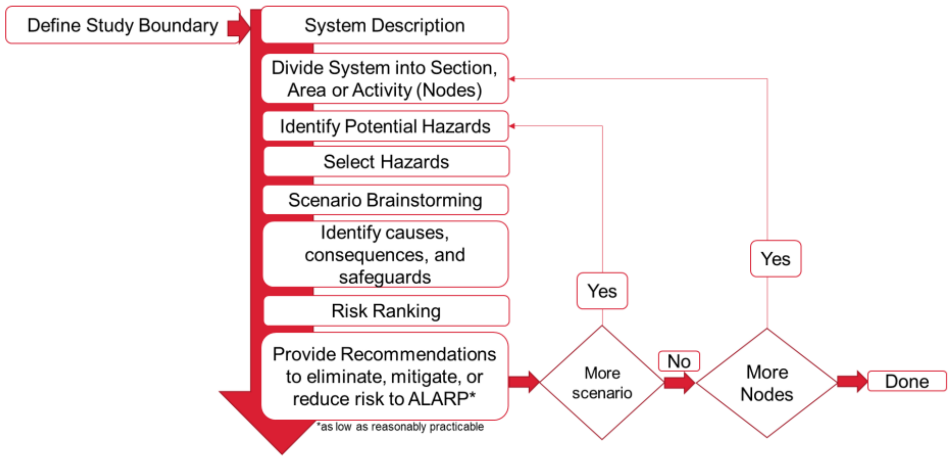

Figure 27. HAZID Process

requirements and safer designs and arrangements. The recommendations developed by the team are listed in Appendix X – List of Recommendations Product Carrier

The recommendations from the HAZID study are listed in the HAZID register Appendix XI – HAZID Register Product Carrier for all major nodes at the systems at the operational levels. Some 131 recommendations were documented in based on discussions with the participants in the preliminary HAZID study.

Table 33. Product Carrier HAZID Risk Ranking Summary

Product Carrier HAZID Risk Profile					
Node #	Key system level HAZID nodes	Risk Ranking of Hazards Identified			
		Low	Moderate	High	Extreme
1	Vessel General Arrangement	-	-	1	1
2	Bunker Station	12	38	68	2
3	Hydrogen Storage System	-	3	30	1
4	Hydrogen Tank Connections & System	-	-	1	-
5	Fuel-Preparation System	-	2	3	-
6	Hydrogen-Supply Piping	-	7	-	1
7	Engine	1	16	18	-
8	Genset				

Source: EMSA/OP/21/2023 Date: 24/06/2024 Authors: Marius Leisner (DNV), Linda Sigrid Hammer (DNV), Ingeranne Strøm Nakstad (DNV), Hans Jørgen Johnsrud (DNV).
www.emsa.europa.eu/

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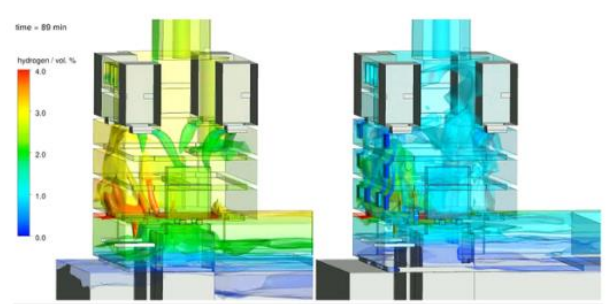
3.3 Preventative measures and risk mitigation

- Safety data sheets and **quality processes** (FMEA, HAZOP)

In hydrogen safety research, methods and tools are developed and investigated that are intended to contribute to the safe introduction and operation of new hydrogen technologies.

A particularly helpful tool here is the numerical flow simulation (CFD = Computational Fluid Dynamics). It makes it possible, for example, to simulate the distribution of hydrogen in a room. In addition, the open-source CFD code OpenFOAM® is used, which is specially adapted to the requirements of hydrogen safety. This makes it possible to show for specific systems how hydrogen is distributed in the room when a leak occurs, at which points potentially flammable gas mixtures can form and whether these are detected by the existing sensors. **In this way, it can be demonstrated, for example, that the intended room ventilation is sufficient to reliably prevent flammable gas mixtures.**

Source: [Wasserstoffsicherheit (fz-juelich.de)]



CFD-Simulation der Wasserstoffverteilung im Maschinenraum eines Flüssigwasserstoff-Tankschiffs im Fall einer Leckage

Copyright:
— Forschungszentrum Jülich GmbH

Source: fz-juelich.de

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3.3 Preventative measures and risk mitigation

SEANERGY

- Training and communication strategies

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3.3 Preventative measures and risk mitigation

- Training and communication strategies

Tipp for a possible Approach to "start":

✓ Best practice - visits

✓ workshops

✓ Professional training

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3.3 Preventative measures and risk mitigation

- Training and communication strategies

There is a international **online and printed** data base of **literature**…

literature

There are several books and guidelines on the market available. Which share fundamental background and give competent answers to the often negative image and the myths.
We recommend as reference/example the following:

„DWV WASSERSTOFF-SICHERHEITSKOMPENDIUM"

Edited by DWV and LBST

ludwig bölkow systemtechnik

DWV Deutscher Wasserstoff- und Brennstoffzellen-Verband

http://www.lbst.de/ http://www.h2de.de/

Safety of hydrogen for large-scale energy deployment in a decarbonized economy

Source: Sandia National Laboratories, Albuquerque, NM, Livermore, CA, USA [(sciencedirectassets.com)](sciencedirectassets.com)

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3.3 Preventative measures and risk mitigation

- Training and communication strategies – **Examples of trainings**

Educational training Lecture 2:

HyResponder

Hydrogen properties relevant to safety

Content

1. Atomic and molecular hydrogen
2. Gaseous, liquefied and slush forms of hydrogen
3. Physical properties of hydrogen (buoyancy as the main safety asset)
4. Combustion characteristics of hydrogen
   - 4.1 Stoichiometric concentration of hydrogen
   - 4.2 Lower and upper flammability limits (LFL and UFL)
   - 4.3 Impact of different factors on LFL and UFL
   - 4.4 Ignition properties
   - 4.5 Detonability limits
   - 4.6 Hydrogen flames quenching
   - 4.7 Micro-flames
   - 4.8 Quenching and blow-off limits
   - 4.9 Leaky fittings
5. Comparison of hydrogen with other fuels

European Hydrogen Train the Trainer Programme for Responders

Source hyresponder.eu/e-platform/training-materials/educational-training/lecture-2-properties-of-hydrogen-relevant-to-safety/

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3.3 Preventative measures and risk mitigation

- Training and communication strategies – **Examples of trainings**

Educational for **Fire fighter, Specialist officer:**

HyResponder

European Train the Trainer Programme for Responders

Lecture 2

Properties of hydrogen relevant to safety

LEVEL I

Firefighter

The information contained in this lecture is targeted at the level of Firefighter and above.

This topic is also available at level IV (Specialist Officer).

This lecture is part of a training material package with materials at levels I – IV : Firefighter, crew commander, incident commander and specialist officer. Please see the lecture introduction regarding competence and learning expectations

Note: these materials are the property of the HyResponder Consortium and should be acknowledged accordingly, the outputs of HyResponse have been used as a basis

Clean Hydrogen Partnership

Co-funded by the European Union

HyResponder

European Train the Trainer Programme for Responders

Lecture 2

Properties of hydrogen relevant to safety

LEVEL IV

Specialist officer

The information contained in this lecture is targeted at the level of specialist officer and above.

This topic is also available at level I (Firefighter).

This lecture is part of a training material package with materials at levels I – IV : Firefighter, crew commander, incident commander and specialist officer. Please see the lecture introduction regarding competence and learning expectations

Note: these materials are the property of the HyResponder Consortium and should be acknowledged accordingly, the outputs of HyResponse have been used as a basis

Clean Hydrogen Partnership

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Lecture 2: Properties of hydrogen relevant to safety

HyResponder

Table of contents

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Source hyresponder.eu/

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3.3 Preventative measures and risk mitigation

- Training and communication strategies – **Examples of trainings**

Mixed e-learning and **virtual reality** pedagogical approach for innovative **hydrogen safety training of first responders**

Ulster University

Mixed e-learning and virtual reality pedagogical approach for innovative hydrogen safety training of first responders

Tretsiakova-McNally, S., Maranne, E., Verbecke, F., & Molkov, V. (2017). Mixed e-learning and virtual reality pedagogical approach for innovative hydrogen safety training of first responders. *International Journal of Hydrogen Energy*, *42*, 7504-7512. https://doi.org/10.1016/j.ijhydene.2016.03.175

Link to publication record in Ulster University Research Portal

Source: 4th ISFEH.dot (ulster.ac.uk)

Figure 3. A screenshot of the VR exercise involving an overturned trailer with liquefied hydrogen.

workshop web-page: http://www.hyresponse.eu/workshop.php

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3.3 Preventative measures and risk mitigation

- Training and communication strategies – **Examples of trainings**

HyFacts is a “Coordination and Support Action” **aiming to develop** and initiate dissemination of **training material for Regulators and Public Safety Officials,** which are responsible persons and work for entities, having to position themselves in the increasing number of upcoming installation of hydrogen-related technologies in public areas, companies, universities, research centres, fairgrounds, harbour sites and other places where fuel cell and hydrogen installations and mobile applications shall be installed and operated in the near future.

