Review and Gap Assessment of Bulk Hydrogen Storage

Report from the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) Regulations, Codes, Standards and Safety Working Group (RCSSWG) Bulk Storage Task Force

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Force

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Abstract

Large-scale storage of hydrogen is being considered around the world, and the safety requirements and oversight of those facilities needs to be carefully considered. In May 2022, the Steering Committee of the International Partnership for Hydrogen and Fuel Cells in the Economy approved the launch of a Bulk Storage Task Force under the Regulations, Codes, Standards and Safety Working Group to evaluate issues of common interests to member countries on critical topics. The Bulk Storage Task Force performed a gap assessment for regulations, codes, and standards for large-scale storage of hydrogen in order to identify critical areas for technical research and regulatory changes to enable bulk storage of hydrogen. Bulk hydrogen storage of >10 tonne capacity in aboveground tanks is relatively rare around the world and no bulk hydrogen storage systems of >10 tonne capacity in underground tanks were reported. Geologic or subsurface storage of hydrogen has been deployed in a few locations around the world. Some requirements for bulk storage in tanks have ambiguity with regard to larger-capacity systems. Some jurisdictions address these ambiguities by requiring more of a case-by-case analysis using commonly accepted hazard and risk assessment methodologies. However, these ambiguities need to be resolved to enable broader deployments of large-scale bulk storage systems accross different applications. Common risk assessment methodologies and models may help to inform the basis for these requirements, but it may also be that systems above a certain capacity should not be subject to prescriptive requirements and instead require a more specialized analysis on a case-by-case basis.

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Executive Summary

Large-scale storage of hydrogen is being considered around the world, whether for electrical grid energy storage, refueling for heavy-duty transportation, or industrial use. In May 2022, the Steering Committee of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) approved the launch of two task forces under the Regulations, Codes, Standards and Safety Working Group (RCSSWG) to evaluate issues of common interests to member countries on critical topics. The Bulk Storage Task Force performed a gap assessment for regulations, codes, and standards for large-scale storage of hydrogen to identify critical areas for technical research and regulatory changes to enable bulk storage of hydrogen. Through collaboration, the RCSSWG aims to share information, lessons learned and best practices with a focus on hydrogen safety, as well as the harmonization of codes and standards developed by relevant industry codes and standards development organizations.

Bulk hydrogen storage of >10 tonne capacity in aboveground tanks is relatively rare around the world. While tank storage is common for smaller systems, multiple countries only report a few large-scale aboveground storage tanks, typically liquid hydrogen for aerospace or for import/export applications. Multiple countries seem to have well-established regulations, codes, and standards for aboveground tanks; some regulate hydrogen storage based on pressure level and others by storage quantity. Multiple jurisdictions have additional rules and requirements for storage systems above a certain storage capacity threshold. Storage above these quantities is not prohibited, but does tend to require additional safety analysis, documentation, and monitoring. Some jurisdictions identified potential gaps in requirements for systems with higher capacities, such as ambiguities on additional requirements.

No bulk hydrogen storage systems of >10 tonne capacity in underground tanks were reported in any jurisdiction, although smaller-capacity systems do exist. Multiple jurisdictions reported the same regulations, codes, and standards apply to underground tanks as apply to aboveground tanks, although some have additional requirements. As such, few additional gaps were identified for underground tanks.

Geologic or subsurface storage of hydrogen has few current projects around the world; there are test projects in Europe (Austria, Germany, France, and the Netherlands), a hydrogen salt cavern in the United Kingdom, a hydrogen hard rock cavern in Sweden, and the United States has three hydrogen storage caverns that have been in operation for years and one under construction. Regulations, codes, and standards for geologic storage tend to include similar requirements as tank storage, but also includes requirements related to mining laws and regulations. Gaps were identified, although some jurisdictions mentioned that current requirements were based on natural gas, so would need to be more closely reviewed and potentially revised for hydrogen.

Some requirements for bulk storage in tanks are ambiguous about specific requirements for larger-capacity systems. Some jurisdictions deal with this by requiring more of a case-by-case analysis using commonly accepted hazard and risk assessment methodologies. However, these ambiguities need to be resolved as more large-scale bulk storage systems are considered for a variety applications. Common risk assessment methodologies and models may help to inform the basis for these requirements, but it may also be that systems above a certain capacity should not be subject to prescriptive requirements and instead require a more specialized analysis on a case-by-case basis. Continuous improvement of these approaches is crucial as additional research is performed and more experience is gained.

1 Introduction

1.1 Background

In May 2022, the Steering Committee of the IPHE approved the launch of two task forces under the Regulations, Codes, Standards and Safety Working Group (RCSSWG) to evaluate issues of common interests to member countries on critical topics:

- Maritime Regulations, Codes and Standards (RCS) Gaps and Risk Analysis
- Bulk Storage Risk, Gaps and Deployment Barriers.

The Bulk Storage Task Force aims to perform an RCS gap assessment and identify critical areas for R&D and for RCS changes to enable bulk storage of hydrogen. Through collaboration, the RCSSWG aims to share information, lessons learned and best practices with a focus on hydrogen safety, as well as the harmonization of codes and standards developed by relevant industry codes and standards development organizations.

1.2 Scope

The IPHE RCSSWG Bulk Storage Task Force scope of this report will cover regulations, codes, and standards gap assessment in the following areas:

- Storage Medium: storing hydrogen as a gas or liquid
- Storage Location: underground caverns and porous media, underground tanks or pressure vessels, aboveground tanks or pressure vessels
- Deployment Barriers: challenges and barriers to the bulk storage of hydrogen
- R&D: identify critical areas for further R&D and for RCS changes to enable bulk storage.

2 Tank Storage

Hydrogen can be stored in a compressed or liquefied (cryogenic) form in various types of tanks. These tanks can be located above ground or under some amount of topsoil below ground. Additional quantities of hydrogen can be stored simply by adding more tanks to a system to increase the overall capacity. Commercially available hydrogen tanks are the most common way in which hydrogen is stored currently.

2.1 Aboveground Tanks

Aboveground hydrogen storage tanks are a very common way to store hydrogen, especially in smaller systems. Bulk hydrogen storage of greater than 10 tonnes can be accomplished simply by adding enough tanks to a system. Larger storage tanks have also been constructed, especially for liquid hydrogen storage.

2.1.1 Current Projects

2.1.1.1 Australia

There are no large-scale (>10 tonne) hydrogen storage systems in Australia currently.

2.1.1.2 Canada

Canada is one of the 10 largest producers of hydrogen worldwide, with six active bitumen upgraders[1] and fifteen refineries[2] and hydrogen electrolysis facilities[3,4]. Details of associated storage infrastructure, in terms of size and operating conditions, are not available in the public domain; however, anecdotal examples indicate that these facilities do employ bulk storage. For instance, Air Liquide/Cummins hydrogen production complex with hydrogen production capacity of ~16 tpd, recently expanded through installation of the world's largest PEM electrolyzer (20 MW) in Bécancour, Québec, which includes a large spherical liquid hydrogen tank[3,4]. Chemrock Cryogenics UK, a perlite supplier referenced two facilities with liquid hydrogen vacuum sphere storage vessels in Canada, one in Bécancour and another in Sarnia, Ontario[5].

2.1.1.3 China

At present, large-scale (>10 tonne) hydrogen storage systems in China are relatively rare. The hydrogen storage systems with maximum reserves are liquid hydrogen storage tanks with volume of 300 m^3. They can store 21.3 tonnes of liquid hydrogen, which are used in the Wenchang Satellite Launch Center in Hainan Province. The maximum volume of the vessel storing compressed hydrogen with pressure of 50 MPa and 98 MPa have reached 7.3 m^3 and 3 m^3, respectively. The hydrogen storage mass of the two vessels are approximately 227 kg and 150 kg, and they have been widely used in hydrogen refueling stations.

2.1.1.4 Germany

Large-scale (>5 tonne) hydrogen aboveground storage systems in Germany are very rare. Only liquefied hydrogen (LH2) is stored in such quantities at a few locations. At the DLR site in Lampoldshausen[6] two large cylindrical LH2 tanks, one with 270 m^3, ~18 tonnes, and one with 600 m^3, ~40 tonnes, are in operation and used for testing rocket motors. At the Linde liquefier site in Leuna, Dresden, LH2 has to be buffered. The two liquefiers have a daily production

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[1] Oil Sands Magazine, "Bitumen Upgrading Explained," *Oil Sands Magazine*, 2019, https://www.oilsandsmagazine.com/technical/bitumen-upgrading

[2] Canadian Fuels Association, "Our Industry/ Fuel Production," Canadian Fuels Association, https://www.canadianfuels.ca/our-industry/fuel-production/

[3] Air Liquide, "Air Liquide inaugurates the world's largest low-carbon hydrogen membrane-based production unit in Canada," Air Liquide, 26 01 2021. https://www.airliquide.com/group/press-releases-news/2021-01-26/air-liquide-inaugurates-worlds-largest-low-carbon-hydrogen-membrane-based-production-unit-canada

[4] Air Liquide, "Air Liquide inaugurates the world's largest PEM electrolyzer in Canada," https://www.youtube.com/watch?v=v6mAuRi9pEI

[5] Chemrock Cyrogenics UK, Ltd., "Reference List," https://www.dicalite-europe.com/reference/

[6] Institut für Raumfahrtantriebe https://de.wikipedia.org/wiki/Institut_f%C3%BCr_Raumfahrtantriebe

capacity of about 10 tonnes[7], and the stored inventory is estimated 120 tonnes. These large LH2 storage sites use cylindrical cryostats either mounted horizontally or vertically.

