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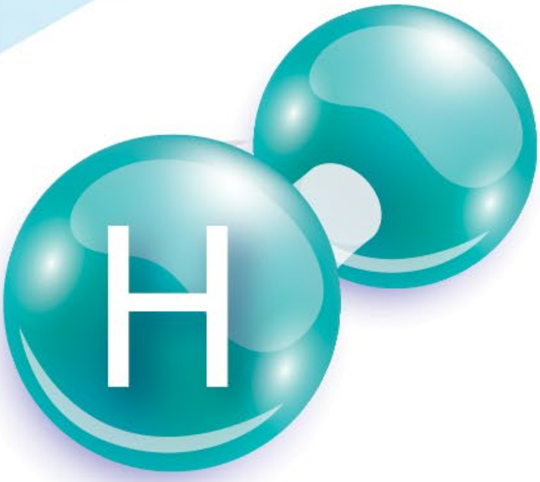
International Hydrogen Ramp-Up Programme (H2Uppp)

# Feasibility Study on Applications of Green Hydrogen to Railways in Thailand

2024

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## Preface

Welcome to this comprehensive feasibility study exploring the potential of green hydrogen in Thailand's railway sector, conducted in collaboration with German-Thai Railway Association under the International Hydrogen Ramp-Up Programme (H2Uppp). As the Director of Transport Project leading this initiative, I am delighted to present our findings, a culmination of dedicated efforts from experts, researchers, and industry partners.

Thailand's commitment to carbon neutrality by 2050 has set the stage for transformative shifts in our energy landscape. Hydrogen, particularly in the form of green hydrogen, emerges as one of a key player. Our report dives deep into the potential of hydrogen applications of hydrogen technologies within the railway sector, exploring how they can power locomotives, enhance efficiency, and reduce emissions.

Just as ammonia evolved from fertilizer to green energy carrier, hydrogen is no poised to revolutionize rail travel. We analyse global trends, production dynamics, and trade patterns, laying the groundwork for understanding Thailand's unique position within Southeast Asia.

A crucial aspect of our study involves analysing the policy and regulatory frameworks that support hydrogen usage in railways. By drawing insights from international case studies and tailoring them to Thailand's unique condition, we outline a roadmap for policy development and regulatory alignment.

Safety remains a paramount concern, and this study rigorously examines the safety standards and practices essential for hydrogen-powered railways. Economic viability is another key focus, with an in-depth analysis of the hydrogen supply chain and a Total Cost of Ownership (TCO) model. This financial assessment provides a clear picture of the economic benefits and challenges associated with green hydrogen in railways.

Finally, we present potential pathways for integrating green hydrogen into Thailand's railway network. By exploring scenarios for production, transportation, and application, we identify the enabling mechanisms and strategies needed to drive this transition.

I extend my heartfelt gratitude to the dedicated team, collaborators, and contributors who have shaped this study. It is my sincere hope that this endeavour not only contributes to academic discourse but also serves as a practical guide for stakeholders invested in Thailand's sustainable energy future.

Thank you for joining us on this transformative journey.

Dr Dominika Kalinowska
Director of GIZ's Transport Projects Thailand/ASEAN

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# EXECUTIVE SUMMARY

The Feasibility Study on Applications of Green Hydrogen to Railways in Thailand report offers a comprehensive examination of the feasibility and implications of integrating green hydrogen technology into Thailand's railway sector. Chapter 1, Background Information, sets the stage by providing context and outlining the significance of green hydrogen technology in advancing sustainable transportation solutions. In Chapter 2, Technological Perspectives of (Green) Hydrogen for Railway Applications, various aspects of hydrogen technology related to railway applications, such as green hydrogen production, storage, refuelling stations, and applications to railway transport modes, are explored, shedding light on the technological landscape. Chapter 3 delves into Policy and Regulation related to Promotion of Hydrogen Usage in Railways, drawing insights from case studies in Germany, China, and Indonesia, while adapting policies to Thailand's unique conditions. Safety Perspectives and Standards of Hydrogen-powered Railway are examined in Chapter 4, ensuring the robustness of safety concerns related to hydrogen utilization, including ongoing standardization activities for hydrogen applications in railways. Chapter 5 explores the Economic Impacts of the hydrogen supply chain and a Total Cost of Ownership (TCO) model tailored for the 196 km rail service from Bangkok to Pattaya, including Ban Phlu Ta Luang and Chuk Samet. In Chapter 6, Thailand's Scenarios Dealing with (Green) Hydrogen Applications in Railways are discussed, presenting potential pathways for implementation consisting of green hydrogen production, hydrogen transportation and delivery, applications to the railway network, and enabling mechanisms for implementing green hydrogen in Thailand's railways. Finally, Chapter 7 presents Recommendations derived from the study's findings, offering actionable insights for policymakers, stakeholders, and industry players to drive forward the adoption of green hydrogen technology in Thailand's railway sector.

# 1 INTRODUCTION

## 1.1 Background information

In recent years, there has been a heightened worldwide emphasis on transitioning towards sustainable and eco-friendly energy sources, driven by the imperative to address climate change and diminish greenhouse gas emissions. The pursuit of alternative energy solutions has intensified to confront these global challenges [1]. The Paris Agreement, established during COP21 in 2015, represents a pivotal international commitment to combatting climate change. The aim was to limit global temperature increases to well below 2°C above pre-industrial levels. However, the ambitious target set is 1.5 °C. An integral aspect of the Paris Agreement is the adoption of net-zero emission targets by signatory nations. The net-zero emission goal signifies the achievement of a balance between emitted greenhouse gases (GHG) and those removed from the atmosphere, primarily through carbon removal or offsetting measures. Countries committed to the agreement pledged to formulate and implement long-term strategies, known as nationally determined contributions (NDCs), outlining their pathways to achieving net-zero emissions. The net-zero target reflected a shared recognition of the imperative to transition to sustainable, low-carbon economies and underscored the global commitment to mitigating the impacts of climate change. The countries depicted in **Figure 1** are those committed to achieving a net-zero emission target under the Paris Agreement. Given that approximately 85% of global energy consumption relies on fossil fuels, concerns about fossil energy scarcity and environmental degradation have become increasingly evident. There is a global inclination towards researching biofuels as a viable alternative. This shift was motivated by the aim to find sustainable substitutes for fossil fuel energy, coupled with the global objective of reducing greenhouse gas emissions to prevent further environmental degradation. Consequently, hydrogen, recognized as a prevalent energy carrier, has garnered escalating attention on a global scale [2].

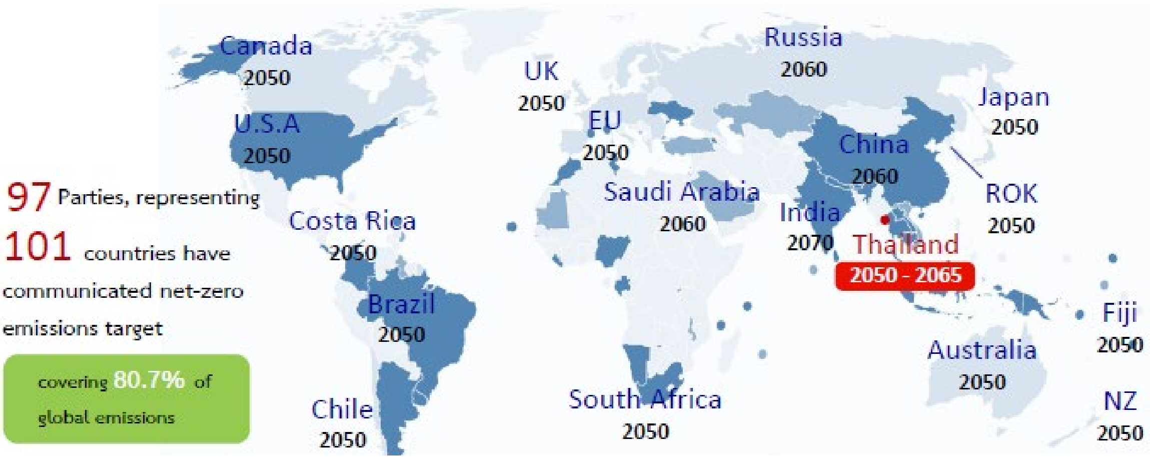



**Figure 1 Countries committed to achieving the net-zero emission target outlined in the Paris Agreement [3]**

Thailand, in its commitment to addressing climate change, submitted a revised Long-Term, Low-Emission Development Strategy (LT-LEDS) during COP27 on November 7, 2022. This revised plan outlined the ambitious targets for achieving carbon neutrality by 2050 and net-zero greenhouse gas emissions by 2065, accelerating the country's previous commitment made before COP26. The passage of these LT-LEDS targets into law would elevate Thailand's Climate Action Tracker (CAT) rating to "Advanced". In addition, the COP26 in Glasgow on November 1, 2021, underscored Thailand's commitment to achieving carbon neutrality by 2050 and net-zero greenhouse gas emissions by 2065 (see **Figure 2**), with the expectation of international financial and technological support and cooperation under the convention framework. The long-term greenhouse gas estimation development strategy for Thailand is shown in **Figure 3** and the timeline of net-zero GHG emission in the transport sector is given in **Figure 4**.

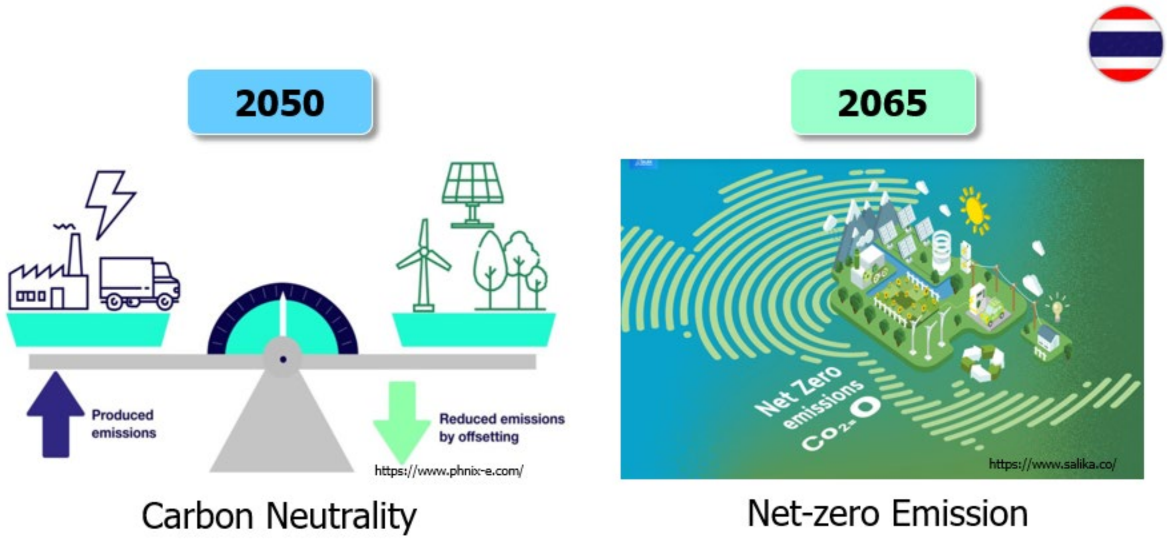



**Figure 2 Thailand carbon neutrality and net-zero greenhouse gas emissions timeline**

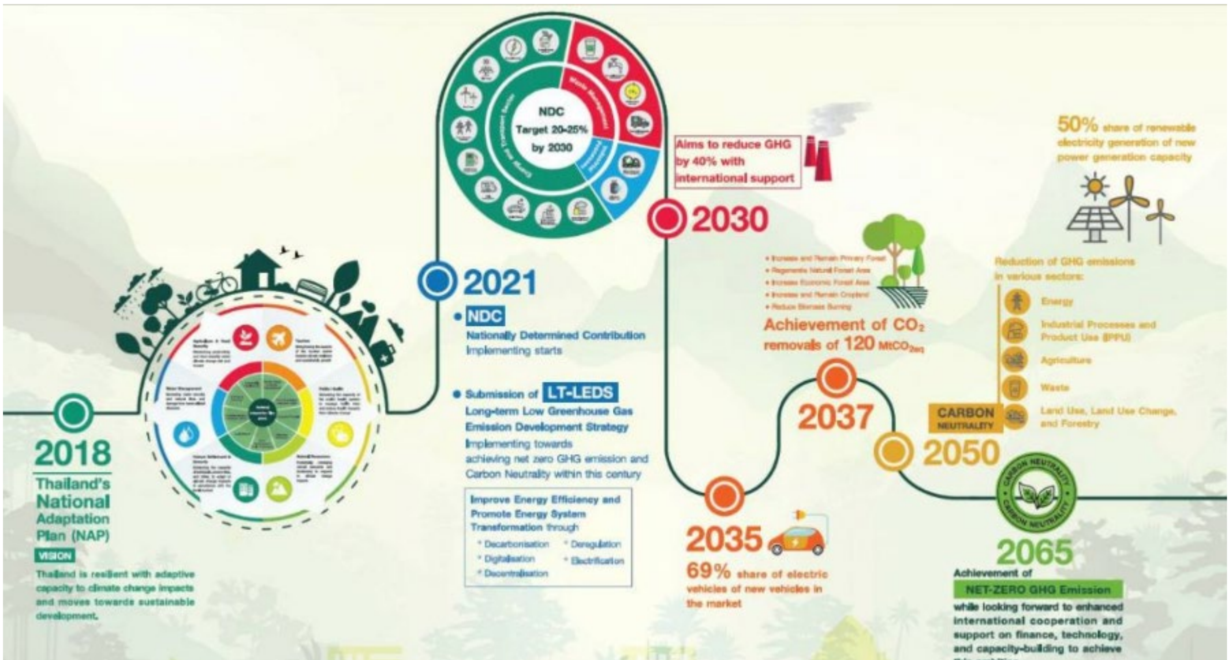



**Figure 3 Thailand's long-term greenhouse gas estimation development strategy [3]**

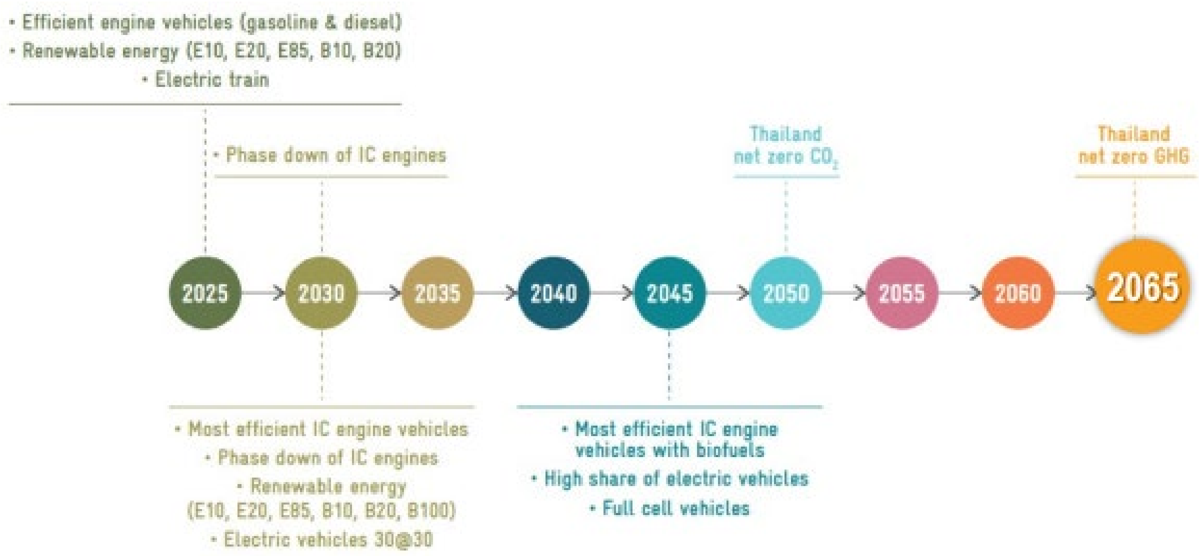



**Figure 4 Timeline of net-zero GHG emissions in the transport sector [3]**

The national transport system development strategy of Thailand 2018 – 2037 outlined the ambitious targets and strategic actions to enhance sustainability in the transport sector. This plan aimed to achieve a 20% reduction in greenhouse gas (GHG) emissions from transportation compared to the 2015 level of 69.1 million tons. Furthermore, it aimed to decrease energy consumption by 15% from the 2015 amount of 36.6% by 2036. The strategic actions for the period 2018 - 2036 have included the expansion of national rail networks, particularly in urban areas, to improve the efficiency of urban public transport systems in Bangkok and major cities. All public transport vehicles, including rail transport, will be transformed into energy-efficient and green technology options such as electrification, battery, and hydrogen. This comprehensive strategy emphasized Thailand's commitment to mitigating the environmental impact caused by transportation activities and to advancing a sustainable and energy-efficient national transport system. The State Railway of Thailand administers the country's railway system, which spans across 47 of the 77 provinces, covering a total distance of about 4,044 kilometres. The national railway networks are composed of four main lines: Northern, Eastern, Northeastern, and Southern, as shown in **Figure 5**. Thailand's railway rolling stocks mainly rely on a non-electrified system, i.e., diesel-based propulsion system, serving both passenger and freight transportation needs.