Source: [HyFACTS-Deliverable-Final-Report.pdf (h2euro.org)]

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3.3 Preventative measures and risk mitigation

- Training and communication strategies – **Examples of trainings**

1. The **EC Network of Excellence** for Hydrogen Safety **HySAFE** contributed to the safe transition to a more sustainable development in Europe by facilitating the safe introduction of hydrogen technologies and applications. EC Project HySAFE
2. Online resource for the National Hydrogen and fuel Cells Codes & Standards Coordinating Committee produced by the Fuel Cell and Hydrogen Energy Association in association with the US Department of Energy.http://www.hydrogenandfuelcellsafety.info/
3. International Energy Agency Task 19 on Hydrogen Safety IEA HIA Task 19
4. International Association for Hydrogen Safety http://www.hysafe.info/
5. Introducing Hydrogen as an energy carrier: safety, regulatory and public acceptance issues (EC publication)
6. Introducing Hydrogen as an energy carrier
7. Hydrogen Safety Best Practices (US) H2 Best Practices
8. Technical Reference for Hydrogen Compatibility of Materials, Sandia National Laboratories (US) Material compatibility
9. Hydrogen Safety Websites of the DoE DoE hydrogen safety

Source: *www.h2euro.org/hyfacts/2014/06/26/hydrogen-safety/*

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3.3 Preventative measures and risk mitigation

- Training and communication strategies – **Examples of trainings**

training material:
HyFACTS » Training Material (h2euro.org)

Education:
This section presents information and links on higher education programs on hydrogen and fuel cells. The intention is to list hydrogen-related undergraduate and postgraduate programmes, single modules or lectures offered by Universities in Europe.
HyFACTS » Education (h2euro.org)

Source: *www.h2euro.org/hyfacts/2014/06/26/hydrogen-safety/*

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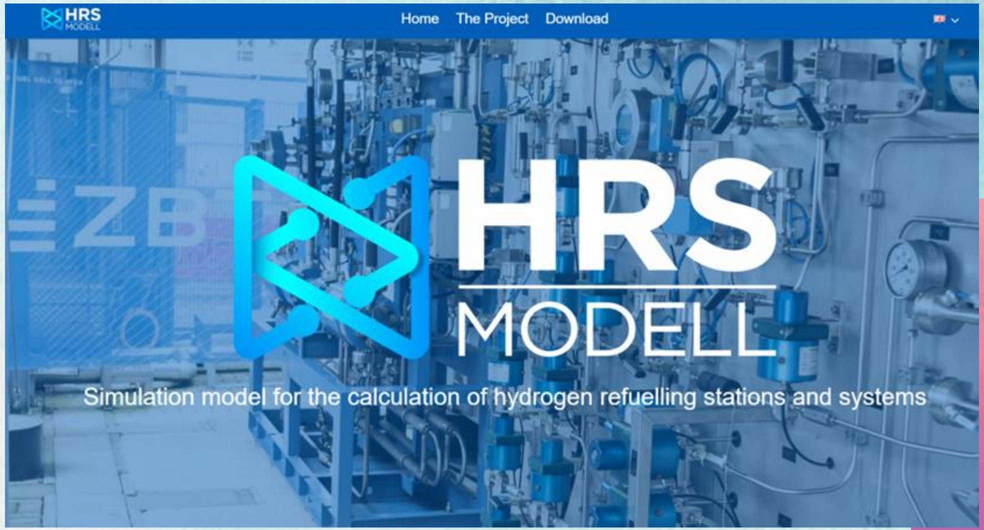
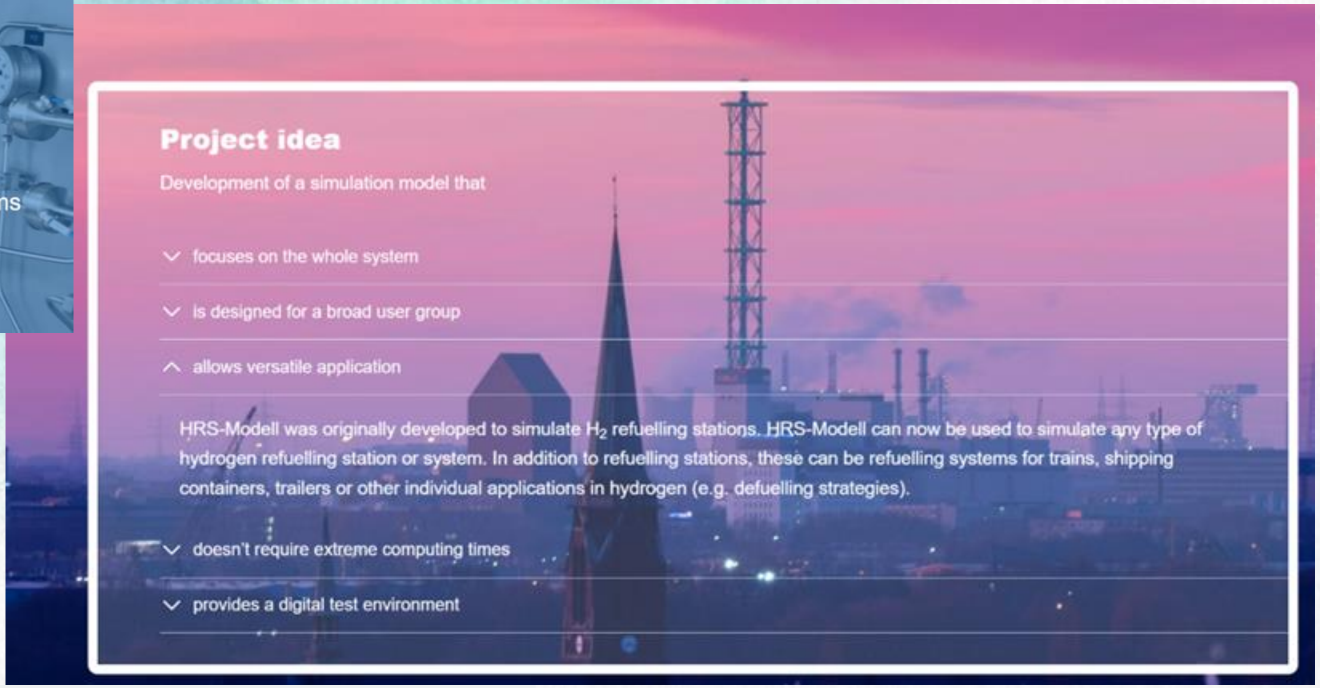
3.3 Preventative measures and risk mitigation

- Training and communication strategies – **Example Software**





Source: https://hrs-modell.de/en/home-pre-en/

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3.3 Preventative measures and risk mitigation

- Training and communication strategies – **Example Software**

<u>Software for Hydrogen storage simulations</u>

The website for the HRS model has been live since the end of August 2024.
The HRS model can also be downloaded there free of charge.
It is initially a beta version that requires a corresponding MATLAB license (+ add ons).

<u>What is HRS-Modell?</u>

HRS-Modell is a simulation model developed to calculate the thermodynamic effects within hydrogen refuelling stations during operation.
It is suitable for simulating almost all types of hydrogen systems.
The model has been developed as part of the “HRS-Modell” project funded by the IGF.

Source: https://hrs-modell.de/en/home-pre-en/

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3.3 Preventative measures and risk mitigation

- Training and communication strategies – **Example of trainings**

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Features

The simulation tool has been developed to model hydrogen refuelling stations. This includes stations and systems for refuelling of cars, buses, trucks, trains, shipping containers and trailers. The level of detail can be freely selected to match the focus of the calculation to the specific issue or application.

Software

The current release version of the simulation model is a beta version. MATLAB Simulink and selected toolboxes are required to use the model . After download the model library can be imported to Simulink. Default values are provided for all relevant operational and model parameters, which can be adjusted as required.

Validation

As part of the funded project, the model's calculations were validated with measured data from ZBT's hydrogen test field. As part of workshops and projects with partners from industry and research, the HRS-Modell is continuously developed and validated with real system data.