Large-scale gaseous storage systems, so-called gasometers, are installed at a few chemical parks such as Infraserv Frankfurt. Gasometers are operated at pressure marginally above ambient pressure. The hydrogen gasometer at Infraserv, considered the largest for hydrogen, provides free volume of about 10 m^3. Therefore, these gasometers store less than a tonne. Only four aboveground gaseous storage systems for natural gas are still in operation (Wuppertal Möbeck 270.000 m^3, 0.6 MPa; Gaswerk Bamberg, Gasometer Neuffen, Gasometer Salzgitter). Although considerably larger than the installed hydrogen gasometers, a conversion to hydrogen is not foreseen. Today, rather, tube storage systems are being discussed for hydrogen. Those systems would use pipeline elements with a typical inner diameter of 0.5 m operated at maximum pressure of 10 MPa and would require a total tube length of 2,500 m (e.g., 25 tubes with 100 m each). The tubes could be installed in a buried mode or floating on water surfaces. However, there is no actual project applying this concept.

In the Mukran project[8] a large, high pressure spherical storage system will be designed for maritime transport of hydrogen. Detailed specification of the storage system is not published yet.

2.1.1.5 Japan

Liquefied hydrogen tanks of 10 tonnes or more are extremely rare; there may be five locations for such storage in Japan. A typical example is the spherical tank at Japan Aerospace Exploration Agency's Rocket Center in Tanegashima, Kagoshima Prefecture, which has three 540 Nm^3 tanks with a total storage capacity of about 100 tonnes. It has been in operation since 1994.

The largest liquefied hydrogen tank is a spherical tank constructed under the HySTRA project, with a size of 2,500 Nm^3 and a capacity of approximately 150 tonnes. Currently, it is used for the demonstration of liquefied hydrogen supply chain, imported from Australia using a liquefied hydrogen ship.

2.1.1.6 Netherlands

At current there are no large scale (>10 tonne) hydrogen storage vessels in operation in the Netherlands, but development initiatives of (fluid) hydrogen have been announced. The H2Sines.Rdam project emphasizes construction of a large-scale liquefaction plant and export facilities, including liquid hydrogen storage at shipment facilities at the Port of Sines (Portugal) and an import terminal in Rotterdam (Netherlands) by 2027. Other similar projects have started to develop fluid hydrogen supply chain between Abu Dhabi and Amsterdam (Netherlands) and between Bilbao (Spain) and Amsterdam. These developments require large scale fluid hydrogen storage. Moreover, some 10 different projects have been initiated over

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[7] Linde errichtet neuen Wasserstoff-Verflüssiger in Leuna https://www.linde-gaz.pl/en/images/2018-10-24_linde_wasserstoffanlage_leuna_tcm47-503008.pdf

[8] Mukran Port Energy& Hydrogen Business https://www.mukran-port.de/de/industrial-site/energy-hydrogen-business.html

the country for the storage of ammonia in large aboveground storage vessels holding over 5 tonnes of hydrogen.

2.1.1.7 Singapore

There are currently no large-scale (>10 tonne) hydrogen storage systems in Singapore. Most hydrogen is piped from the source of production for immediate consumption at the point of delivery or piped to customers with hydrogen metering stations. Currently, transfer facilities are not considered as large-scale storage due to their transient operations.

Hydrogen trailers carrying 187.5 kg hydrogen are typically used as transient storage instead of bulk storage tanks for activities such as downpacking of hydrogen into hydrogen cylinders in Singapore and are therefore not considered large scale.

2.1.1.8 United Kingdom

There are currently no large-scale (>10 tonne) aboveground tank hydrogen storage systems in the United Kingdom. Some small-scale tank storage is planned in future projects, for example the H100 Fife project, which is a first-of-a-kind demonstration project investigating the potential use of hydrogen in home heating and cooking. As part of the project, hydrogen will be stored in six purpose-built aboveground tanks with enough to potentially heat up to 300 homes[9].

2.1.1.9 United States

Publicly reported large-scale (>10 tonne) hydrogen storage systems in the United States are relatively rare. One prominent example is the storage of liquid hydrogen as rocket fuel in aboveground spherical tanks at the National Aeronautics and Space Administration (NASA). The world's largest liquid hydrogen storage tank is almost complete at the NASA Kennedy Space Center[10]. This sphere has a usable capacity of 4,732 m^3, which equates to roughly 335 tonnes of liquid hydrogen. Additionally, the same site has another tank that was originally constructed in the 1960s; this smaller tank has a usable capacity of 2,918 m^3, or roughly 207 tonnes of liquid hydrogen. Current typical liquid hydrogen installations (e.g., at transfer facilities or fueling stations) and transport trailers are on the order of 1–5 tonnes and are therefore not considered large scale (>10 tonne).

2.1.2 Regulations, Codes, and Standards

2.1.2.1 Australia

In Australia, nationally, any amount of hydrogen storage above 50 tonnes has to be licensed under Major Hazard Facility legislation[11]. This is a Safety Case regime, requiring detailed safety assessment and safety case to be submitted and accepted by the regulator before being able to operate. Hydrogen storage facilities less than 50 tonnes are required to conform to Dangerous Goods Storage and Handling regulations specific to each state and territory in

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[9] https://www.h100fife.co.uk/

[10] A. Swanger, "World's Largest Liquid Hydrogen Tank Nearing Completion," NASA-KSC, March 11, 2022, https://ntrs.nasa.gov/api/citations/20220004276/downloads/Cold%20Facts_LH2%20Sphere%20Update.pdf

[11] https://www.safework.sa.gov.au/workplaces/work-sites-and-facilities/major-hazard-facilities

Australia. Thus, Australia has existing regulatory frameworks to be able to license and regulate bulk storage projects should they arise.

AS 1210 and AS 4343 are the main Australian standards that have application for hydrogen storage vessels, both above and underground. AS 1210 governs the requirements for the material, design, manufacture, testing and inspection certification for operating pressures up to 21 MPa and temperatures within the limits for the various materials and components[12]. Whereas AS4343 specifies criteria for determining the hazard levels of various types of equipment and classifies fluids for use in pressure equipment[13].

Some jurisdictions are also examining the introduction of hydrogen safety-specific legislation. For example, in South Australia the Hydrogen and Renewable Energy Act 2023 was recently passed[14]. This legislation seeks to establish a one-window-to-government approach for all regulation pertaining to hydrogen and renewable energy projects. The specific technical expertise into areas such as hydrogen safety, including bulk storage, will reside in the agency administering this new Act.

2.1.2.2 Canada

While hydrogen storage technology is generally established with codes and standards for compressed gas and liquefied hydrogen from the oil and gas industry applications, the expected increase in hydrogen production and handling brings about new technical and commercial design challenges[15,16].

Some natural gas codes and standards are applied to renewable gases such as hydrogen, including:

- CSA B51 and ASME BPVC setting requirements for boilers, pressure vessels, and pressure piping
- CAN/BNQ 1784-000 setting installation requirements for hydrogen systems
- ASME B31.12 listing requirements for design, construction, operation, and liquid and gaseous hydrogen pipelines maintenance[15], i.e., in addition to ASME B31.3 with requirement for all piping systems[17].

Some gaps pertaining to renewable gas standardization are, in part, being addressed by CEN technical committee 234 (CEN/TC 234), Gas Infrastructure, in a working program designed to provide requirements for the plants to inject renewable gases into natural gas networks[15].

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[12] https://www.standards.org.au/standards-catalogue/standard-details?designation=as-1210-2010

[13] https://store.standards.org.au/product/as-4343-2014

[14] https://www.energymining.sa.gov.au/public-consultations/hydrogen-and-renewable-energy-act

[15] I. Driscoll, R. Facey, K.J. Kowalishen and B. Moore, "Codes and Standards for Renewable Gas Pathways - Current Status and Future Directions," Canadian Standards Association (CSA), Toronto, January 2022

[16] J. Dalziel, A. Davidson, B. Oliver, R. Smith, T. Hussain, M. Khan and I. Monner, "Alternative Fuels and Energy Systems for the Marine Sector," Canadian Standards Association, Ottawa, 2020

[17] Government of Canada, "2030 emissions reduction plan: Canada's next steps to clean air and a strong economy," Environment and Climate Change Canada, Gatineau, 2022

Chapter 13 of NFPA 2 sets requirements for hydrogen generation systems, namely the fundamental safety provisions for hydrogen generation, installation, storage, piping, use, and handling in compressed gas form or cryogenic liquid form[15].

