ANNEX A

Technical Review on Production, Transportation, Storage and Use of Hydrogen to Achieve Net Zero in Hong Kong

Prepared by the Technical Committee
with the following membership:

Chairman: Ir Dr Hon-fai (HF) Chan, BBS
HonF (EI), FHKIE, FFHKQEP
Honorary Advisor of EI (HKB)

Ir Jeffrey Kwok
Ir Professor Dennis Leung
Ir Professor Michael Leung
Ir Chris Chong
Ir Don Cheng
Ir Raymond Fong

Table of Contents

1. Introduction

This is a technical review of hydrogen safety and current technologies in the production, transportation, storage, conversion, and utilization of hydrogen.

1.1 Hong Kong's Carbon Emission Reduction Commitment

Hong Kong is among the earliest cities in Asia taking actions to combat climate change. Local power companies ceased constructing new coal-fired power plants in 1997, and since then have been gradually replacing coal with natural gas and zero-carbon sources for power generation. Due to efforts in the past, the carbon emissions in Hong Kong peaked in 2014.

To respond to the Paris Agreement, the Government issued the first Hong Kong's Climate Action Plan 2030+ in 2017, laying down plans and actions to reduce the carbon intensity by 65-70% by 2030 against the 2005 baseline. In 2020, the carbon emissions were about one-fifth below the baseline of 2005, with a per capita emission of about 4.5 tonnes per year, which had dropped by almost 30% from the peak level of 6.2 tonnes per capita in 2014.

Following the publication of Hong Kong Climate Action Plan 2030+ in 2017, the Hong Kong Government published another major policy plan, called "The Hong Kong's Climate Action Plan 2050" in 2021. It brings together the overall strategies, plans, targets, and actions for Hong Kong to achieve carbon neutrality before 2050.

1.2 Current Technologies/Feasible Options available to Hong Kong

Hong Kong must derive energy supplies almost entirely from external sources as there are no indigenous energy resources. Energy is either imported directly (as in the case of oil products and coal products or electricity from Daya Bay), or produced through some intermediate transformation processes using imported fuel inputs (as in the case of electricity and Towngas). Small amount of energy is produced by renewable energy sources such as solar and wind energy.

Currently, about 66%, 18% and 7% of Hong Kong's carbon emissions comes from power generation, transportation, and waste (mainly from landfills) respectively.

To achieve carbon neutrality, the Government has laid down four major tasks to go for net-zero carbon emissions, i.e., net-zero electricity generation, green transport, energy saving and green buildings and waste reduction.

Hydrogen is receiving increasing attention for achieving carbon abatement in various sectors, including transport, logistics, power, heat, and industrial feedstock, etc. Hydrogen can also support distributed power supply that improves national energy security. Both commercial and industrial sectors share a common vision that increasing the cost-effectiveness of renewable hydrogen represents their strategic achievement towards substantial carbon reduction opportunities. Hydrogen can play several roles in the energy transition which include (a) large-scale integration of renewable energy into the power grid, (b) as a medium for storing and distributing energy across sectors and/or regions, (c) a buffer to increase the electric system resilience and (d) as a clean fuel for fuel cell vehicles to decarbonise transport. Besides, hydrogen can (e) decarbonise building energy consumption and (f) serve as feedstock using captured carbon.

For Hong Kong, using hydrogen as fuel to replace diesel and gasoline to decarbonize the transportation section may be the easiest way to implement in the short and medium term as there are almost 50,000 fuel-cell vehicles world-wide on the road, including cars, taxis, vans, and light commercial vehicles where Hong Kong can learn and apply their success stories.

Fuel Cell Electric Vehicles (FCEV) have the following benefits in decarbonising the transport sector (Trencher, 2020). Firstly, the high energy to mass ratio of hydrogen allows FCEV to travel longer distances (>500 km) without refilling. Secondly, the refuelling time of FCEV can be completed within a few minutes which is in par with the time required for petrol /diesel cars. Thirdly, as hydrogen has a higher energy density resulting in much more energy that can be stored inside the fuel tank, FCEV is particularly suitable to take heavy load and travel long distances. Lastly, existing petrol stations and associate infrastructures can easily be converted to supply hydrogen to FCEV, including passenger cars, vans, buses, trucks, trains, and non-electrified trains. For Hong Kong, it is easier to start implementing FCEV with buses and heavy good vehicles as they are key air pollutant contributors with 47% of NOx and PM_{10} emissions in congested areas. Besides, hydrogen refueling stations (HRS) can be located inside the depot of bus or truck companies with sufficient safety distances from nearby communities.

1.3 The need for a Hydrogen Economy

Hong Kong needs to develop a Hydrogen economy, whereby hydrogen is used as the major energy carrier and a clean fuel to decarbonize the economic activities and to achieve carbon neutrality by 2050 [37]. In order to achieve this goal/vision, we need to set a policy for the transition of fossil fuels to hydrogen with a clear roadmap for:

a. Conversion of all gasoline passenger vehicles, diesel-engine medium and heavy vehicles to either electrical vehicles or fuel cell driven vehicles,
b. Planning and building of infrastructure for the delivery, conversion, storage of hydrogen incl. refueling stations, piping, storage tanks, etc.
c. Upgrading of existing gas network for Towngas.
d. Supporting industrial cluster development, accelerate hydrogen blending and mandate hydrogen-ready appliances.
e. Setting safety codes and standards for the delivery, storage, and use of hydrogen

Due to limited space and resources available, Hong Kong is not in a good position to produce Hydrogen in bulk quantities, and this would require that Hong Kong Government should arrange with major hydrogen suppliers in Mainland China, e.g., Sinopec, to deliver hydrogen to Hong Kong, even though the current Towngas supplied by The Hong Kong and China Gas Company Limited (HKCG) contains about 50% v/v of hydrogen and a limited production of Hydrogen can be obtained using landfill gas.

Meanwhile, Hong Kong Government needs to demonstrate that hydrogen is safe in all aspects including transportation, especially in tunnels, storage, utilization, etc. and allow time to enable the Government, the industry, and the users to "learn by doing". In this respect, training of engineers, competent and skillful workers to operate Hydrogen facilities are needed to support the Hydrogen economy.

Hong Kong Government needs also to explain to and gain support from the public the extra cost to consumers and industry by the choice of the technology and the fuels to use to achieve net zero by 2050.

1.4 Potential barriers for the implementation of these technologies options in Hong Kong (Challenges)

- Lack of legislation for using hydrogen as a fuel – the existing legislation classify hydrogen as dangerous goods.
- Lack of approved safety rules and code of practices
- Lack of infrastructure particularly hydrogen refueling stations
- Lack of policy and incentive to support FCEV – government not committed to phase out diesel and gasoline vehicles in the medium and long term, and so far, no support incentives, except that Government would cease registration of new gasoline vehicles by 2035.
- Lack of experience and competent technical personnel to operate and maintain hydrogen and related infrastructure and the FCEVs.

2. Why Hydrogen

2.1 Hydrogen as Fuel for the Future

- Burning Hydrogen reduces air pollution and greenhouse gas emissions, even though the adoption of low-emission hydrogen as a clean industrial feedstock and energy vector is at an early stage [36].
- A solar/wind hydrogen system could fundamentally resolve energy supply and environmental problems.
- Expanded use of Hydrogen can ultimately resolve energy security, climate change and air quality problem.
- Even when using hydrocarbon as fuel, fuel cells offer substantial reductions in CO_{2e} emissions.
- Hydrogen is not an energy source, rather it is an energy carrier and a storage medium because the energy to make elemental hydrogen is more than the energy one can obtain by burning it.

2.2 Limitations of Hydrogen as Energy Carrier

- Most hydrogen is derived from compounds such as water or methane, and energy is required to break the hydrogen free from these compounds, then separate, purify, compress and/or liquefy the hydrogen for storage and transportation to usage points. Widespread production, distribution and use of hydrogen will require many innovations and investments to be made in efficient and environmentally-acceptable production systems, transportation systems, storage systems and usage devices.
- Lack of an infrastructure for producing, transporting, and storing large quantities of hydrogen inhibits its growth and practicality.
- Currently, hydrogen provides less than 1% of power worldwide.
- Hydrogen can be transported by pipelines like those used to transport natural gas. There are some additional problems, because hydrogen tends to leak more (as it is such a small molecule) and can embrittle some metals used for pipelines.

- The most practical way of using hydrogen as a motor fuel is to accept the difficulties of handling liquid hydrogen and solve them. There are four main problems.

    - Low density: A hydrogen fuel tank will have three times the size of a gasoline tank. Also, it must be insulated, and this will add to its bulk volume, which seems entirely bearable.
    - Safety problems: Liquid hydrogen at about 20K is cold enough to freeze air and water, and accidents have occurred from pressure build-up following plugged valves due to the freezing. In a collision the hydrogen tank may rupture, as can a gasoline tank. Limited accident experience suggests that the danger is somewhat less with hydrogen than with gasoline, because the hydrogen dissipates rapidly. The release of hydrogen into a confined space like a garage risks an explosion.
    - Evaporative loss: Since the insulation cannot be perfect, hydrogen will gradually leak and evaporate, typically 1.7 percent per day. This is too fast for a car to sit for months between uses. A tank of compressed hydrogen holding enough to get to a hydrogen station would solve this. If the engine is flexible enough to burn gasoline as well as hydrogen, a half-gallon gasoline tank would suffice. Some automobile companies, e.g., BMW, have experimented with vehicles powered by liquid hydrogen. However, hydrogen cannot come into common use until the political obstacles to nuclear expansion are overcome or the technological obstacles to large scale solar energy, e.g., cost of solar power, intensity of solar radiation, required land intake, transmission of power to urban centres where power is needed, reliability of solar power, etc., are overcome.
    - High cost: It is unlikely that Hydrogen will be used as long as gasoline remains so cheap unless Government bans its use by law, i.e., as long as oil remains cheap and fear of global warming does not prevent its use.

- Hydrogen Ignition
    - There are several potential ignition sources for flammable mixtures of hydrogen with an oxidant, which include flames, electrical sparks, fused wires, incendiaries, hot surfaces, heating, rapid adiabatic compression,

    shock waves and catalytic materials. All these processes heat a portion of the combustible mixture to a sufficiently high temperature such that adjacent un-combusted layers also react, producing a flame, which propagates throughout the mixture.

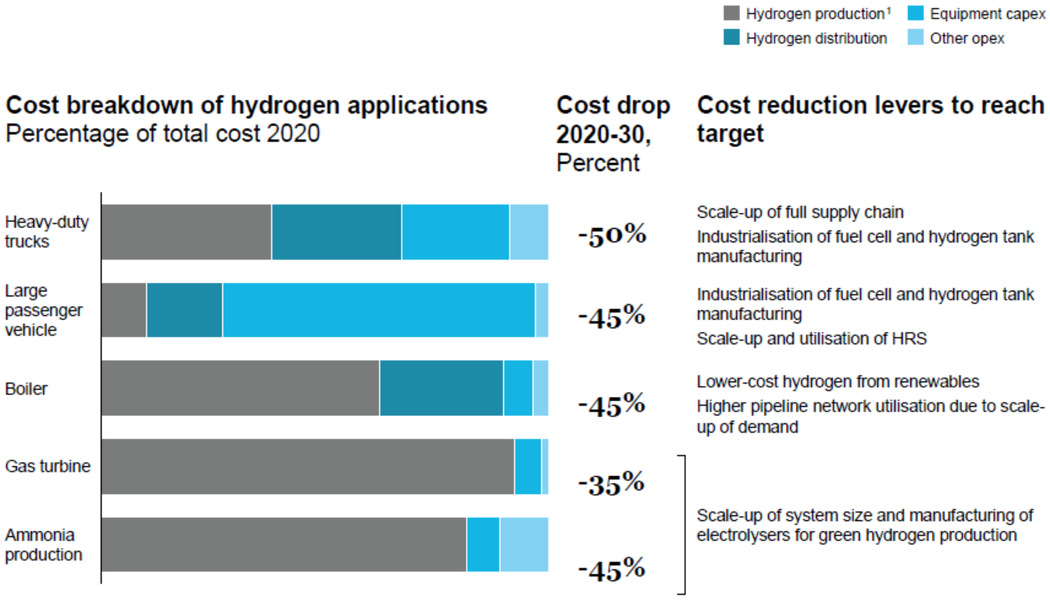
  - For hydrogen, the minimum ignition energy is low at 0.017 MJ for mixtures with air (ISO, 2004), and even lower at 0.0012 MJ for mixtures with oxygen [38]. Hydrogen has such a low minimum ignition energy that it is often difficult to determine the exact mechanism and cause of an ignition when it occurs. In some incidents where hydrogen has been involved in an explosion or fire, it has not been certain as to the source of ignition and the mechanism of the release. Some incidents have had obvious ignition sources such as flames or grinding sparks, but other incidents had releases of hydrogen where all obvious sources of ignition had been excluded, and self-ignition had been blamed. The propensity of hydrogen to ignite in this fashion for no apparent reason has been reported several times previously, by Reider [44], Lees, [45], Anon [46], and Fenning and Cotton [47]. In these incidents, no specific cause for ignition was identified. Several mechanisms have been suggested, of which two are worthy of note for discussion. The first mechanism is that of the reverse Joule-Thomson effect exhibited by hydrogen, and the second, the so-called "diffusion ignition" mechanism.