What can the model be used for?

Scope

- Filling of tanks
- Defuelling of tanks
- Booster-filling / Direct compression
- Back-to-back refuellings
- Parallel refuellings
- Modelling of operation strategies
- Single events
- Operation cycles
- Trailer-Swap

Applications

- Iterative system and operation design of hydrogen stations and systems
- Time-resolved visualisation of dynamic processes at every point in the system
- Analysis of operation strategies for existing and planned systems

Source: HRS-Modell
Contact:
Lukas Willmeroth, l.willmeroth@zbt.de
Department Hydrogen Infrastructure,

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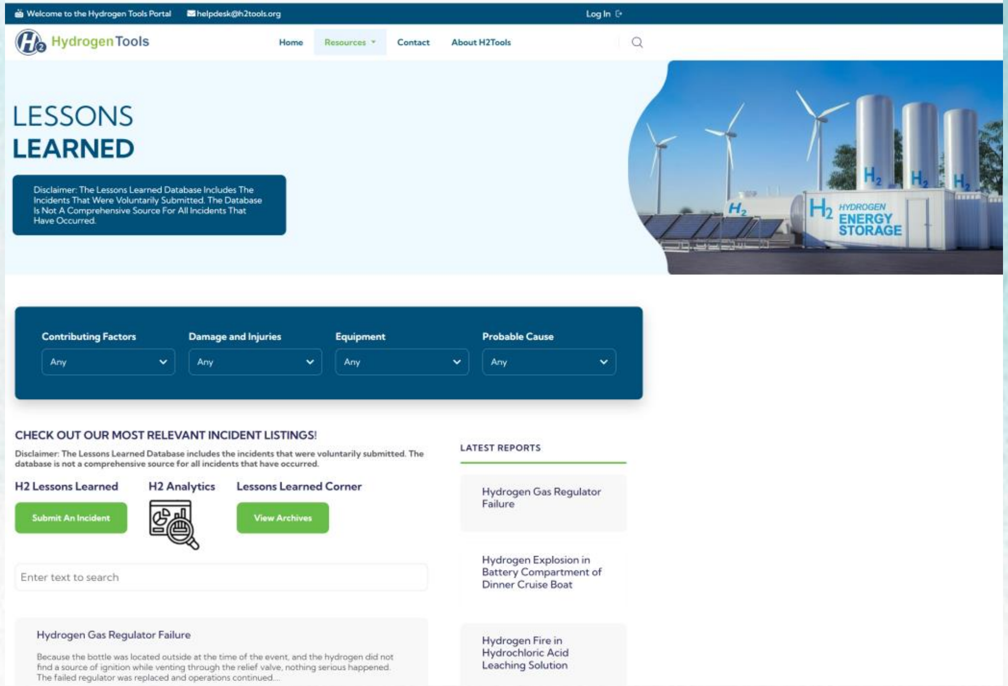
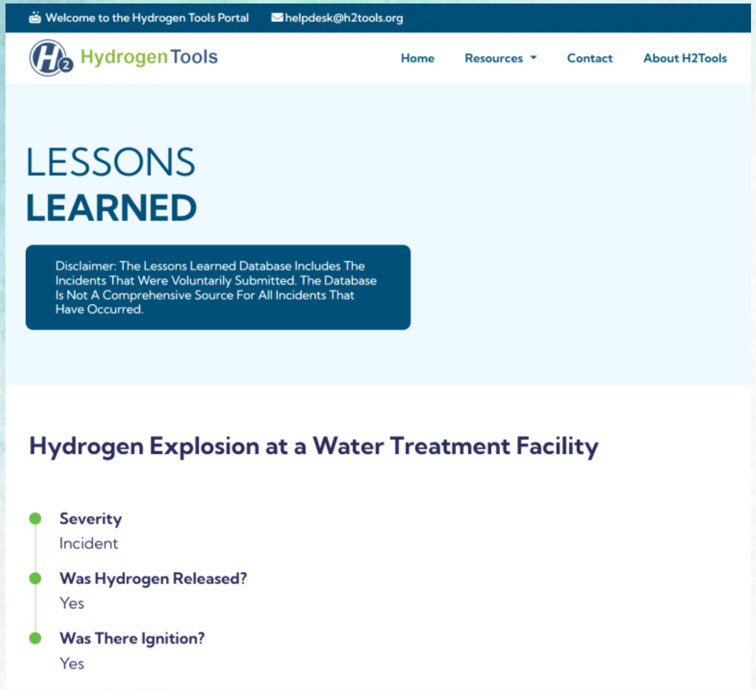
3.3 Preventative measures and risk mitigation

- Training and communication strategies

Data base of incidents, results, lesson learned – Examples





Source: h2tools.org/lessons

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3.3 Preventative measures and risk mitigation

- Training and communication strategies

Data base of incidents, results, lesson learned – **Examples**

Process Vessels
Pump
DAMAGE AND INJURIES
Human Life
Property Damage
PROBABLE CAUSE
Design Flaw
Lack of Hydrogen Detection Equipment
CONTRIBUTING FACTORS
Equipment Failure
Flammable Mixture in Confined Area
Inadequate Maintenance
Lack of Protocol/SOP
Situational Awareness
WHEN INCIDENT WAS DISCOVERED
During Maintenance

Describe the incident, including corrective steps taken and their result.

A water treatment plant used an electrolytic process to generate sodium hypochlorite (NaOCl) from sodium chloride (NaCl). The strategy of using liquid sodium hypochlorite for disinfecting water instead of gaseous chlorine (CL_2) is popular because the liquid is generally safer and falls under fewer OSHA and EPA standards. The further idea of generating the liquid sodium hypochlorite on an as-needed basis and in limited quantities also has certain obvious safety advantages.

One of the disadvantages of the electrolytic process is that hydrogen gas is also created as a byproduct. The hydrogen is supposed to be vented, by design, to the atmosphere before the liquid sodium hypochlorite passes into a holding tank.

For various reasons, in this instance it is believed that the hydrogen vent line was closed, thereby forcing the hydrogen gas into the liquid holding tank where it accumulated. In order to repair a leak in the tank, plant workers had drained the tank to within a few inches and then lowered an electric pump into the tank to remove the remaining liquid. When the switch was thrown to turn on the pump, the tank exploded. One worker was killed by the blast.

Lessons Learned

The mechanisms and rates by which hydrogen gas is generated and subsequently accumulated in the holding tank need to be fully understood by vendors and employees alike. Active venting, warning signs, and local alarms designed to activate when hydrogen ventilation lines are obstructed are essential.

Source: Hydrogen Explosion at a Water Treatment Facility | H2tools | Hydrogen Tools

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3.3 Preventative measures and risk mitigation

- Training and communication strategies

<u>Data base of incidents, results, lesson learned</u> – **Examples**

<u>Lessons Learned</u>

Specific response drills/exercises need to be conducted yearly. In this case, all safety systems worked as they should and outside emergency responders were not needed.

…Most premature failures of hydrogen tube trailer PRD burst discs occur during the fill process.

Grounding, as was done in the incident, should always be done during hydrogen filling. However, even when the fill vessel is grounded, it is not unusual for a hydrogen release to immediately ignite.

….

Emergency responders assumed that adjacent tube trailers were heating up from single-cylinder vent flare as a 300°F (149°C) reading was obtained with a thermal device. This slightly delayed the closing of the cylinder isolation valves on the tube trailer. …

Securing hydrogen fill valve(s) at the back of the tube trailer was not dependent on the temperature at the vent stack, as this area was covered by deluge nozzles and located 40 feet (12.2 meters) away from the vent stack.

Media involvement and resulting speculation can portray a situation as being much worse than it actually is.

Source: https://h2tools.org/lessons/hydrogen-tube-trailer-burst-disc-ruptures-prematurely-while-filling

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3.4 Storage solutions and standards

SEANERGY

- Current and future hydrogen storage technologies

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3.4 Storage solutions and standards

- Current and future hydrogen storage technologies

Current storage:
Example "On-site" buffer tank bench (ISO I) for HRS etc.

Source: ToughtCo

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3.4 Storage solutions and standards

- Current and future hydrogen storage technologies

SEANERGY

Gas transport (virtual pipeline) & temporary on-site storage, in order to distribute and/or buffer hydrogen for HRS, Micro-grids, Gen-sets, mobile applications (high consumption demand) etc.

Source: „We engineer and deliver gas solutions", Dirk Fischer Head of Sales, Argo-Anleg GmbH, 16.04.2024, Webinar hosted by Hydrogen Moves GmbH

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3.4 Storage solutions and standards

- International standards and regulations

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3.4 Storage solutions and standards

- International standards and regulations

Introduction

International codes and standards
Codes and regulations that govern the safety of hydrogen systems have been in place for decades. However, those regulations considered only the traditional, industry-based applications.