A detailed list of applicable Canadian codes and standards for aboveground hydrogen storage systems and associated infrastructure is provided below. It is important to note that the list delineates the codes that are mandatory through referencing legislation, regulations, or by-laws from those that are not.

Liquid Hydrogen Storage:

- CSA B51:19 Boiler, Pressure Vessel, and Pressure Piping Code (referenced in regulation/legislation)
- CGA H-3 Cryogenic Hydrogen Storage (not referenced in regulation/legislation)
- CGA H-5-2014 Standard for Bulk Hydrogen Supply Systems (referenced in regulation/legislation via another standard)
- CGA P-12-2017 Safe Handling of Cryogenic Liquid (not referenced in regulation/legislation)
- CGA P-28 OSHA Process Safety Management and EPA Risk Management Plan Guidance Document for Bulk Liquid Hydrogen Supply Systems (not referenced in regulation/legislation)
- CGA P-41 Locating Bulk Liquid Storage Systems in Courts (not referenced in regulation/legislation)

Gaseous Hydrogen Storage:

- CSA B51:19 Boiler, Pressure Vessel, and Pressure Piping Code (referenced in regulation/legislation)
- CSA B340 Selection, Use, Handling and Filling of Cylinders, Spheres, Tubes, and Other Containers for The Transportation of Gases in Class 2 (referenced in regulation/legislation)
- CGA H-5-2014 Standard for Bulk Hydrogen Supply Systems (referenced in regulation/legislation via another standard)
- CGA V-9 Standard for Compressed Gas Cylinder Valves (not referenced in regulation/legislation)

Compression Stations and Compressors:

- CSA/ANSI HGV 4.1 Hydrogen-Dispensing Systems (referenced in regulation/legislation via another standard)
- CSA/ANSI HGV 4.2 Hoses for Compressed Hydrogen Fuel Stations, Dispensers and Vehicle Fuel Systems (referenced in regulation/legislation via another standard)
- CSA/ANSI HGV 4.4 Gaseous hydrogen — Fuelling stations — Valves (referenced in regulation/legislation via another standard)
- CSA/ANSI HGV 4.6 Manually Operated Valves for Use in Gaseous Hydrogen Vehicle Fueling Stations (not referenced in regulation/legislation)

- CSA/ANSI HGV 4.7 Automatic Valves for Use in Gaseous Hydrogen Vehicle Fueling Stations (not referenced in regulation/legislation)
- CSA/ANSI HGV 4.8 Hydrogen Gas Vehicle Fueling Station Compressor Guidelines (not referenced in regulation/legislation)
- CSA/ANSI HGV 4.9 Hydrogen Fueling Stations (referenced in regulation/legislation via another standard)
- CSA/ANSI HGV 4.10 Standard for Fittings for Compressed Hydrogen Gas and Hydrogen Rich Gas Mixtures (not referenced in regulation/legislation)
- CAN/BNQ 1784-000 Electrical Systems in Hydrogen Installations (referenced in regulation/legislation)
- CGA H-5-2014 Standard for Bulk Hydrogen Supply Systems (referenced in regulation/legislation via another standard)

Hydrogen Mobile Storage in Gaseous or Liquid Form (and Solid-State Storage):

- CSA/ANSI HGV 2 Compressed Hydrogen Gas Vehicle Fuel Containers (not referenced in regulation/legislation)
- CSA HPRD 1 Thermal Activated Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers (not referenced in regulation/legislation)
- HGV 3.1 Fuel System Components for Compressed Hydrogen Gas Powered Vehicles (not referenced in regulation/legislation)
- CSA HPIT 1: Compressed Hydrogen Powered Industrial Trucks On-Board Fuel Storage and Handling Components (not referenced in regulation/legislation)
- B34 UN Pressure Receptacles and Multiple-Element Gas Containers for the Transport of Dangerous Goods (referenced in regulation/legislation)
- CSA SPE-2.1.3 Best Practices for Defueling, Decommissioning, and Disposal of Compressed Hydrogen Gas Vehicle Fuel Containers (not referenced in regulation/legislation)
- CGA H-5-2014: Standard for Bulk Hydrogen Supply Systems (referenced in regulation/legislation via another standard)
- CSA HGV 5.2 Compact Hydrogen Fueling Systems (not referenced in regulation/legislation)

2.1.2.3 China

Both gaseous and liquid hydrogen storage tanks in China are regulated by the Special Equipment Safety Supervision Bureau (SESSB) of the State Administration for Market Regulation (SAMR) based on the Regulations on Safety Supervision of Special Equipment. This regulation provides for the scope of application of vessels: the highest working pressure greater than or equal to 0.1 MPa (gauge pressure); the product of pressure and volume greater than or equal to 2.5 MPa·L; and the medium for gas, liquefied gas, or the highest working temperature shall not be lower than the standard boiling point of the liquid medium. In addition, TSG 21-2016 Safety Technical Supervision codes for Fixed Pressure Vessels and TSG R0005-2011 Safety Technical Supervision codes for Mobile Pressure Vessels promulgated by the General Administration of Quality Supervision, Inspection and Quarantine (GAQSI, now it was integrated into SAMR) are adopted. The above two codes specify a series of safety requirements for the design, manufacture, installation, repair, operation, inspection, and testing of fixed and mobile pressure vessels in all parts of the process. The standards that relate to hydrogen storage vessels include GB29279-2022 Essential requirements for the safety of hydrogen systems, GB 50177-2005 design codes for hydrogen station and GB 50516-2010 technical codes for hydrogen fueling station, which give the relevant information for the design and installation of hydrogen fueling station.

2.1.2.4 Germany

Large-scale hydrogen storage in Germany is regulated by TRB 610 (and TRB 600) "Aufstellung von Druckbehältern zum Lagern von Gasen"[18]. The European norm, mirrored as German standard DIN EN 13480 and the German regulation Gasdruckleitungsverordnung GasHDrLtgV, actually addresses transfer pipelines but is applicable to storage systems and associated components as well. DIN EN 17533 explicitly addresses hydrogen storage cylinders and tubes. There are guidelines for converting natural gas infrastructure for hydrogen use summarized in DVGW G 409 (M) and DVGW Information GAS Nr. 29 (H2 readiness).

Any storage above 5 tonnes of hydrogen will legally require reporting schemes according to the Federal Immission Control Act "Bundesimmesionsschutzgesetz BImSchG" (Sections 16, 23a, 23b, 23c and 73) and in the Major Accidents Ordinance "Störfallverordnung," which constitute the German implementation of the European Seveso III Directive[19]. Additional regulation for these inventories are set by the Environmental Impact Assessment Act "Umweltverträglichkeitsprüfung (UVPG)" [20] and the Environmental Legal Remedies Act "Umwelt-Rechtsbehelfsgesetzes (UmwRG)"[21]. For storing more than 50 tonnes of hydrogen the BImSchG requires an extended safety report, including special safety planning and management. Further regulation with regard to separation distances and permitting procedures for the complete implementation of the Seveso directive are under preparation.

Further regulatory requirements for the storage systems will be imposed by the German interpretations/implementations of the European ATEX directives 2014/34/EU (product specific)[22] and 1999/92/EG (ATEX 137, operations)[23]. Both are intended to prevent ignition in the frame of explosion protection and require hazard area classification and protective classes of devices installed in these areas.

All the technical RCS referred so far is generally applicable and does not discriminate the thermodynamic state or phase of the stored hydrogen.

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[18] Technische Regeln zur Druckbehälterverordnung Druckbehälter Aufstellung von Druckbehältern zum Lagern von Gasen (TRB 610) https://www.arbeitssicherheit.de/schriften/dokument/05b48a1a-886a-39f8-ace4-b58958e21024.html

[19] Seveso III Directive 2023/18/EU https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32012L0018

[20] Gesetz über die Umweltverträglichkeitsprüfung https://www.gesetze-im-internet.de/uvpg/

[21] https://www.gesetze-im-internet.de/umwrg/

[22] LEITLINIE ZUR ANWENDUNG DER RICHTLINIE 2014/34/EU https://www.bgrci.de/fileadmin/BGRCI/Downloads/DL_Praevention/Explosionsschutzportal/Dokumente/ATEX_2014-34-EU-Guidelines_3rd-Edition_dt_Fassung_2020.pdf

[23] Nicht verbindlicher Leitfaden für bewährte Verfahren im Hinblick auf die Durchführung der Richtlinie 1999/92/EG https://vorschriften.bgn-branchenwissen.de/daten/gv/atex137lf/titel.htm

From a market regulation perspective, the vertical unbundling stipulated in § 28 l of the Energiewirtschaftsgesetz EnWG between the individual stages of the hydrogen value chain is an important requirement for potential operators. According to this, operators of hydrogen networks are, among other things, not permitted to hold ownership of, construct, or operate hydrogen storage facilities. This regulation obviously applies also to any of the following storage variants.