- Transporting energy as hydrogen uses much more energy than transporting it as oil or natural gas because of the low density of hydrogen, either as a liquid or as a compressed gas.
- Water resources could be a problem for hydrogen production by electrolysis in sunny regions well suited for solar power. A study by the World Resources Institute in Washington DC estimated that more than 4 trillion gallons of water yearly would be required if adequate hydrogen production by electrolysis is required. This is equal to the flow over Niagara Falls every 90 days [48].
- Hydrogen is flammable. It is hazardous as it can leak during transportation and storage. Compressed hydrogen gas could be ignited with the static discharge of a cell phone.

- Running an engine with hydrogen extracted from natural gas could produce a net increase of CO_2 in the atmosphere.
- In terms of energy contained, 9.5 kg of hydrogen is equivalent to 25kg of gasoline [39]. Storing 25 kg of gasoline requires a tank with a mass of 17 kg, whereas the storage of 9.5 kg of hydrogen requires 55kg, [39]. Part of the reason for this difference is that the volume of hydrogen fuel is about 4 times greater for the same energy content of gasoline. Although the hydrogen storage vessel is large, hydrogen burns 1.33 times more efficiently than gasoline in automobiles [40]. In tests a BMW 745h liquid-hydrogen test vehicle with a 75 kg tank and the energy equivalent of 40 liters of gasoline had a cruising range in traffic of 400 km, or a fuel efficiency of 10 km per liter [41].
- At present, commercial hydrogen is more expensive than gasoline. Assuming US$0.05 per kWh of electricity from a nuclear power plant during low demand, hydrogen would cost US$0.09 per kWh [40]. This is the equivalent of US$0.67 per liter of gasoline. Gasoline sells at the pump in the United States for about US$0.30 per liter. However, estimates of the real cost of burning a liter of gasoline ranges from US$1.06 to US$1.32 when production, pollution, and other external costs are included [42]. According to the Hydrogen Council, the economy of scale will reduce equipment cost significantly across the hydrogen value chain [34]. Therefore, based on these calculations, hydrogen fuel may eventually become competitive, as shown in Exhibits 7 and 8 below [34].

Exhibit 7 | Drivers of hydrogen's cost competitiveness

Cost breakdown of hydrogen applications
Percentage of total cost 2020



	Cost drop 2020-30, Percent	Cost reduction levers to reach target
Heavy-duty trucks	-50%	Scale-up of full supply chain Industrialisation of fuel cell and hydrogen tank manufacturing
Large passenger vehicle	-45%	Industrialisation of fuel cell and hydrogen tank manufacturing Scale-up and utilisation of HRS
Boiler	-45%	Lower-cost hydrogen from renewables Higher pipeline network utilisation due to scale-up of demand
Gas turbine	-35%	Scale-up of system size and manufacturing of electrolysers for green hydrogen production
Ammonia production	-45%	

1. Assumes 50/50 blend of low-carbon and average renewable hydrogen

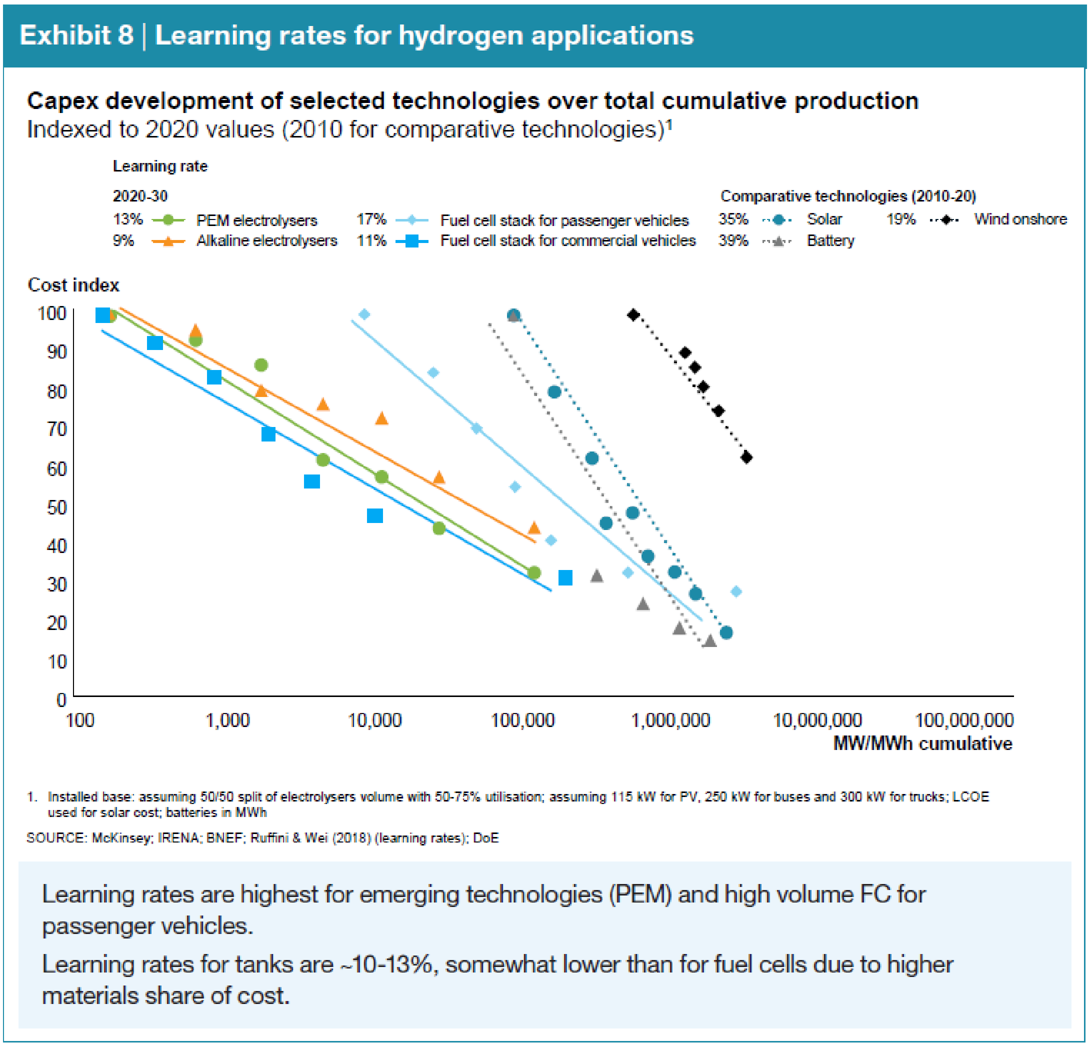


Exhibit 8 | Learning rates for hydrogen applications

Capex development of selected technologies over total cumulative production

Indexed to 2020 values (2010 for comparative technologies)[1]

[1] Installed base: assuming 50/50 split of electrolysers volume with 50-75% utilisation; assuming 115 kW for PV, 250 kW for buses and 300 kW for trucks; LCOE used for solar cost; batteries in MWh

SOURCE: McKinsey; IRENA; BNEF; Ruffini & Wei (2018) (learning rates); DoE

Learning rates are highest for emerging technologies (PEM) and high volume FC for passenger vehicles.

Learning rates for tanks are ~10-13%, somewhat lower than for fuel cells due to higher materials share of cost.

- Reforming on board allows the hydrogen to be transported in a form that is easy to move, such as methanol, natural gas, or gasoline. The disadvantage is reforming on board is not as efficient as central generation.

3. **Safety & Policies** (Policy change is necessary to enable switching from fossil fuels to hydrogen)

3.1 Properties of Hydrogen related to Safety

- Hydrogen is the universe's most abundant and simplest element. On earth, it mainly exists as an essential component of water (H_2O). Hydrogen gas (H_2) is composed of two hydrogen atoms stuck together, each containing just one proton and one electron. This simple chemical structure is what makes hydrogen gas flammable and relatively easy to ignite. This is also why hydrogen gas is non-toxic, odorless, tasteless, small, and light allowing it to permeate through materials more easily.
- Hydrogen has a very high gravimetric energy density of 120 – 142 MJ/kg but due to its low density, the volumetric energy density of liquid hydrogen is 9 MJ/L.
- Although hydrogen has a high auto-ignition temperature of 858 K, it has a very low minimum ignition energy of only 0.02 MJ at the stoichiometric mixture of 29.5% in air than gasoline or natural gas, which means it can ignite more easily.
- Hydrogen is flammable in concentrations from 4% - 75% and this makes it more hazardous than natural gas and other gaseous and liquid fuels, e.g., LNG. For example, methane which is the main component of LNG has a narrower flammability limit of 5.3-15%.
- A hydrogen flame has a high temperature of up to 2318 K, depending on the mixture, but emits very little radiation, making the flame invisible.
- Hydrogen has a high laminar burning velocity of up to a maximum of 3.46 m/s in a flame front velocity of up to 24 m/s. A turbulent and realistic flame can reach a burning velocity of several hundreds of m/2. The detonation velocity can reach 2,000 m/2 and the occurrence of a detonation is favoured by the high flame velocity but limited to concentrations between 18 and 59% v/v.
- Because of its small molecular size, hydrogen can easily diffuse in other materials. For example, hydrogen will diffuse in ferritic steel when in contact, causing the so-called hydrogen embrittlement, which can result in sudden failure of a system without the chance to prevent a failure.
- On the other hand, several hydrogen's properties make it safer to handle and use than the fuels commonly used today. For example, hydrogen is non-toxic. In

addition, because hydrogen is much lighter than air, it dissipates rapidly when it is released, allowing for relatively rapid dispersal of the fuel in case of a leak.

3.2 Safety Philosophy

Safety is and remains a key concern in the storage, transportation, refilling and utilization of hydrogen. Between 2000-2020, there were 90 incidents in the hydrogen energy industry chain at home and abroad such as the explosion of hydrogen storage tanks in South Korea in 2019 and a hydrogen explosion in a Taiwan power plant in 2022. Reasons for the explosion are: (1) design defects (2) seal failure (3) equipment failure (4) operation errors or improper maintenance (5) traffic accidents.

In Hong Kong, two hydrogen gas cylinders exploded at Castle Peak power station in 1992, spreading debris over a 400-metre radius and killing two workers bd injuring 19 others.

The evaluation of safety is important for hydrogen installations as a new technology in general and for hydrogen given its specific hazard features. However, since there is no harmonized approach yet on the issue, while various standards and documents are under review and harmonization process yet, the most expected to be adopted approach to the topic is the one considering hydrogen installation as hazardous systems and apply for them risk oriented safety approach, which is currently used for other similar installations. In applying this approach, it can be considered that a hydrogen installation is a complex system subject to various challenges, which could induce undesired effects, with various levels of damage impact and hence having various levels of risk.

The main philosophy of reducing the level of risk generated by various hazards to acceptable levels is based on a layer type concept, i.e., considering that the risks are being kept at a low level by using three groups of protection / safety layers. i.e., by:

- Developing a design of the installation, that has inherently safe features
- Implementing in the design of the installation special systems, called safety systems designed to cope with specific challenges

- Developing a set of procedures and managerial approaches to deal with emergency cases, once the previous layers of defense failed.

The safety layers approach applies to the installation for which a set of groups of challenges (initiating events) are considered. The most representative initiating events for hydrogen installations are as follows:

- Undetected and/or not vented breaks
- Undetected and/or not vented leaks
- Over-pressurization
- Combustion / Fires
- Low temperatures
- Hydrogen exposure
- Hydrogen embrittlement and other passive effects on pipes/components
- Explosions
- External events (earthquake, harsh climate, winds etc.)
- Security threats

For each of the above-mentioned challenges the installation must have available features of the three safety layers mentioned above:

- Inherently safe features assuring that the installation will be designed in such manner that it will have a level of protection embedded in the solutions adopted, combined with a prudent operating philosophy, which should try to reach production objectives without endangering the safety level and by performing continuous inspection and maintenance of the installation.
- Safety barriers to decrease the effect of the systems reacting to a set of detection signals on the existing challenges, which will be followed by mitigation functions performed by technical systems
- Mitigation functions and emergency procedures designed as a last layer of protection to decrease the risk on population, environment, and workers if all the other layers have failed.