Some hydrogen applications require the development of entirely new codes and standards. For example, standards that govern the safety of refueling vehicles with hydrogen are being developed, whereas recently developed codes for mixing hydrogen into the natural gas pipeline delivery systems require updating.

The nature of codes, standards, and regulations for hydrogen safety means that different countries and jurisdictions can issue their own unique documents, or they can refer to model codes or international standards in their local regulations.

Source: www.sciencedirect.com/science/article/

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3.4 Storage solutions and standards

- International standards and regulations

A selection…

<u>international standardisation bodies:</u>

ISO/TC 197 ‘Hydrogen Technologies’
CEN-CENELEC/JTC 6 ‘Hydrogen in Energy Systems’
CEN/TC 268 WG 5 ‘Specific Hydrogen Technologies Applications’

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3.4 Storage solutions and standards

- International standards and regulations - **Examples**

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<u>Standardization:</u>

- Marine: ongoing process (EU- CESNI, UN…)
- Automotive: EC79, UN R134, ISO 2626-2
- Tank protocols SAE..
- Gas transport: ADR (road) ADN (inland shipping), IMDG (offshore), CSC, RDN (Rail)

Hydrogen-specific regulations:

The transportation of hydrogen by road in Europe is regulated by the European Agreement concerning the International Carriage of Dangerous Goods by Road ADR5 ('Accord européen relatif au transport international des marchandises Dangereuses par Route'), its transportation by water by the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways ADN ('Accord européen relatif au transport international des marchandises dangereuses par voie de navigation intérieure,')

and on railroads by the Regulations concerning the International Carriage of Dangerous Goods by Rail RID ('Règlement concernant le transport international ferroviaire de marchandises Dangereuses'). The UN has also included the handling of dangerous goods in its recommendations ('Recommendations on the Transport of Dangerous Goods') and regulated it internationally.

The PED (Pressure Equipment Directive) is applicable to all pressure equipment, including all hydrogen pressure equipment or accumulators that are exposed to a pressure of more than 0.05 MPa (0.5 bar).

Source: www.umweltwirtschaft.com

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3.4 Storage solutions and standards

- International standards and regulations

Examples for Hydrogen Refilling Stations (HRS)

There are different protocols dedicated for different specific applications taking into account the specitify of the vessel and customer requirements. Several of them are standardized by ISO, SAE or CEN:

- SAE J2601 - Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles [1],- maximum flow rate is limited to 60 g/s
- SAE J2601-2 - Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles [2],- maximum flow rate is limited to 120 g/s
- JPEC-S 0003 [3].
- ISO 19880-1

There are also protocols which are the intellectual property (IP) of HRS operators (OEM), for example:

- NEL (**control of the mass flow**)
- Linde (pressure ramp)
- Air Liquide (pressure ramp)
- ITM (pressure ramp)
- Air Products (pressure ramp)

Source: www.sciencedirect.com/science/article/

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3.4 Storage solutions and standards

- International standards and regulations - **Examples**

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For the first time, all hydrogen standards are bundled in a publicly accessible directory.
The currently available technical rules and standards for hydrogen technologies have been bundled in a publicly accessible directory for the first time.

It comprises **919 documents** and represents the current state of technical regulation in this field.

Source: Database: www.din.de/de/forschung-und-innovation/themen/wasserstoff/normensuche

Standardisation in the field of hydrogen - Part 1: Hydrogen production

Source: stiftung-umweltenergierecht.de (German language) 30.01.2023

Regulations, Codes and Standards for the field of hydrogen and fuel cell technology
The focus of this website is on international and national regulations, codes and standards (RCS) for hydrogen and fuel cell technology in the field of mobility.

Source: *rcs.now-gmbh.de/en/*

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3.4 Storage solutions and standards

- International standards and regulations - **Examples**

The **ISO** (International Organization for Standardization in Geneva) pursues **a globally harmonized approach** in its Technical Committee 197, where **important documents such as ISO 17268 and ISO 20100 are developed for hydrogen**.

ISO 17268 deals with the standardization of requirements for the **refuelling interface of compressed hydrogen** (25, 35, 50 and 70 MPa) for use in road vehicles.

ISO 20100 proposes harmonized requirements **for the design, operation and maintenance of hydrogen refuelling stations**
The ISO standards developed **in the Technical Committees TC58 for compressed gases and TC197 for hydrogen technologies are particularly relevant for hydrogen storage.** They are intended to ensure functionality, compatibility and safety.

There are already **over 20 ISO standards that are relevant and can be used for hydrogen applications.**
In addition, there are many whose scope of application includes hydrogen as well as other gases. In some areas, such as refuelling procedures, despite efforts to formulate internationally harmonized standards, national or industry-internal standards have established themselves rather than internationally accepted standards (e.g. SAE J2600, SAE J2601), which are only gradually being transferred to international standards such as ISO 17268

Source: https://rcs.now-gmbh.de/en/

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3.4 Storage solutions and standards

- International standards and regulations - **Examples**

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Electrolysis

Many international technical standards for electrolyzers are currently available.
One of them is: **ISO 22734:2019 Hydrogen generators using water electrolysis** – Industrial, commercial, and residential applications.
Technical Standards:
ISO 22734-1:2008 Hydrogen generators using water electrolysis process **Part 1: Industrial and commercial applications**, Edition 1
ISO 22734-2 Hydrogen generators using water electrolysis process **Part 2: Residential applications**, Edition 1

Source: https://seshydrogen.com/en/h2-safety-2-electrolyzer/

Steam Reforming

ISO 16110-1:2007 Hydrogen generators using fuel processing technologies
Part 1: Safety, Edition 1 Applicable to stationary hydrogen generators intended for indoor and outdoor commercial, industrial, light industrial and residential use **with a capacity of less than 400 m3 /h** .

This part of ISO 16110 **is a product safety standard** suitable for conformity assessment as stated in IEC Guide 104, ISO/IEC Guide 51 and ISO/IEC Guide 7.

Source:(h2euro.org)

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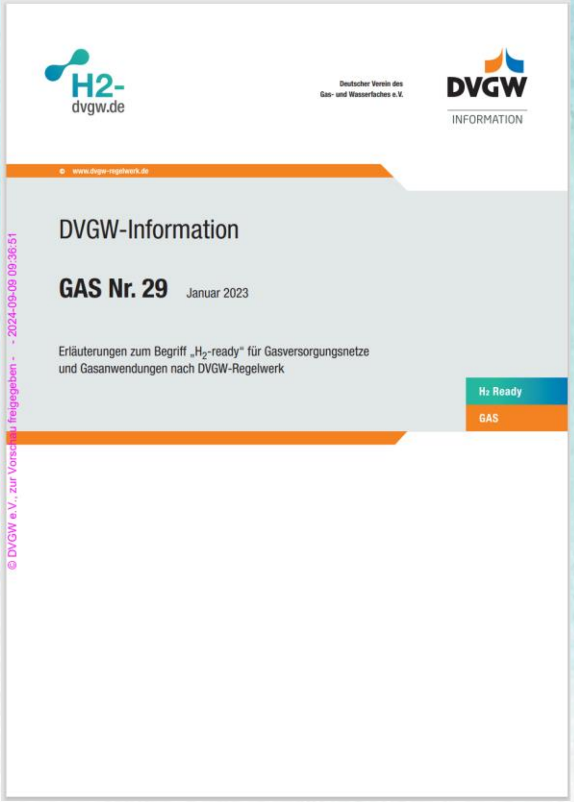
3.4 Storage solutions and standards

- International standards and regulations - **Examples**

SEANERGY

Pipelines


H2-
dvgw.de

Deutscher Verein des Gas- und Wasserfaches e.V.

DVGW
INFORMATION

www.dvgw-regelwerk.de

DVGW-Information

GAS Nr. 29 Januar 2023

Erläuterungen zum Begriff „H_2-ready" für Gasversorgungsnetze und Gasanwendungen nach DVGW-Regelwerk

H_2 Ready

GAS

Hazard	Safety measures
Rupture of pipes and fittings because of hydrogen embrittlement	**Hydrogen compatible materials** should be chosen.
Corrosion for underground piping	Piping must be externally coated to an approved specification, to protect against **soil corrosion by cathodic protection**.
Rupture of the pipe material due to lightning strikes or ground fault conditions	**Electrical continuity** between underground hydrogen piping and above ground piping, or other metal structures, **should be adhered**. All above-ground pipelines shall have electrical continuity across all connections, except insulating flanges, and shall be earthed at suitable intervals to protect against the effects of lightning and static electricity
Rupture due to external forces	Piping should **not be exposed to external forces** which can cause a failure or dangerous situation. **The main cause of pipe rupture is attack by external operation** (e.g. when a mechanical digger knocks on a pipe).
Hazards specific to underground piping	It is preferable to have no flanged or other mechanical joints underground. Only gaseous hydrogen pipes **with welded joints** may be buried.