Thailand is currently enhancing its railway infrastructure. This presents a prime opportunity for a transition from diesel-powered trains to cutting-edge low-carbon technology. This strategic evolution places emphasis on embracing alternative propulsion technologies, including battery-powered, overhead catenary, and hydrogen-powered systems.

As reported in various publications, it is clear that the railway line equipped with a full electrification system, i.e., overhead catenary system (OCS), is recognized as the best option to decarbonize railway operations and services due to its traction efficiency of around 80 – 90% obtained without any concern about tailpipe emission. An OCS train generally comprises an overhead line or wire, which functions as an electrical cable transmitting electrical energy to electric traction systems. While the overhead line offers certain benefits, it also comes with drawbacks. A notable disadvantage is the visual disruption caused by wires and supporting structures to the surrounding scenery. Additionally, a significant challenge arises from the necessity for extensive modifications to the infrastructure. Structures such as bridges, tunnels, and others along the railway route must be compatible with technical constraints to ensure adequate clearance for the overhead wires and enabling devices. This process can incur substantial costs and time delays. In terms of long-distance travel, the construction expenses for OCS train infrastructure become notably high, particularly when covering extensive distances of intercity routes. Therefore, OCS might not be a viable choice for long-distance routes where the traffic density of railway operations is relatively low due to the associated costs of investment.

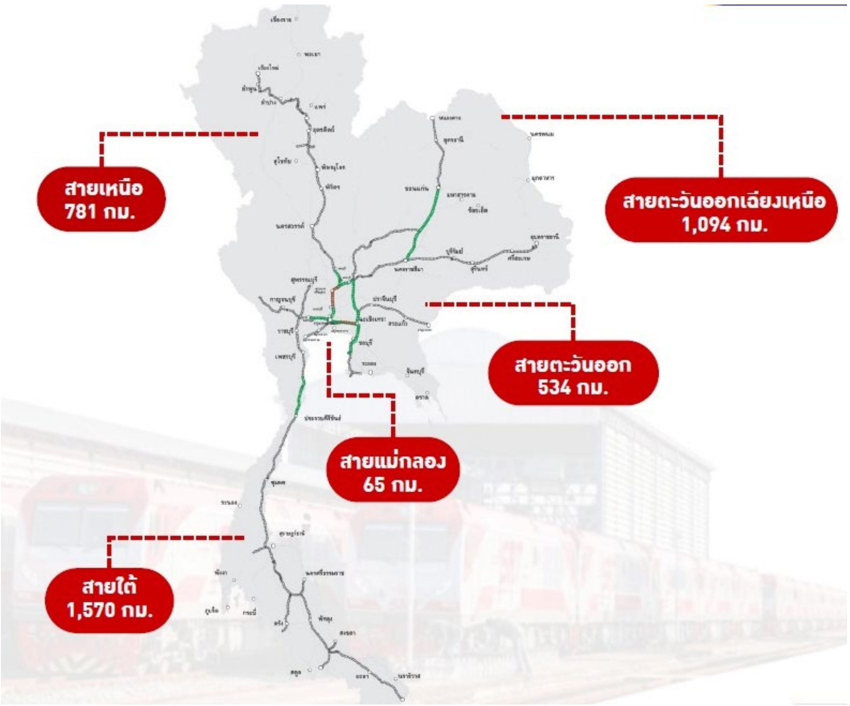



**Figure 5 Thailand railway network [3]**

Another notable example of electrification on railways is the battery-powered train. This type of train employs advanced battery technology to provide traction and power to trains, thus eliminating the need for traditional fuel sources or electrification infrastructure. The primary advantage of battery-powered trains is that they demand less maintenance due to their simpler design with fewer moving parts compared to diesel-powered traction systems. As mentioned previously, electrifying train tracks can be costly and logistically challenging. Battery-powered trains present a viable alternative to such scenarios, eliminating the need for extensive electrification efforts. Additionally, these trains can seamlessly transition between electrified and non-electrified track sections, preventing disruptions in service when moving between different rail systems.

However, battery-powered trains have several drawbacks. One significant challenge is the total weight of the battery energy storage system. The addition of batteries significantly increases the tare weight of trains, posing difficulties in climbing steep grades and navigating challenging terrain. Furthermore, the added weight of the batteries may reduce the cargo and passenger capacity of the trains, potentially diminishing their cost-effectiveness. Another obstacle is the limited cruising range of the trains run solely on electricity stored in batteries. In fact, for any type of railway vehicle designed for long-distance operations, it is crucial to minimize frequent stops for battery recharging. Charging the on-board batteries can take much longer than refuelling the trains with diesel fossil fuel. Fast-changing technologies are being developed, but even these solutions might require extended stops at stations, impacting operation schedules. Although advancements in battery technology have extended the operational range of the trains, they still fall short of matching the distance covered by a tank of diesel fuel. In terms of cost, battery-powered trains are currently quite expensive due to the relatively high cost of batteries used for the on-board energy storage system. While the cost of batteries is expected to decrease over time as the technology becomes more widespread, it is still unclear how long it will take for the battery-powered trains to compete with diesel-powered trains.

To tackle the challenges posed by OCS and battery-powered trains, hydrogen emerges as a compelling option with zero-emission operation, extended range, and quick refuelling capabilities. Hydrogen-powered trains represent a pioneering step in the evolution of sustainable and eco-friendly transportation. Hydrogen-powered trains harness the potential of hydrogen fuel cells, offering a clean and efficient alternative to traditional diesel-powered trains. In this innovative mode of transportation, hydrogen gas as an energy carrier reacts with oxygen gas in a fuel-cell unit for production of electricity to power the electric traction motors of the trains. A hydrogen-powered system employed for the trains cannot only eliminate direct emissions of GHG into the atmosphere, but also provides a reasonable solution to the challenges associated with electrification and battery-powered trains, such as operational range limitations and lengthy recharging times.

Furthermore, the significance of advancing hydrogen-powered trains becomes increasingly apparent, initiating a unique opportunity to invest in Thailand's railway business, by transitioning from supporting diesel-powered trains to hydrogen-powered trains. This strategic shift not only transforms the railway system but also capitalizes on the opportunity to replace diesel-powered trains with environmentally friendly, efficient, and flexible hydrogen trains, playing a pivotal role in shaping the future of rail systems in the country.

Hence, the primary goal of this study is to create an in-depth white paper that thoroughly explores essential aspects of implementing hydrogen technology within Thailand's rail transport sector. This comprehensive document will analyze crucial elements, ranging from technological intricacies and safety measures to standardization protocols. Additionally, it will conduct a detailed examination of the economic and environmental impacts linked to the incorporation of hydrogen technology in the country's rail infrastructure. Beyond analysis, this study adopts a pragmatic approach by offering suggestions for the technology demonstration phase (see **Figure 6**), aiming to provide actionable insights that foster the seamless and successful integration of hydrogen technology into Thailand's rail transportation system.

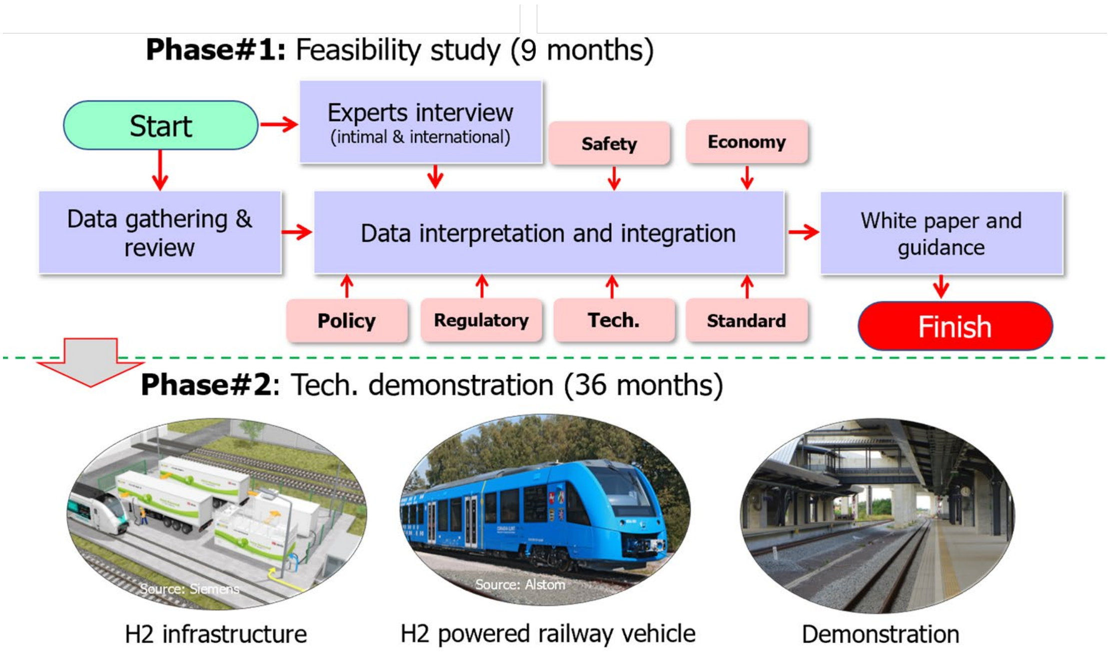



**Figure 6 Diagram showcasing all the components of phase #1 and phase #2 of the project**

# 2 TECHNOLOGICAL PERSPECTIVES OF (GREEN) HYDROGEN FOR RAILWAY APPLICATIONS

As mentioned in the previous chapter, electrification is one option to reduce tailpipe emissions on railways. However, for challenging topographic railway stretches, or routes facing prolonged overhead wire approval processes, employing fuel cells or hydrogen-powered internal combustion engines emerges as a viable option for achieving decarbonization. Multiple manufacturers are actively working on trains featuring hydrogen fuel-cell propulsion, either currently operational or slated for future deployment. **Figure 7** illustrates a comprehensive overview of hydrogen projects and research endeavours pertaining to railways, encompassing historical initiatives, ongoing developments, and anticipated projects. The geographical focus extends to regions such as the USA, Canada, China, Japan, South Korea, and Europe, with specific attention given to countries like Germany, the UK, Austria, and Spain [4].

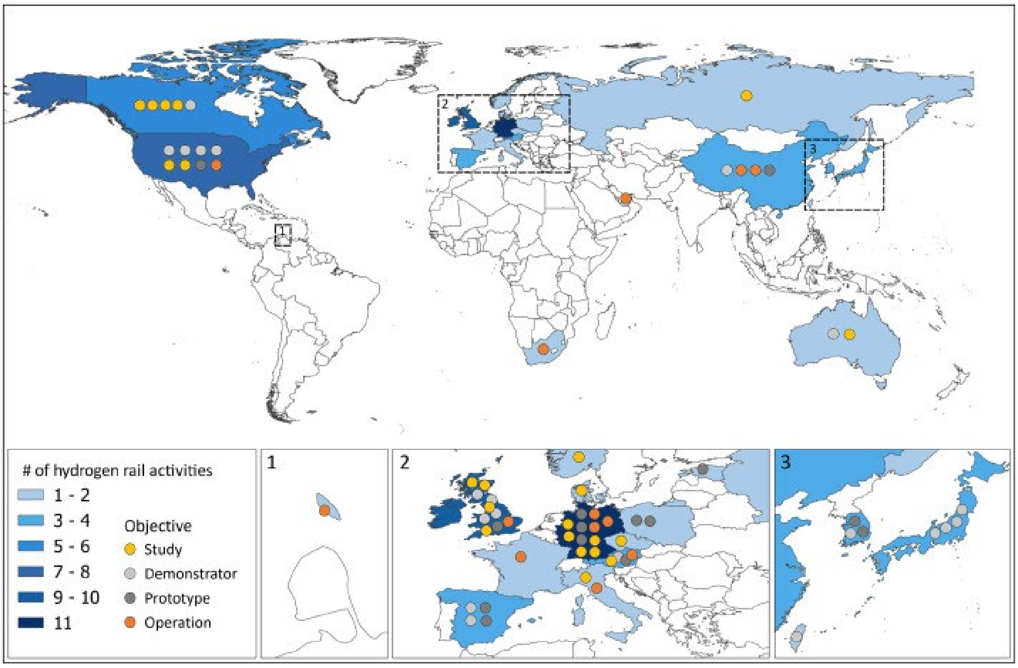



**Figure 7 Global hydrogen rail initiatives and goals [4]**

In this chapter, a thorough technical perspective of hydrogen within the railway domain will be reviewed. The discussion will cover different aspects of hydrogen-based solutions, examining their efficacy, advancements, and specific applications within the context of railway systems.

## 2.1 Key domains of a hydrogen railway

The implementation of green hydrogen in railway applications encompasses several key domains crucial for its successful integration, as shown in **Figure 8**. Firstly, the production phase involves the utilization of renewable energy sources, such as wind or solar power, to generate hydrogen through electrolysis, ensuring a low-carbon footprint. Subsequently, storage and distribution infrastructures need to be established to facilitate the efficient supply of green hydrogen to railway systems. The deployment of hydrogen fuel cells in trains constitutes another vital domain, wherein these cells serve as clean energy converters to power locomotives. Moreover, advanced control and management systems play a pivotal role in optimizing the use of green hydrogen in railway operations, ensuring seamless integration with existing infrastructure while maximizing energy efficiency.

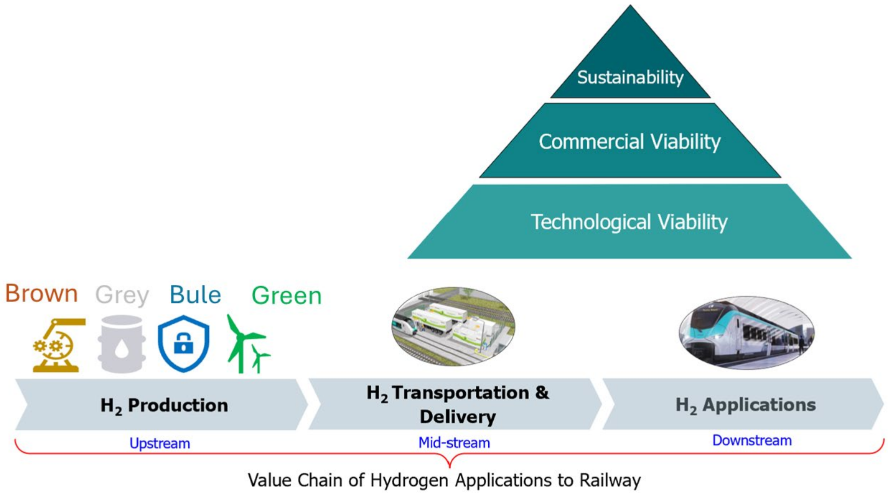



**Figure 8 Value chain of hydrogen applications in the railway sector**

The value chain of hydrogen-powered railway systems is a comprehensive and interconnected process contributing to the establishment, deployment, and operation of environmentally sustainable train networks. This chain encompasses hydrogen production, where processes like electrolysis generate hydrogen from water using renewable energy sources. Efficient storage methods, such as compression or liquefaction, follow the production phase. Hydrogen is then distributed from production facilities to strategically placed refuelling stations along railway networks via pipelines or tanker trucks. The key component of hydrogen refuelling infrastructure facilitates seamless operations with technology-equipped stations. Hydrogen-powered trains, utilizing fuel cells to convert hydrogen into electricity, form the core of the value chain, offering a clean alternative to traditional rail systems, as shown in **Figure 9**.