2.1.2.5 Japan

Relevant regulations to liquefied hydrogen storage facilities depends on the intended usage of the hydrogen. If the hydrogen is used for power generation, the Electricity Business Act shall apply. If hydrogen is distributed to consumers through pipelines, the Gas Business Act shall apply. If hydrogen is used for applications other than these, the High-Pressure Gas Safety Act shall apply. For example, JAXA's liquefied hydrogen storage tank and HySTRA's liquefied hydrogen storage tank are subject to the High-Pressure Gas Safety Act.

The design and engineering of storage tanks, pipes, valves, and other components as well as inspections (commission and periodical) and operations are subject to the relevant Act. In addition to such legislations, workers’ safety should be ensured by the Industrial Safety and Health Act.

There is a difference in licensing among regulations. The national government has the authority to issues licenses for the Electricity Business Act and the Gas Business Act, whereas local governments have the authority for the High Pressure Gas Safety Act.

2.1.2.6 Netherlands

The Environment and Planning Act (Omgevingswet 2024) combines and modernizes laws for spatial planning, housing, infrastructure, the environment, nature, and water. It focuses on a healthy physical environment that meets the needs of society. The Environment and Planning Act combined and modernized laws for spatial planning, housing, infrastructure, the environment, nature and water. For instance, the erection of building facilities the Netherlands are executed under this Act but also applicable for hydrogen vessels and all other so called “environmentally harmful activities.”

Furthermore, the Environmental Activities Decree of the Netherlands (Besluit Activiteiten Leefomgeving) concerns rules about activities in the physical living environment. Another decree is concerning rules about structures in the physical living environment (Besluit Bouwwerken leefomgeving).

The Seveso III Directive for control of major-accident hazards involving dangerous substances (European Directive 2012/18/EU) is aimed at controlling major chemical accident hazards by preventing such incidents and minimizing their risks. As all EU countries are obliged to adopt measures at national and company level to prevent major accidents and to ensure appropriate preparedness and response should such accidents nevertheless happen, it is also implemented in Dutch national legislation and is enforced by national chemical safety authorities.

The Occupational Health and Safety Act for control of major-accident hazards involving dangerous substances is aimed at raising awareness by preventing incidents and minimizing their risks. It requires that employees know what the risks are of the hazardous substances present and that they know how to work healthily and safely (so called ARIE-regeling). The aim is to prevent major accidents involving certain hazardous substances.

In addition, Dutch and European norms and guidelines are applicable. For pressure vessels, pipelines and installations with allowable pressure above 0.5 bar the European guideline for pressure equipment PED (2014/68/EU) is applicable, as described in the Dutch “Warenwetregeling drukapparatuur.” The referred European norms, however, have not been specifically written for hydrogen storage; calculation guidelines for strength and cyclic load changes might require additional calculation.

Furthermore, the PGS Directive (Publicatiereeks Gevaarlijke Stoffen) provides guidelines related to activities in which hazardous substances are used. This directive describes most important risks of these activities for environmental safety, fire safety and employee safety, possible consequences, the relationship with legislation, and possibilities to manage the risks and limit the negative effects on people and the environment. PGS guidelines are applied in the Netherlands and are intended for a broad group of users. These guidelines are determined in mutual consultation between the business community and the authorities. Recently several PGS guidelines for ammonia have been introduced. At current, only hydrogen storage systems related to transport (filling installations) are covered (PGS 35) but it does not cover large-scale (>10 tonne) storage systems.

EIGA (European Industrial Gases Association) provides best practice guidelines for design and operation and include pressurized hydrogen vessels. EIGA is a safety and technically oriented organization representing the vast majority of European and also non-European companies producing and distributing industrial, medical, and food gases. The member companies closely cooperate in technical and safety matters to achieve the highest level of safety and environmental care in the handling of gases. EIGA is in frequent touch with Standardization and Regulatory Organizations and Authorities as well as trade and industrial organizations.

2.1.2.7 Singapore

In Singapore, facilities with hydrogen inventories exceeding 25 tonnes are classified as Major Hazard Installations (MHIs). MHIs are required to comply with environmental, health and safety requirements under the Environmental Protection and Management Act (EPMA), Workplace Health and Safety Act (WSHA), and Fire Safety Act (FSA) administered by the National Environmental Agency (NEA), Ministry of Manpower (MOM), and Singapore Civil Defence Force (SCDF).

The main requirements stipulated under these Acts include:

- Licensing of storage tanks with professional engineer’s endorsement on design and inspection and maintenance regime of tanks
- Licensing as an MHI and subjected to Safety Case Regime
- Quantitative Risk Assessment (QRA) for occupied building and offsite risks
- Spacing and layout of open plant processing facilities for onsite separation distance between equipment
- Process Hazard Analysis (PHA)

- Fire Protection systems under requirements from Singapore's Fire Code and U.S. National Fire Protection Association (NFPA)
- Emergency Response Plan (ERP).

Additionally, if the facility is operating as a town gas operator, it will be subjected to a Safety Case Regime under the Gas Safety Act administered by Energy Market Authority (EMA). Under the Safety Case Regime, MHIs are required to demonstrate to regulators how risks from Safety Critical Events (SCEs) are being reduced to as low as reasonably practicable (ALARP). MHIs are required to state which code they are referencing with respect to key equipment and to demonstrate the basis of safety and design. Where codes are not referenced, authorities would refer to established international codes and standards and request MHI to demonstrate compliance to them or perform engineering studies to prove that the risk was well mitigated.

Examples of these standards for hydrogen include:

- Singapore Standard (SS) 634 2018 code of practice for fire safety for open plant processing facilities in oil, chemical, and process industries
- SS512, code of practice for the design, construction, and operation of pipeline service corridor
- SS634 fire safety for open plant processing facilities in oil chemical and process industries
- NFPA 2 hydrogen technologies code
- NFPA 55 compressed gases and cryogenic fluid code
- European Industrial Gas Association (EIGA) 15/21 Gaseous Hydrogen Installation
- Fire code for package storage in warehouse.

Offsite setback distances and occupied building locations are determined from QRA results. They are required to fall within criteria thresholds which are made up of sensitive receptors, boundaries, and land types. The risk thresholds are shown in **Table 1**.

Table 1: Risk Thresholds for Offsite Setbacks of Hydrogen Storage Tanks

Type	Individual Risk	Criteria
IR (Fatality)	5×10^{-5}/yr	Confined within boundary
IR (Fatality)	5×10^{-6}/yr	Confined to industrial developments only
IR (Injury)	3×10^{-7}/yr	Confined to industrial and commercial developments and shall not reach sensitive receptors
Cumulative Escalation	1×10^{-4}/yr	Confined within boundary
IR (Fatality) for on-site occupied buildings	1×10^{-3}/yr	Shall not exceed

2.1.2.8 United Kingdom

The provisions of the Planning (Hazardous Substances) Regulations 2015 (equivalent versions in Wales/Scotland/Northern Ireland) require site operators who wish to bring or generate hazardous substances over a certain threshold (2 tonnes for hydrogen) on site to obtain consent from the Hazardous Substance Authority (HSA) which is often the local authority. The Health and Safety Executive (HSE) is a statutory consultee to the Hazardous Substance

Consent (HSC) process in Great Britain. HSE undertakes the public safety risk assessment, which helps to maintain public safety assurance in the land use planning system and is central to the public acceptance of sites storing large quantities of dangerous substances. The assessment is a complex process and involves assessing the compatibility of the proposal to store quantities of hazardous substances in specific locations against the risks to the offsite population. HSE provide the outcomes from this assessment to the HSA to inform their decision making.

The HSC process enables land use planning zones to be established which place an obligation on the local authority to consult HSE should development, such as housing, be proposed in the zones. This then allows HSE the opportunity to raise concerns where they may exist. Any amendments to the consent, e.g., changes in type of substances or quantities, may require a further application for HSC, on which the HSA would seek the views of relevant statutory consultees, including HSE.

In Great Britain the large-scale onshore storage of hydrogen (above and below ground) is regulated through the provisions of the Control of Major Accident Hazard Regulations 2015 (COMAH)[24], which apply to sites storing above 5 tonnes of hydrogen (lower tier) or above 50 tonnes (upper tier). Similar requirements apply in Northern Ireland. COMAH is a major hazards regime that aims to prevent major accidents involving dangerous substances and limit the consequences to people and the environment of any accidents which do occur. It relies on duty holders taking all measures necessary to prevent major accidents.