Source: [Gas-Information Nr. 29 - DVGW Regelwerkverzeichnis (dvgw-regelwerk.de)]

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3.4 Storage solutions and standards

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- Components of hydrogen storage systems (HSS)

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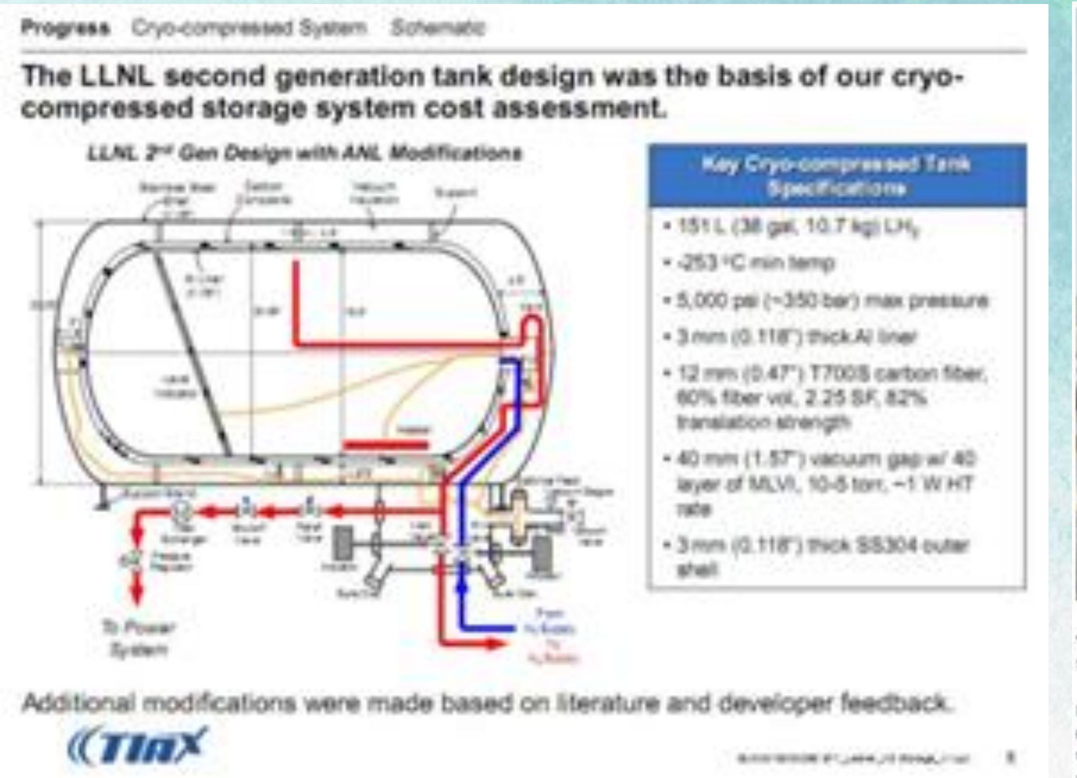
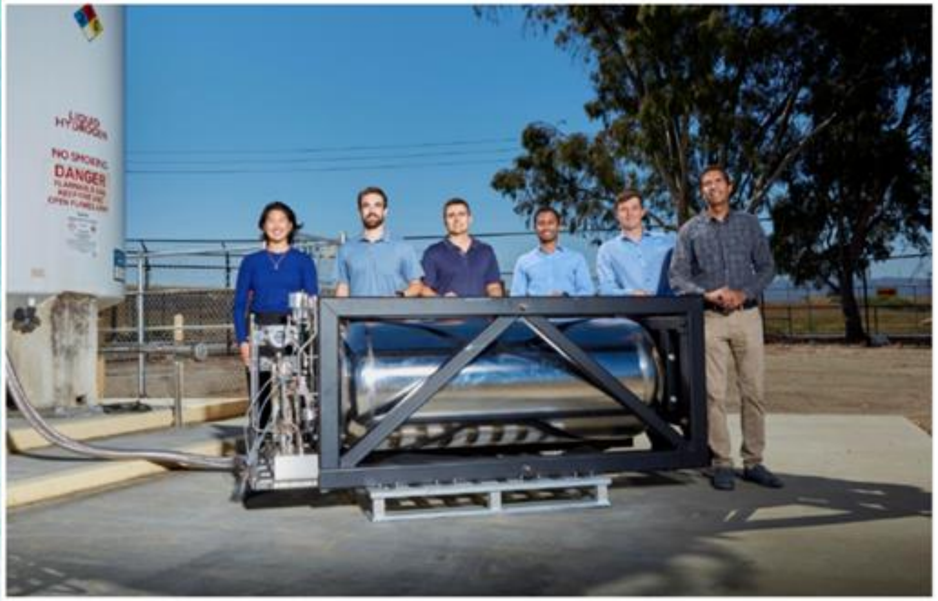
3.4 Storage solutions and standards

- Components of hydrogen storage systems (HSS)

Reference: Cryo Compressed Hydrogen Storage Systems (**CC**HSS)



Source:(energy.gov)



Verne and Lawrence Livermore National Laboratory tripled previous records for cryo-compressed hydrogen storage, achieving the first demonstration of a CcH2 system large enough to meet the energy storage needs of semi-trucks.

Livermore, California— Verne and Lawrence Livermore National Laboratory (LLNL) demonstrated a single cryo-compressed hydrogen (CcH2) system with a capacity of 29 kilograms, close to three times greater capacity than previously known examples. This system is the first CcH2 system large enough for use in heavy-duty transportation systems. For example, two such systems can be frame-mounted to a Class 8 truck, and enable a range of over 500 miles, according to Verne analysis.

Source: fuelcellsworks.com/news/ (Picture: copyright of VERNE Inc. CA, USA)

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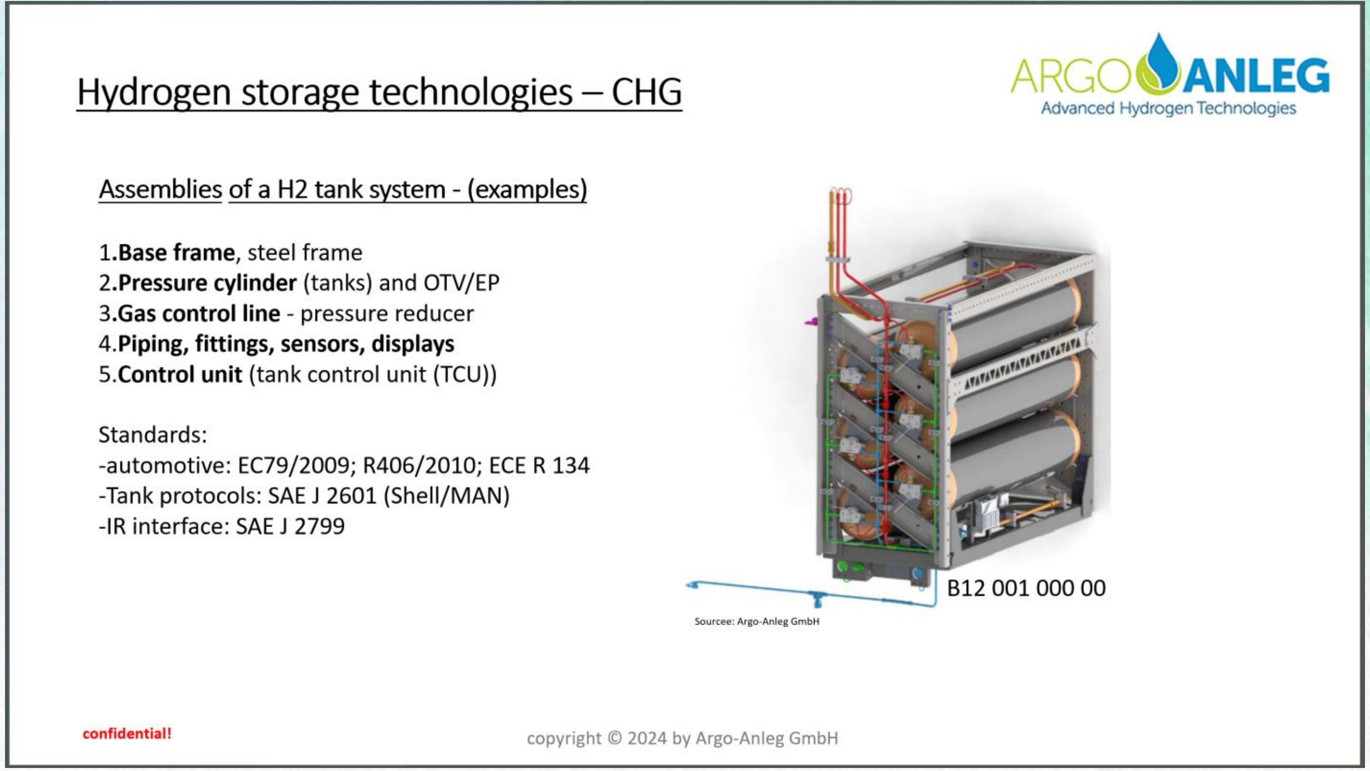
3.4 Storage solutions and standards