Inherently safety features are assured by design in order to minimize the severity of the consequences of a certain hazard, which results if the installation is challenged by undesired events. There is a set of strategies adopted for the inherently safe design of hydrogen installations, as follows:

- The quantity of hydrogen in the system is minimized as much as possible
- Hydrogen is isolated from substances, which could lead to hazards, as for instance oxidizers, hazardous materials etc. This is assured by various means as for instance by protection walls or other passive systems
- A set of physical barriers and a zoning concept is adopted in order to separate public or workers from the sources of potential fires, explosions, etc in the installation
- A suitable and highly elevated ventilation system of the hydrogen installation is provided
- It is assumed that all the compartments and closed spaces of the installation, where there could be potential accumulation of hydrogen, functions of ventilation and/or avoidance of reaching critical volumes of hydrogen and/or contact with hazardous materials are provided
- The working staff present on a given moment in time in the installation is minimized
- Operating and maintenance procedures are provided to assure a good level of inspection over the installation
- Protection by distance and weather condition studies are provided for public and environment in case of undesired events by studying the conditions on the chosen site for the installation and by developing emergency procedures in case of totally undesired events posing risk to public, environment, or workers.

Furthermore, a Quantitative Risk Analysis is performed for each design adopted the systematic evaluation of the risks and the actions to be taken to keep the risk below the tolerable limits. Based on the results from the design and operating experience the inherently safety features and preventive actions and functions are provided for the operation of hydrogen installations. They include, but are not limited to:

- Control of ignition sources
- Provision of inerting methods and inerting control features
- Use of recombiners
- Minimization of possibility for fires and explosions by using adequate electrical equipment
- Provision of ventilation functions in the installation
- Development of a comprehensive set of safety procedures for normal and abnormal situations and operating staff training
- Development of a maintenance plan.
- Use of verified and validated tools and methods, i.e., computational codes, standards and guides, experimental results etc.

In case that the first safety layer of the hydrogen installation as described so far fails, then the safety layer of the barriers provided to decrease the risk impact of undesired events is activated.

Safety barriers are activated based on manual / direct human intervention and/or (what is preferable and intended by design) based on the results of detection of dangerous releases and/or accumulation of hydrogen.

There are specific features provided for each installation in order to have a good detection of:

- hydrogen leaks,
- hydrogen accumulation in closed spaces,
- hydrogen flames,
- hydrogen fire detectors.

The mitigation function is assured by a series of mitigation measures, as for instance:

- Pressurization of the installation (pipeline or vessel)
- Explosions of installation followed or not by fires. This can be assured by:
    - providing venting of equipment and buildings
    - explosion suppression and fast acting valves

    - use of maximum experimental safe gap
    - deflagration flame arresters
    - detonation arresters
- Hazards due to hydrogen interaction with other dangerous substances. This can be assured by:
    - hydrogen inerting,
    - hydrogen suppression
    - hydrogen isolation systems,
    - constant inert gas dilution to prevent ignition and combustion
    - Pre-ignition inert gas dilution
    - Water based protection systems
- Combustion / fires. This can be assured by various measures, as for instance
    - Flame arresters
    - Flame quenching and quenching diameter
- Hydrogen leaks and hydrogen accumulation in closed spaces
    - Ventilation to mitigate hydrogen accumulation in closed spaces
- Challenges to the installation due to other sources than hydrogen, i.e., by mitigating flooding, spilling etc of various liquids in the installation
- Definition of safety distances for various components
- Emergency response and emergency response plan based on the best results from similar cases and experience as well as based on weather and other environmental conditions simulations, as for instance:
    - Forecast of blast wave propagation and impact force to the protective wall
    - Experimental evaluation and numerical simulation of the damage of surrounding structures by an explosion accident.

3.3 Comparison of Hydrogen and Conventional Fuels in terms of Safety

To evaluate hydrogen’s safety, it must be compared to that of other conventional fuels like gasoline, propane, and diesel. While no fuel is 100 percent safe, hydrogen has been shown to be *safer* than conventional fuels in a multitude of aspects.

- Hydrogen is not toxic, unlike conventional fuels. On the other hand, many conventional fuels are toxic or contain toxic substances, including powerful carcinogens. Moreover, when it comes to vehicles that run on hydrogen fuel cells, hydrogen produces only water, while vehicle combustion of conventional fuels generates harmful air pollution. A hydrogen leak or spill will not contaminate the environment or threaten the health of humans or wildlife, but fossil fuels can pose significant health and ecological threats when leaked, spilled, or combusted.

- Hydrogen is 14 times lighter than air and 57 times lighter than gasoline vapor. This means that when released, hydrogen will typically rise and disperse rapidly, greatly reducing the risk of ignition at ground level. However, propane and gasoline vapor are heavier than air, making it more likely that they will remain at ground level, increasing the risk of fires harming people and buildings.
- Hydrogen has a lower radiant heat than conventional gasoline, meaning the air around the flame of hydrogen is not as hot as around a gasoline flame. Therefore, the risk of hydrogen secondary fires is lower.
- Hydrogen has a higher oxygen requirement for explosion than fossil fuels. Hydrogen can be explosive with oxygen concentrations between 18 and 59 percent while gasoline can be explosive at oxygen concentrations between 1 and 3 percent. This means that gasoline has greater risk for explosion than hydrogen for any given environment with oxygen.
- When handled responsibly, hydrogen is less dangerous than other flammable fuels that we rely on today. Moving forward, industry and government institutions must build on existing robust safety protocols and continue to make safety a key priority for investment and refinement to ensure that hydrogen becomes part of a clean and thriving economy

3.4 Safety Measures in Use

- Storing hydrogen in tanks within fuel-cell trucks and hydrogen-powered airplanes in a cost-effective way without sacrificing safety presents an engineering challenge. Both the fuel cell trucking and aviation industries will need to achieve similar or better safety targets than those of fossil fuel-burning trucks and aircraft, given that transportation safety of any kind is extremely important.
- New hydrogen refueling stations and hydrogen pipelines must be engineered in a way that mitigates any risk of dangerous leakage and combustion. Groups like the Centre for Hydrogen Safety (CHS), a global non-profit dedicated to promoting hydrogen safety, are tackling these issues by providing resources to those tasked with designing or using various hydrogen systems and facilities, as well as training for incident response. With 45-plus member organizations

within CHS (Shell, Hyundai, Argonne National Laboratory, National Grid, to name a few), industry is prioritizing safety.

- In view of hydrogen embrittlement when exposed to hydrogen, appropriate materials, e.g., austenitic steels, copper, and aluminum, etc. should be selected in the design of safe hydrogen systems.
- Training in safe hydrogen handling practices is a key element for ensuring the safe use of hydrogen.
- Testing of hydrogen systems—tank leak tests, garage leak simulations, and hydrogen tank drop tests, should form an essential component in the safe production, storage and refilling and delivery of hydrogen.
- Despite higher burning velocity, greater flashback tendency, lower limits of flammability and ignition energy than natural gas, hydrogen has been used for more than 90 years in the industry with an excellent safety record in the area of production, storage, transport, and utilization [43]. Hydrogen can be as safe as other fuels when sufficient safety standards, guidelines, and procedures have been established along its entire value chain and duly observed when handling it. Besides, the general public and customers should be well informed of hydrogen's characteristics.
- Adequate ventilation and leak detection are important elements in the design of safe hydrogen systems. Because hydrogen burns with a nearly invisible flame, special flame detectors are required.
- A hydrogen sensor shall be able to detect hydrogen in a large detection range. Highly selective and highly sensitive and anti-interference ability.
- Most hydrogen sensors work on electrochemical principles and sparks may be generated during usage. A better option is optical fibre sensors with smaller size, lightweight and anti-interference performance and intrinsically safe. The existing sensors are mainly: interferometer sensor, micro-mirror sensors, evanescent sensor, fibre grating sensor, and surface plasmon resonance sensor.
- However, optical fibre hydrogens sensors generally have the following problems:
    - Hydrogen sensitive film is easy to crack and bubble which affects the sensitivity
    - High cost due to limitation of optical fibre signal demodulation technology and film preparation technology

  - Some operation e.g., tapering and etching during sensor fabrication may reduce mechanical strength of the sensor.
  - Response time and sensitivity are difficult to achieve independent optimization.

Safety of Fuel Cell Vehicles

- Fuel-cell vehicles are usually mounted with fully wrapped aluminum lined carbon fibre cylinders because of their high hydrogen storage density and light weight together with seamless steel pipe for the transmission pipes.
- A safety pressure monitoring and protection device is installed to depressurize and cut off the hydrogen source if the pressure is too high.
- A collision sensor is installed to detect accidental collision and the device will interrupt the hydrogen supply to avoid hydrogen leakage.
- Hydrogen detectors are installed at pipeline interfaces and valves and these will give alarm to ensure the vehicles takes emergency measures.
- The fuel cell stacks are designed to resist vibration and impact and work under a high temperature environment. Hydrogen leakage can also be detected in advance by monitoring the voltage change caused by membrane rupture.

Safety at Hydrogen Refueling Stations (HRS)

- HRS are necessarily built along main roads and around urban areas to facilitate refueling of hydrogen for transit vehicles. The potential risks arise from possible hydrogen leakage caused by liquid hydrogen spillage, high-pressure storage tank rupture with consequences of a fire, explosion, or blast wave propagation, and various hydrogen related equipment failure and electrical equipment irregular operation.
- Safety measures are: (1) strictly control of equipment and material to meet relevant standards. (2) installation of hydrogen leakage detector, hydrogen concentration detector, flame detector where hydrogen easily accumulates, (3) installation of safety valves on hydrogen storage equipment, (4) Use of explosion proof equipment, (5) installation of solid barriers between the HRS and the neighbouring facilities, e.g., schools, building, libraries, etc. where the

safety separation distances are not met. [29]

- Safety Management Measures are: (1) Setting up an organization structure with dedicated personnel, incl. manager and technicians who are responsible for the daily operation, inspection, maintenance, emergency handling, of the HRS.
- In Korea, the recommended separation distance under the local regulations varies according to the capacity of the storage tank or the processing facility and the level of the protected facilities as shown in Table 1 below:

Table 1. Separation Distance between the HRS and the Protection Facility[1]

Components in the HRS	Compressed Gas (m^3) or Liquefied Gas (kg)	Protected Facility 1st Class (m)	Protected Facility 2nd Class (m)
Storage tank or Processing facility	<10,000	17	12
	10,000 to 20,000	21	14
	20,000 to 30,000	24	16
	30,000 to 40,000	27	18
	40,000 to 50,000	30	20
	50,000 to 90,000	30	20
	>990,000	30	20

Note: the first class of protected facilities includes kindergartens, schools, hospitals, libraries, and buildings with internal area greater than 1000 m^2. The second class includes houses and building with an internal area of 100 to 1000 m^2.

Safety of Hydrogen Vehicles in Road Tunnels

- Limited research studies have been carried directly related to hydrogen powered vehicles in road tunnels. The findings drawn from the limited work done, including the experimental work and CFD studies by HyTunnel[2], so far indicate that under

---

[1] KGS. *Facility/Technical/Inspection Code for Fuel Vehicles Refueling by Type of On-Site Hydrogen Production*; Technical Standards, KGS, FP216; Ministry of Trade, Industry & Energy: Sejong-si, Korea, 2020.

KGS. *Facility/Technical/Inspection Code for Fuel Vehicles Refueling by Type of Compressed Hydrogen Delivery*; Technical Standards, KGS, FP217; Ministry of Trade, Industry & Energy: Sejong-si, Korea, 2020

[2] A pre-normative research organization for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces

normal circumstances, hydrogen powered vehicles do not pose a significantly higher risk than those powered by petrol, diesel or CNG, but more search is needed to confirm. It is found that the shape of the tunnel, tunnel ventilation and vehicle pressure relief device operation are potentially important parameters in determining explosion risks and the appropriate mitigation measures. Key findings from various studies are summarized below:

- Simultaneously releasing a large mass of hydrogen, e.g., from a city bus, through multiple vents, was found to be more hazardous compared to when the same mass was released through a single vent.
- While the consequence of a release from a 20MPa natural gas system was comparable to that from a 20MPa hydrogen system, the consequence of a similar release from a higher-pressure hydrogen system was significantly more severe, with respect to predicted overpressures from a subsequent explosion of the hydrogen cloud. The significant difference in the explosion hazard associated with the 20 and 35 MPa release, despite a similar energy, was attributed to the different distribution of hydrogen mass within the flammable clouds formed.
- CFD studies highlighted that the ignition point and timing inside the dispersed hydrogen cloud significantly affects the combustion regime. Based on the predicted overpressures, typical effects could be the damaged vehicle windows or tunnel lighting units. However, the results also indicated that fast deflagration, or potentially detonation, could be produced by the most severe hydrogen releases and ignition timing from the worst-case events.
- Tunnel ventilation reduces the hazard dramatically, and it is suggested that suitable ventilation of a tunnel can significantly reduce the chance of an explosion. However, there may be the possibility that, even in a well-ventilated tunnel, a high release rate of hydrogen can produce a near homogeneous mixture at close to stoichiometric conditions, with a correspondingly increased explosion hazard. Nevertheless, imposing a minimum ventilation rate would help to reduce the size of any flammable gas clouds.
- Significant levels of overpressure can be generated in confined or semi-confined spaces in a tunnel by the ignition of a hydrogen-air mixture filling only a small faction, of the order of a few percentages of the space. These could be high enough to cause damage to tunnel services e.g., ventilation ducting. For larger percentage

fills of hydrogen-air mixture, then possibility of deflagration to detonation transition cannot be ruled out. Hydrogen explosions are more prone to produce an oscillatory pressure-time profile than hydrocarbon explosions, which may have implications for the response of structures subjected to a hydrogen explosion.