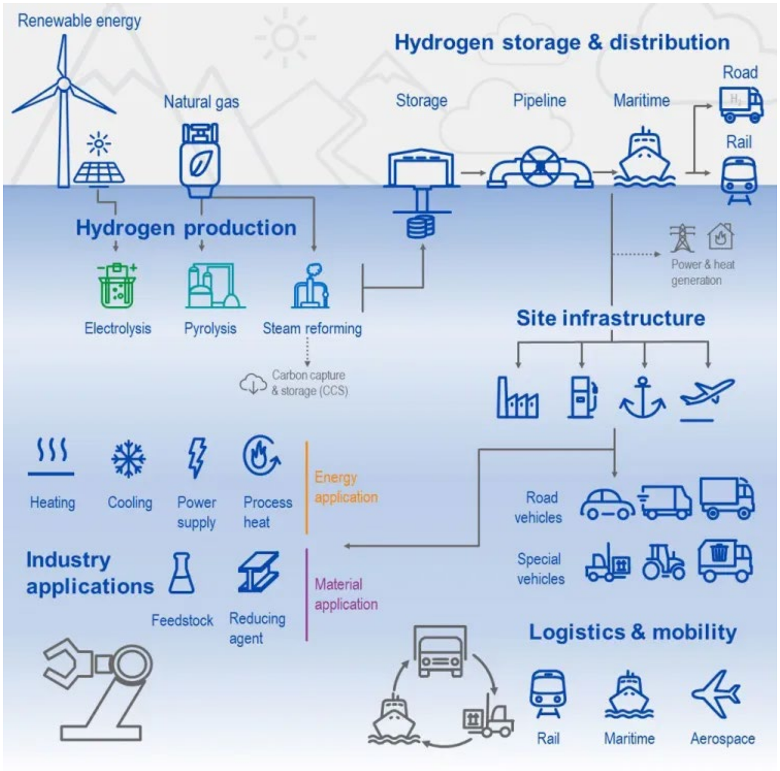



**Figure 9 Hydrogen value chain in the transportation sector [5]**

### 2.1.1 Green hydrogen production

Hydrogen production derives from a diverse array of primary energy sources, and the resultant costs and associated emissions exhibit considerable variation, contingent on the specific production process and type of energy employed. This pivotal distinction necessitates the classification of hydrogen generation technologies into distinct categories, often referred to as "colours". These colours include green, pink, purple, blue, grey, black and brown, see **Table 1**, in which each represents a unique method of hydrogen generation with varying environmental and economic implications [6].

**Table 1 Hydrogen colour spectrum and their production route**

| Nomenclature | Production feedstock | Production method | Key concerns in production |
|---|---|---|---|
| Green hydrogen | Water | Electrolysis powered by renewable energy | Significant quantity of power needed<br>Significant quantity of freshwater needed. |
| Pink/purple hydrogen | Water | Electrolysis powered by nuclear energy | Nuclear safety issues<br>Significant quantity of freshwater needed. |
| Blue hydrogen | Natural gas | Steam methane reforming with carbon capture and storage (CCS) | High-production cost due to CCS |
| Grey hydrogen | Natural gas | Steam methane reforming | GHG emission |
| Black/brown hydrogen | Coal | Gasification | GHG emission |

In 2021, a mere 0.04% of the total hydrogen production, which stood at 94 million metric tons, was derived from water electrolysis fuelled by renewable energy sources, commonly referred to as 'green hydrogen'. This approach supplies electricity and purified water to an electrolyzer, yielding hydrogen and oxygen output [7]. Green hydrogen is broadly defined by its association with zero $CO_2$ emissions, primarily derived from renewable or carbon-neutral technologies. Additionally, hydrogen sourced from biomass, being $CO_2$ neutral, aligns with the "green" categorization [8, 9]. The majority of hydrogen (> 83%) continues to be sourced from fossil fuels, primarily through steam methane reforming without carbon capture, utilization, and storage (CCUS) technologies, denoted as grey hydrogen. Furthermore, the implementation of CCUS technologies has enabled the production of hydrogen with minimal or negligible $CO_2$ emissions, even when derived from fossil fuel sources, referred to as blue hydrogen. Moreover, over thirty countries have initiated their respective Hydrogen National Plans, Strategies, or Roadmaps. **Figure 10** provides an overview of the hydrogen categorizations outlined in various nations' strategies and plans [10].

In the process of green hydrogen production, a water electrolyzer is used to split water molecules into oxygen and hydrogen ions based on an electrochemical reaction by the passage of electrical current generated by renewable means, such as wind, solar PV, etc., to the system as shown in **Figure 11a**. At the stack level (**Figure 11b**), multiple electrochemical cells are connected in series. The basic principle of electrolysis cells consists of two electrodes, i.e., anode (oxygen side) and cathode (hydrogen side) separated by electrolyte.

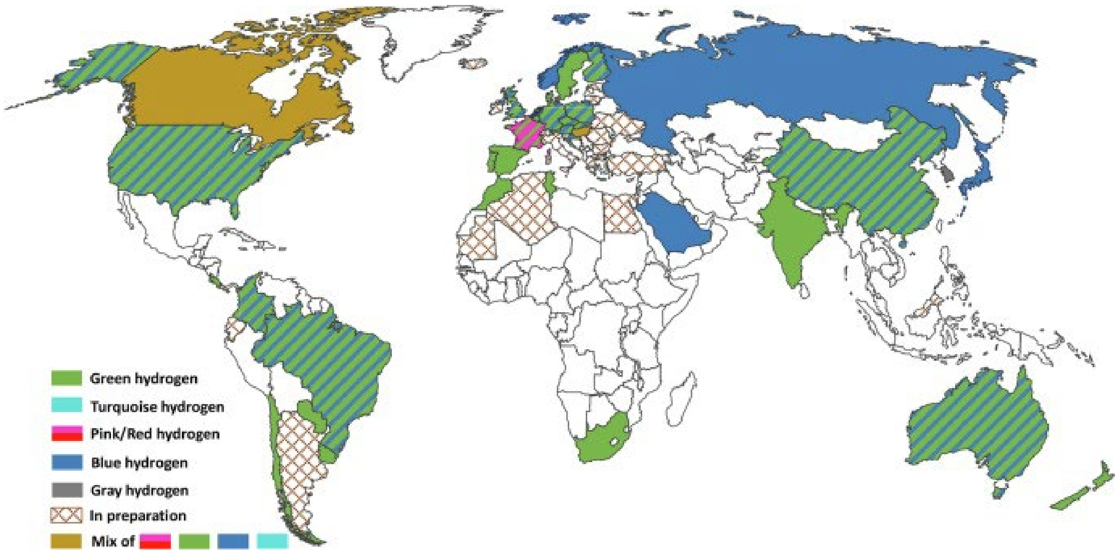



Figure 10 Main colours considered in each country's Hydrogen National Plan, Strategy, or Roadmap [10]

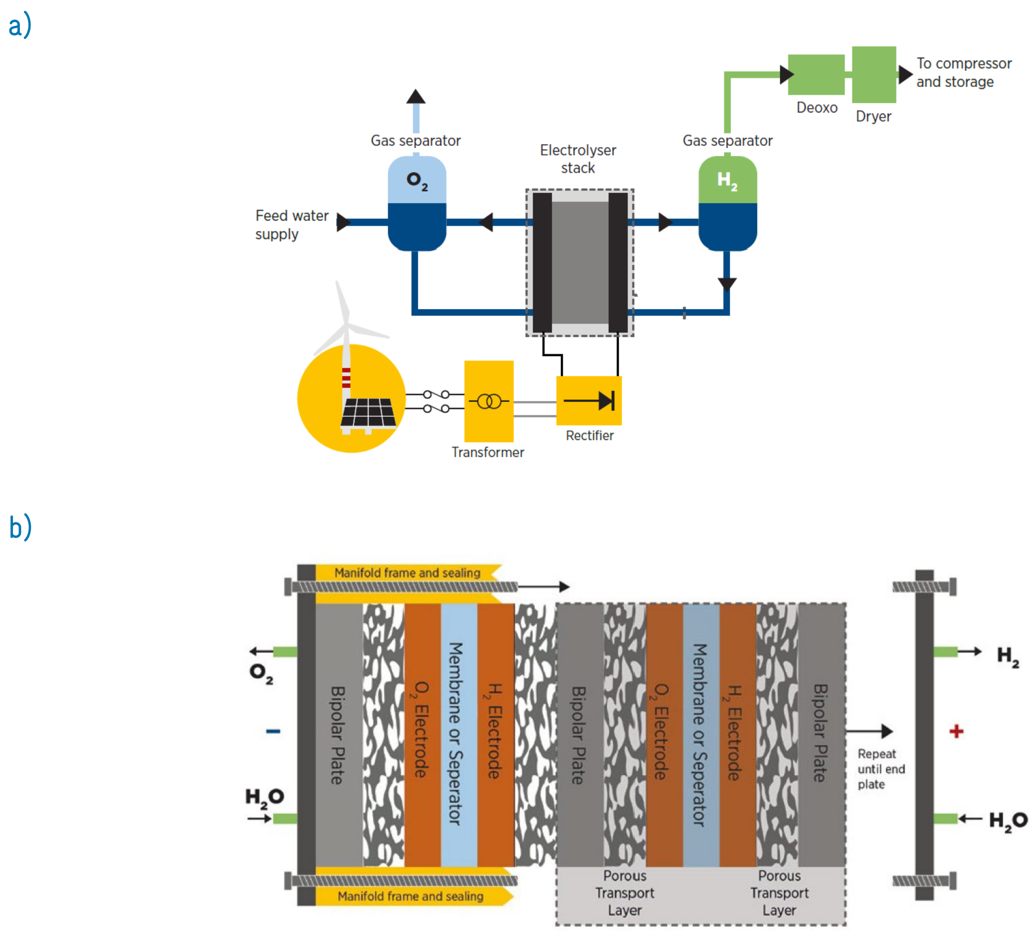



Figure 11 Basic components of water electrolyzers a) system level [11] and b) stack level [12]

**Figure 12** shows four major types of electrolysis technologies commercially available, which are alkaline, proton exchange membrane (PEM), anion exchange membrane (AEM), and solid oxide. Among these, AEM and solid oxide technologies are less mature than PEM and alkaline technologies. The fuel cell technologies, including alkaline, PEM, AEM, and solid oxide, exhibit distinct advantages and challenges.

Alkaline fuel cells offer high efficiency and cost benefits but are sensitive to carbon dioxide and have a shorter lifespan. PEM fuel cells, known for quick start-up and high-power density, face challenges related to fuel purity, expensive catalysts, and durability concerns. AEM fuel cells, with potential cost savings and tolerance to carbon monoxide, are hindered by limited commercial availability and durability issues. Solid oxide fuel cells boast high efficiency and fuel flexibility but encounter challenges with high operating temperatures, longer start-up times, and material costs. **Table 2** summarizes the characteristics of operating conditions and major components for four types of electrolysis technologies. With the existing electrolyzer technology boasting an efficiency of around 70%, the generation of one kg of hydrogen necessitates 9 litres of purified water as a feedstock and 50 kWh of electricity, as illustrated in **Figure 13**.

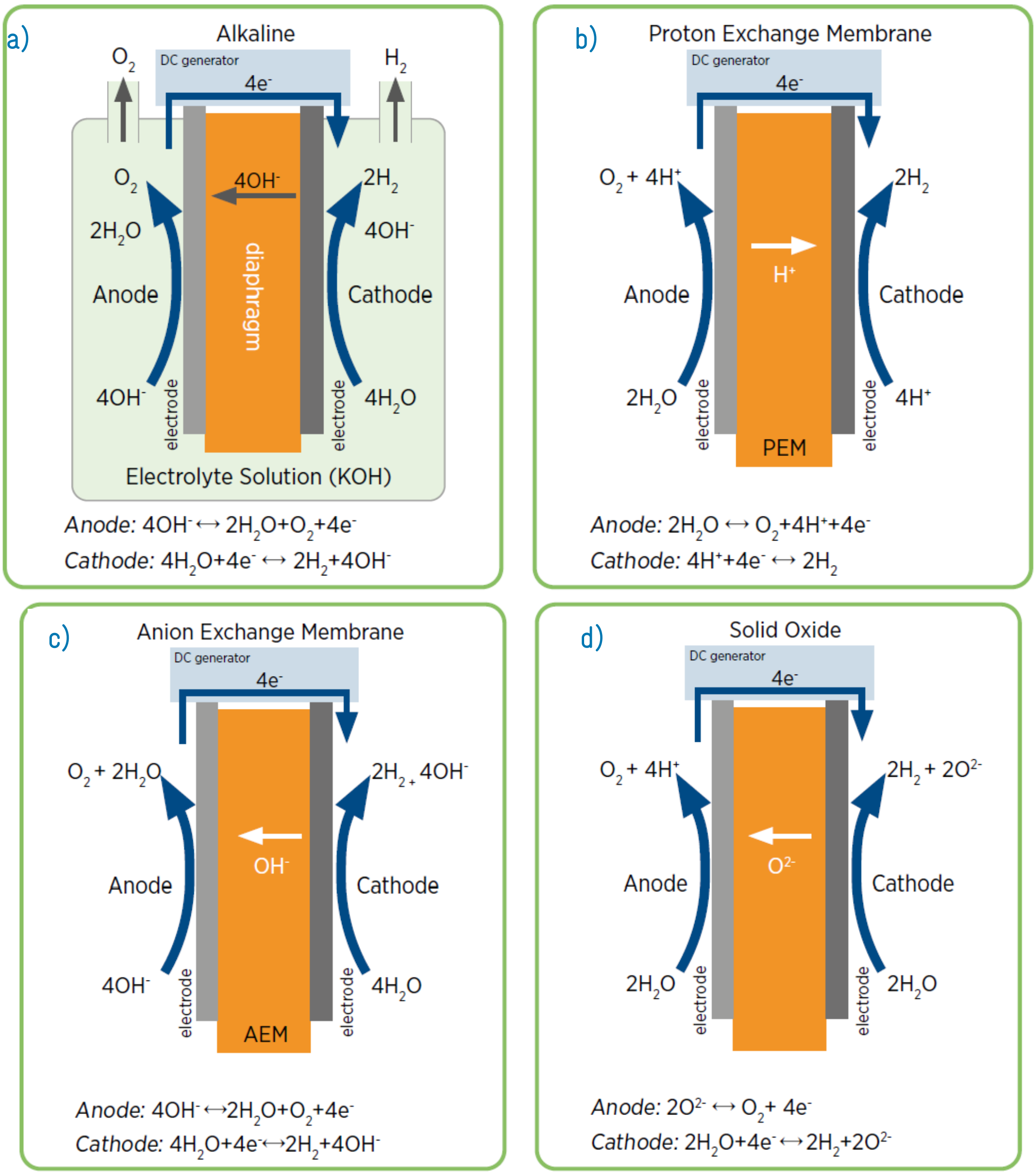



**Figure 12 Various types of electrolysis technologies commercially available [12]**

Table 2 Characteristics of each water electrolysis technology [13]

| | Alkaline | PEM | AEM | Solid Oxide |
|---|---|---|---|---|
| Operating temperature | 70-90 °C | 50-80 °C | 40-60 °C | 700-850 °C |
| Operating pressure | 1-30 bar | <70 bar | < 35 bar | 1 bar |
| Electrolyte | Potassium hydroxide (KOH) 5-7 $molL^{-1}$ | PFSA membranes | DVB polymer support with KOH or NaHCO3 1 $MolL^{-1}$ | Yttria-stabilized Zirconia (YSZ) |
| Separator | $ZrO_2$ stabilized with PPS[2] mesh | Solid electrolyte (above) | Solid electrolyte (above) | Solid electrolyte (above) |
| Electrode/ catalyst (oxygen side) | Nickel-coated perforated stainless steel | Iridium oxide | High surface area Nickel or NIFeCO alloys | Perovskite-type (e.g. LSCF, LSM) |
| Electrode/ catalyst (Hydrogen side) | Nickel-coated perforated stainless steel | Platinum nanoparticles on carbon black | High surface area Nickel | Ni/YSZ |
| Porous transport layer cathode | Nickel mesh (not always present) | Platinum- coated sintered porous titanium | Nickel foam | Coarse Nickel-mesh or foam |
| Porous transport layer anode | Nickel-mesh | Sintered porous titanium or carbon cloth | Nickel foam or carbon cloth | None |
| Bipolar plate anode | Nickel-coated stainless steel | Platinum-coated titanium | Nickel-coated stainless steel | None |
| Bipolar plate cathode | Nickel-coated stainless steel | Gold-coated titanium | Nickel-coated stainless steel | Cobalt-coated stainless steel |
| Frames and sealing | PSU, PTFE, EPDM | PTFE, PSU, ETFE | PTFE, Silicon | Ceramic glass |

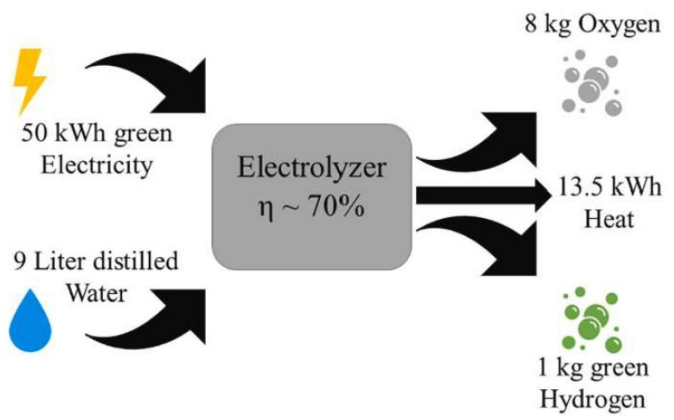



Figure 13 Schematic illustration of 1-kilogram green hydrogen produced with 50-kWh electricity and 9-litres purified water (70% Efficiency) [14]

In order to get green hydrogen commercially used as an energy carrier in the transport sector, for example, its cost must be competitive with other kinds of fossil fuel. At the production stage of green hydrogen from electrolysis, two main drivers are identified that affect the production cost of green hydrogen: 1) high capital cost of production equipment and 2) cost of electricity. As reported by the Asia Pacific Energy Research Center in 2018, the cost of green hydrogen produced by using electricity from solar PV was 3.70 USD/kg. (in the USA), 4.12 USD/kg. (in China), 6.02 USD /kg. (in Japan), and 6.65 USD/kg. (in South Korea). Apart from green hydrogen, the production cost of hydrogen through a natural gas reforming process in China was 1.80 USD/kg which increased to 2.30 USD/kg. if CCS was applied, as shown in **Figure 14**.