- Components of hydrogen storage systems (HSS)

SEANERGY

Reference: Compressed Hydrogen Storage Systems (**C**HSS)



Source: Paul Nutzfahrzeuge GmbH

Source: „Wir geben GAS !“ 350 & 700 bar Wasserstofftanksysteme für LKW-Anwendung und Infrastrukturlösungen für den schnellen Markthochlauf, 05.06.2024, PIN 21, Vilshofen a.d. Donau, Jan Andreas Managing Director Argo-Anleg GmbH

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3.5 Examples of hydrogen applications

SEANERGY

- Case-studies in automotive, rail, and marine sectors

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3.5 Examples of hydrogen applications

- Case-studies in automotive, rail, and marine sectors

Examples – Mobile (automotive…) sector

Source: Isabel François (WaterstofNet)

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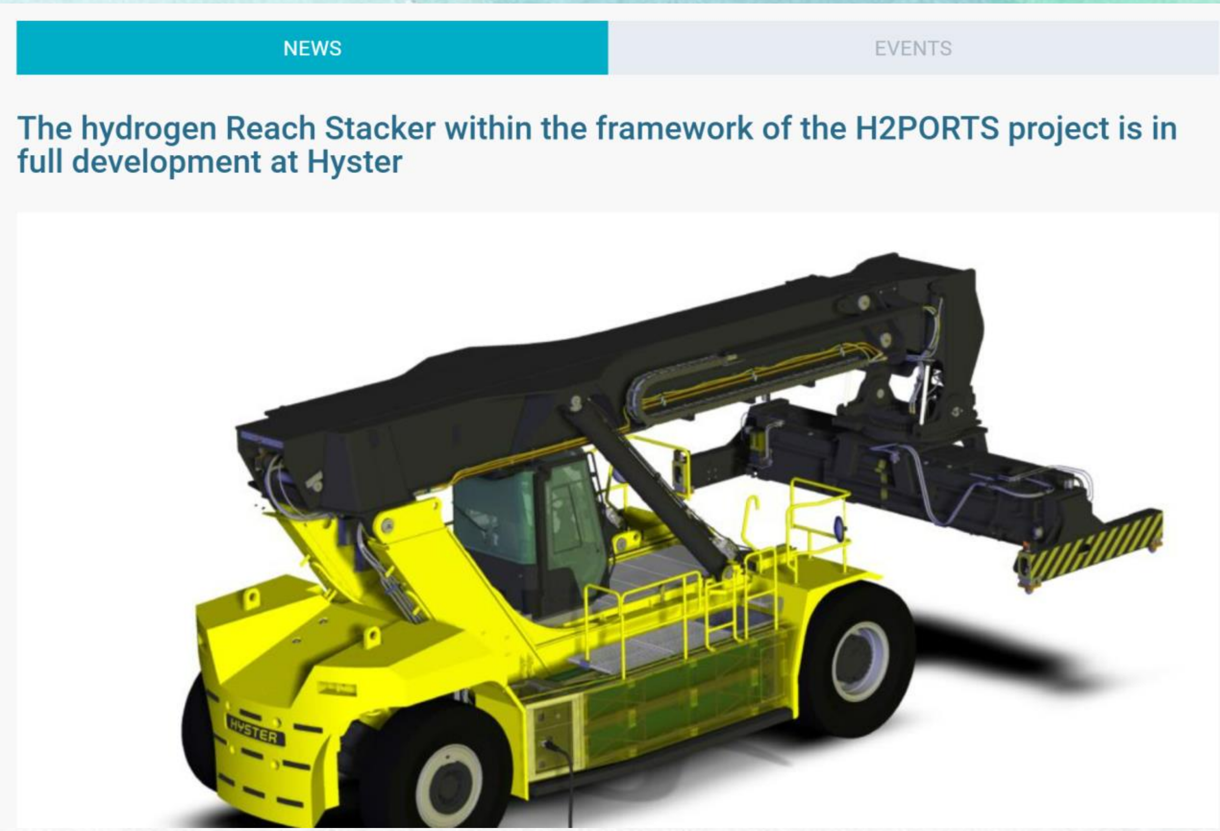
3.5 Examples of hydrogen applications

- Case-studies in automotive, rail, and marine sectors

Examples – Intra-logistic



"Project: H2PORTS "

Source: www.fundacion.valenciaport.com/en/news-events/

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3.5 Examples of hydrogen applications

- Case-studies in automotive, rail, and marine sectors

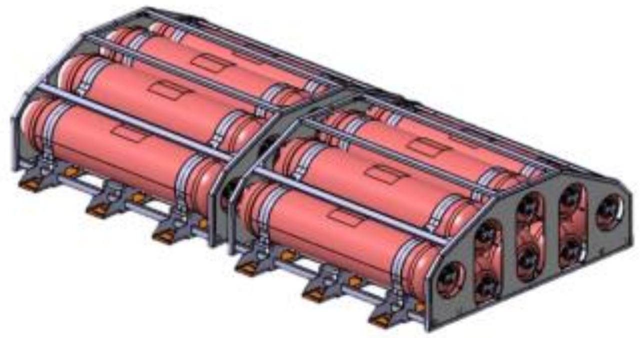
Examples - sector – **“Rail”**

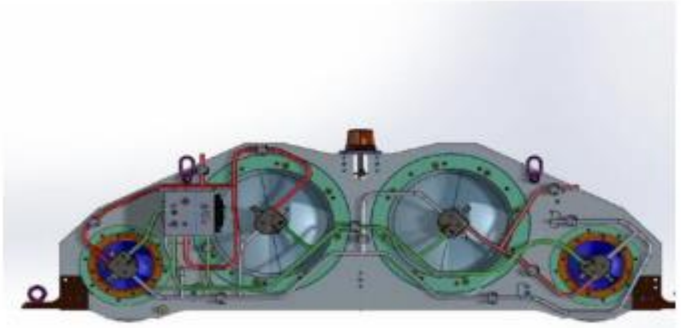
<u>Best practice example Port Hamburg:</u>
128.7 million tons of seaborne cargo handled in 2021: the Port of Hamburg is the third largest seaport in Europe and benefits from its good connection to the rail network.

The world's first hybrid locomotives are shunting at Container Terminal Altenwerder. They produce up to 50 percent less CO_2 and up to 70 percent less nitrogen dioxide. Container Terminal Altenwerder was certified by TÜV in 2019 as the world's first climate-neutral handling facility.

Intralogistic in ports:
Die Fahrzeuge in der Terminallogistik, darunter klassische (Klein-) Stapler, Reach Stacker und Portalhubwagen („Van Carrier“ oder „Straddle Cars“) mit einem Eigengewicht bis zu 100 t und einer Nutzlast bis zu 50 t, haben außergewöhnliche Anforderungen an Leistungsfähigkeit und Verfügbarkeit. Hier sind für batterie- und brennstoffzellenbetriebene Sonderfahrzeuge neue technische Lösung zu erarbeiten und ggf. auch betriebliche Abläufe neu zu konzipieren, jeweils angepasst auf die Bedingungen eines spezifischen Einsatzorts.