- Obstructions in the tunnel, particularly at ceiling level have the potential to increase the risk of fast deflagration or even detonation and could add some turbulence to flame propagation and make explosions more severe.
- Increasing the ceiling height associated with arched cross-section tunnels has been identified as reducing the hazard associated with the release of hydrogen, due to increased dilution of the hydrogen stream and a reduction in momentum of the impinging jet.
- In new tunnels, a minimum distance from the pressure relief device vent of the hydrogen powered vehicles to the ceiling should be allowed for to make dispersion of any released hydrogen gas more safely and to make more dilution prior to impingement to the ceiling thus reducing the momentum of the impingent jet. Reducing congestion at the ceiling (lighting, etc.) reduces explosion hazards.

Safety during Road Transport of Hydrogen

- Hydrogen is commonly transported on road using composite pressure vessels. Leaking from these pressure vessels is highly susceptible to spontaneous explosion due to its combustion characteristics, which may cause jet fire or explosion accidents, resulting in serious causalities and property damage.
- Hydrogen leakage is usually followed by a mixture of air in a certain space to form a gas cloud. If it encounters an ignition source, hydrogen cloud explosions easily occur. Even without ignition sources, high pressure hydrogen leakage may cause spontaneous combustion and explosion.
- Pressurized vessels are susceptible to rupture, resulting in an explosive release of hydrogen and creating a shockwave which is potentially lethal to people within the danger zone of the vessel [30]. Rupture of the vessels can also cause splinters to fly off several tens of meters away, hitting people/damaging property. This is usually caused by a fire near the vessel. The fire drastically increases the temperature and causes the pressure to increase beyond the vessel's material can withstand and hence

ruptures. The initial fire can cause the hydrogen to explode. In order to prevent this from happening, gas cylinders should be equipped with a pressure relief device (PRD) so that it will release some or all hydrogen in the cylinder before a rupture can occur. However, it should be emphasized that a regular PRD may not prevent rupture if the vessel is a Type III or Type IV tank which is made of a composite material, with a metal or high-density polymer liner, instead of a metal casing because the fiber-reinforced plastic in the tank can deteriorate and the matrix polymer can burn without triggering a significant rise in the internal temperature of the tank.

- The operation and handling of hydrogen transport vehicles should be a qualified driver, with pre-determined routes and frequent inspections for leakage and over-pressure. Regular vibration and collision tests should be carried out to prevent leakage of the pressure vessels, valves, and piping. Technical details of the testing procedures should be clearly established.
- The hydrogen transport vessels shall be type-approved by the local authority.
- Legally binding criteria should be established for the approval and usage of transport vehicles.

3.5 Safety Standards of Hydrogen Energy and Technology

No doubt, there are general concerns about safety of hydrogen on use in onboard vehicles, filling stations, tunnels, storage and transfer stations and transportation/delivery in highly urbanized and congested living environment of Hong Kong.

Worldwide standards/codes in regulating safety in Hydrogen (e.g., US NFPA 2 Hydrogen Technology Code (version 2020), China National safety code, Canadian safety code for compressed gases, etc.) have addressed the above concerns. Worldwide Safety Code and Standards on Hydrogen. Fuel Cells, and Infrastructure Safety can be found in **Appendix D**. Specially:

a. Safety in on-board vehicles (e.g., high-pressure tank rupture with fire, etc.)

b. Safety at filling stations (e.g., ISO 198801-1 Gaseous hydrogen – Fueling Station. Part 1 (hazard distance), liquid hydrogen spillage, high-pressure tank rupture with fire, etc., US NFPA 2)
c. Safety inside tunnels (e.g., pressure and impulse from blast waves, high temperature and radiative heat flux associated with fireballs in a tunnel, etc.)
d. Safety at transfer stations (e.g., liquid hydrogen spillage, high-pressure tank rupture with fire, etc.),
e. Safety during transportation/delivery (e.g., leakage in underground pipelines, rupture of pressure tanks during land-based transportation, spillage of liquid hydrogen, (if this option is adopted) etc.

Hydrogen safety standards have come a long way. Although there has been a lot of recent hype around hydrogen, it is not a new technology. Industry has been using hydrogen in rocket fuel, oil refineries, and fertilizer production for the past 40 years—more than enough time for scientists and engineers to develop and adopt robust safety protocols. Today, the Hydrogen Industry Panel on Codes, International Code Council, and National Fire Protection Association work together to develop stringent standards for hydrogen systems and fuel cells. Years of R&D and experience have made it possible to develop the appropriate engineering controls and guidelines to mitigate the risks of hydrogen's high flammability and low ignition energy (the energy required to ignite something). For example, because hydrogen is colorless and odorless, sensors are a requirement for hydrogen fueling stations, equipment, and facilities. Today's technology enables remote hydrogen sensing to ensure robust detection of any hydrogen leak. Hydrogen storage tanks in fuel cell cars are also subject to rigid testing standards, such as exposure to extreme temperatures and pressures, before they can be deployed. These are just a few examples of the standards and codes that have supported a safe hydrogen industry for the last four decades.

Safety Standardization of Hydrogen Energy

- Technical Committee for Standardization of Hydrogen Energy Technology (ISO/TC197) is the technical committee within International Standards

Organization to develop standards for Hydrogen Technology.

- In 2008 China established a Committee for Hydrogen Energy (SAC/TC309) and Fuel Cell and Flow Battery (SAC/TC342) to undertake the standardization work for hydrogen energy.
- ISO issued the first hydrogen safety standards, ISO/TR15916 in 2004.
- China issued the first hydrogen safety standard in 2013, GB/T129729-2013, which is applicable to preparation, storage, and transportation of hydrogen.
- In 2008, China issued the first safety standard for hydrogen system which is applicable to the preparation, storage, and transportation of hydrogen.
- Zhejiang University of China has established a hydrogen research laboratory to conduct systematic studies on hydrogen leakage, explosion, fire resistance of vehicle mounted hydrogen cylinders, and hydrogen risk assessment.
- In 2017, China issues GB/TC35544-2017 to cover vehicle mounted hydrogen storage cylinders. But the standard is applicable to fully wrapped carbon fiber cylinders with an aluminum liner but not applicable to Class 1, Class II, and Class IV cylinders. It should be noted that the standard is partly copied from foreign standards and therefore lack consistency with actual situation.
- Safety codes and standards have been established for the production, transportation, storage, and use of hydrogen. **Appendix D** gives a list of international safety codes and standards. An overview of the safety standards in China and overseas is summarized in **Table 2** and the main differences are summarized in **Table 3** below.

Table 2. Overview of hydrogen safety standards in China and abroad [18]

Order	Organization	Standard number	Standard names
1	Standardization Administration of the People's Republic of China (SAC)	GB/T 23751.1-2009	Micro fuel cell power systems—Part 1: Safety
2		GB/T 24549-2009	Fuel cell electric vehicles-Safety requirements
3		GB/T 27748.1-2017	Stationary fuel cell power systems—Part 1: Safety
4		GB/T 29729-2013	Essential requirements for the safety of hydrogen systems
5		GB/T 30084-2013	Portable fuel cell power system-Safety
6		GB/T 31036-2014	Proton exchange membrane fuel cell backup power system-Safety
7		GB/T 31037.1-2014	Fuel cell power system used for industrial lift truck applications—Part 1: Safety
8		GB/T 31139-2014	Safety technical regulations for mobile hydrogen refueling facility
9		GB/T 34539-2017	Safety requirements on hydrogen-oxygen generator

10		GB/T 34544-2017	Safety test methods for onboard low pressure hydrogen storage devices for small fuel cell vehicles
11		GB/T 34583-2017	Safety technical requirements for hydrogen storage devices used in hydrogen fuelling station
12		GB/T 34584-2017	Safety technical regulations for hydrogen refueling station
13		GB/T 36288-2018	Fuel cell electric vehicles-Safety requirement of fuel cell stack
14	International Organization for Standardization (ISO)	ISO/TR 15916:2015	Basic considerations for the safety of hydrogen systems
15		ISO 16110-1:2007	Hydrogen generators using fuel processing technologies Part1: Safety
16		ISO/TS 19883:2017	Safety of pressure swing adsorption systems for hydrogen separation and purification
17		ISO 21266-1:2018	Road vehicles — Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blends fuel systems—Part 1: Safety requirements

18		ISO 23273:2013	Fuel cell road vehicles — Safety specifications — Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen
19	American National Standards Institute (ANSI)	ANSI/AIAAG-095A-2017	Hydrogen and Hydrogen Systems

Table 3. Main Differences between Chinese and Foreign Standard Clauses [18]

Standard	Scope of applications	Gas cylinder test items	Normative requirements of the industrial chain	Other quality assurance terms
GB/T 35544-2017	Aluminum liner carbon fiber fully wound gas cylinder	Winding layer mechanical property test, winding layer appearance inspection, hydraulic pressure test, air tightness test, hydraulic burst test, normal temperature pressure cycle test, fire test, extreme temperature pressure cycle test, accelerated stress rupture test, crack tolerance test, environmental test, drop test,	The packaging, transportation, and storage of cylinders after the completion of the manufacture are specified, without involving the storage and transportation of relevant raw materials	Only manufacturing units are required to provide mass inspection quality certificates

		hydrogen gas cycle test, gunshot test, durability test, performance test		
ANSI HGV2-2014 and ISO/CD 19881:2015	Four types of gas cylinders	Environmental cycling test, extreme temperature cycling test, hydraulic burst test, defect tolerance test, drop test, fire test, accelerated stress fracture test, high strain rate impact test, penetration test, torque test, hydrogen cycle test, leakage test before fracture	No related terms	The manufacturing units needs to establish and operate a quality management system in accordance with the provisions of ISO9001.

\\

4. Control and Regulation of Hydrogen-related Facilities

In the USA, National Fire Protection Association (NFPA) standards, Part 2 - Hydrogen Technology Code, controls and regulates hydrogen related facilities. Specially it stipulates requirements for:

- Life safety in the building or structure in which hydrogen is stored, handled, or used.
- Proximity of hydrogen storage system for outdoor facilities that use or produce hydrogen.
- Local zoning, quantity restrictions, location.
- Permits for operation of the facilities.
- Prescriptive designs or performance-based designs of the facilities where hydrogen is handled is stored, produced, handled or use.
- Buildings and facilities to be designed, constructed, and maintained to protect occupants who are not intimate with the initial fire development to evacuate.
- Buildings to be designed and constructed to protect reasonable safety for fire fighters and emergency responders during search and rescue operations.
- Buildings to be designed and constructed to reasonably protect adjacent persons from injury or death as a result of a fire.
- Buildings to be designed and constructed to protect reasonable access to the building for emergency responders.
- Operations to be conducted at facilities in a safe manner that minimizes, reduces, controls or mitigate the risk of fire injury or death for the operators, while protecting the occupants not intimate with initial fire development to evacuate, relocate, or defend in place.
- The storage, use, or handling of hydrogen in a building or facility to be accomplished in a manner that provides a reasonable level of safety for occupants and for those adjacent to a building or facility from illness, injury, or death due to (a) an unplanned release of hydrogen, (b) a fire impinging upon the hydrogen piping or containment system or the involvement of hydrogen in a fire; (c) the application of an external force on the hydrogen piping or containment system that is likely to result in an unsafe condition.

- The facility to be designed, constructed, and maintained, and operations associated with the facility to be conducted, to prevent unintentional explosions and fires that result in failure of or damage to adjacent compartments, emergency life safety systems, adjacent properties, adjacent outside storage, and the facility's structural elements.
- Records to be maintained on the premises or other location and retention of records for not less than 3 years and records to be made available for inspected by Authority Having Jurisdiction (AHJ) and a copy to be provided to AHJ upon request.
- An emergency plan to be prepared wherever GH_2 or LH_2 are produced, handled, stored, or used in amounts exceeding the maximum allowable quantity per control area or where required by AHJ. The plan shall be available for inspection by AHJ and shall include (a) the type of emergency equipment available and its locations, (b) a brief description of any testing or maintenance programs for the available emergency equipment; (c) an indication that hazardous identification labeling is provided for each storage area; (d) the location of posted emergency procedures; (e) a safety data sheet or equivalent for GH_2 or LH_2 stored or used on the site; (f) a list of personnel who are designated and trained to be liaison personnel for the fire department and who are responsible for.

In the Ontario province of Canada, Ontario Regulation 214/01 - Compressed Gas stipulates the following requirements, among others:

- The Ontario province of Canada regulates the operation, installation, alternation, repair, servicing or removal of any equipment or appliance employed or to be employed in the handling or use of compressed gas or GV[3] or any use, supply, storage, transport, handling, transfer of compress gas or GV.
- Employers have the duty to instruct their employees to comply with the relevant Act and Regulation.
- Any person who handles compressed gas or GV must have a certificate for the purpose.