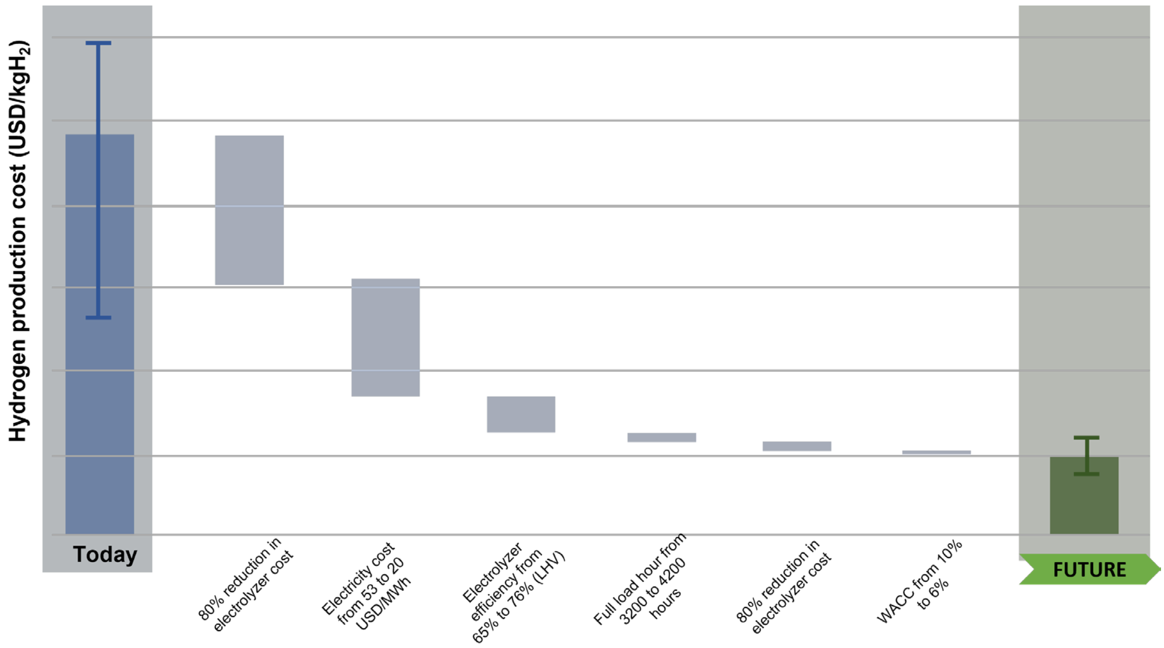



**Figure 14 A combination of cost reductions in electricity and electrolyzers, combined with increased efficiency and operating lifetime, can deliver 80% reduction in hydrogen cost [15]**

In addition to the hydrogen production cost, transportation, storage, delivery, and refilling of hydrogen are also costly before being in place for the subsequent applications at end-users. In the case of Japan, APERC reported that the final cost of hydrogen at the end-user of fuel-cell electric vehicle (FCEV) reached 12.6 USD/kg. if hydrogen came from solar PV-based production in Indonesia. The cost of hydrogen produced through natural gas reforming from Russia was around 8.28 USD/kg. available for FCEV applications. The cost mentioned encompasses hydrogen production, transportation, and the establishment of hydrogen refilling stations.

Regarding the applications of hydrogen in the transport sector, the Economic Research Institute for ASEAN and East Asia (ERIA) (2019) reported that the cost of hydrogen should be in the range of 4.24 to 5.00 USD/kg in order to compete with conventional fossil fuels used for ICE vehicles in Japan. By contrast, the competitive cost of hydrogen ranged between 3.78 and 4.53 USD/kg found in Indonesia.

In pursuit of mitigating greenhouse gas (GHG) emissions and lessening the reliance on fossil fuels within the energy market, numerous countries are placing substantial emphasis on advancing the development and utilization of renewable energy sources (RESs). This strategic focus aims to facilitate a significant energy transition while simultaneously reducing dependency on fossil fuels. Among Renewable Energy Sources (RESs), hydrogen is characterized by high energy density, environmental cleanliness, versatility in applications, and renewable properties. Its benefits encompass efficient combustion, recyclability, low environmental impact, and high utilization rates, making it a valuable and sustainable energy carrier [16].

Consequently, hydrogen energy has garnered considerable attention, particularly in the context of large-scale energy storage applications. Hydrogen production, as the fundamental source for hydrogen energy utilization, assumes a paramount role in the overall efficiency and viability of hydrogen energy systems. Accordingly, the achievement of large-scale hydrogen production holds immense significance in advancing the practicality and widespread adoption of hydrogen energy utilization [17].

**Table 3 Technical characteristics and cost of different hydrogen storage methods [20]**

| Storage methods | Hydrogen storage principle | Hydrogen storage density | Advantages | Disadvantages | Technology readiness level | Cost ($/kg) |
|---|---|---|---|---|---|---|
| Compressed Gas Storage | Under specific temperature and volume conditions, elevating the pressure results in a higher gas content within the system, effectively compacting hydrogen gas into high-pressure storage tanks. | 1.0 – 5.7(wt.%) | - Relatively mature technology<br>- Low capital cost<br>- Quick refuelling | - Requires high-pressure storage vessels which can be heavy and bulky<br>- Limited energy density<br>- Compression process can be energy intensive | Developing rapidly | 0.15–25.5 |
| Liquid Hydrogen Storage | Under standard atmospheric pressure conditions, hydrogen transitions from a gaseous to a liquid state at temperatures as low as -253 °C.. | 5.7 – 10(wt.%) | -Higher energy density than compressed gas<br>- Can be refuelled quickly | - Requires cryogenic temperatures (–253°C)<br>- Cryogenic storage vessels can be expensive<br>- Boil-off losses can occur over time | Mature technology | 0.59–4.57 |
| Solid hydrogen storage | Hydrogen storage materials like metal hydrides are employed for hydrogen storage, capitalizing on their capability to reversibly absorb and release hydrogen. | 1.0 – 4.5(wt.%) | - Can offer high volumetric and gravimetric energy density<br>- No cryogenic temperatures required<br>- Potentially safer than gas or liquid storage | - Emerging technology<br>- Relatively low energy density compared to fossil fuels<br>- Can be expensive to manufacture and scale up<br>-To date, material with moderate operating condition has low gravimetric hydrogen storage density<br>-Material with high hydrogen storage density has extreme operating condition | Early stage of industrialization | 0.40–4.00 |

## 2.2 Hydrogen storage for railway

As the utilization of hydrogen energy continues to grow across various sectors, achieving efficient storage methods is critical for its widespread application at a large scale. Within the complete industrial framework of the hydrogen energy sector, the pivotal and indispensable components are hydrogen storage and transportation. To ensure the effective and extensive utilization of hydrogen energy, as well as the high-quality advancement of the hydrogen energy industry, a fundamental requirement lies in the progress of secure and cost-effective hydrogen storage and transportation technologies [18].

### 2.2.1 Hydrogen storage

One of the primary challenges linked to hydrogen storage is its notably low volumetric energy density. Hydrogen exhibits a significantly lower energy content per unit volume compared to conventional fossil fuels like gasoline or diesel. Consequently, a substantial volume of hydrogen is needed to store an equivalent amount of energy [19, 20]. Basically, hydrogen storage methods can be categorized into physical and material-based technologies, which encompass high-pressure gaseous storage, cryogenic liquid storage, organic liquid storage, and solid-state storage [4]. The expense of the storage method is contingent upon both its capacity and the duration of storage. Technical characteristics and cost of hydrogen storage methods, are shown in **Table 3** [18, 20]. Moreover, the concepts of hydrogen transportation and delivery potentially applied for fuel cell-based railway vehicles are shown in **Figure 15**.

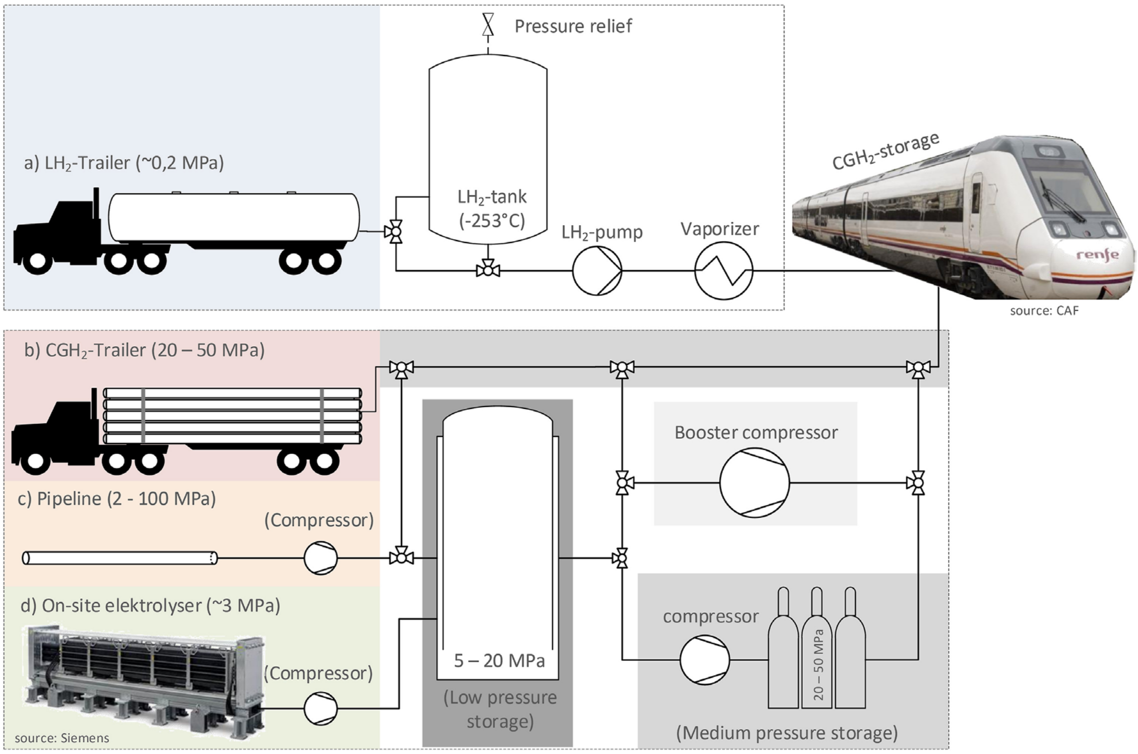



**Figure 15 Concepts of hydrogen transportation and delivery potentially applied for fuel cell-based railway vehicles [4]**

### 2.2.2 Compressed gas storage

High-pressure gaseous hydrogen storage is based on the compression of hydrogen gas within high-pressure gas cylinders, making it the prevailing and widely adopted hydrogen storage method due to its uncomplicated technical design and quick refuelling characteristics. This method boasts advantages such as swift hydrogen refuelling, well-established technology, operation at ambient temperature, and cost-effectiveness. However, it is accompanied by disadvantages like limited energy density, energy consumption during compression, the need for larger storage space compared to gasoline, and stringent safety container requirements. Increasing the storage pressure can enhance hydrogen density, but it substantially raises both tank costs and energy consumption during compression [21, 22].

### 2.2.3 Liquid hydrogen storage

Cryogenic hydrogen storage, facilitated by hydrogen liquefaction, includes the cooling and preservation of hydrogen at very low temperatures of - 253 °C and elevated pressures. This method stands out for its benefits, notably the high mass density and compact storage tank volume, making it ideal for road, marine, and specific aviation transport [21, 23]. Additionally, the practicality of liquid hydrogen storage technologies has been validated in aerospace and selected civilian vehicle sectors [24]. However, liquid hydrogen, with its low latent heat of vaporization, easily evaporates. Typically, storage tanks are crafted from stainless steel and aluminium and employ multi-layer insulation. Innovations such as integrated refrigeration and storage systems, as well as the utilization of glass bubble insulation, have been introduced to enhance the storage of liquid hydrogen ($LH_2$) and reduce losses [25].

### 2.2.4 Solid hydrogen storage

Solid-state hydrogen storage technology utilizes specific temperature and pressure conditions to enable the reversible absorption and release of hydrogen within materials characterized by a significant surface area. These valuable advantages of being lightweight, economical, high-capacity, reliable, volumetrically efficient, and displaying swift kinetics, positions them as a compelling choice compared to alternative techniques. This approach streamlines the effective management of hydrogen [18, 26].

## 2.3 Hydrogen refuelling station for railway

Hydrogen refuelling stations (HRSs) play a vital role in the infrastructure of the hydrogen energy industry, and their construction is an essential prerequisite for driving the growth of the hydrogen energy sector. Several nations, including Japan, Germany, the United States, and China, have embarked on ambitious endeavours to establish hydrogen refuelling stations (HRSs). Japan, a frontrunner in this regard, currently operates more than 100 HRSs and has plans to increase this number to 900 by 2030. Germany is also actively expanding its HRS network, with a goal of having 400 stations in operation by 2025 [27]. The United States is making a substantial commitment, aiming to construct 40,000 HRSs by 2030 [28].

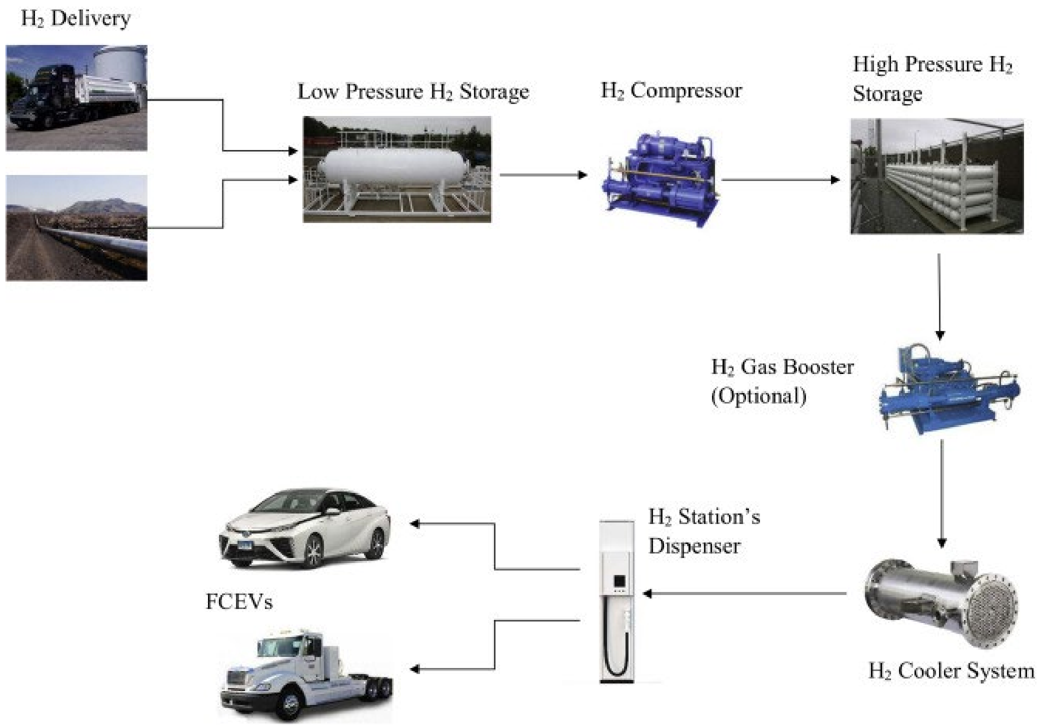
HRSs can be classified into two key types, depending on the method of hydrogen supply: standalone stations, which depend on external hydrogen transport (**Figure 16a**), and integrated stations, which possess on-site hydrogen production capabilities (**Figure 16b**). However, stations may adopt a hybrid approach, incorporating both on-site hydrogen production and the utilization of externally delivered hydrogen to meet their operational needs as necessary [29, 30].