A new establishment is required to notify the Competent Authority at pre-construction and pre-operation stages. The Competent Authority is made up of the HSE, or the Office for Nuclear Regulation for nuclear licensed sites, working with the relevant environmental agency, Environment Agency in England, Scottish Environment Protection Agency (SEPA) in Scotland, or Natural Resources Wales (NRW) in Wales. All operators are required to produce a major accident prevention policy document and upper tier sites are required to produce a COMAH safety report and provide the Competent Authority with updates/revisions to the report following any significant modification or, if necessary, after the 5-year review of the safety report. COMAH also sets out requirements for emergency planning.

2.1.2.9 United States

Large-scale hydrogen storage in the United States is regulated at the federal level by the U.S. Department of Labor Occupational Safety and Health Administration (OSHA) through 29 CFR 1910.103[25]. This regulation applies to gaseous hydrogen systems with a total content of more than 400 cubic feet (approximately 1 kg at atmospheric pressure[26]) or liquid hydrogen systems of more than 150 L (ca 11 kg) but does not apply to hydrogen manufacturing plants or supplier distribution facilities. At the local level, a hydrogen storage system is regulated by the local building, fire, and mechanical codes that have been adopted

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[24] https://www.hse.gov.uk/comah/

[25] https://www.ecfr.gov/current/title-29/subtitle-B/chapter-XVII/part-1910/subpart-H/section-1910.103

[26] https://www.ecfr.gov/current/title-43/subtitle-B/chapter-II/subchapter-C/part-3170/subpart-3175#p-3175.10(a)(Standard%20cubic%20foot%20(scf))

in the local jurisdiction. While not universal, the National Fire Protection Association Hydrogen Technologies Code (NFPA 2)[27] is commonly used. This code contains design, installation, and operational requirements for the safety of hydrogen systems. It also points to other codes and standards, including the ASME Boiler and Pressure Vessel Code for the design, fabrication, testing, and marking of gaseous or liquid hydrogen tanks. NFPA 2 also specifies that piping for these systems must follow ASME B31.12: Hydrogen Piping and Pipelines.

2.1.3 Potential Gaps

2.1.3.1 Australia

Australia recognizes the need for consistent application of safety standards for hydrogen storage across all jurisdictions. To this end, in late 2022, all Australian governments completed a coordinated review of legislation regulating the hydrogen supply chain. This review identified a number of regulatory barriers impeding the development of the hydrogen industry. These included:

- Lack of transparency over what regulation applies to hydrogen projects
- Uncertainty on how to meet regulatory obligations
- Inconsistent regulation of hydrogen projects between different states and territories.

2.1.3.2 Canada

With the emergence of hydrogen economies, cryogenic liquid storage is expected to be more prevalent. NFPA 2 sets an upper maximum of 283,907 L for stationary liquid hydrogen storage[15]. This, combined with the growth in demand for large aboveground storage, suggests codes and standards need to be developed or updated to support the deployment of larger liquid hydrogen storage systems[15].

Additionally, concerns are present about durability associated with long exposure to contaminants and their types and nature, such as those from hydrogen derived from conversion of biogas/renewable gas[15]. A CSA study notes the need for research and development on physical renewable gas diffusion mechanisms involving gas build up and combustion in enclosed spaces; flammable cloud formation; ignition; deflagration-detonation transition; and renewable gas flashing, pooling, and vaporization. Safe and effective operation of renewable gas technologies through testing of components and systems under operational and environmental conditions replicating real-world use needs to be validated[17].

CSA is promoting hydrogen standards by reference in relevant codes such as the Canadian Hydrogen Installation Code (CHIC) for smaller scale applications in addition to the Hydrogen Technologies Code (NFPA 2)[28]. However, its exceptions and limitations in scope may preclude its applicability to many bulk hydrogen storage applications (e.g., industrial facilities where

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[27] NFPA 2, “Hydrogen Technologies Code” National Fire Protection Association, 2020 Edition.

[28] Canadian Standards Association, "An overview of CSA Group standards, codes, and activities for the hydrogen ecosystem," https://www.csagroup.org/article/an-overview-of-csa-group-standards-codes-and-activities-for-the-hydrogen-ecosystem/

hydrogen is produced, handled, and stored for off-site end use)[29]. ISO/TC 197 is currently developing ISO/AWI 19884 standard to provide guidance on hydrogen stationary storage, specifically cylinders and tubes, however the details are not publicly available to confirm if it meets the threshold for bulk storage[15].

2.1.3.3 China

The GB 50177-2005 specifies fire separation distance to compressed hydrogen storage vessels, buildings, and lines. The fire separation distance is determined according to the standard hydrogen storage capacity, but gaseous hydrogen storage vessels with a storage capacity larger than 500,000 Nm^3 are not mentioned. At present, the standard GB 50177 is being revised, and the fire separation distance for liquid hydrogen storage vessels will be added in the standard, which is determined by the mass of liquid hydrogen. However, the liquid hydrogen vessels with a storage mass larger than 20,109 kg are not mentioned. The degree of danger of a hydrogen storage vessel is related to the capacity of hydrogen storage, the larger the capacity the greater the fire separation distance. The requirements for fire separation distance for hydrogen storage vessels over 500,000 Nm^3 and 20,109 kg need additional research.

2.1.3.4 Germany

Specific setback distances are missing, but this gap is expected to be closed by the complete implementation of Seveso III in Germany. Currently, and as long there is not a larger number of corresponding projects, there seem to be no relevant gaps for storing large inventories above ground. Obviously the described, largely generic, RCS framework offers sufficient guidance and flexibility on the other hand.

2.1.3.5 Japan

The government has several governing legislations, such as Electricity Business Act, Gas Business Act, High Pressure Gas Safety Act, and Fire Service Act, which have inconsistency on designing, engineering, and inspections. With increasing number of installations, such inconsistency may become critical.

For liquefied hydrogen, the safety distance is defined by the High Pressure Gas Safety Act, which refers to flammable gas such as LNG, so the safety distance should be modified in accordance with the behaviors of liquefied hydrogen. This is currently under discussion in Japan.

Especially in Japan, large volume storages, including hydrogen tanks, should have water sprinklers and dikes, which are usually not mandatory outside Japan. Also, listed (approved) materials for high pressure devices are limited, compared to the North America and Europe.

Like LNG, liquefied hydrogen can be stored in FSRU (floating storage and regasification unit) in the future. So, RCS is also needed for FSRU for hydrogen.

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[29] Bureau de normalisation du Québec, "CAN/BNQ 1784-000/2022 Canadian Hydrogen Installation Code," Bureau de normalisation du Quebec, Québec, 2022

2.1.3.6 Netherlands

Above referred guidelines and norms are not (necessary) specifically written for hydrogen storage; calculation guidelines for strength and cyclic load changes might require additional calculation.

Furthermore, H_2 is considered as a “chemical component” within aforementioned regulations based on chemical processing activities. Whereas natural gas (i.e., CH_4) does also have a status as “energy carrier” and is treated as such.

2.1.3.7 Singapore

Singapore does not yet have hydrogen specific codes and standards or regulations for the bulk storage of the chemicals. The general requirements based on flammables and chemicals are applicable. Current regulations have yet to take into consideration the new applications in which Singapore is interested in using the chemicals, e.g., power generation plants and bunkering.

The QRA requirements for pipelines and vehicular transportation differ from bulk storage. Singapore refers to NFPA 55, Section 10.1, 10.2, 10.3, 10.4, 11.1, 11.2, 11.3, 11.4 for the hydrogen storage setback distance related requirements. For compressed gas storage of hydrogen, it would be limited by the constraints when the maximum pipe size and pipe pressures were exceeded. For liquified hydrogen, it will be limited by the constraints when total bulk liquified hydrogen storage inventory limits were exceeded under the code.

2.1.3.8 United Kingdom

HSE is also working to assess the current health and safety regulatory framework relevant to the gas network and has undertaken a call for evidence to gather views from stakeholders on the suitability of the current regulatory regime. Only regulations made under Health and Safety at Work Act 1974, etc., were within scope of the call for evidence with the focus on regulations that may be relevant to the safe distribution, storage, and use of 100% hydrogen gas in domestic, industrial, and commercial premises.

2.1.3.9 United States

Current OSHA regulations specify setback distances to various exposures based on the storage capacity of the system; for gaseous hydrogen storage systems, the same setback distances apply for all systems with greater than 15,000 standard cubic feet capacity (approximately 38 kg). This implies that a storage system with 40 kg and a storage system with 400,000 kg of gaseous hydrogen would have the same setback distances. This may not be appropriate, as larger systems can lead to worse consequences due to longer leak durations or cascade failures. By contrast, the current setback distances in NFPA 2 are based on pipe diameter and system pressure, rather than system storage capacity. While this relates the hazard and risk of a leak more directly to parameters that affect leak size and rate, it also implies that storage capacity does not impact the risk of a leak. This should be examined more closely; it may be that systems above a certain storage capacity need additional requirements.