---

[3] Means a gas that is used as an engine fuel for a gas vehicle

- The distributor of gas to a premises shall examine and be satisfied that the installation of any appliance intended to use the gas complies with the regulation before it can be used for the first time. The distributor has the right of access to examine and disconnect the supply if the use does not comply with the regulation.
- Any person responsible for the operation of an appliance employed in the handling or use of compressed gas shall ensure that it is operated under a safe operating condition.
- A valid license is required for the operation of a retail outlet, a marina, a vehicle conversion centre, transport compressed gas, refueling station
- The working pressure of the piping downstream of the meter station of the distributor must not be more than 410 kPa
- Any alternation of a fuelling station must be approved.

Since the publication of the Law-Decree No 2021-167 of 17 February 2021, France has developed regulations concerning the use of hydrogen in the mobility sector for the injection of hydrogen into the gas networks. However, legal and regulatory framework, specifically for hydrogen, is not yet available in many other countries, including e.g., Germany and Japan.

5. Policies, Strategies and Plans of Leading Countries to promote Hydrogen Utilization

Various leading countries have promulgated their hydrogen strategies or Hydrogen Plans including USA, UK, China, EU, Germany, France, and Japan to produce, deliver, store, utilize and invest in Hydrogen technologies in the next 20-50 years to achieve net zero. A summary of the key actions is given below:

Table 4

Country	Document, year	Deployment Targets (2030)	Production	Uses	Public Investment committed
European Union	EU Hydrogen Strategy 2020	40 GW electrolytes	Electrolysis (renewables Transitional role of natural gas with CCUS	Transportation, Power generation, Industry	EUR 3.77 bln by 2030 (~US$4.3bln)
France	Hydrogen Deployment Plan 2018, National Strategy for Decarbonized Hydrogen Development, 2020	605GW electrolysis 20,000-50,000 FCEV, 400-1,000 HRSs	Electrolysis	Transportation, Power generation, Industry	EUR 7.2 bln by 2030 (~US$8.2 bln)
Japan	Strategic Roadmap for Hydrogen and Fuel Cells, 2019	Total use 3 Mt H_2/yr. Supply 420 kt low carbon H_2	Electrolysis fossil fuels with CCUS		JPY 699.6 bln (~US$6.5 bln)

	Green Growth Strategy, 2020, 2021 (revised)	800,000 FC EVs 1200 FC buses 10,000 FC forklifts 900 HRSs 3 Mt NH_3 fuel demand			
Korea	Hydrogen Economy Roadmap 2019	EUR 7.2 bln by 2030 (~USD 8.2 bln); 630,000 FCEV (2030)			KRW 2.6 Un om 2020 (~US$2.2 bln)
Germany	National Hydrogen Strategy, 2020	5 GW of generation capacity 14 TWh production capacity by 2025; 500 FCEV		Transport, Refinery and Chemical Industry	1.4 billion euros under National Innovation Program on Hydrogen and Fuel Cell Technology between 2016 – 2026; 310 million euro under Energy and Climate Fund between 2020-2023; 200 million euro on R&D; 600 million between 2020-2023 on regulatory sandboxes for energy; transition

USA	Hydrogen Program Plan	US$2/kg for hydrogen production and US$2/kg for delivery and dispensing for transportation application, US$1/kg hydrogen for industrial and stationary power generation applications; Fuel cell system cos of $80/kW with 25,000 hour durability for long-haul heavy-duty trucks; On-board vehicular hydrogen storage at US$8/kWh, US$2.2 kWh/kg and US$1.7 kWh/L; Electrolyser capital cost of US$300/kW, 80,000 hour durability and 65% system efficiency; Fuel cell system cost of US$900/kW	95% of the hydrogen is produced by catalytic steam-methane-reforming in large central plants	Transport, Chemicals and Industrial, Stationary Power Generation, Integrated/Hybrid Energy Systems	

		and 40,000 hour durability for fuel-flexible stationary high-temperature fuel cells; 40,000 FCEV (2023)			
China	Medium and Long-term Plan for Hydrogen Energy Industry Development (2021-2035), 2022	50,000 FCV by 2025 and 1 million FCEV (2030)	100,000-200,000 tonnes of green hydrogen by 2025 with 38 GW of electrolyser capacity by 2030		

6. Supply of Hydrogen - Production, Storage, Conversion and Delivery

6.1 Production of Hydrogen

6.1.1 General Outlook

- Even though hydrogen is the most abundant element in the Universe, it is not available in significant quantities in nature in pure form.
- The annual world production of hydrogen is about 88.7 billion kgs in 2020 [35]. About 50% of this is produced from natural gas and almost 30% comes from oil. Coal accounts for about 15% and less than 1% is produced by low-emission processes such as water electrolysis.
- Hydrogen production in the US is about 10 billion kg in 2020 [35], of which about 80% is by steam reforming of methane and 20% is a by-product of chemical processes such as chlor-alkali production. Water electrolysis represents only a niche segment of the market.
- Hydrogen demand increased by more than 20% per year during the 90' and has been growing at more than 10% per year since then. Most of this growth has been due to seasonal gasoline formulation requirements.
- Hydrogen can be produced from natural gas, gasoline, coal gas, methanol, propane, landfill gas biomass, anaerobic digester gas, other fuel containing hydrocarbons, and water.
- The abundant distribution and high energy content by weight (about 3 times that of gasoline) render it a promising substitute for traditional energy. There are three types of classifications of hydrogen based on the production method, including grey hydrogen, blue hydrogen, and green hydrogen. The price of the natural gas is about 0.25 €/m^3, while the prices of the three types of hydrogen are 0.12 €/m^3, 0.17 €/m^3, and 0.41 €/m^3 for grey, blue, and green hydrogen, respectively [2].
- Electrolysers using low-emission electricity are needed to produce low-emission hydrogen. According to Global Hydrogen Review 2022, [36], the current electrolyser manufacturing capacity sits at nearly 8 GW/yr. and it could exceed 60 GW/yr. by 2030 depending on government targets being translated into real-world projects beyond the current project pipeline.

6.1.2 Grey hydrogen (from steam reforming of fossil fuels) (approx. 80%)

Steam Reforming

- The most common large-scale process for manufacturing hydrogen is steam reforming of hydrocarbons, especially natural gas (mostly methane) as long as methane is cheap and in large quantities.
- Using fossil fuels to make hydrogen can take more energy than that contained in the hydrogen.
- Steam reforming converts methane and other hydrocarbon in natural gas into hydrogen and carbon monoxide using a nickel catalyst. This is achieved in a processing device called a reformer which reacts steam at high temperature with the fossil fuel. The steam methane reformer is widely used in industry to make hydrogen.
- Industrial production is mainly from the steam reforming of natural gas, and less often from more energy-intensive methods like the electrolysis of water. Commercial bulk hydrogen is usually produced by the steam reforming
- This reaction is favored at low pressures but is nonetheless conducted at high pressures (2.0 MPa, 20 atm or 600 inHg). This is because high-pressure H_2 is the most marketable product and Pressure Swing Adsorption (PSA) purification systems work better at higher pressures. The product mixture is often used directly to produce methanol and related compounds. Hydrocarbons other than methane can be used to produce synthesis gas with varying product ratios. One of the many complications to this highly optimized technology is the formation of coke or carbon:

  $CH_4 \rightarrow C + 2\ H_2$
- Consequently, steam reforming typically employs an excess of H_2O. Additional hydrogen can be recovered from the steam by use of carbon monoxide through the water gas shift reaction, especially with an iron oxide catalyst. This reaction is also a common industrial source of carbon dioxide:

  $CO + H_2O \rightarrow CO_2 + H_2$
- Steam reforming of fossil fuels is a mature technology for producing hydrogen with existing infrastructure, which accounts for 80-85% of hydrogen production among all the fuel processing paths, and the hydrogen production efficiency can

achieve 74-85%. Carbon emission inevitably happens during the steam reforming process, which is one of the main disadvantages of this technology of hydrogen production. Grey hydrogen is the cheapest among the three types of hydrogen and natural gas is the main feedstock. The price of natural gas influences the price of grey hydrogen. However, to pursue cost parity, hydrogen transfer efficiency should be enhanced, device price and raw material cost reduced, and eventually, production scaled up. The direct CO_2 exhaustion of grey hydrogen is 8 kg of CO_2 per kg of H_2, and the related cost of grey hydrogen is $1.60/kg in 2020. In addition to the high cost of production, environmental problems restrain the long-lasting adoption and production of grey hydrogen, such as carbon emission, which is against the original intention of achieving carbon neutrality.

6.1.3 Blue Hydrogen (from reforming of fossil fuels with carbon capture and sequestration) (approx. 10-20%)

Blue hydrogen is the hydrogen with Carbon Capture and Storage (CCS) involved in the grey hydrogen. In other words, although no direct CO_2 emission from blue hydrogen production, the generated CO_2 requires additional capture and storage. The carbon emissions of blue hydrogen produced from fossil fuel are safely mitigated but demand extra cost. There are many decisive factors for hydrogen production, such as fossil feedstock, CO_2 abatement strategies, technology readiness level (TRL), and their economics.

Relatively cleaner hydrogen can be obtained through CCS technology, and the greenhouse gases emission can be reduced at the same time. CCS technology is the key process of blue hydrogen production, but there remains a challenge to integrating it into the industrial procedure. The Global CCS Institute announced that 8 large-scale CCS projects were operated globally and 9 were under construction in 2013. Despite the achieved progress, economic factors are also taken into consideration to satisfy the hydrogen production on a large scale in the future

6.1.4 Green hydrogen (from renewable sources, e.g., solar, nuclear, electric grids, and biomass) (Increasing in percentage)

Green hydrogen is produced from renewable sources, which represents clean hydrogen with low carbon emissions. Also, one of the most important reasons for green hydrogen production is that the high cost of CCS can be avoided compared with the blue hydrogen. Green hydrogen has the promise of sustainable development in the future. Green hydrogen mainly includes nuclear hydrogen production, water electrolysis, solar water splitting, and so on.

By Electrolysis

- Electrolytic water splitting for hydrogen production is an established technology that has zero carbon emission, and oxygen is the byproduct of the electrolysis process. Electricity is required for this technology, which can be generated from renewable sources, such as solar and wind power. Green hydrogen can also be produced from biomass through microbial electrolysis technology, in which numerous substrates have been applied as fuels (such as glucose and acetate). When the price of methane goes up to more than three times its present price because of scarcity, hydrogen will be obtained more cheaply by splitting water H_2O into hydrogen H_2 and oxygen O_2 using any source of electricity.
- Electrolysis of water produced hydrogen and oxygen but is energy intensive. Steam adds heat to the process, making the process more energy efficient. A study by the MIT and Harvard concluded that hydrogen production by electrolysis of water will depend on the low-cost nuclear power.
- Using high temperature electrolysis, an electric current is sent through water that is heated to about 1,000 °C. But this process produces about half of the energy compared with the energy required for the process.

By Photocatalysis

- Photocatalysis water splitting shows great potential for hydrogen production without carbon emission, abundant feedstock (water) also provides the feasibility. The apparent quantum efficiency (AQE) over the irradiation wavelengths of 420 nm is low (<30%), despite the AQE being up to ~100% in the UV ranges from 350 nm to 360 nm. As a result, the maximum solar to hydrogen (STH) efficiencies are still at a low level, only around 1−2%, along with the unsatisfactory long-lasting stability, restraining its practical application and remaining challenges to achieve competitive performance (at least 10% STH efficiency with 10 years lifetimes). Thus, more efforts should be paid to enhance STH efficiency and durability by developing efficient photocatalysts and devices. Bio-photolysis consumes CO_2 and produces a low yield of hydrogen under mild conditions. However, enough sunlight and a large reactor are necessarily required. The material involved in this process is high-cost and oxygen-sensitive.

Use of Nuclear Power

- Water electrolysis using nuclear power offers a clean source of hydrogen.
- Nuclear power for hydrogen production is not producing hydrogen directly but produces clean electricity first that subsequently drives water electrolysis to produce hydrogen. International Energy Agency (IEA) predicts that to achieve the goal of net-zero carbon emissions by 2050, over 50% of all energy should come from clean electricity, and 70% to 80% of which should be produced by renewable sources with 20% to 30% by nuclear energy. Hydrogen storage and transportation are the main challenge in electrolytic water splitting, and the electrocatalyst fabrication and development should be economic-oriented and durable.

Use of Solar Electricity and Other Renewable Sources of Electricity

- New electrical production options include coal and nuclear power plants or solar technologies, such as photovoltaic wind and ocean thermal systems.

Dark and Photo Fermentation

- Hydrogen can be produced by biological methods from organic substances. Dark fermentation is an anaerobic process whereby in the absence of oxygen, organic substances can be decomposed by several microorganisms into Hydrogen, alcohol, and volatile fatty acid. On the other hand, under photo fermentation sunlight and two main types of bacteria (green Sulphur) and purple non-Sulphur bacteria are utilized to decay organic substances to produce hydrogen.