Hydrogen refuelling stations operate on the same fundamental principles as conventional gasoline stations. They involve the storage of hydrogen in tanks, its transfer to dispensers, and the subsequent refilling of on-board hydrogen tanks in hydrogen-powered vehicles. High-pressure hydrogen dispensers resemble those used for liquefied petroleum gas or compressed natural gas and connect to vehicle tanks in a similar manner. Establishing a functional retail hydrogen station typically entails the integration of the following essential components:

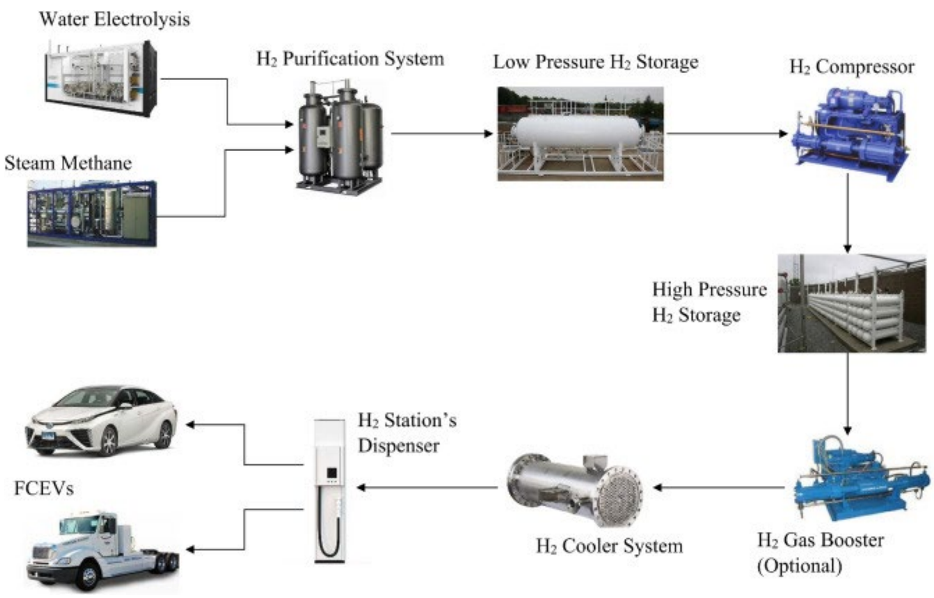
1. Hydrogen sourced either through on-site production or delivered from an external source for storage and distribution.
2. Purification Unit: A purification system is essential to guarantee the hydrogen's purity meets the stringent criteria for fuel cell supply.

3. Hydrogen Compressor: High-pressure hydrogen storage within the station's primary hydrogen tanks necessitates the presence of a hydrogen compressor.
4. Hydrogen Storage Tanks: These tanks accommodate either compressed hydrogen gas or liquid hydrogen ($H_2$).
5. Hydrogen Gas Booster: This component regulates pressure during the refuelling process, ensuring it reaches 350 bar or 700 bar as required.
6. Cooling Unit: To maintain safe operating temperatures, a cooling unit lowers the temperature of hydrogen gas to -40 °C, preventing the vehicle's hydrogen tank from exceeding 85 °C during fast refills.
7. Safety Equipment: This category includes pressure relief valves, hydrogen sensors, and waterless fire suppression systems, all crucial for ensuring station safety.
8. Mechanical and Electrical Equipment: Components such as valves, piping, control panels, and high-voltage connections are essential for the station's operational infrastructure.
9. Dispensers: These devices play a pivotal role in supplying hydrogen to vehicles' high-pressure tanks from the station's compressed storage tanks.

These components collectively form the core elements of a hydrogen refuelling station, facilitating the efficient and safe delivery of hydrogen fuel to hydrogen-powered vehicles [29].




a) Off-site




b) On-site

**Figure 16 Off-site and on-site $H_2$ production hydrogen gas refuelling station's main components [29]**

Within the railway industry, hydrogen supply and associated refuelling infrastructure have primarily relied on temporary refuelling solutions operating at 350 bars, without the implementation of large-scale infrastructure testing. A significant development is the initiation of the Multiple Units project in Northeast Germany, marking the debut of a substantial refuelling solution for fleet operations, led by The Linde Group. This groundbreaking project aims to provide hydrogen to 14 Multiple Units at a single station, commencing in 2021.

The refuelling stations for the aforementioned trains operating at 350 bars consist of electrolysis systems, hydrogen storage systems at electrolysis system pressure, hydrogen compression up to 500 bars, high-pressure hydrogen storage (using type III tanks at around 500 bars), and high-flow hydrogen dispensers as shown in **Figure 17** [31].

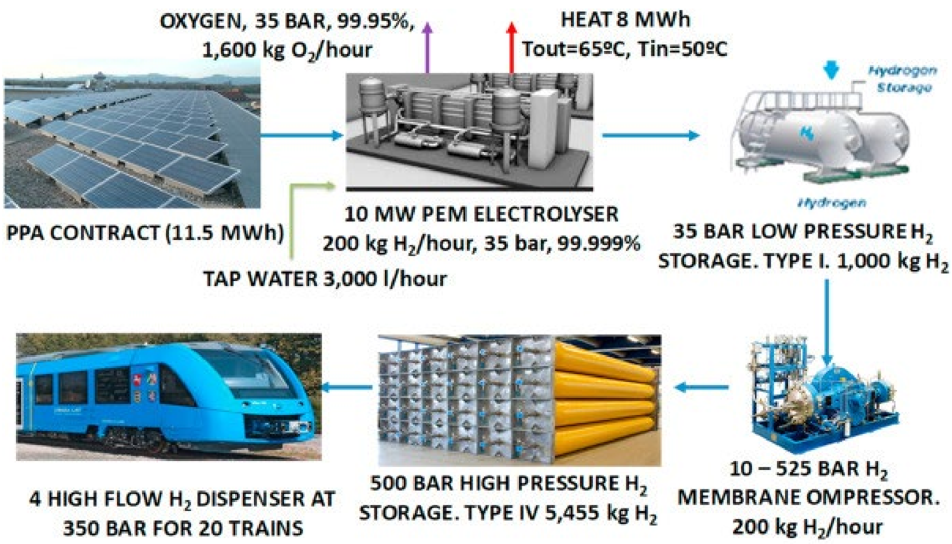



**Figure 17 Hydrogen refuelling station for supply of up to 20 Coradia iLint trains [31]**

## 2.4 Hydrogen applications to railway transport mode

The way hydrogen is transported hinges on how it's stored and the volume to be transported. Three primary transportation methods exist: gaseous, liquid, and solid hydrogen transport. The choice of transportation mode, which can include pipelines, tube trailers, rail, trucks, or ships, depends on the hydrogen's storage state and the suitability of the transport method for a given situation [18, 20]. The characteristics of the transportation hydrogen methods are shown in **Table 4 and Figure 18**.

**Table 4 Characteristics of transportation hydrogen methods [20, 32]**

| Transmission Type | Efficiency (per 100 km)) | Capacity | Advantages | Disadvantages |
|---|---|---|---|---|
| Pipeline | 99.2% | Up to 100 tons $h^{-1}$ (3.9 GW) | Large and very large quantities can be transported to any distance with high efficiency, low running costs, and very low variable expenses. This method also provides storage and buffering possibilities | Relative expensive investment costs and requirement for very large amounts of hydrogen delivery to be justified |
| Tube trailer | ≈ 94% | Up to 400 kg per truck | Small-scale deployment possibilities | Small-scale delivery per vehicle, energy inefficiency, short-distance transportation |
| Liquid trucks | ≈ 99% (liquefaction efficiency is around 75%) | Up to 4,000 kg per truck | Larger volumes than gas transportation | Costs and inefficiency of liquefaction and boil-off product losses |

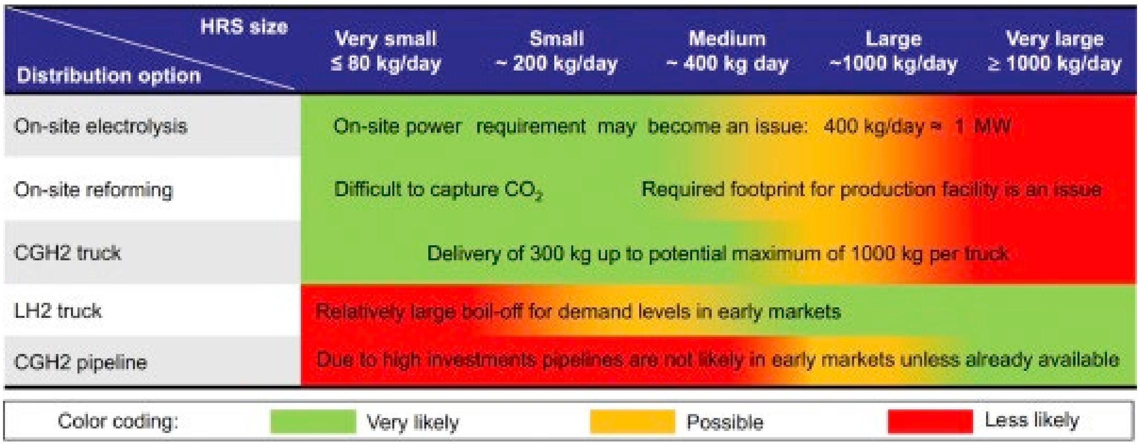



**Figure 18 Feasibility of various hydrogen distribution options [33]**

### 2.4.1 Pipeline

Hydrogen transportation via pipeline is a primary method for efficiently conveying hydrogen across extended distances. Dedicated pipelines have been used for hydrogen transportation from the production facilities to the end-users, with compressor stations ensuring continuous gas flow by supplying the required energy for pressure and temperature control [34-36].

Hydrogen gas transmission through pipelines reveals numerous advantages. It excels in enabling widespread hydrogen distribution, catering to the needs of industrial, commercial, and residential users. This method ensures a stable and dependable hydrogen supply, reducing the demands for frequent transportation and storage. It is also cost-effective, particularly for large-scale power plants, and aligns with environmental sustainability. The gas transportation pipeline is serving as a long-term operation means. Furthermore, the flexibility of pipeline infrastructure allows for integration with existing natural gas pipelines, enabling the efficient transportation of hydrogen by repurposing established infrastructure [37, 38].

While pipeline transportation offers numerous advantages, certain challenges need to be addressed. For instance, hydrogen possesses distinct properties compared to natural gas, necessitating specialized pipeline materials, coatings, and design considerations to mitigate issues like hydrogen embrittlement and gas leakage [38]. Safeguarding the integrity of the pipeline is vital, requiring the implementation of safety measures such as monitoring systems, leak detection technologies, and rigorous maintenance protocols to prevent accidents. Furthermore, the expansion of hydrogen pipeline infrastructure entails significant investments and meticulous planning. This involves considerations like route selection, regulatory approvals, and coordination with various stakeholders. As the hydrogen infrastructure continues to mature, the establishment of standardized codes and regulations tailored to hydrogen pipeline transportation becomes paramount, ensuring safety and interoperability [35, 38].

### 2.4.2 Tube trailer

Hydrogen produced at a central plant can be transported through a transmission pipeline to a distribution centre. Here, the hydrogen is compressed and loaded into specialized pressure vessels on a trailer called a "tube trailer." These tube trailers are responsible for transporting compressed hydrogen to hydrogen refuelling stations. The design of the tube trailer and the pressure at which the hydrogen payload can be determined [33].

The selection of pressure vessels affixed to the trailer significantly influences the maximum payload capacity, which, in turn, has economic implications for hydrogen delivery. The particular pressure vessel type, along with its operational pressure, sets the minimum weight necessary for containing a unit of hydrogen [33]. Currently, five diverse pressure vessel types exist, categorized as types I to V that are designed for the storage and transport of gases as shown in **Table 5** and **Figure 19** [39-41].

The physical characteristics of pressure vessels installed on the tube trailer, for a given pressure rating, are determined by the vessel type. These attributes, such as wall thickness, have a direct impact on the weight, volume, and payload of the vessel. Type-I pressure vessels are typically constructed from steel and adhere to the American Society of Mechanical Engineers (ASME) Section VIII Division 1 pressure vessel code. On the other hand, Type IV pressure vessels are manufactured using a carbon-fibre-reinforced composite material wound around a high-density-polyethylene (HDPE) liner and are designed through netting analysis [42-44]. While Type-V vessels represent a relatively recent technology approved for gas storage, they have not undergone testing for hydrogen storage. Tube trailers equipped with Type-I pressure vessels can transport up to 250 kg of hydrogen at pressures of 200 bar, while Type-III and Type-IV pressure vessels can carry up to 1000 kg of hydrogen at pressures of 500 bar [33, 41].

Table 5 Diverse pressure vessel types [19, 33, 35, 41]

| Tank type | Material | Advantages | Disadvantages |
|---|---|---|---|
| Type I | Steel | Relatively low material cost<br>Low manufacturing cost due to high production volumes and mature technologies | Relatively high material density and low material strength resulting in a high vessel-to-hydrogen weight ratio<br>Possibility of hydrogen permeation; prone to hydrogen embrittlement |
| Type II | Aluminium | Lower vessel to hydrogen weight ratio compared to type I vessel | Higher cost compared to type I vessel |
| Type III | Fibre-reinforced plastic | Lower vessel-to-hydrogen weight ratio compared to type I and II vessels | Higher cost compared to type I and II vessels |
| Type IV | Carbon fibre-reinforced plastic | Lower vessel-to-hydrogen weight ratio compared to type I, II and III vessels | Higher cost compared to type I, II and III vessels.<br>Possibility of hydrogen permeation through the liner |
| Type V | Full composite (fibre-reinforced shell) | Lower vessel-to-hydrogen weight ratio compared to type I, II, III and IV vessels | Higher cost compared to type I, II, III and IV vessels |

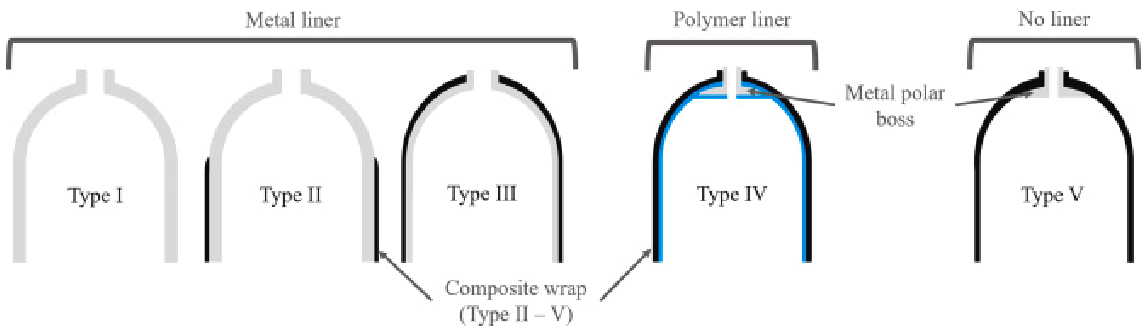


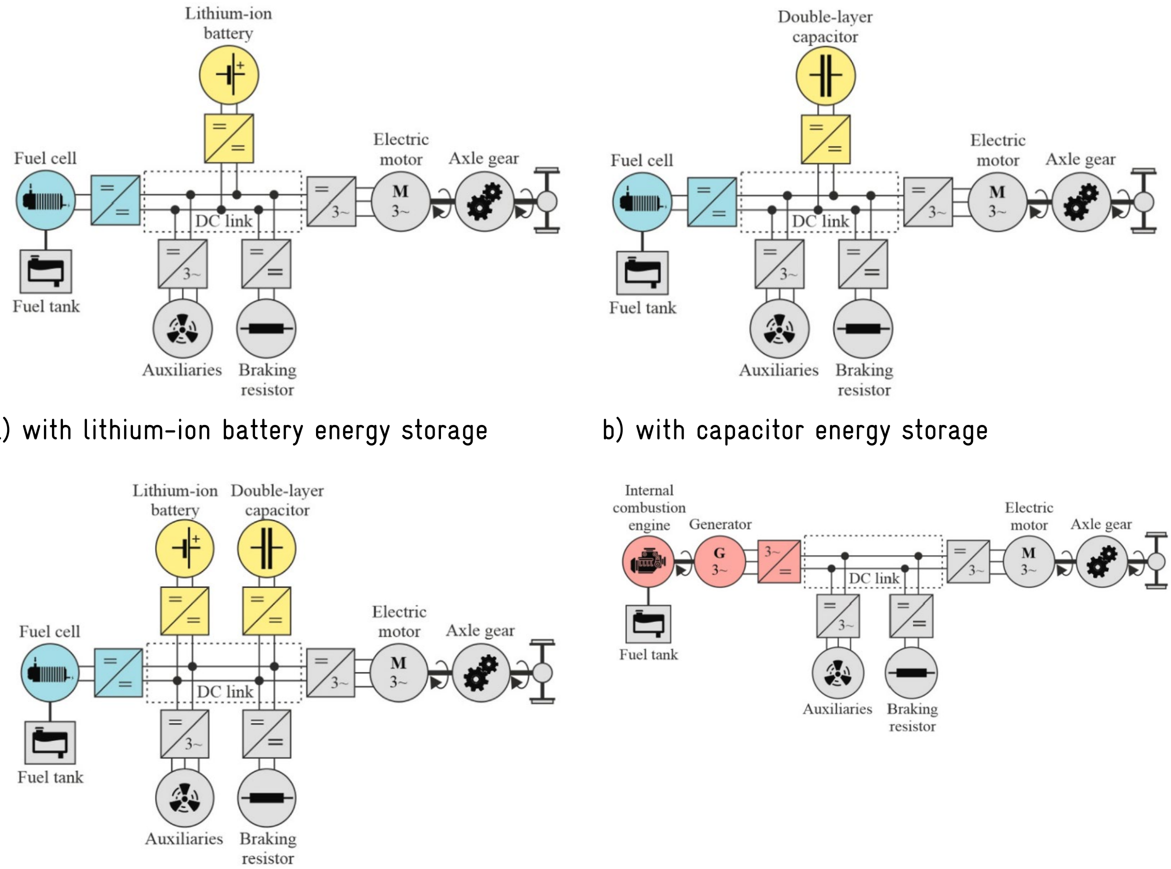

Figure 19 Five common types of pressure tank [41]