For aboveground liquid hydrogen storage tanks, current OSHA regulations and NFPA 2 setback distances are based on system capacity. However, there is ambiguity in both sets of requirements due to the fact that the setback distances are only given for systems up to a certain capacity (30,000 gallons [approximately 8,000 kg] for OSHA, 75,000 gallons [approximately 20,000 kg] for NFPA 2). While there is no prohibition on systems above this capacity, existing requirements do not clearly define how to determine setback distances. Recent revisions to NFPA 2 relate liquid hydrogen setback distances to system pressure and pipe size (analogous to gaseous hydrogen requirements) but still only apply to systems below 75,000 gallons (approximately 20,000 kg). These requirements need to be clarified for larger system capacities.

2.2 Underground Tanks

Hydrogen can also be stored in tanks underground, typically in an underground vault/room or buried under topsoil. Because these tanks are not out in the open air, they can potentially be subject to different requirements.

2.2.1 Current Projects

2.2.1.1 Australia

There are no current large-scale underground tank storage projects in Australia.

2.2.1.2 Canada

No project was identified in Canada involving underground storage tank installations for hydrogen in the public domain.

2.2.1.3 Germany

Linde proposed underground LH2 storage for LH2 based hydrogen refueling stations. This concept, inherited from conventional fuel storage at refueling stations, would drastically reduce the spatial requirements and would provide advantages with regard to passive protection of the tank, inerting, etc. Hazard areas might be limited and spreading of accidentally released hydrogen is obviously limited. However, there are currently no projects for underground tank storage identified, and even if this concept would be further pursued, the locally stored inventory would stay very likely below 5 tonnes to avoid reporting requirement rooted in the BImSchG (see above).

2.2.1.4 Netherlands

No large-scale underground storage vessel projects in the Netherlands are announced.

2.2.1.5 Singapore

There are no large-scale underground hydrogen tank storage projects in Singapore today.

2.2.1.6 United Kingdom

There are no currently large-scale underground tank storage projects in the UK.

2.2.1.7 United States

There are no current large-scale underground tank storage projects in the United States.

2.2.2 Regulations, Codes, and Standards

2.2.2.1 Australia

Underground tanks in Australia are regulated similarly to aboveground tanks (see Section 2.1.2.1).

2.2.2.2 Canada

Below-grade storage of gaseous hydrogen is noted in the CHIC, which suggests it should be enclosed in vaults constructed in accordance with document UL 2245 (Standard for Below-Grade Vaults for Flammable Liquid Storage Tanks). However, CHIC's exceptions and limitations in scope may preclude its applicability to many bulk hydrogen storage applications[29].

The Storage Tank Systems for Petroleum Products and Allied Petroleum Products Regulations, under the Canadian Environmental Protection Act 1999 (CEPA), has established requirements for storage tank systems under federal jurisdiction. Some of these requirements are found in the Environmental Code of Practice for Aboveground and Underground Storage Tank Systems Containing Petroleum and Allied Petroleum Products. Based on these regulations, an underground storage tank shall be designed, built, and approved in conformance with the following (refer to original source for amendments and updates)[30]:

- CAN/ULC-S603-1992 Underground Steel Tanks
- ULC-S615-1998 Underground Reinforced Plastic Tanks
- ORD-C58.10-1992 Underground Jacketed Steel Tanks
- ULC-S652-1993 Tank Assemblies for Collection of Used Oil
- CAN/ULC-S603.1-1992 Galvanic Corrosion Protection Systems for Underground Steel Tanks.

While the code is likely applicable to liquid organic hydrogen carriers, its applicability to hydrogen and ammonia is unclear, as they are not explicitly referenced. For the code to apply to underground hydrogen and ammonia tank storage, its scope should include adaptations in design standards needed for these gases.

2.2.2.3 Germany

In principle identical to the framework described for Aboveground Tank Storage.

2.2.2.4 Singapore

The current regulations in Singapore do not discriminate the type of storage (aboveground, underground, or geologic), but are based on the chemical inventory at the site. Therefore,

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[30] Government of Canada, "Environmental Code of Practice for Aboveground and Underground Storage Tank System containing Petroleum and Allied Petroleum Products," Environment and Climate Change Canada, Gatineau, 2003

underground tank storage with hydrogen inventories exceeding 25 tonnes would be classified as MHIs and be subjected to the same regulations as mentioned earlier.

2.2.2.5 United Kingdom

Regulations, codes, and standards would be the same as for aboveground tanks; see previous wording on the COMAH regulations in Section 2.1.2.8.

2.2.2.6 United States

Current OSHA regulations do not mention underground tank storage; it is not prohibited, but also not specifically covered. NFPA 2 does contain requirements for buried storage tanks for both gaseous and liquid hydrogen, as well as requirements for gaseous hydrogen storage tanks in an underground vault. These requirements include parameters such as tank spacing and location as well as securement and depth/cover of earth.

2.2.3 Potential Gaps

2.2.3.1 Australia

Underground tanks in Australia are regulated similarly to aboveground tanks (see Section 2.1.3.1).

2.2.3.2 Canada

Codes and standards pertaining to underground tank storage of hydrogen and its carriers do not appear to be available explicitly; however, their low prevalence and lesser popularity relative to their aboveground counterparts does not appear to call for urgent action.

2.2.3.3 Germany

Currently no gaps are identified.

2.2.3.4 Singapore

Underground tanks are subjected to the same Safety Case Regime as aboveground tanks. Gaps identified would be the same as aboveground storage.

2.2.3.5 United Kingdom

Gaps identified would be the same as aboveground tank storage.

2.2.3.6 United States

Current federal regulations do not mention underground tank storage at all; it is not prohibited, but also unclear how some of the requirements in the regulations (such as nonflammable foundations and supports) would apply. The NFPA 2 code, by contrast, does contain prescriptive requirements for underground tanks. However, none of the requirements specify any sort of separation distance or other leak mitigations should an underground tank leak. This may be especially relevant for bulk storage systems, which could have many more (or larger) tanks than smaller retail systems. More information on hydrogen permeation and dispersion in topsoil could better inform how these systems should be treated and what safety measures may be needed for large-scale underground tank storage.

3 Subsurface Storage

Gaseous hydrogen can be stored underground in salt caverns or other geologic formations like depleted oil/gas fields or aquifers. While the pressure of this storage is typically much less than tank storage, and liquid hydrogen is too cold to store in this way, the potentially huge storage volumes can offer a very large hydrogen storage capacity. This storage capacity makes these types of sites attractive for large-scale deployments that are located near favorable geologic features.

3.1 Current Projects

3.1.1 Australia

No such projects are currently operating in Australia but there are several initiatives to develop hydrogen storage salt caverns[31].

3.1.2 Canada

There are no commercial underground hydrogen storage facilities in Canada noted in the public domain. However, Canada is home to some of the largest geological storage sites, such as salt caves and depleted wells. Salt caves and aquifer storage are among the most cost-effective solutions for bulk compressed gas hydrogen storage[32, 33]. Extensive potential for hydrogen storage exists in underground caves in the Western Canadian Sedimentary Basin and southern Ontario[33]. Alberta has the largest capacity available in Canada to store hydrocarbons underground. Existing salt cavern storage facilities include ATCO Energy Solution's Strathcona Salt Cavern Storage Project with the potential to hold up to 400,000 m^3 of hydrocarbons with its four storage caverns[32,34]. Keyera also operates several underground salt cavern storage facilities with capacities of ~12 million barrels for natural gas liquids[32].

3.1.3 China

At present, underground gas storage wells are being researched to be used for hydrogen storage in China. The vessel has previously been used to store compressed natural gas. However, underground hydrogen storage wells still face many technical problems and have not been applied on a large scale.

3.1.4 Germany

At present no commercial operated hydrogen storage facility is operated in Germany, but several pilot projects have been initiated. These national or European sponsored projects (e.g.,

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[31] https://ecossaus.com/

[32] Alberta Ministry of Energy, "Alberta Hydrogen Roadmap," Govnerment of Alberta, Edmonton, 2021

[33] B. Ghorbani, S. Zendehboudi, N. M. C. Saady and M. B. Dusseault, "Hydrogen storage in North America: Status, prospects, and challenges," *Journal of Environmental Chemical Engineering,* vol. 11, no. 3, p. 109957, 2023

[34] ATCO, "Energy Infrastructure - Energy Storage," https://www.atco.com/en-ca/business/energy-infrastructure/energy-storage.html

H2STORE, HYINTEGER, H2VL, H2_ReacT, SUBI, SAMUH2, H2CAST)[35] have proven salt caverns to be suitable, safe storages also for hydrogen.

Since the energy crisis in the 1970s, German law requires storage of natural gas to satisfy an average three months of national demand. So, a natural gas storage capacity of ~24 billion m³ (260 TWh) has been realized via 16 porous rock storage facilities and 31 salt cavern storage facilities[36, 37, 38]. Because of the massive presence of salt structures in the northern part of Germany, cavern storage has prevailed as the technical solution as the north part of Germany alone provides 40% of all European potential for salt caverns.