Coal gasification

- Hydrogen can also be manufactured from coal-gasification facilities
- The coal reaction can serve as a prelude to the shift reaction

$C + H_2O \rightarrow CO + H_2$

Gasification of MSW

Gasification is a thermochemical process that converts any carbon-based raw material or feed into fuel gas or synthesis gas also known as syngas. A primary feed/feedstock of gasification is biomass, natural gas, coal, municipal solid waste, and a variety of solid fuel. The process runs in a confined and controlled chamber known as gasifier where endothermal and exothermal reactions convert the feed into syngas and the residue or slag. The syngas is mainly composed of carbon monoxide and hydrogen which will be purified to remove impurities gases, e.g., hydrogen sulphide, Sulphur dioxide, etc. The syngas can be further converted to H_2 and carbon dioxide by the steam reaction.

Use of Landfill gas (biomethane)

Landfill gas can be used as feedstock for producing Hydrogen as it contains approx. 40-60 % v/v methane. Using reforming, hydrogen can be split through reforming from the biomethane to become Hydrogen and CO_2. The

CO_2 can be captured before it is released into the atmosphere.

Other Methods

- Other methods include generation recovery of byproduct hydrogen from electrolytic cells used to produce chlorine and other products, and dissociation of ammonia.
- Hydrogen can be manufactured from water with algae and other microorganisms.
- Other important methods for H_2 production include partial oxidation of hydrocarbons:

$$2\ CH_4 + O_2 \rightarrow 2\ CO + 4\ H_2$$

- For small volume production on site, small packaged electrolytic and hydrocarbon reforming systems are used. Highly packaged, compact hydrocarbon reformers are used on site to produce hydrogen.

6.1.5 Current Trends

- In the near term, the most viable options to produce hydrogen are via reforming of natural gas or renewable liquid fuels such as ethanol or methanol, and via small scale water electrolysis.
- In the longer term, large, centralized hydrogen production facilities (e.g., based on coal gasification with sequestration and biomass gasification are needed.
- Successful R&D is required for photolytic technologies to produce commercially viable systems that produce hydrogen directly from sunlight and water or other renewable sources.
- The cost for production must be competitive. DOE has a target of \$2.00~\$3.00/gge (which is gasoline gallon equivalent on an energy basis). Current production and delivery cost is 2~3 times higher.
- Cost for large scale production and large facilities approach the DOE target of \$2.00~\$3.00/gge. However, hydrogen delivery is more than double the cost of fuel.
- Distributed hydrogen generation with small hydrogen stations generating 1,500 kg/H_2/day offer an alternative to centralized production.

- For distributed hydrogen generation stations, the system will be mechanically and thermally integrated reformers with shift converters and the steam generators to maximize heat recovery, minimize heat loss and minimize the no. of BOP (Balance of Plant) components.
- By having reformers in buildings and even in home garages in combination with local power generation could reduce the delivery cost. Larger reformers in neighborhood facilities could be the services stations of tomorrow.

6.2 Purification

- Hydrogen can be purified by the following processes:
  - Pressure Swing Adsorption (PSA) is the common method
  - Gas permeation
  - Adsorption
  - Absorption
  - Distillation
  - Partial condensation
  - Catalytic oxidation

- The principle of PSA is that under pressure gases tend to adsorb to solid surfaces; the higher the pressure, more the gas is adsorb. When the pressure is reduced, the gas is released.
- Different gases tend to be adsorbed to different solid surfaces more or less strongly.
- A stream of hydrogen with impurities is passed under pressure to an adsorption bed, such as activated carbon, silica gel, alumina, and zeolites, that attract CO, N_2, O_2 and so on more strongly than it does to Hydrogen. Nearly pure hydrogen will leave the adsorption bed. The adsorption bed can be regenerated by reducing the pressure, thereby releasing the adsorbed molecules.
- PSA removes impurities such as CO, CO_2, CH_4, H_2O and H_2S. A typical PSA system involves a cyclic process where several connected vessels that contain adsorbent materials undergo successive pressurization and depressurization steps in order to produce a continuous stream of purified product gas.

6.3 Storage and Conversion

- Hydrogen can be stored as compressed gas, a cryogenic liquid or in solid form. To store as liquid, hydrogen must be cooled below its critical point of 33 K and compressed at 13.3 atmospheric pressure to form Liquid Hydrogen (LH). In order to be in a full liquid state without evaporation at atmospheric pressure, the gas must be cooled to 20.28 K which is the boiling point of LH.

- Three common approaches are used to store hydrogen
  - Compressed gas vessels operating at high pressure (typically 350 – 700 bar) and near ambient temperature, in typically tanks made of carbon fibre composite wound around an aluminum (Type III vessel) or polymer (Type IV tanker trucks/ships/vessels) liner
  - Liquid hydrogen vessels for low pressure (~6 bars) and temperature below H2 critical point (20~30K); consists of an inner stainless-steel vessel surrounded by vacuum insulation and an outer metallic vacuum jacket.
  - Cryogenic pressure vessel sometimes called cryocompressed vessels, compatible with both high pressure (350 bar) and cryogenic temperatures down to LH2 (20K) and comprising a Type III aluminum –composite vessel surrounded by a vacuum space and an outer metallic vacuum jacket.
- Compression in gas cylinders is a common method for hydrogen storage, which has been applied for ammonia synthesis and hydrocracking of heavy petroleum. Cryogenic liquid hydrogen storage exhibits advantages over compression in gas cylinders, which presents high storage volume and energetic density than the gaseous storage counterpart, but low temperature (-243 ºC) storage requires further consideration.
- Ammonia is a promising carrier for sustainable and large-scale hydrogen storage, which reaches an energy density of 3 $kWh\ kg^{-1}$ and a hydrogen capacity of 17.6 wt%. It is noted that there is no carbon emission using ammonia as feedstock. Catalytic thermal and electrochemical ammonia decomposition are two common methods for ammonia conversion to hydrogen.
- Use of Ammonia as a storage and distribution medium has several advantages e.g., liquefiable under mild conditions, low vapor pressure, and several disadvantages e.g., toxicity, social acceptance, etc.
- H_2 can be produced from stored ammonia through (a)Ammonia decomposition, (b) Hydrogen separation and purification, (c) Hydrogen storage and

compression. In contrast to other hydrogen storage materials, ammonia exhibits the merits of a high hydrogen capacity, a mature technology for production and distribution, liquefiable under mild conditions, and easy catalytic decomposition [17]. Besides, the advantage of ammonia is that there is no CO_2 emission at the end-user compared with other hydrocarbon energy sources. The drawbacks are that the liquid ammonia is toxic and is difficult to separate trace amounts of ammonia in hydrogen.

- Liquid hydrogen fuel systems would require changes in the energy infrastructure and end use system, such as stoves, engines and fueling systems.
- Cryogenic fuels are difficult to handle. A self-service liquid hydrogen pumping station was built decades ago at Los Alamos National Laboratory where it was shown to be feasible for refueling vehicles over an extended period of time without any major problems.
- Today, there are a number of hydrogen refueling stations in various parts of the world.
- Cryogenic storage is used by the National Aeronautics and Space Administration (NASA) for hydrogen, which along with liquid oxygen is used for rocket fuel since World War II.
- Liquid hydrogen can be stored in newer vessels that are relatively compact and light weight. General Motors has designed a 90-kg cryogenic tank that holds 4.6 kg (34 gallons) of liquid hydrogen.
- LH exists in its para-hydrogen isomer form to avoid exothermic reaction. Conversion to the para-hydrogen isomer form is by means of catalyst e.g., iron III oxide, activated carbon, chromium (III) oxide, etc.
- Liquid hydrogen must be stored in highly insulated tanks.
- Liquefying hydrogen requires special equipment and is very energy intensive. Then refrigeration requires multiple stages of compression and cooling and about 40% of the energy of the hydrogen is required to liquefying for storage.
- Smaller liquefaction plants tend to be more energy intensive and this make it a problem for local fueling stations.
- For large, centralized liquefaction units, about 12~15 kWh/kg of H2 is needed.
- Liquefied hydrogen tends to boil off and escape from tanks. It must also be handled carefully because of its low temperature.

- Compressing hydrogen is less expensive compared with liquefying hydrogen. The hydrogen is compressed to 3,600 ~ 10,000 psi. But even at this pressure, energy density per unit volume is low compared with gasoline.
- Compressing hydrogen requires an energy input equal to 10~15% of the fuel's energy. Compressing to 10,000 psi can take 5 kWh/kg hydrogen or more energy.
- The technical issues are the weight of the storage tanks. Stronger and lightweight materials are now used for making tanks and the tank volume is much reduced with the use of higher pressure. The current technology enables 20,000 psi (700 bars) tanks to be used. GM has developed a 20,000 psi storage system.
- Higher pressure increases cost and complexity requiring special materials, seals, and valves. Pressure tanks are usually cylindrical. On the other hand, liquid fuel tanks can be shaped according to their needs.
- Metal hydrides have been developed steadily for hydrogen storage ascribed to tunable material properties. Nanostructure construction endows these metal hydrides with accelerated interfacial reaction, enhanced reversibility, and altered heats of hydrogen absorption/desorption.
- Metal hydrides have been considered to be a competitive transformative technology for hydrogen storage [15]. The morphology of individual nanomaterials and the nature of interactions influence the properties of the metal hydride. Reducing particle size to nanoscale dimensions provides a new feasible way to optimize the property of hydrogen storage by metal hydrides. Various porous host matrixes have been proposed to support the metal hydride nanomaterials, such as carbon nanotubes, mesoporous zeolite, metal-organic framework (MOF), etc. However, important challenges still exist considering both fundamental understanding and practical application of metal hydrides.
    - At high enough pressure and temperature, the adsorbed hydrogen molecule can be dissociated by transferring an electron between the metal and the hydrogen and becomes chemisorbed.
    - Cyclic stability is an important parameter as it determines the ability of the metal hydride to retain its reversible storage during repeated hydrogenation and dehydrogenation cycles.

  - DOE storage target specifies 1500 cycles for a good hydrogen storage material.
  - There are intrinsic and extrinsic degradations governing the cycling stability.
  - Gas impurities such as O_2, CO, CO_2, SO_2, H_2O, H_2S and NH_3 could react and poison or corrode the metal or metal hydrides surfaces, reducing hydrogen adsorption/desorption.

6.4 Delivery and Transportation of Hydrogen

Delivery/transportation or the fuel distribution system from the site of manufacture of the hydrogen to the end user is crucial for any hydrogen-based economy. Hydrogen presents unique challenges because of its extremely low density as a gas and liquid, high diffusivity, and flammability relative to hydrocarbons. These unique properties present the biggest challenges for integrating hydrogen into the energy system. Also critical is the form of hydrogen being transported. Hydrogen can be transported in its elementary form as a pressurized gas or a cryogenic liquid, or in the form of hydrogen made into compounds or physically adsorbed onto various substances. Typical examples of the latter form are ammonia, methanol, and metal hydrides.

In order to transport and distribute hydrogen, different technologies are possible. These technologies not only allow for the transport of hydrogen, but also for its storage:

- Pressurised hydrogen: hydrogen can be pressurised for storage and transportation. This pressurisation can be applied to pure hydrogen or to hydrogen mixtures with other gases.
- Liquefied hydrogen: hydrogen liquefies at −253°C. Liquefaction increases the density of hydrogen by a factor of around 800, and the storage volume falls correspondingly. Once liquefied, it can be maintained as a liquid in pressurized and thermally insulated containers. At the end-use, liquefied hydrogen is vaporized into its gaseous form before use.

- Synthetic gas: hydrogen can be combined with CO_2 through a chemical reaction and transformed into methane. This results in synthetic gas (which is mainly methane, the main component of natural gas) and it can easily be transported and stored within the existing gas infrastructure with no modification.
- Ammonia: hydrogen can be combined with nitrogen to produce ammonia which allows for the transportation/storage in liquid state (liquefaction at around −30°C) in refrigerated tanks. At the end-use, the ammonia is broken down into its components, nitrogen, and hydrogen, through an endothermic cracking process.
- Liquid organic hydrogen carriers (LOHC): hydrogen can be converted to an easy-to-handle organic liquid which enables a safe and effective high-density hydrogen storage, thus eliminating the need for pressurized tanks for storage and transportation. At the end-use, the hydrogen is released via an endothermic dehydrogenation process. The dehydrogenated LOHC can then be transported back to the hydrogen manufacturer for reuse. Common organic carrier substances available are toluene, dibenzyltoluene and benzyltoluene.
- Methanol: Hydrogen can be combined with CO_2 to produce methanol, which allows transport and storage of hydrogen in liquid state.

Different forms of hydrogen mentioned above can have different transportation methods. In general, transportation can be broadly classified into (a) continuous transportation and (b) batch transportation. Pipelines are commonly used for continuously transporting hydrogen in gaseous or liquid form. Regarding the batch transportation of hydrogen, it could involve transportation of pressurized hydrogen, liquid hydrogen, or chemicals such as ammonia or metal hydrides, etc., stored in vessels that are loaded onto mobile units.