### 2.4.3 Liquid hydrogen trucks

As demand steadily rises, the storage of liquid hydrogen (LH) has emerged as an optimal solution for fulfilling the requirements of large-scale and long-distance transportation, bridging the gap between liquefaction plants and refilling stations. The transportation of liquid hydrogen involves moving hydrogen when it is in its liquid form, generally under the extremely low temperature of approximately -253°C. [35, 45, 46]. Within the domain of road transport, trailers are a prevalent choice, characterized by tank capacities ranging from 30 to 60 $m^3$, providing the capability to store hydrogen quantities between 2100 and 4200 kg. Safety measures dictate that vessel refilling is limited to around 85% of its total capacity, assuring operational safety and accounting for thermal expansion. Selecting the transportation of liquid hydrogen at atmospheric pressure is advantageous due to its effectiveness in minimizing losses when compared to higher-pressure transport methods. Dealing with liquid hydrogen is generally more straightforward and safer compared to the management of high-pressure gaseous hydrogen [35]. However, it is crucial to recognize that imperfect thermal insulation renders this storage solution susceptible to hydrogen boil-off. This leads to a gradual loss of stored hydrogen, typically ranging from 0.03 to 0.10% per day, with additional boil-off possible during the transfer of liquid hydrogen from the tanker to the storage vessel [47].

## 2.5 Hydrogen-powered propulsion technology applied to railways

Rail transportation presents an advantageous, congestion-free option with high safety standards. Basically, it represents the best advantages in terms of economic, environmental, social, and energy intensity. Moreover, it ensures reduced emission output and improved fuel efficiency per passenger. In comparison to alternative transportation methods, rail transport optimizes land use per traffic volume. This mode of transportation primarily caters to freight applications [48]. Hydrogen-powered vehicle technologies offer a promising alternative to the commonly used diesel-electric multiple units (DEMU) for regional non-electrified railway networks passenger transportation. Fuel cells (FC) stand as a prominent technology for generating on-board power in hydrogen-oriented railway applications. Compared to internal combustion engines (ICE), FCs provide distinct advantages, notably high efficiency, quiet and emission-free operations on-site, resulting in water vapour and heat as the sole byproducts [49, 50]. The schematic mode of powered propulsion technology on railways is shown in **Figure 20**.




a) with lithium-ion battery energy storage

b) with capacitor energy storage

c) with hybrid energy storage system (Li-ion battery + capacitor)

d) standard internal combustion engine

**Figure 20 Schematic illustration of fuel cell-based propulsion systems (a to c) compared with ICE propulsion system (d) applied in railway vehicles [49].**

### 2.5.1 Hydrogen fuel cell technology for railway applications

For the fuel cell (FC) designs, the systems exhibit variability based on factors such as fuel type, operational temperature, and the specific characteristics of the electrolyte. Various FC types are prevalent, each distinguished by its operational features, including proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), direct methanol fuel cell (DMFC), alkaline fuel cell (AFC), molten carbonate fuel cell (MCFC), and phosphoric acid fuel cell (PAFC) [51]. The distinctions among these FC types lie in their electrolyte composition, with PEMFC and DMFC utilizing solid polymer membranes, SOFC employing ceramic solid electrolytes, and AFC, PAFC, and MCFC relying on liquid electrolytes [52]. **Table 6** presents the typical properties of existing commercial and research FC structures. Categorized by operational temperature, low-temperature FCs include PEMFC, DMFC, PAFC, and AFC, while SOFC and MCFC are recognized as high-temperature FC types [53, 54]. Moreover, fuel cells can be used in different applications based on the required power output scale as shown in **Figure 21**.

**Table 6 Characteristics and properties of fuel cells [55]**

| Typical Values | PEMFC | SOFC | DMFC | AFC | MCFC | PAFC |
|---|---|---|---|---|---|---|
| Electrolyte | Polymer membrane | Ceramic | Polymer membrane | Potassium hydroxide | Molten carbonate | Phosphoric acid |
| Fuel | Pure H2 | H2, CO, CH4 | CH3OH | Pure H2 | H2, CO, CH4 | Pure H2 |
| Cell voltage (V) | ~1.1 V | 0.8–1 V | 0.2–0.4 V | ~1 V | 0.7–1 V | ~1.1 V |
| Efficiency (%) | 40–60 % | 50–70 % | 20–40 % | 60–70 % | ~50–70 % | ~40–55 % |
| Operating Temperature | <100 °C | 600–1000 °C | 90–120 °C | 65–220 °C | 620–660 °C | 150–200 °C |
| Power rating | 10 W–500 kW | 1 kW–2 MW | 1 W–1 kW | 10–200 kW | 10 kW–200 MW | 200 kW–50 MW |

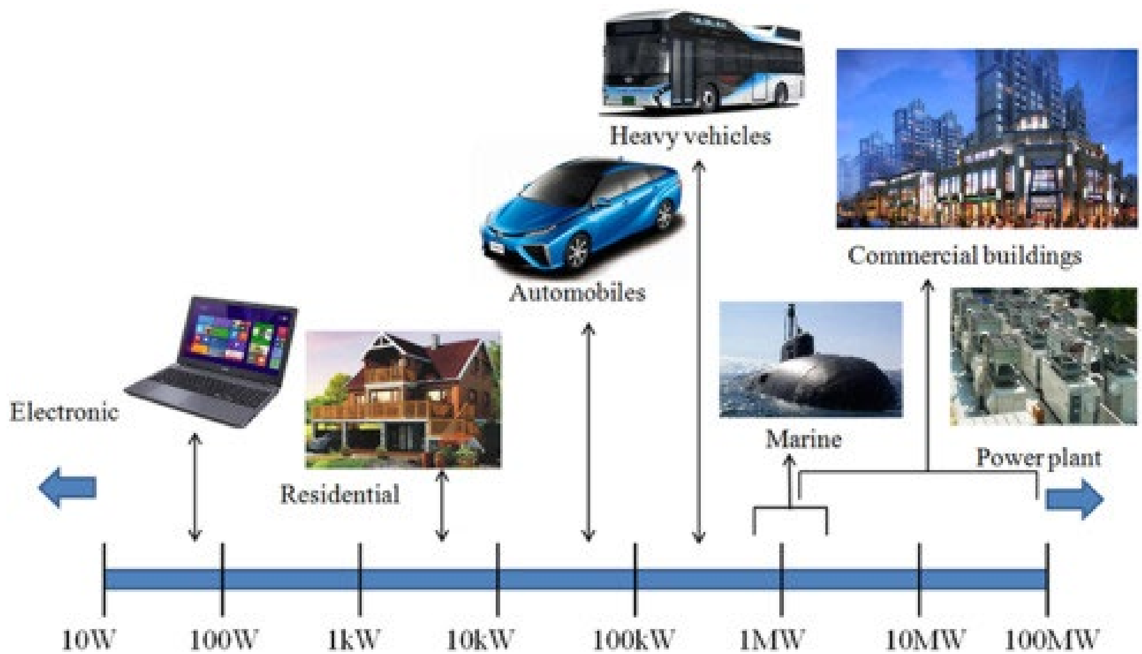


**Figure 21 Example of some typical applications of fuel cells [56]**

In terms of retrofitting vehicles to hydrogen-powered versions, the pivotal stage in the vehicle powertrain design process is the careful selection of appropriate technology. The selection of suitable technology is crucial when retrofitting vehicles to hydrogen-powered versions. This involves evaluating diverse FC types based on factors like start-up time, efficiency, operational temperature, materials used, and costs. A thorough overview and comparison of FC technologies are essential for informed decision-making. Among these, the PEMFC stands out for its simplicity, quick start-up, high power density, long cycle life, and efficient operation at lower temperatures. However, when considering train applications, PEMFCs have faced challenges, including high operating temperatures, specific operational requirements, and constraints in fuel storage and efficiency. These issues limit their suitability for the dynamic and space-constrained environment of trains, emphasizing the dominant role of PEMFCs in meeting the stringent demands of such applications [57-59].

In recent years, significant advancements have been made in the integration of hydrogen technology into railway applications. Alstom's groundbreaking introduction of the Coradia iLint in 2016 marked a milestone as the world's first hydrogen fuel cell-powered passenger train, capable of travelling substantial distances and achieving impressive speeds [60]. Furthermore, research studies have explored innovative approaches to clean railway vehicles, such as a novel system integrating a solid oxide fuel cell with an Ammonia Dissociation and Separation Unit for on-board hydrogen production and utilization in locomotive trains [61]. Another focus has been on hydrogen electrification using PEMFCs, particularly in applications like taxis, buses, and logistics vehicles, where minimal hydrogen infrastructure is required [56]. A noteworthy contribution comes from a study introducing a predictive power flow control strategy for hydrogen-powered city rail trains, emphasizing fuel efficiency during operations over non-electrified lines [62]. These developments collectively showcase the growing potential and diverse applications of hydrogen technology in advancing the railway industry.

### 2.5.2 Hydrogen fuel cell hybrid technology for railway applications

FCs are a significant technology for producing onboard power in hydrogen-driven applications. However, during transition periods such as start-up, acceleration, or climbing, there is a delay in the reaction gas's response rate within the fuel cell compared to the changing load rate. This delay impacts the vehicle's performance during these dynamic states [63, 64]. Consequently, the fuel cell system (FCS) faces challenges in providing precise power during transitional phases. Additionally, the FCS directly transforms chemical energy into electrical energy, limiting its capacity to store regenerative braking energy produced during deceleration and braking. To address these drawbacks, fuel cell technology typically incorporates a secondary energy storage system, such as a battery or ultra-capacitor (UC), in a hybrid power system alongside the fuel cell. This hybrid setup effectively mitigates the previously mentioned issues. The fuel cell hybrid system can be categorized into three main groups: 1) FCS hybridization with a battery, 2) FCS hybridization with an ultra-capacitor (UC), and 3) FCS hybridization with both the battery and UC [64].

1. FCS hybridization with battery

   The integration of FCS with a battery is the most common topology within the fuel cell hybrid system. This arrangement leverages a mature industry ecosystem and efficient, cost-effective production methods [65]. In this setup, the fuel cell, recognized for its substantial energy density, acts as the main power provider, ensuring a steady power supply. Meanwhile, a high-power-density battery complements by supplying peak power and storing energy during regenerative braking. This setup alleviates the strain on the fuel cell system during load fluctuations or sustained high-load usage, ultimately enhancing the efficiency of the entire power system.

2. FCS hybridization with UC

   Integration of the FCS with UC presents significant benefits, such as heightened power density, enhanced cold start performance, prolonged theoretical cycle life, improved charging and discharging efficiency, and minimized energy wastage in comparison to conventional batteries [58, 66, 67]. Moreover, UC possesses the feature of rapid discharge, allowing for an immediate enhancement of the vehicle's power performance during acceleration. In contrast to batteries, UC exhibits reduced specific energy, constrained stored energy capacity, and a lower safety voltage. Moreover, their swift charging rate and high discharge efficiency pose challenges to effective control [68].

3. FCS hybridization with both battery and UC

   Achieving optimal acceleration performance in logistics vehicles necessitates a blend of high-power density and high-energy density. Recognizing the complementary strengths of batteries and UC, the FCS hybridization with both battery and UC (FCS + Battery + UC) ensures a more balanced energy distribution across various operational circumstances [69-71]. However, this hybrid topology aids in prolonging the battery's lifespan. UC effectively absorbs the peak currents generated during braking or deceleration, mitigating the adverse effects of high current on the battery and contributing to its longevity [64].

Recent research has explored the integration of hydrogen and battery energy systems in electric trains and investigated emergency backup scenarios. The study compared fuel cell hybrid powertrains with 350- and 700-bar tanks alongside Nickel-Manganese-Cobalt (NMC) and Lithium-Iron-Phosphate battery systems, emphasizing the suitability of 700-bar tanks for innovative powertrains in traditional trains [72]. Another notable application is the implementation of vehicle-to-grid technology in a hydrogen-based tram, featuring PEMFC with lithium iron phosphate battery and electrochemical double-layer supercapacitor for enhanced efficiency and longevity [73]. A hierarchical eco-driving and energy management control system for hydrogen-powered hybrid trains utilized the Model Predictive Controller (MPC) to optimize eco-driving and energy distribution, focusing on fuel economy and punctuality [74]. Additional research explored the reliability-constrained optimal sizing and rechargeable battery selection for improved load distribution in a fuel-cell hybrid railway propulsion system, aiming to address the issues related to battery sizing and charging limitations [75]. A multi-method control strategy is proposed for numerically testing a fuel cell-battery-supercapacitor tramway, achieving an overall efficiency of approximately 42.5% [76]. Lastly, the analysis of fuel cell hybrid powertrains for Southern Italian railways demonstrates the versatility of fuel cells across various rail applications [77]. These studies collectively contribute to the advancement and optimization of hydrogen technology in railway systems.

# 3 POLICY AND REGULATION RELATED TO PROMOTION OF HYDROGEN UTILIZATION IN RAILWAYS

A significant number of countries, more than thirty in total, have initiated their respective Hydrogen National Plans, Strategies, or Roadmaps, as illustrated in **Figure 22**. The year 2020 witnessed the highest number of plan announcements, with 2021 trailing closely behind in terms of plan introductions [10].

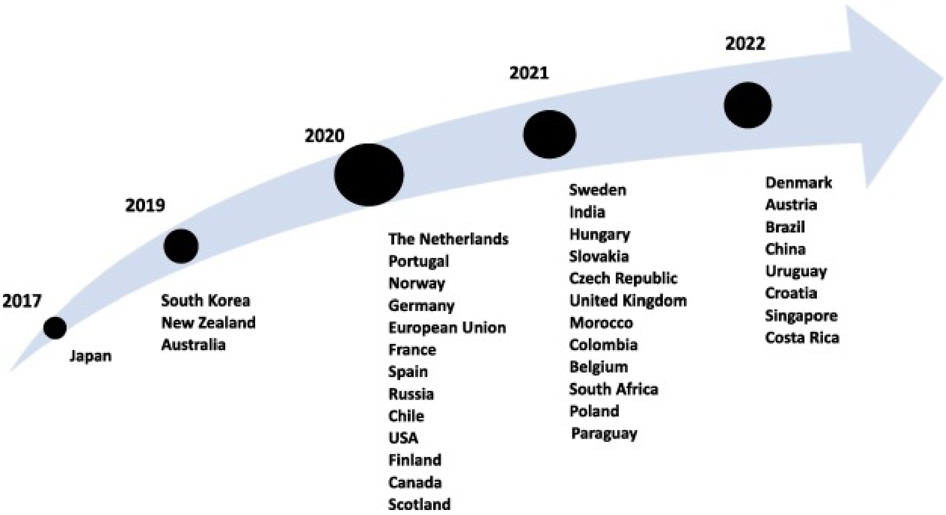



**Figure 22 Hydrogen National Plans, Strategies, and Roadmaps released by the end of 2022 [10].**

## 3.1 Germany's case study

With the aim of achieving GHG neutrality by 2045, Germany has recognized the imperative to enhance energy efficiency and decarbonize its energy and materials supply. Consequently, the federal government introduced the National Hydrogen Strategy in 2020 to propel the adoption of eco-friendly hydrogen technologies. Beyond the goal of net zero carbon emissions, the strategy has tried to solidify and expand Germany's prominent position in hydrogen technologies. Key objectives included establishing renewable energy-produced hydrogen as a pivotal element in the energy transition to mitigate greenhouse gas emissions, creating a domestic market, formulating a regulatory framework for essential transport and distribution infrastructure, enhancing the competitiveness of German companies in hydrogen technologies, and ensuring a future supply of hydrogen from renewables through international partnerships, particularly at the European level.