Source: www.hysolutions.de/schiene-wasser-luft/umschlagterminals-emissionsfrei/





Source: Anleg GmbH

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3.5 Examples of hydrogen applications

- Case-studies in automotive, rail, and marine sectors

Examples - sector **“Marine”**

Source: Isabel François (WaterstofNet)

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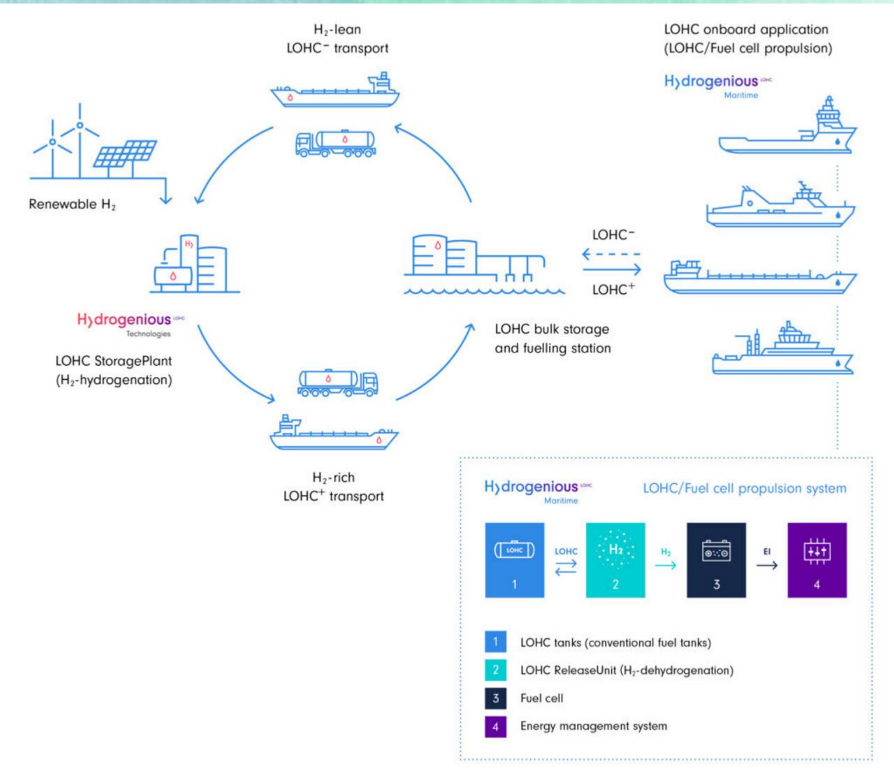
3.5 Examples of hydrogen applications

- Case-studies in automotive, rail, and marine sectors

Examples - sector **“Marine”**

Funded by the European Union



LOHC project: Ship-aH2oy

<u>Ship-aH2oy provides a solution:</u>
Green hydrogen from LOHC combined with high-power solid oxide fuel cells to generate zero emission power onboard ships.

Source: shipah2oy.eu/about/

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3.5 Examples of hydrogen applications

SEANERGY

- Comparison of hydrogen technologies (ICE vs. FC)

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3.5 Examples of hydrogen applications

- Comparison of hydrogen technologies (ICE vs. FC)

ICE (internal combustion engine)

Source: Keyou GmbH Link: KEYOU

FC (Fuel Cell)

Source: Ballard Marine Blog

(ICE) Hybrid design of the rotary engine:
electric motor and combustion engine form a single unit
Source: evs-hydrogen.de

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3.5 Examples of hydrogen applications

- Comparison of hydrogen technologies (ICE vs. FC)

- **ICE (internal Combustion Engine) based on a DIESEL concept, consist of** more parts
- higher compression by combustion higher flame temp.
- Faster flame speed
- Motor block to upgrade
- Allow less H2 quality grade

- **FC (Fuel Cell’s)** do more leak
- Are more sensivitve regarding environmental impact by vibration and dust
- H2 quality (requires 5.0) dust and moisture content (to dry and to much moisture is not good
- Both require leak detection

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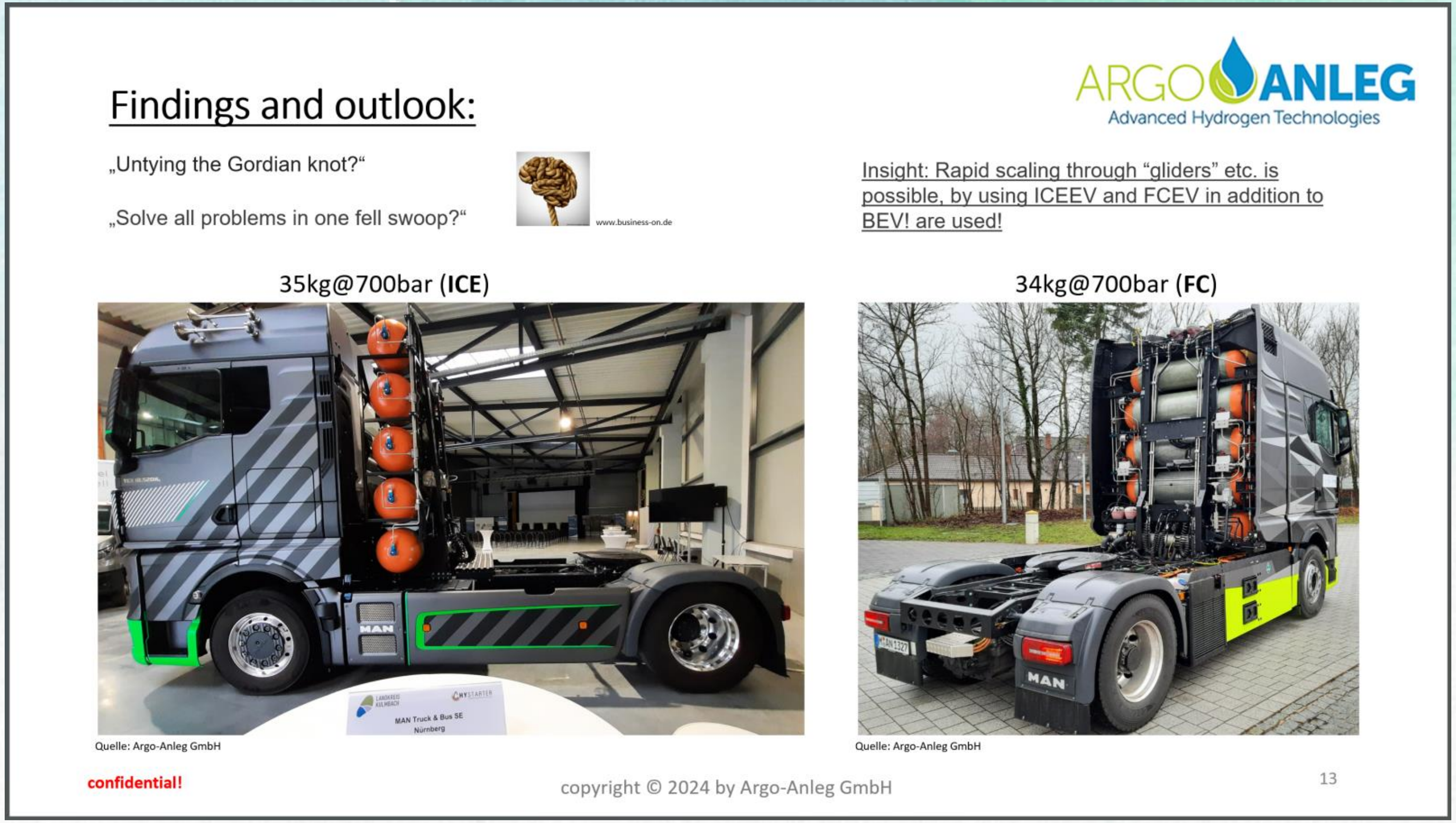
3.5 Examples of hydrogen applications

- Comparison of hydrogen technologies (ICE vs. FC)

Mobile application



Source: 8.Netzwerktreffen Niederrhein – Kreis Wesel, Asdonkshof Kamp-Lintfort 20.03.2024, Argo-Anleg GmbH

ICE, left

versus

FC, right,

Note: same OEM

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3.5 Examples of hydrogen applications

- Comparison of hydrogen technologies (ICE vs. FC)

Stationary (or mobile = vessel powertrain) application

Potential of Hydrogen as Fuel for Shipping — European Maritime Safety Agency

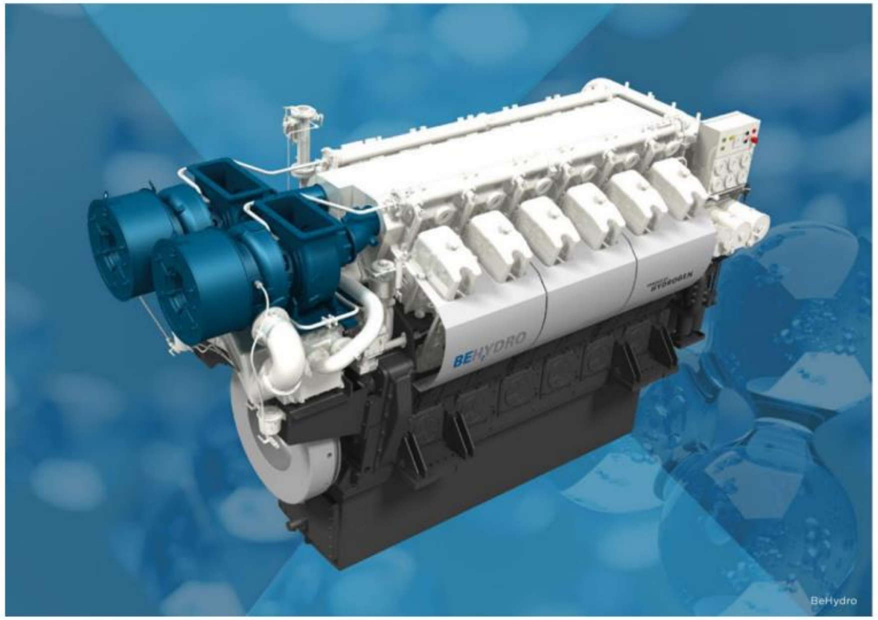

Figure 9. Main engine design for the ABC BeHydro© engine, the dual-fuel hydrogen 4-stroke engine; it is available with up to 16 cylinders and delivers 2.6MW.