In general, gaseous hydrogen is usually transported by either pipelines or tube trailers, while liquid hydrogen is moved by road tankers. For short distances and small amounts, delivery of gaseous hydrogen by tube trailers is usually the option of choice. For medium amounts and long distances, liquid tankers are likely preferred, while large amounts over long distance are usually moved by pipelines, if available.

(a) Continuous Transportation of Gaseous Hydrogen by Pipeline

Hydrogen in pressurized gaseous form, and liquid or slush hydrogen are two viable forms for transporting hydrogen by pipeline. At present liquid hydrogen is only transported by pipeline for limited purposes in limited areas such as space rocket launching bases. On the other hand, there are many successful cases of pipeline transportation of gaseous hydrogen, like natural gas and Towngas, throughout the world for both small-scale local network and long extensions over wide areas such as in Europe and North America. Pipeline supply of gaseous hydrogen is effective for delivering hydrogen to many high-capacity users. However, the energy required for compressing and pumping hydrogen is considerable.

Current pipeline systems are based on steel pipes, typically 25-30 cm in diameter and operate at a pressure of 10-20 bar, but there is potential for using fibre-reinforced polymer pipes for cost reduction and better performance. Before injection, the hydrogen is mechanically compressed to the operating pressure of the pipeline and may be required to recompress at certain distances along the pipeline before it reaches its end-users.

Instead of building new pipelines, existing natural gas or Towngas pipelines can be repurposed to transport hydrogen. The injection of hydrogen into existing gas grids is under trial, with blends of up to 20% hydrogen currently being tested in pilot projects.

Hydrogen transportation through pipeline is proven with successful operations in Europe and the US and has the advantages of low operational costs and long lifetimes. Pipelines can also act as a storage buffer, especially for off-grid green hydrogen production as their pressure can be adapted to ensure continuous supply. The repurposing of existing pipelines is also advantageous in terms of public acceptance. However, there are concerns about the viability of repurposing old natural gas pipelines due to material compatibility.

On the other hand, the high initial capital costs and long construction lead times of new pipelines constitute a major barrier of pipeline transportation. Due to its high capital costs, large volume of hydrogen is necessary to guarantee acceptable utilization rates. Moreover, distribution is limited due to the fixed routing in distribution infrastructure.

(b) Batch Transportation of Hydrogen

For large volumes of hydrogen transportation, pipelines are a low-cost option and will play a major role in the transportation system in the future. However, due to its fixed routing and the high dispersion of large-scale hydrogen demand across geographies, many end-users will still leave unsupplied. In addition, pipelines will not be a feasible or the most cost-efficient option to support future import routes from outside China. More flexible hydrogen transportation options will be needed to fill the gap.

Therefore, batch transportation should also be considered to best suit potential off takers not located along a pipeline grid, and that enable the long-distance transportation of hydrogen in the forms of hydrogen carriers, like LPG tankers. In Hong Kong, hydrogen trailers are used to deliver hydrogen to power plants for generator cooling. At normal temperature and pressure, hydrogen has a very low density and large volume. Therefore, to minimize its apparent volume before transporting and storing, apart from the transport via pipelines, hydrogen can be also transported in batch via:

- Pressurized hydrogen in vessels: a common method of transporting hydrogen gas in batch to fill in pressure-proofed vessels to be carried by vehicles. Cylinders each with an internal capacity of about 50L, a filling pressure of 1.5 MPa to 2 MPa, and a hydrogen capacity of 7 to 10 m^3N are usually used, although long vessels of 700L are also used. Dozens of hydrogen vessels are put together in a cradle, or a self-loader or a trailer, which can be transported by a truck. The quantity of hydrogen that can be transported at one time using pressure vessels is small. Thus, transportation by pressurized hydrogen in a vessel is still only a small percentage of all methods.

- Liquefied hydrogen in vessels: Dewar vessels are commonly used for transporting 1,000 L or less and containers are used for transporting up to 10,000 L. Loss occurs due to hydrogen flash when the liquid hydrogen is transferred from one vessel to another, thus dual-purpose storage/transportation vessels are commonly used to reduce loss from transfer between vessels. Tanker trucks with large tank capacities up to 60 kL are used to transport liquid hydrogen over relatively long distances (up to 2,000 km). However, the quantity of energy transported per day is also small.
- Hydrogen carriers (e.g., methanol, ammonia, metal hydrides) in vessels: Among hydrogen carriers, the methanol system, ammonia system and metal hydrides system are already in common practical use, giving efficient and economical storage. Metal hydrides with large hydrogen packing densities have been developed to adsorb and release hydrogen at relatively low temperatures and the waste heat is needed to be used as the source of the heat needed for hydrogenation and dehydrogenation. Example of transporting vessels developed is outer wall electric heater type aluminum vessels using Ti-Fe-Mn base metal hydride, and atmospheric heat exchange type vessels made of stainless steel or copper using Mn-Ni-Fe base metal hydride. For transportation of hydrogen using organic compounds and carbon materials, ammonia system, methanol system and methyl cyclohexane system are most promising for ocean transportation or long-distance transportation.

  Typical vessels are tankers and tube trailers. Tankers typically have a larger capacity of 400 to 4,000 kg of liquid hydrogen, while tube trailers typically contain 300 kg of gas stored at a pressure of up to 200 bar and are used for small deliveries to customers who usually are close to the hydrogen production plant or terminal in order to reduce the high cost of carrying small amounts of product. The key advantage of tube trailers is the flexibility, e.g., to deliver hydrogen to new users if they are not yet connected to a distribution pipeline.

Vessels of hydrogen can be transported via different typical means:

- Hydrogen truck loading: transportation of hydrogen by truck in gaseous or liquefied form, or via liquid or gaseous hydrogen carriers.
- Transportation by rail: transportation of hydrogen in gaseous form or gaseous hydrogen carriers using compressed gas cylinders via tube trailers or as a liquid in specialized containers for transporting hydrogen in liquid form or via liquid hydrogen carriers.
- Hydrogen shipping: transportation of hydrogen over large distances by ship in gaseous or liquid form, or via liquid or gaseous hydrogen carriers
- Marine terminals: hydrogen can be exported or imported via sea-side terminals including LNG terminals with designs suitable for that task. These terminals can be multi-purpose to act as multi-energy carrier entry gates in providing maritime logistics, storage, conversion, pipeline connections and quality management.

7. Demand in Hydrogen - Application and Utilization

7.1 <u>Transportation</u>

- The potential for future use of hydrogen in road transport is very large. Any road transport mode can technically be powered using hydrogen, either directly using fuel cells or via hydrogen-based fuels in internal combustion engines. According to a recent PreScouter Intelligence Brief, [21] in the absence of an infrastructure to enable Fuel Cell Electric Vehicles (FCEV), Battery Electric Vehicles (BEV) remain the more appealing option today. However, this could change within the next five to 10 years as investments in hydrogen production and infrastructure increase, potentially pushing FCEVs to outperform BEVs in some segments and become the more sustainable alternative.
- FCEVs have nevertheless been slow to take off. Technical challenges and high prices have delayed their market introduction. While the Hyundai Tucson-ix 35 was introduced in 2013 and the Toyota Mirai in 2014, there is a need to further reduce costs and build up refuelling station networks concurrently with vehicle uptake if more automakers are to be attracted to the market.
- Global FCEV deployment has been primarily focused on light-duty passenger

cars. However, the geographical distribution of FCEVs varies significantly. Korea, the United States and Japan have concentrated on passenger cars, with a small number of buses and commercial vehicles.

- On the other hand, with its fuel cell bus and commercial vehicle policies, China today dominates worldwide stocks in these segments. This trend is anticipated to continue, as China's 2020 fuel cell car subsidy policy focuses on employing fuel cells in medium- and heavy-duty commercial vehicles. China has set a goal of using over one million FCEVs for commercial purposes by 2030.
- There will be more fuel cell buses and trucks in Europe in the near future. More than a thousand buses are planned during the next decade. The Port of Rotterdam and Air Liquide have developed an initiative to deploy 1,000 fuel cell trucks by 2025, and a joint call signed by over 60 industrial partners aims for up to 100,000 trucks by 2030. The IEA forecasts that fuel cell manufacturing could produce six million FCEVs by 2030, meeting roughly 40% of the "Net Zero Emissions by 2050 Scenario" needs.
- Global technical regulations are continually updated to assure global FCEV safety. International standards are used to build localized safety regulations and laws for FCEVs. They usually incorporate electrical and hydrogen safety requirements.
- Because hydrogen has a poor volumetric energy density, storing enough onboard poses weight, volume, kinetics, safety, and cost challenges. Hydrogen can only be stored under high pressure, at extremely low temperatures as a liquid, or in metal hydride systems to maximize volumetric energy density.
- Compressed hydrogen is the most used method for storing hydrogen in cars. Passenger FCEVs' compressed hydrogen tanks are cumbersome and take up a lot of space. This is a flaw in the current generation of electric cars powered by hydrogen fuel cells. Hydrogen metal or non-metal hydrides could be used in the future as a replacement for heavy hydrogen tanks. This is just beginning to take shape, with hydrogen evaporation remaining a key technical problem to overcome.
- Honda and Nissan chose a 350 bar (5,000 psi) pressurized tank, while Toyota employs 700 bar (10,000 psi) tanks. Although the 10,000 psi composite tanks have been proved to be quite safe as needed by various regulatory requirements,

the public is concerned about their safety. Moreover, the tank proportions require more space than traditional petrol tanks.

- FCEVs will not be commercially viable unless buyers are satisfied that they will be able to easily access refueling stations. Thus, the adoption of fuel cell vehicles should be complemented with enabling infrastructure.
- A potential problem with the Proton Exchange Membrane fuel cells is life span. Internal combustion engines have an average life span of 15 years or about 170,000 miles. Membrane deterioration can cause PEM fuel cells to fail after 2,000 hours or less than 100,000 miles.
- Several figures on Hydrogen fuel Cells technology:

  - Hyundai will deliver a consumer SUV in California
  - Connecticut is using fuel cell to power the grid
  - AT&A is using fuel cell to power server farms
  - Walmart uses hydrogen powered fork-lifts.
  - FedEx will use hydrogen powered cargo tractors at its Memphis air hub.
  - Hydrogen fuel cells used to be expensive, but technological advancements in recent years have lower the cost
  - According to IEA Advanced Fuel Cells Technology Collaboration Programme statistics, there are about 34,804 fuel cell vehicles, of which 25,932 are passenger cars and 540 hydrogen refueling stations in operation in 2020 [27].
  - South Korea has most passenger cars equipped with fuel cell technology on its roads. China leads global markets for buses and medium-duty trucks. Refueling stations in Japan, Germany, China, and the U.S. represent a significant share of 63% of the total number of stations worldwide.
  - AT&T is the largest non-utilities fuel cell customer in the US. It has 17.1 MW of fuel cells operating at 28 sites in California and Connecticut. Fuel cells are reliable. AT&T uses fuel cells to ride through power disruption.

7.2 Domestic Cooking and Heating

- Hydrogen gas has the highest calorific value i.e., 150 kJ/kg. In addition, it is a clean fuel and hence Hydrogen can be used for domestic cooking and heating, just like natural gas or Towngas in Hong Kong. However, it is not yet used as a fuel due to several technical problems to be resolved at this stage.
- First are the utilities' urban gas distribution networks. Hydrogen is much smaller than natural gas. Natural gas distribution networks leak all the time. The first major problem is that hydrogen will leak a lot more. Substantial retrofit costs to plug a lot more leaks than they bother to plug today. Venting 8 times more expensive hydrogen to the atmosphere will change the economics of that very rapidly.
- Second is that the pumps in natural gas systems are hard steel, and hydrogen embrittles hard steel. All the pumps need to be replaced, even if the plastic piping in modern urban utilities' distribution systems might be fit for purpose.
- Third is the problem is that hydrogen is harder on electronics than natural gas, so most of the sensors in the system must be replaced too, along with technicians' kit.
- Fourth is that hydrogen being much less dense, takes 3 times the energy to push it through pipes as natural gas. This is roughly 8× the cost delivered per GJ.
- Fifth is that people living with natural gas are already living with a bunch of risks that they think are normal. These includes gas explosions which kill them and their families, gas leaks which simply cause fires which burn their houses down, carbon monoxide poisoning from incomplete combustion of natural gas which can kill them or their families or simply leave them with severe brain damage, and finally nitrous oxides which cause indoor air pollution leading to cardiovascular problems.
- Hydrogen only eliminates the carbon monoxide risk. All the other risks persist. A lot of careful engineering and building codes work has been done to make natural gas safe for use in homes and buildings, and must be redone with inevitable mistakes for hydrogen.
- The next problem is that hydrogen furnaces and stoves do not exist outside of prototypes. None are manufactured and sold today. None of the current gas appliances will work with hydrogen. Once again, hydrogen is harder on hard steels and electronics, and the burning characteristics are different. Getting a gas stove to work with hydrogen would require replacing almost everything

inside the gas stove. Getting a gas furnace to work with hydrogen would require replacing almost everything inside the furnace.