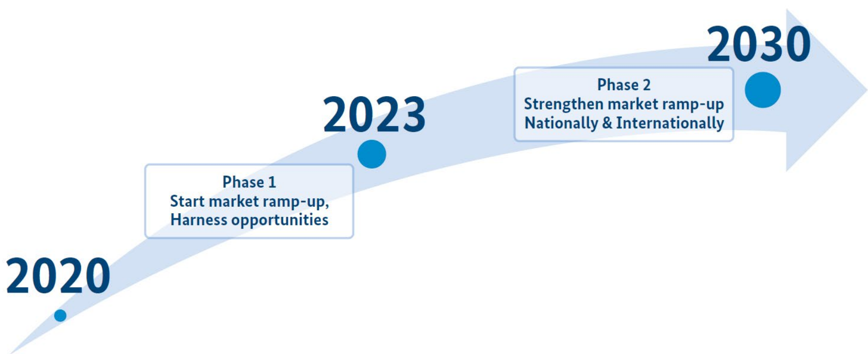



**Figure 23 Germany's national hydrogen strategy [78].**

The National Hydrogen Strategy outlined the initial plans for launching a market ramp-up of innovative hydrogen technologies by the end of 2023 as shown in **Figure 23**. An accompanying action plan delineated specific measures to promote hydrogen utilization across various sectors, encompassing hydrogen production, transportation, industrial sectors, heat, infrastructure and supply, as well as research, education, and innovation. Recognizing the need for collaborative efforts at the European level and fostering international partnerships, the strategy positioned Germany as a leader in the global hydrogen market and contributing to external economic collaborations. According to the strategy, the strategic roadmap encompassed a detailed action plan delineating specific measures to be undertaken, with the primary objective being to establish a foundation conducive to private sector investments in hydrogen production, transportation and utilization. The strategy emphasized the necessity for reliable and sustainable hydrogen production at costs competitive with conventional energy sources. Industrial-scale generation plants, particularly electrolyzers, are quite important for producing "green" hydrogen.

In addition, hydrogen plays a crucial role in achieving sustainable and climate-friendly mobility, offering significant potential across diverse transportation modes. Particularly impactful in large and heavy vehicles such as road haulage, air traffic, and maritime transport, hydrogen can be utilized either in fuel cells or as a feedstock for renewable electricity-based fuels. While considering the unsuitability of battery-electric drives in certain applications, the strategy emphasized the promotion of green hydrogen in fuel production and as an alternative to conventional fuels, with targeted funding for research, development and investments in hydrogen vehicles, especially within road haulage, air traffic and maritime transport [78, 79].

The successful implementation and development of the National Hydrogen Strategy demanded vigilant monitoring of progress and the adept identification of potential adjustments. To accomplish this, a flexible and output-oriented governance structure has been meticulously devised as illustrated in **Figure 24**. This framework has been designed to ensure the active engagement of pertinent stakeholder groups, fostering streamlined and efficient cooperation.

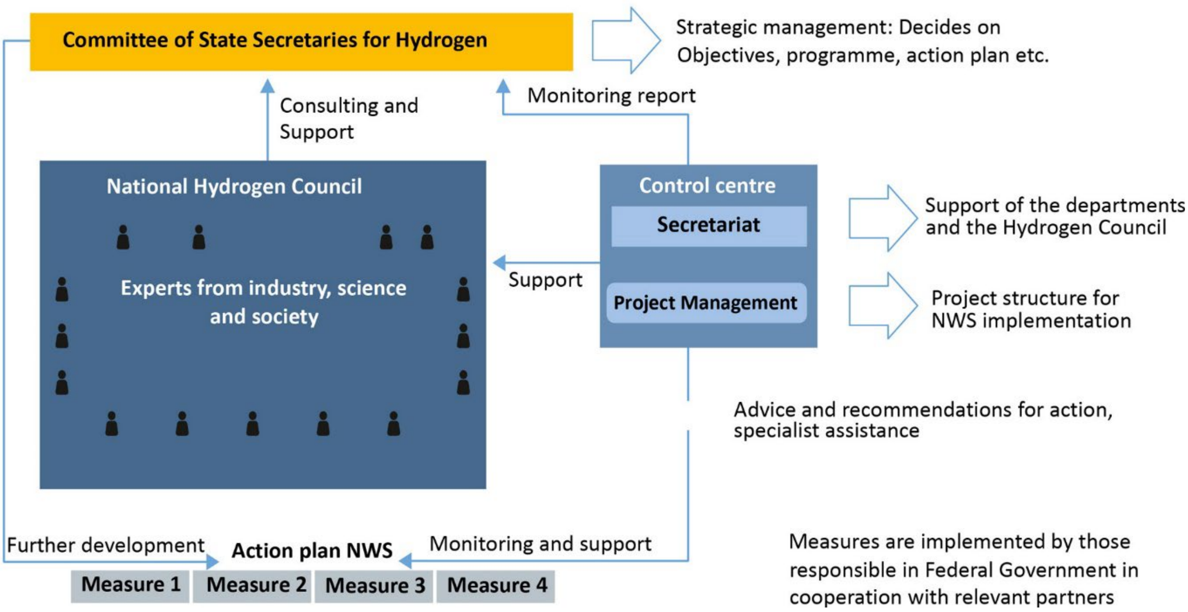



**Figure 24 Established structure of governance of the hydrogen Strategy [79]**

Furthermore, the Federal Government is actively fostering the competitiveness of the German economy while exploring opportunities in new markets. The Federal Ministry of Education and Research is actively endorsing initiatives that delve into the foundational aspects of the hydrogen economy, addressing crucial questions related to the cost-effective and efficient production, storage, transportation, and utilization of hydrogen.

Simultaneously, the Federal Ministry for Economic Affairs is championing the establishment of living labs, serving as pilot projects for the energy transition. Support is extended to companies and research institutions engaged in the development of novel technologies and solutions for the energy transition, with real-world testing conducted on an industrial scale. Additionally, the National Innovation Programme for Hydrogen and Fuel Cell Technology, under the auspices of the Federal Ministry of Transport, is backing projects focused on the utilization of hydrogen in various transport modes, including road, rail, water, and air. [79].

### 3.1.1 Applications to the railway network in Germany

In March 2022, Germany marked a significant milestone with the commencement of regular operations of the first 14 hydrogen-powered trains, known as "Coradia iLints", as shown in **Figure 25**. Those hydrogen-powered trains were manufactured by Alstom, a prominent global player in the train manufacturing sector [80]. Operating on a regional line between Buxtehude and Cuxhaven, those trains successfully performed an 18-month commercial demonstration trial, covering over 200,000 km and emitting only water vapour. Concurrently, various global manufacturers are also venturing into hydrogen-powered rail projects. To facilitate refuelling infrastructure, Alstom is collaborating with oil and gas companies like Linde in Germany and PKN Orlen in Poland. The Coradia iLints trains revealed an impressive operational span of over 18 hours between refuellings, and Alstom is actively partnering with Hynamics and Deutsche Bahn to develop mobile stations capable of refuelling within 15 minutes, similar to diesel refuelling and significantly quicker than electric battery recharging. In this case, it was expected that battery recharging might need approximately 4 hours to be in a fully charged state [81]. Germany initiated the construction of the world's first HRS designed for trains at the end of 2020, and this project is anticipated to continue.

**Figure 25 The "Coradia iLint" hydrogen-powered trains [81]**

## 3.2 China's case study

In the case of the People's Republic of China (PRC), the National Development and Reform Commission of China formulated the action plan for energy technology revolution and innovation (2016 to 2030) in 2016. Three strategic development directions have been announced for acceleration of the plan: 1) hydrogen industry (hydrogen production, hydrogen storage & transportation and hydrogenation station), 2) advanced fuel cell development, and 3) distributed power generation. In 2020, hydrogen energy policies were announced to promote the development of the hydrogen energy industry in the country. It is worth noting that the announced policies of the hydrogen industry have mainly focused on the field of transportation. Therefore, hydrogen fuel cell-powered vehicles and hydrogen refuelling stations have become the key factors in propelling the development of the hydrogen energy industry in many regions of China [82].

Regarding China’s energy law, hydrogen has been listed as “Energy” since April 2020. A financial subsidy policy has been implemented to enhance the promotion and application of new energy in transportation vehicles, i.e. hydrogen fuel cell vehicles. Three key aspects of hydrogen fuel cell vehicles have been considered: 1) demonstration and application of fuel cell vehicles, 2) technology research and industrial application of key components, and 3) awards for new technology replacement. The national goal in association with two new national policies is to establish a complete industrial chain and fuel cell vehicles, break through the core technologies, and establish a good situation of reasonable layout and coordinated development [82].

Additionally, in September 2021, China introduced a significant environmental initiative known as the "Dual Carbon Goal" that targets a peak reduction in carbon emissions by 2030 and carbon neutrality by 2060. Aligning with this commitment, the State Council of China has launched a comprehensive action plan for Carbon Dioxide Peaking before 2030, with a keen focus on the transformative role of hydrogen in vital sectors like steel, petrochemicals, and transportation, particularly in heavy-duty freight. Recognizing hydrogen as a pivotal technology, especially in renewable hydrogen production, this plan reinforced China's commitment to achieving its ambitious environmental targets. Subsequently, a National Plan was unveiled, outlining the strategic vision for China's hydrogen industry by 2035. This visionary roadmap strategically positions hydrogen as a foundational element in China's future energy system, a key facilitator in the transition to low-carbon energy, and a crucial player in emerging industries, shaping the trajectory of China's industrial development. The distribution of existing hydrogen demand, industrial clusters, and renewable hydrogen projects in China is shown in **Figure 26**. In addition, the Chinese government has outlined a strategic medium- and long-term development plan for hydrogen spanning the period between 2021-2035. As part of this initiative, China has aimed to deploy 50,000 hydrogen fuel-cell vehicles and establish a network of hydrogen refuelling stations by 2025. The plan has emphasized the production of green hydrogen through renewable feedstock resources, targeting an annual output of 100,000 - 200,000 tonnes by 2025. Beyond the transport sector, the plan has also envisioned the utilization of clean hydrogen in diverse industries such as energy storage, electricity generation and industrial applications. **Figure 27** illustrates the distribution of enterprises across various segments of China's hydrogen industry chain. Currently, China stands as the world's largest producer and consumer of hydrogen [83].


**Figure 26 Mapping hydrogen demand, industrial clusters, and renewable hydrogen projects across China [83].**

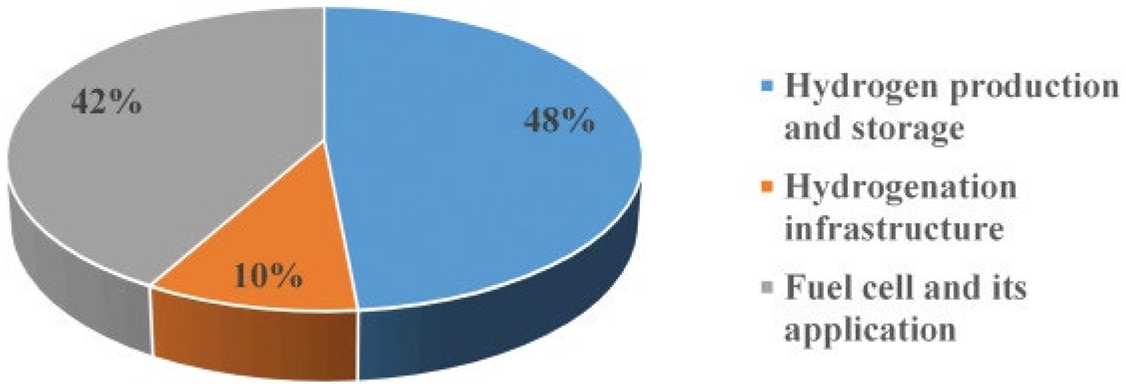



**Figure 27 Key segments of hydrogen industry chain in China [82]**

The National Plan also underscores the goal to establish a hydrogen supply system utilizing both industrial by-product hydrogen and renewable hydrogen. Notably, the short-term emphasis on by-product hydrogen has been attributed to the substantial volume of wasted by-product hydrogen, primarily fossil-based, extracted from industrial waste gas in sectors like coking, chlorine, and propane dehydrogenation. Many local governments prioritize by-product hydrogen as the primary supply source through 2025, aligning with the broader plan. This strategic shift has positioned China to become a global leader in hydrogen technologies, including fuel cell vehicles and electrolyzers [83].

China's hydrogen development strategy is dynamically evolving, with a primary focus on the application of hydrogen energy in transportation. This includes a diverse range of vehicles such as hydrogen fuel cell passenger cars, business vehicles, heavy-duty trucks, forklifts, freight cars, ships, trams, intercity train electric multiple units (EMU), and even aeroplanes. The National Development and Reform Commission of China, in alignment with its 2016 "Action Plan for Energy Technology Revolution and Innovation," has delineated three strategic development directions for the hydrogen industry, namely hydrogen production, storage & transportation, and hydrogenation stations. The plan has also underlined the significance of advanced fuel cells and distributed power generation. Key technological areas emphasized within the plan encompass large-scale hydrogen production, distributed hydrogen production, hydrogen storage and transportation, hydrogen/air polymer electrolyte membrane fuel cell (PEMFC) technology, methanol/air polymer electrolyte membrane fuel cell (MFC) technology, and fuel cell distributed power generation technology [82].

### 3.2.1 Applications to the railway network in China

As urbanization expands, the mounting pressure on urban traffic infrastructure has given rise to challenges such as traffic congestion and air pollution. In response, China is strategically steering its new energy vehicle development towards pure electric vehicles, including fuel cell vehicles predominantly applied in public transportation. The key role of urban rail transit, spanning subway networks, light rail systems, trams, and urban powered trains, has emerged as a linchpin in advancing the urbanization process and ameliorating existing transportation challenges. However, the substantial energy consumption and environmental impact associated with traditional rail transit systems necessitate some innovative solutions.

Hydrogen fuel cell trams, urban light rail networks, and intercity multiple units are positioned as transformative alternatives, offering compelling advantages such as environmental friendliness, extended driving ranges, swift construction timelines, and autonomy from complex power supply systems. Those innovations do not only manifest positive environmental effects but also yield noteworthy social and economic benefits, constituting a critical driver for the sustainable evolution of rail transit in China. The world's first hydrogen-powered trams, constructed through a collaboration between Canada’s Ballard Power

Systems and China's CRRC Sifang, have been in operation in Foshan city since 2019. The pilot projects in Foshan and Yunfu have demonstrated the feasibility of hydrogen buses, emphasizing China's readiness for large-scale integration of hydrogen energy in transportation. Notably, the Foshan Gaoming District's modern tram test line, covering a 6.5-km route, has shown the potential utilization of hydrogen energy in transport modes by replacing 28 buses with just eight modern trams, signifying the foundational conditions for widespread adoption of hydrogen energy in China's transportation sector [82].

China has been actively engaged in long-term research in the hydrogen energy field, resulting in significant breakthroughs. China currently has only 130 km of tram tracks spread across seven cities. Nevertheless, there is optimism as the Chinese government is committed to expanding hydrogen-powered tram technology. They have allocated over 200 billion yuan for the next five years to expand the tram network more than tenfold, extending it to 1,900 km [84]. This foresight can suggest a potentially enormous market for fuel cell rail vehicles in the future, catalyzing the rapid development of hydrogen fuel cell vehicles for rail transit.

## 3.3 Indonesia's case study

During the UN Climate Change Conference (COP 26) in 2021, Indonesia declared its ambitious goal to achieve net zero emissions by 2060. In 2023, Indonesia was among the top ten global $CO_2$ emitters, primarily due to its sizable population, which exceeds 280 million. In addition, the reliance on non-renewable energy sources further compounds this issue. Acknowledging the pressing need to curtail $CO_2$ emissions, Indonesia has sets more ambitious reduction targets aligned with the 2015 Paris Agreement. Through collaborative efforts with other nations, the government has aimed for a 43% reduction in carbon emissions by 2030 with international support. Additionally, Indonesia aspires to transition to a net zero-emission economy by 2060, emphasizing its dedication to environmental sustainability.