The technical readiness level of pore storages like aquifers or depleted natural gas fields is lower and requires further research, so is not currently considered ready for commercial use, though one pilot project was started in south Germany[39]. With a projected yearly hydrogen demand in Germany of 250–500 TWh/a in 2050 and assuming a 10–25% seasonal storage demand, retrofitting salt caverns is technically mature and the most economical solution[40].

In the HyCAVmobil project[41], DLR is researching how hydrogen can be stored safely and sustainably in salt caverns. With a free volume of 500 m^3, the cavern will store up to 6 tonnes. The H2CAST Etzel project[42] is intended to demonstrate the feasibility of large-volume underground storage of hydrogen and to prove the suitability of the salt caverns in Etzel for hydrogen storage. Operational hydrogen storage will be tested and serve to build a hydrogen service industry. H2CAST stands for H2 CAvern Storage Transition, i.e., the conversion of existing caverns and facilities in Etzel for the future necessary storage of hydrogen as a building block for a future energy system. A large storage facility for green hydrogen is being created in the Bad Lauchstädt Energy Park, Saxony-Anhalt[43]. The cavern, which forms part of a combined system of caves and warehouse storage belonging to VNG Gasspeicher GmbH (VGS), has a capacity of around 50 million cubic meters and will hold up to 4,500 tonnes of hydrogen. The project is based on preliminary work carried out as part of several research projects under the umbrella of the HYPOS consortium, Hydrogen Power Storage and Solutions East Germany. In addition, UNIPER is planning a pilot salt cavern storage with 250.000 m^3 free volume in Krummhörn and is testing a pore storage in Bierwang for its hydrogen readiness.

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[35] https://www.fvee.de/wp-content/uploads/2022/07/th2021_05_01.pdf

[36] Untertägige Speicherung von Wasserstoff – Status quo, Matthias Warnecke & Simone Röhling, Z. Dt. Ges. Geowiss. *J. Appl. Reg. Geol.*, September 2021

[37] https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/2022/2021-10-29_NWR-Grundlagenpapier_Wasserstoffspeicher.pdf

[38] Factsheet: Wasserstoffkavernenspeicher https://www.energy4climate.nrw/fileadmin/Service/Publikationen/industrie-und-produktion/factsheet-kavernenspeicher-cr-energy4climate.pdf

[39] https://www.uniper.energy/hystorage

[40] WASSERSTOFF SPEICHERN – SOVIEL IST SICHER Transformationspfade für Gasspeicher https://www.bveg.de/wp-content/uploads/2022/06/20220610_DBI-Studie_Wasserstoff-speichern-soviel-ist-sicher_Transformationspfade-fuer-Gasspeicher.pdf

[41] HyCavMobil https://www.ewe.com/en/shaping-the-future/hydrogen

[42] H2CAST https://h2cast.com/project

[43] https://www.hypos-eastgermany.de/blog/single/news_weltneuheit-energiespeicherung-von-wasserstoff-in-kavernen/

3.1.5 Netherlands

In the Netherlands, no underground hydrogen storage is in operation, yet. In 2022 a hydrogen storage demonstration project (A8 Demonstration project) was finished, which proved feasibility and safe hydrogen storage operation in a cavern. By 2028, the HyStock project expects to start commercial operation of a 6,000 tonne hydrogen storage cavern (1,000,000 m^3), followed by three additional caverns (each 1,000,000 m^3) with a total of 24,000 tonnes hydrogen stored by 2032. In the immediate vicinity, compressed natural gas storage caverns are operated by EnergyStock.

3.1.6 Singapore

There is no current geologic storage for hydrogen. Presently, there is only one man-made geologic storage in Singapore which is presently used for the storage of liquid hydrocarbons such as crude oil and condensate.

3.1.7 United Kingdom

In the UK, there is one example of underground geological storage of hydrogen. This is a relatively small-scale salt cavern facility that has been operating in Teesside since the 1970s, serving nearby chemical plants. There are also some salt cavern proposals in development for storage in the UK. These include the HyNET, SSE Aldbrough, and Portland Energy Hub projects. A short summary of these projects is provided below

- HyKeuper[44]: Keuper Gas Storage Limited (KGSL), a wholly owned subsidiary of INOVYN, is planning to develop a new underground hydrogen storage facility and associated development at the southern end of the Holford Brinefield and surrounding area, to the north of Middlewich in Cheshire.

- SSE Aldbrough[45]: SSE Thermal is developing a first-of-a-kind project in the Humber that would unite hydrogen production, storage, and power generation in one location by the middle of this decade.

- Portland Energy Hub[46]: UK Energy Storage (UKEn), a subsidiary of UK Oil & Gas (UKOG), has proposed to build a salt cavern hydrogen site beneath the Isle of Portland, Dorset. The site is planned to consist of 19 caverns, with 15 onshore and 4 offshore, giving a total capacity of ~1 billion m^3.

In addition to the planned salt cavern projects, Centrica Storage Limited is undertaking a feasibility study into repurposing the Rough gas field, located in the Southern North Sea, from natural gas to hydrogen storage. If the proposal goes ahead, Rough could provide a hydrogen storage capacity of over 9 TWh, which would make it by far the world's largest hydrogen storage site.

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[44] https://www.kgsp.co.uk/

[45] https://www.ssethermal.com/flexible-generation/development/aldbrough-hydrogen-pathfinder

[46] https://www.ukogplc.com/index.php

Further information on UK hydrogen storage projects is also available in the Analytical Annex of the November 2022 Transport and Storage consultation[47].

3.1.8 United States

Gaseous hydrogen has been stored in underground caverns for several decades, with usable capacities on the order of 2,500 tonnes[47]. This includes the ChevronPhillips Clemens Terminal, which has been operating since 1986 in the state of Texas. There is also a similar cavern built by Praxair (now Linde), which has been operating in Texas since 2007[48]. Finally, Air Liquide opened a much larger geologic storage facility in 2017 in Beaumont, Texas[49]. Additionally, the Advanced Clean Energy Storage (ACES) hub under construction near Delta, Utah, is estimated to be able to store up to 11,000 tonnes of hydrogen in two caverns (5,500 tonne working capacity each)[50].

3.2 Regulations, Codes, and Standards

3.2.1 Australia

No such projects are currently operating in Australia. However, in some states, legislation already exists to license and regulate geological storage should such projects be proposed. For example, in South Australia amendments to the Petroleum Act have been recently passed to allow for licensing and regulating for hydrogen geological storage and withdrawal[51]. This new provision has also been extended to other regulated substances such as methane, should such a need arise.

3.2.2 Canada

Two specific codes that are under development in Canada pertaining to underground hydrogen storage are the CSA Z341 Supplement Document for geological storage and CSA Z625 Amendment Document for well design.

3.2.3 China

Gas storage wells are regulated as special equipment by SESSB. The relevant standards are SY/T 6535-2002, underground storage well for high-compression gas, and SH/T 3216-2020, technical specification for gas storage well engineering. SY/T 6535-2002 applies to compressed natural gas storage wells with a nominal pressure of 25 MPa and a nominal

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[47] W. Leighty, “Running the world on renewables: Hydrogen transmission pipelines and firming geologic storage,” *International Journal of Energy Research* 32(5), pp. 408-426, March 2008. https://doi.org/10.1002/er.1373

[48] “Praxair Commercializes Industry’s Only Hydrogen Storage” https://investors.linde.com/archive/praxair/news/2007/praxair-commercializes-industrys-only-hydrogen-storage

[49] “USA: Air Liquide operates the world’s largest hydrogen storage facility” https://www.airliquide.com/group/press-releases-news/2017-01-03/usa-air-liquide-operates-worlds-largest-hydrogen-storage-facility

[50] Advanced Clean Energy Storage Hub, https://aces-delta.com/hubs/

[51] https://www.legislation.sa.gov.au/lz?path=/v/p/2023/petroleum%20and%20geothermal%20energy%20(energy%20resources)%20amendment%20act%20(commencement)%20proclamation%202023_14.12.2023%20p%2041344

volume of 1–10 m^3. SH/T 3216-2020 applies to gas storage wells with a design pressure of not more than 50 MPa and a nominal volume of not more than 60 m^3.

3.2.4 Germany

Underground storage facilities are mining operations, and therefore follow the Federal Mining Act (see § 2 Abs. 2 S. 1 Nr. 2 Bundesberggesetz BBergG)[52]. The legal definition of an underground storage facility states there is "a facility for the underground tankless storage of gases, liquids, and solids other than water" (see § 4 Abs. 9 BBergG). According to § 51 Abs. 1 i. V. m. § 126 Abs. 1 S. 1 BbergG, construction and management of underground storage facilities are allowed only on the basis of operating plans that have been approved by the competent authority ("Operating plan obligation," "Betriebsplanpflicht" in German). Additional regulation imposed by the BBergG are prerequisites for licensing "Zulassungsvorraussetzungen" (authorization for exploration or extraction; reliability, expertise and physical fitness of the operator; precautions against dangers to life, health and for the protection of property, employees and third parties; no impairment of mineral resources; protection of the surface; waste disposal; protection of other operations), mining regulations for building the storage (drilling, general safety, exploration, surveying and recording of ground movements), and further requirements.