Engine Type	Layout	Alternative Fuel	Combustion Cycle	Year of first engine delivery (*expected)
Himsen	4-stroke, medium speed	Methanol	Diesel	2023
Himsen (under development)	4-stroke, medium speed	Ammonia	Diesel/Otto	2024*
Himsen (under development)	4-stroke, medium speed	Hydrogen	Otto	2026*
Kawasaki (under development)	4-stroke, medium speed	Hydrogen	Otto	2027*
MAN B&W ME-LGIA (under development)	2-stroke, slow speed	Ammonia	Diesel	2024*
WinGD X-DF-A (under development)	2-stroke, slow speed	Ammonia	Diesel	2025*
WinGD X-DF-M (under development)	2-stroke, slow speed	Methanol	Diesel	2024*
Wärtsilä DF (under development)	4-stroke, medium speed	Ammonia	Otto	2023*
Wärtsilä LG (under development)	4-stroke medium speed	Ammonia	Diesel	2025*
Himsen (under development)	4-stroke, medium speed	Ammonia	Diesel	2024*
MAN-ES	4-stroke, medium speed	Ammonia	Diesel	2026*
MAN-ES (under development)	4-stroke, medium speed	Methanol	Otto	2024*
ABC	4-stroke, medium speed	Hydrogen	Otto	2020
ABC (under development)	4-stroke, medium speed	Methanol	Otto	2024*
Wärtsilä (under developemnt)	4-stroke, medium speed	Hydrogen	Otto	2024*

Source: www.emsa.europa.eu/

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3.5 Examples of hydrogen applications

- Comparison of hydrogen technologies (ICE vs. FC)

Stationary (or mobile = vessel powertrain) application

Table 8. Lifecycle GHG emissions and air-pollutant emissions from green hydrogen vs fossil marine fuels

	HFO, MGO*	LNG*	Green hydrogen - combusted in engines	Green hydrogen – used in fuel cells
Lifecycle GHG emissions				
N_2O	Present	Present	Not present	Not present
CH_4	Low	Present at Otto engines	Not present	Not present
CO_2	Present	Present	From manufacturing wind turbines and solar panels	From manufacturing wind turbines and solar panels
H_2 (indirect)	Not present	Not present	From venting, purging and boil-off	From venting, purging and boil-off
Air pollutant emissions				
SO_2 and metals	Present	Not present	Not present	Not present
Carbon monoxide and hydrocarbons	Present	Present or increased	Not present	Not present
VOCs and PAHs	Present	Reduced	Not present	Not present
NO_x	Needs SCR for Emission Control Area	Otto engines meet Emission Control Area without SCR	No significant NO_x emissions with SCR	Not present
Direct particulate matter	Present	Reduced	Not present	Not present

Notes: HFO = heavy fuel oil; LNG = liquefied natural gas; MGO = marine gas oil; SCR = selective catalytic reduction.

*: *Adapted from* (Ash & Scarbrough, 2019). *Pilot fuel is not considered in this table.*

Source: www.emsa.europa.eu/

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Conclusions and take-home message

"SAFETY FIRST"

Risks and mitigation strategies for hydrogen applications

Conclusion

Thesis / summary:

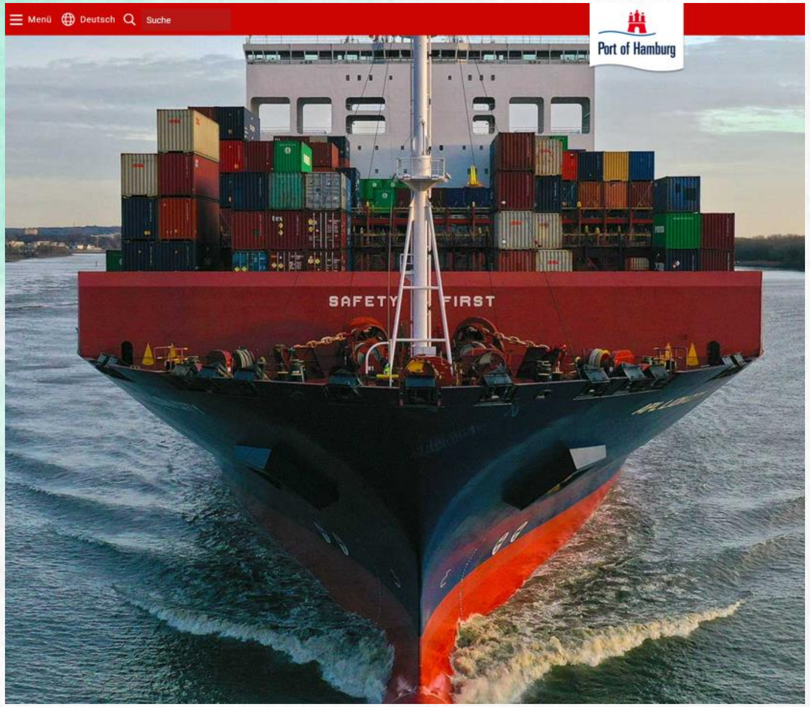
- Wide scientific, notified-body and industrial knowledge basis

Facts / oppotunities:

- Proofed and long term-based knowledge, use know-how from other industries
- Hydrogen technology is sustainable, emission-free, safe, economic use cases possible
- Different hydrogen technologies available (ICE, FC, hybrid), retrofits possible

Strategy outlook:

- Compressed Hydrogen storage and processing can be handled economic, emission-free and relatively safe under defined conditions.
- Skill-up and frequent trainings / audits necessary
- Intensive work with classification societies, use of new digital tools like monitoring etc.



Source: www.hafen-hamburg.de

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Conclusions and take-home message

From the review of hydrogen-related accidents – Lesson learned

As described before, the production, transportation and handling of H2 has been common practice for decades.

But due to the high demand and large volumes, the risks are increasing and handling should therefore be done more sensitively.

Risk assessments, trainings, regulations must therefore be carried out to reduce, limit or, in the best case, eliminate the risks.

Source: www.aria.developpement-durable.gouv.fr

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Conclusions and take-home message

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Module 2: Conclusion and future outlook for hydrogen applications

- Strategic recommendations for ports adopting hydrogen

Guidelines based on the study for an inland port

Activities (approach for an H2 economy in an port)

- Initial identification of potential H2 supply sources, transport routes and infrastructures
- Identify which elements of value creation in a hydrogen economy could be filled or supported by local players:
- Etc.

Please refere in detail to the worksheet (attachement)
Thank you.

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Conclusions and take-home message

Tools for follow-up and consolidation of the information shared

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HyRAM+
Hydrogen Plus Other Alternative Fuels Risk Assessment Models

Hydrogen Plus Other Alternative Fuels Risk Assessment Models (**HyRAM+**) is a **software toolkit** that integrates publicly available data and models relevant to assessing the safety in the use, delivery, and storage infrastructure of hydrogen and other alternative fuels (i.e., methane and propane).

The HyRAM+ risk assessment calculations incorporate probabilities of equipment failures for different components for both compressed gaseous and liquefied fuels, and probabilistic models for the effect of heat flux and overpressure on people.

Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 5.1 Technical Reference Manual
link: [2369637 (osti.gov)]() released / printed December 2023

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Conclusions and take-home message

Tools for follow-up and consolidation of the information shared

Hydrogen Risk Assessment Models Update 2.0 Webinar 01/2020 www.energy.gov/
Video link: (approx. 55Min.) www.youtube.com/watch?v=4NHZCqpwNFQ

This webinar discussed updates to the Hydrogen Risk Assessment Models (HyRAM) software,

A toolkit for assessing key barriers to hydrogen use in multiple applications.

Video courtesy of the Department of Energy DOE

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