7.3 Stationery and Power Generation Applications

Coal, oil and petroleum, and natural gas have been the main fuels for electricity generation in many countries. In Hong Kong the fuel mix as at 2020 (on sent-out basis) is 48% natural gas, 24% coal and 28% nuclear energy and renewable energy. The electricity consumption increased from 150,705 TJ in 2010 to 159,124 TJ in 2020, an increase by 5.6%, according to Hong Kong Energy statistics 2020 Annual Report. In order to meet the increasing power demand due to population growth and economic development, there is an urgent need to find alternative fuels that can maintain stable supply of energy while contributing to decarbonization of thermal power generation and carbon neutrality.

Power companies worldwide, including Mitsubishi Power in Japan are working to apply non-CO_2 emitting fuels such as hydrogen and ammonia to power generation.

The hydrogen power technology can replace natural gas, the fuel for gas turbine combined cycle power (GTCC) generation which currently releases the least amount of CO_2 among thermal power generation systems, e.g., coal-fired power plants. According to Mitsubishi Power, a 400 MW class GTCC power plant uses about the same amount of hydrogen as 2 million fuel-cell vehicles. Mitsubishi Power is also developing solid oxide fuel cells (SOFC) for distributed power supply. Launched in 2019, Mitsubishi Power has put in place a Hydaptive Integrated package and Hydaptive Storage package. The Hydaptive Integrated package provides a near-instantaneous power balancing resource that greatly enhances the ability of a simple cycle or combined cycle power plant to ramp output up or down to provide grid balancing service. It integrates a hydrogen and natural gas fueled gas turbine power plant with electrolysis to produce green hydrogen using 100% renewable power and onsite storage of green hydrogen. Hydaptive Storage package combines the Hydaptive Integrated package with access to a large-scale off-site hydrogen production and storage infrastructure to sustain the supply of carbon free green hydrogen during the peak energy demand period. The two combined will solve the challenges faced by power plant operators and power transmission companies by integrating renewable energy, gas turbine, green hydrogen, and fuel storage technology, etc. to drive the momentum towards a 100% carbon free power generation. The Hydrogen produced by wind and solar power is stored in a salt dome with the capacity to store the equivalent of 150GWh of energy. In 2018, Mitsubishi Power had already achieved 30% hydrogen co-combustion by burning a mix of LNG and 30% hydrogen which reduces about 10% in CO_2 emissions compared with GTCC, while allowing suppression of NOx emissions to the level of gas-fired thermal power and aims to make this 100% hydrogen by 2025.

According to Mitsubishi Power:

- Standard coal-fired power generation: 863 g-CO_2/kWh
- Ultra-critical (USC) coal-fired power generation: 820 g-CO_2/kWh
- GTCC power generation: 340 g-CO_2/kWh
- Hydrogen 30% mixed-combustion gas turbine: 305 g-CO_2/kWh

Burning 100% hydrogen increases the risk of flashback and NOx concentration. A combustor for hydrogen-fired power generation demands technology that enables efficient mixing of hydrogen and air and stable combustion.

Improvements are being made by Mitsubishi Power in the fuel delivery nozzles to increase the mixing of hydrogen with air before burning on a smaller scale and low-NOx combustion can be accomplished. Currently, Japan needs hydrogen infrastructure for the stable supply and delivery of Hydrogen and the technology for collecting and retaining the CO_2 emitted during the process.

Fuel cells can be installed in buildings to provide combined heat and power (CHP). Japan is the global leader in micro-CHP fuel cell technology with 430,000 units installed at end of 2021. Apart from Japan, Europe, Korea and United Stated have also installed stationary fuel cell units in their building sector [36].

References

[1] M.-K. Kazi, F. Eljack, M.M. El-Halwagi, M. Haouari, Green hydrogen for industrial sector decarbonization: Costs and impacts on hydrogen economy in Qatar, Computers Chemical Engineering (New York) 145 (2021) 107144.

[2] M. Mayrhofer, M. Koller, P. Seemann, R. Prieler, C. Hochenauer, Assessment of natural gas/hydrogen blends as an alternative fuel for industrial heat treatment furnaces, International Journal of Hydrogen Energy 46 (2021) 21672-21686.

[3] F. Dawood, M. Anda, G. Shafiullah, Hydrogen production for energy: An overview, International Journal of Hydrogen Energy 45 (2020) 3847-3869.

[4] S. Moon, Y. Lee, D. Seo, S. Lee, S. Hong, Y.-H. Ahn, Y. Park, Critical hydrogen concentration of hydrogen-natural gas blends in clathrate hydrates for blue hydrogen storage, Renewable Sustainable Energy Reviews 141 (2021) 110789.

[5] A. Boretti, There are hydrogen production pathways with better than green hydrogen economic and environmental costs, International Journal of Hydrogen Energy 46 (2021) 23988-23995.

[6] G. Kakoulaki, I. Kougias, N. Taylor, F. Dolci, J. Moya, A. Jäger-Waldau, Green hydrogen in Europe–A regional assessment: Substituting existing production with electrolysis powered by renewables, Energy Conversion Management 228 (2021) 113649.

[7] A. Oni, K. Anaya, T. Giwa, G. Di Lullo, A. Kumar, Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions, Energy Conversion Management 254 (2022) 115245.

[8] N. Muradov, Low-carbon production of hydrogen from fossil fuels, Compendium of hydrogen energy, Elsevier2015, pp. 489-522.

[9] M.H.A. Khan, R. Daiyan, P. Neal, N. Haque, I. MacGill, R. Amal, A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage & utilisation, International Journal of Hydrogen Energy 46 (2021) 22685-22706.

[10] A. Kadier, Y. Simayi, M.S. Kalil, P. Abdeshahian, A.A. Hamid, A review of the substrates used in microbial electrolysis cells (MECs) for producing sustainable and clean hydrogen gas, Renewable Energy 71 (2014) 466-472.

[11] H. Song, S. Luo, H. Huang, B. Deng, J. Ye, Solar-Driven Hydrogen Production:

Recent Advances, Challenges, and Future Perspectives, ACS Energy Letters 7 (2022) 1043-1065.

[12] G. Sdanghi, G. Maranzana, A. Celzard, V. Fierro, Review of the current technologies and performances of hydrogen compression for stationary and automotive applications, Renewable Sustainable Energy Reviews 102 (2019) 150-170.

[13] C. Correa-Jullian, K.M. Groth, Data requirements for improving the Quantitative Risk Assessment of liquid hydrogen storage systems, International Journal of Hydrogen Energy 47 (2022) 4222-4235.

[14] F. Chang, W. Gao, J. Guo, P. Chen, Emerging Materials and Methods toward Ammonia-Based Energy Storage and Conversion, Advanced Materials 33 (2021) 2005721.

[15] A. Schneemann, J.L. White, S. Kang, S. Jeong, L.F. Wan, E.S. Cho, T.W. Heo, D. Prendergast, J.J. Urban, B.C. Wood, Nanostructured metal hydrides for hydrogen storage, Chemical Reviews 118 (2018) 10775-10839.

[16] K.E. Lamb, M.D. Dolan, D.F. Kennedy, Ammonia for hydrogen storage; A review of catalytic ammonia decomposition and hydrogen separation and purification, International Journal of Hydrogen Energy 44 (2019) 3580-3593.

[17] A. Klerke, C.H. Christensen, J.K. Nørskov, T. Vegge, Ammonia for hydrogen storage: challenges and opportunities, Journal of Materials Chemistry A 18 (2008) 2304-2310.

[18] Xianfeng Chen et al, 2022, “Research and Development of Hydrogen Energy Safety”

[19] http://www.hysafe.net/wiki/BRHS/BRHS on the biennial reports on hydrogen safety

[20] https://www.nrdc.org/experts/christian-tae/hydrogen-safety-lets-clear-air on hydrogen safety

[21] https://www.brinknews.com/the-battle-over-electric-vehicles-could-hydrogen-win/ on performance of fuel-cell electric vehicles and battery electric vehicles

]22] https://h2tools.org/hystep-hydrogen-station-equipment-performance-device on Hydrogen Station Equipment Performance (HyStEP) Device.

[23] http://www.hysafe.net/wiki/BRHS/GlobalAgreementsonRoadVehicles on global agreement on road vehicles

[24] The Future of Hydrogen: Seizing Todays' Opportunities, report prepared by IEA for G20, Japan, June 2019

[25] Kim Ki Chui, 2017, "A review on design strategies for metal hydrides with enhanced reaction thermodynamics for hydrogen storage applications", International Journal of energy Research.

[26] Hydrogen Power Generation Handbook, Mitsubishi Heavy Industries Limited, Energy system

[27] Deployment Status of Fuel Cells in Road Transport: 2021 Update", IEA Technology Collaboration Programme, ISSN 1866-1793, 2021

[28] Kumar, S. Miles, S.D., Adams P., Kotchourko, A., Hedley, D., Middha, P., Molkov, V., Teodorczyk, A., and Zenner, M." (2009), "HYTUNNEL Project to Investigate the use of Hydrogen Vehicles in Road Tunnels", http://conference.ing.unipi.it/ichs2009/images/stories/papers/241.pdf

[29] Hyung-Seok Kang, Sang-Min Kim and Jongtae Kim, (2022) "Safety Issues of a Hydrogen Refueling Station and a Prediction for an Over pressure Reduction by a Barrier Using OpenFoam Software for an SRI Explosion Test in an Open Space". Energies, 2022, 15,7556.

[30] G.W. Mair, S. Thomas, B Schalau, and B. Wang, "Safety criteria for the transport of hydrogen in permanently mounted composite pressure vessels", International Journal of Hydrogen Energy 46 (2021) 12577-12593

[31] Hao Li, Xuewen Cao, Yang Shao, Zilong Nan, >Lin Teng, Wenshan Peng, Jiang Bian, (2022), "Safety of Hydrogen Storage and Transport: An Overview on Mechanisms, Techniques and Challenges", energy Reports 8, 6258-6269

[32] Green, M.A., 2006. Hydrogen safety issues compared to safety issues with methane and propane. AIP Conf. Proc. 823, 319–326.

[33] Joren Depken, Alexander Dyck, Lukas Roβ and Sören Ehlers, (2022), "Safety Considerations of Hydrogen application in Shipping in Comparison to LNG, Energies 15, 3250. http://doi.org/10.3390/en15093250

[34] Hydrogen Council Report, (Jan 2020) "Path to Hydrogen Competitiveness. A cost perspective"

[35] "Hydrogen's Present and Future in the US Energy Sector", 2021

[36] "Global Hydrogen Review, 2022", International Energy Agency, 2022

[37] Wikipedia: Hydrogen Economy

[38] Kuchta, Joseph M., (1985), *Investigation of Fire and Explosion Accidents in the Chemical, Mining, and Fuel-Related Industries A Manual*, U.S. Bureau of Mines Bulletin 680.

[39] Peschka, W,, (1987), "The status of handling and storage techniques for liquid hydrogen in motor vehicles." in *International Journal of Hydrogen Energy*, 12:753-

764, [40] Bockris, J O'M and J.C. Weiss., (1988), "About the real economics of massive hydrogen production at 2010 AD" by in *Hydrogen Energy VII*, edited by T.N. Veziroglu and A. N. Protsenko, pp. 101-151. New York. Pergamon Press.

[41] Winter, C. J., (1986) "Hydrogen energy - expected engineering break-throughs", , in *Hydrogen Energy Progress VI*, edited by N. Veziroglu, N. Getoff and P. Weinzierl, pp. 9-29, New York, Pergamon Press.

[42] "State of the World" (1989), Worldwatch Institute.

[43] Molkov, V., (2020), " The progress in hydrogen safety research". 8th International Symposium on Nonequilibrium Processes, Plasma, Combustion, and Atmospheric Phenomena

[44] Reider, Roy, (1965) An Unconfined, Large-Volume Hydrogen-Air Explosion, Pyrodynamics, 2, 249-261.

[45] Lees, F.P., (1991), in *Loss Prevention in the Process Industries*, Vol 3, Butterworth Heinemann Ltd., Oxford - Case History A77, at Ilford, Essex, Appendix 1 page 48; Case History A126, at Richmond, California, Appendix 1 page 62; Case History B33, at an unreported location, Appendix 1 page 72.

[46] Anon, (1922), Spontaneous Ignition of Escaping Hydrogen, Engineering, **113**, April 21, page 502.

[47] Fenning, R.W., & Cotton, F.T., (1930), Two Unexpected Hydrogen-Air Explosions, Engineering, 130, August 22, page 252.

[48] Hydrogen and Fuel Cells: Advances in Transportation and Power, http://what-when-how.com/Tutorial/topic-1153g5p/Hydrogen-and-Fuel-Cells-Advances-in-Transportation-and-Power-39.html