Again, all requirements introduced above for AboveGround Storage (BImSchG, UVG,etc.) apply also for the geological storages.

3.2.5 Netherlands

Underground storage facilities are mining operations and therefore follow the Mijnbouwwet (Federal Mining Act) and The Environment and Planning Act (Omgevingswet 2024).

There is no specific Act that covers transport of hydrogen, hence temporary guidelines have been issued by the Authorities that also cover pilot projects. Furthermore, codes and standards based on decades of operations in the oil and gas industry are applied in hydrogen storage where applicable and adapted when necessary.

The current Gas Act (dated 2000) regulates the transport of natural gas, but there is no legislation for hydrogen. The Gas Act contains rules in the field of transport and supply of natural gas within the Netherlands and also implements European regulations. The Energy Chamber of the Consumer and Markets Authority supervises the Gas Act, and SodM (Staatstoezicht op de Mijnen) supervises transport safety.

For above ground facilities the Seveso III Directive for control of major-accident hazards involving dangerous substances (European Directive 2012/18/EU) aimed at controlling major chemical accident hazards by preventing such incidents and minimizing their risks. As all EU countries are obliged to adopt measures at national and company level to prevent major accidents and to ensure appropriate preparedness and response should such accidents

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[52] Rechtlicher Rahmen für den Transport und die Untergrundspeicherung von Wasserstoff https://www.efzn.de/fileadmin/documents/Niedersaechsische_Energietage/Vortr%C3%A4ge/2019/NET2019_FF3_03_Klaws.pdf

nevertheless happen, it is also implemented in Dutch national legislation and is enforced by national chemical safety authorities.

3.2.6 Singapore

The current regulations in Singapore do not discriminate the type of storage (aboveground, underground, or geologic), but are based on the chemical inventory at the site. Therefore, any geologic storage for hydrogen inventories exceeding 25 tonnes would be classified as MHIs and be subjected to the same regulations as mentioned earlier.

3.2.7 United Kingdom

Please see the prior points about the COMAH regulations which would apply to on shore geological storage.

3.2.8 United States

Large-scale hydrogen storage in the United States is regulated at the federal level by the U.S. Department of Labor's OSHA through 29 CFR 1910.119, which provides requirements to enable worker safety where hydrogen is stored.

3.3 Potential Gaps

3.3.1 Australia

To facilitate and support the development of the hydrogen industry, National Hydrogen Codes of Best Practice are now being developed in Australia[53]. A major area that these Codes will address is hydrogen production and storage safety. These Codes are intended to assist in informing proponents when preparing their safety case submissions for approval under the respective relevant legislation and as part of their ongoing safety compliance obligations under such legislation. Australia has kick started these initiatives to address what it sees as significant knowledge gaps in the safety regulation of all aspects of hydrogen supply chain including storage.

3.3.2 Canada

Recent studies show potential challenges that come with underground storage of hydrogen, including fluid flow behaviour of hydrogen in subsurface reservoirs; hydrogen interaction with subsurface minerals and biotic reactions of hydrogen-consuming microbes; hydrogen loss due to geochemical reactions and potential leakage; as well as geo-mechanical response to changes in pressure, stress, and temperature[54,55]. As these challenges bring safety risks in

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[53] https://www.dcceew.gov.au/energy/hydrogen/regulatory-review

[54] A. O. Oni, K. Anaya, T. Giwa, G. Di Lullo and A. Kumar, "Comparative assessment of blue hydrogen from stream methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions," *Energy Conversion and Management,* vol. 254, p. 115245, 2022

[55] N. Heinemann, J. Alcalde, J. M. Miocic, S. J. T. Hangx, J. Kallmeyer, C. Ostertag-Henning, A. Hassanpouryouzband, E. M. Thaysen, G. J. Strobel, C. Schmidt-Hattengerger, K. Edlmann, M. Wilkinson, M. Bentham, S. R. Haszeldine, R. Carbonell and A. Rudloff, "Enabling large-scale hydrogen storage in porous media – the scientific challenges," *Energy & Environmental Science,* vol. 14, no. 2, pp. 853-864, 2021

operation of such storage sites, it is important for Canada to address the associated codes and standards and regulatory gaps to ensure their safe operation[33,54].

3.3.3 China

There are currently no regulations, codes, or standards for gaps of geologic hydrogen storage in China.

3.3.4 Germany

Currently no gaps are identified.

3.3.5 Netherlands

The current regulations for underground storage in the Netherlands are primarily related to natural gas and oil. Assessment of applicability of regulations for hydrogen is ongoing process. Results from experimental works and pilot tests serve for confirmation, adaptation, or development of codes and guidelines.

3.3.6 Singapore

The current man-made geologic storage was done with engineering experts who specified the design to crude oil and condensate storage based on various engineering studies. Given the significant difference in properties between hydrogen and liquid hydrocarbons, there are limited means to replicate the design. Any new geologic tanks for hydrogen would need to undergo new engineering studies.

3.3.7 United Kingdom

More broadly, the UK Hydrogen Economy team is working to exploring regulatory issues in priority order across the hydrogen economy. In 2024, the team aims to work with industry and relevant regulators to ensure the regulatory framework is fit for purpose for hydrogen activities, including storage.

3.3.8 United States

While OSHA regulations currently provide requirements for process safety, requirements for construction, operation, monitoring, and maintenance of bulk underground ground storage are not currently promulgated at a federal level in a manner comparable to U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) requirements for underground natural gas storage. Different physical properties of hydrogen versus natural gas as well as hydrogen effects on containment materials will need to be taken into account in the integrity and risk assessments for underground storage of hydrogen. The regulations themselves, as well as other documents included by reference (e.g., API Recommended Practice 1171) will need to be reviewed carefully for differences that may be relevant to hydrogen.

4 Summary

Bulk hydrogen storage of >10 tonne capacity in aboveground tanks is relatively rare around the world. While tank storage is common for smaller systems, multiple countries only report a few large-scale aboveground storage tanks, typically for liquid hydrogen for aerospace applications or for import/export via ship. Multiple countries seem to have well-established regulations, codes, and standards for aboveground tanks; some regulate hydrogen storage based on pressure level and others by storage quantity. Multiple jurisdictions (e.g., Germany, Singapore, United States) have additional rules and requirements for storage systems above a certain threshold, which can be at ~5, 25, or 50 tonnes, depending on jurisdiction. Storage above these quantities is not prohibited, but does tend to require additional safety analysis, documentation, and monitoring. Some jurisdictions mentioned potential gaps in requirements for systems with higher capacities, such as separation distances in which systems above a given capacity are not disallowed but it is not clear what setback distance should apply to them.

No bulk hydrogen storage of >10 tonne capacity in underground tanks were reported in any jurisdiction around the world. However, jurisdictions mentioned smaller systems that store tanks underground. Multiple jurisdictions reported that similar regulations, codes, and standards apply to underground tanks as apply to aboveground tanks, although some report additional requirements. Given this, few, if any, gaps were reported for bulk storage in underground tanks.

Geologic or subsurface storage of hydrogen has few current projects around the world; there are a couple of test projects in Germany and a few hydrogen storage caverns in the United States have been in operation for years. Regulations, codes, and standards for geologic storage tend to include similar requirements as tank storage, but also includes requirements related to subsurface drilling/mining. Few specific gaps were identified, although some jurisdictions mentioned that current requirements were based on natural gas, so would need to be more closely reviewed and potentially revised for hydrogen.

Some requirements for bulk storage in tanks have some ambiguity about specific requirements for larger-capacity systems. Some jurisdictions deal with this by requiring more of a case-by-case analysis using commonly accepted hazard and risk assessment methodologies. However, these ambiguities need to be resolved as more large-scale bulk storage systems are considered for all sorts of different applications. Common risk assessment methodologies and models may help to inform the basis for these requirements, but it may also be that systems above a certain capacity should not be subject to prescriptive requirements and instead require a more specialized analysis on a case-by-case basis. More consistent requirements or approach can help to enable global hydrogen trade.

This case-by-case basis is more common for geologic storage. The implicitly large hazard potential and large investments associated with large-scale storage justify more sophisticated, dedicated safety assessments and approvals. Effectiveness of mitigation methods and appropriateness of operational procedures have to be demonstrated and implemented by known, good engineering solutions rather than on a probabilistic basis. The specific efforts and costs for safety seem to be appropriate; more prescriptive and specific regulations, codes, and standards are only reasonable for larger number of identical solutions. So, it is expected that the current flexible regulations, codes, and standards framework for geologic storage might satisfy the needs of all stakeholders. Continuous improvement of these approaches is crucial as additional research is performed and more experience is gained.