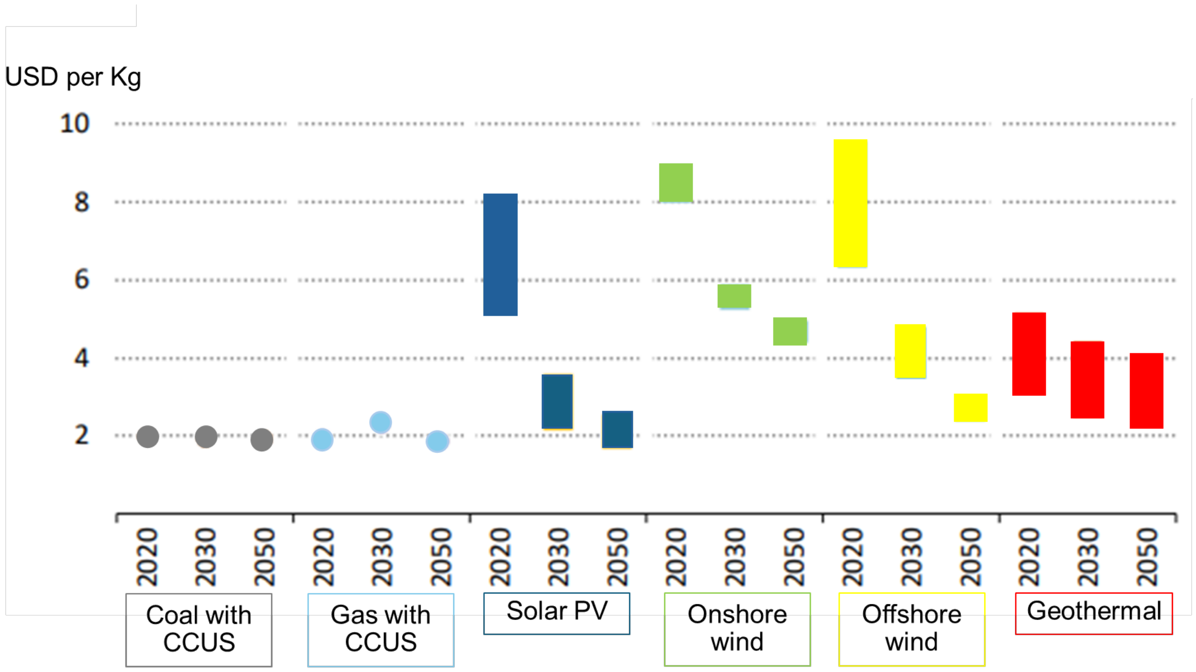



**Figure 28 Costs associated with hydrogen production in Indonesia under the Announced Pledges Scenario [85]**

In 2021, Indonesia's hydrogen demand stood at approximately 1.75 million tonnes, primarily serving the chemical and refining sub-sectors, predominantly reliant on natural gas. The country, rich in renewable energy resources, has the potential to produce low-carbon hydrogen through water electrolysis using renewable electricity. Alternatively, the combination of carbon capture, utilization and storage (CCUS) with natural gas or coal provides another low-emission production avenue, although current costs for low-emission hydrogen are higher than those for unabated fossil fuels as shown in **Figure 28**. Nevertheless, advancements in electrolyzers, renewable electricity, and CCUS technologies indicate a promising outlook for cost reduction, making low-emission hydrogen increasingly competitive. Projections suggest that hydrogen production costs from solar PV could drop to USD 1.7 per kg by 2050 in regions with favourable solar conditions. Locations harnessing offshore wind or geothermal electricity are also forecast to achieve competitive costs below USD 2.5 per kg by 2050. Additionally, stable hydrogen production from coal with CCUS is anticipated at projected costs of USD 1.9 per kilogram by 2050. However, considering declining domestic gas production, natural gas with CCUS may become less attractive due to the need for imports after 2030, raising concerns about energy security and domestic value chain considerations.

The inception of green hydrogen development within the Indonesian energy sector is anticipated to commence gradually in 2031, evolving into rapid expansion beyond 2050. Projections indicate a substantial increase in hydrogen generation capacity, reaching 328 MW from 2031 to 2035, 332 MW from 2036 to 2040, 9 GW from 2041 to 2050, and an impressive 52 GW from 2051 to 2060. This substantial growth always requires substantial investments, estimated to range from USD 0.8 billion in 2031 to USD 25.2 billion cumulatively by 2060. An analysis foresees Indonesia's demand for blue and green hydrogen to reach around 4 million tonnes per year in 2025, with projections indicating a doubling by 2030 and a quadrupling by 2040, reaching 17 million tonnes. The surge in demand is primarily attributed to the transportation sector, followed by power generation, ammonia, steel, methanol, refinery, and the cement industry. Emphasizing the transition to green hydrogen derived from renewable sources emerges as a pivotal strategy for enhancing energy efficiency, particularly in Indonesia's energy-intensive industries. However, hydrogen production costs in Indonesia are comparatively higher than those in regions with superior renewable resources, such as Australia or the Middle East, as shown in **Figure 29**. Nevertheless, the additional costs of shipping hydrogen from these resource-rich areas to Indonesia, ranging from USD 1 to 2 per kg, offset the advantages of importing hydrogen, making domestic production more economically viable [85].

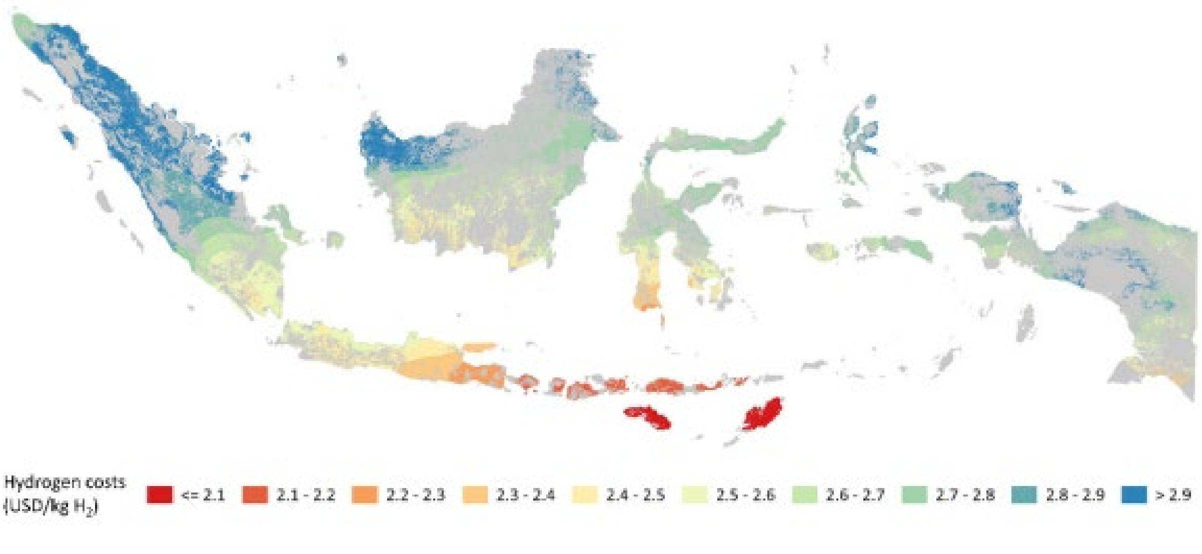



**Figure 29 Hydrogen production costs at around USD 2/kg $H_2$ from some regions in Indonesia by hybrid solar PV and wind systems in the Announced Pledges Scenario, 2030 [85]**

However, Indonesia currently lacks comprehensive policies and regulations to facilitate the development of its green hydrogen industry. Although the utilization of green hydrogen is acknowledged in the net zero roadmap outlined by the Ministry of Energy and Mineral Resources (MEMR), there are no dedicated key policy documents specifically addressing hydrogen development, aside from a few references within the broader national energy plan (RUEN). Recognizing that green hydrogen production is contingent on renewable electricity, regulations governing the electricity sector will also have implications for green hydrogen production. The lists of policy and regulatory documents in Indonesia that are related to green hydrogen development are shown in **Table 7** [86, 87].

**Table 7 Relevant policy and regulatory framework of green hydrogen development in Indonesia [87].**

| Regulation | Title | Description |
|---|---|---|
| Law No. 30/2007 | Energy Law | Puts the emphasis on energy security, sustainable development, energy resilience, and environmental preservation. |
| Law No. 30/2009 | Electricity Law | Regulates the electricity sector planning and governance. It also stipulates the prioritization of new and renewable energy. |
| Government Regulation No. 79/2014 | National Energy Policy (KEN) | Targets an increase of NRE share in primary energy mix to 23% in 2025 and 31% in 2050. |
| Presidential Regulation No. 22/2017 | National Energy Plan (RUEN) | Sets up an NRE development plan until 2050, including a general action plan for hydrogen development, such as preparation of regulatory frameworks, technological and manufacturing capacity development, and incentives provision. |
| New and renewable energy bill | New and renewable energy bill | Regulates NRE development, including pricing, incentives, etc. In the latest draft, hydrogen is mentioned as a new energy. |

The key government stakeholders in the development of green hydrogen in Indonesia include the Ministry of Energy and Mineral Resources (MEMR), primarily responsible for its utilization in the energy sector, overseen by the Directorate of Various New and Renewable Energy within the ministry. The Ministry of Industry (MOI) is actively engaged in managing hydrogen production, given its classification as an industrial inorganic gas, regulated within the basic chemical industry. MOI's role extends to overseeing manufacturing activities, including electrolyzer manufacturing. Financial support is integral, and the Ministry of Finance (MOF) manages fiscal incentives for green hydrogen projects, indirectly contributing to facilitation. State-owned enterprises (SOE), including PLN, Pertamina, and Pupuk Indonesia, significantly influence the green hydrogen landscape, as evidenced by their joint initiative, the Green Industry Cluster, focusing on long-term development. Additionally, the non-ministerial Investment Coordinating Board (BKPM) plays a vital role in formulating government policies related to investment and business licensing, advising companies interested in green hydrogen projects to collaborate with the board [87].

In the realm of investment and fiscal policies in Indonesia, the government has enacted regulations to address carbon pricing and taxation, exemplified by the Carbon Economic Value (CEV) and carbon tax integration into the taxation law. Carbon pricing mechanisms, including carbon trading, result-based payment, and a carbon levy or tax, are envisaged. The Ministry of Finance is set to determine a minimum carbon tax of USD 2 per kg CO2e, initially applicable to coal-fired power plants and anticipated to extend to the transportation and industry sectors with timelines determined by respective ministries. Additionally, fiscal incentives for green hydrogen projects are outlined in the Indonesia Investment Guidebook. These incentives encompass the import duty exemption for capital goods, a tax holiday for pioneer industries with investments exceeding USD 7 million, tax allowance covering reduced net income, accelerated depreciation, and amortization, as well as tax deductions for research and development activities, including those in the new and renewable energy sector. Although the pioneer industry list has yet to explicitly include green hydrogen, its alignment with related industries and criteria for pioneer status suggests eligibility for these fiscal benefits.

### 3.3.1 Applications to the railway network in Indonesia

As of July 2023, Spectronik has achieved a significant milestone by completing the installation, commissioning, and training for its hydrogen fuel cell system incorporated into a hybrid train developed by PT Industri Kereta Api (INKA) in Madiun, East Java, Indonesia. INKA, a state-owned rolling stock manufacturer in Indonesia, is renowned for producing a diverse range of railway products, including locomotives, Light Rail Transit (LRT), passenger railroad cars, goods wagons, diesel multiple units (DMU), and electric multiple units (EMU). The 2-car hybrid train powered by four energy sources (Pantographs, Diesel Electric, Batteries, and Hydrogen Fuel Cell) is uniquely tailored for Politeknik Negeri Madiun (PNM), a tertiary vocational institution specializing in train operation and maintenance as shown in **Figure 30**. This initiative has underlined INKA and PNM's foresight in addressing the imperative to educate the next generation workforces in emerging technologies like hydrogen fuel cells, with potential applications in the decarbonization of a rail transport mode [88].

**Figure 30 Example of a hybrid train with four energy sources [88]**

## 3.4 Strategic plan for hydrogen energy development in other countries

In the United States, a collaborative effort led by the Stark District Transport Authority is set to formulate an action plan for establishing alternative fuel transportation corridors in the Midwest states. The initiative aims to create the routes for electric, fuel cell, and compressed natural gas (CNG) powered vehicles, encompassing passenger cars, trucks, and buses. As of February 2018, there were 3,500 fuel cell electric vehicles and 39 hydrogen refuelling stations operating in the region. Meanwhile, Japan's comprehensive hydrogen strategy is outlined ten key action plans covering technology research, cost optimization, hydrogen sourcing, and more. Priorities have included low-cost utilization of hydrogen energy, the development of economical storage and transportation technology, hydrogen production from renewable energy sources, and the widespread adoption of fuel cell vehicles. The strategy of Japan for hydrogen and fuel cells is shown in Figure 31. In South Korea, a national hydrogen energy bill is slated for introduction, accompanied by substantial subsidies totalling 2 billion euros over the next five years. South Korea's investment of 2.6 trillion Won in fuel cell vehicle development targeted 9000 vehicles and 80 hydrogenation stations by 2020, with a vision for fuel cell vehicles constituting 10% of total vehicle output and 520 hydrogenation stations by 2030 as shown in Figure 32. Finally, France's national hydrogen energy plan, commencing in 2019, involves a 100-million-euro investment by ADEME (French Agency for Environment and Energy Management) in hydrogen energy, transportation, and energy storage. The plan aims to establish 100 hydrogenation stations, deploy 5000 fuel cell light commercial vehicles, and introduce 200 fuel cell heavy-duty vehicles by 2020.

By 2028, there are plans to increase between 400 and 1000 hydrogenation stations, 20,000 to 50,000 light commercial vehicles, and 800 to 2,000 heavy-duty vehicles.

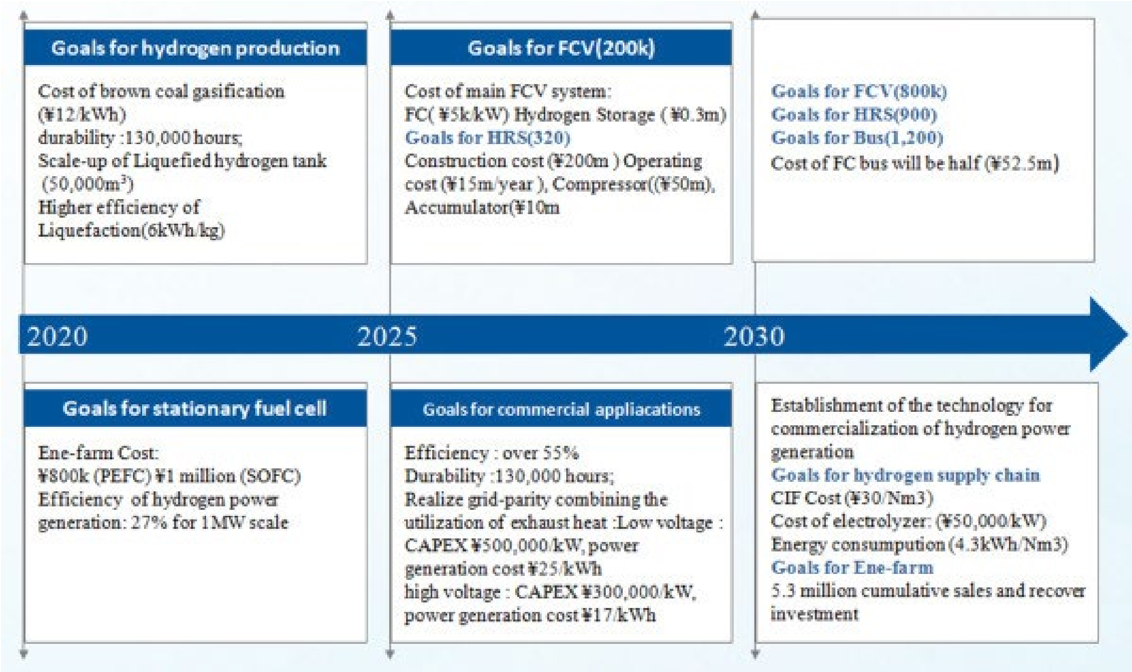



Figure 31 Strategy and roadmap of Japan for hydrogen and fuel cells from 2020 to 2030 [56]

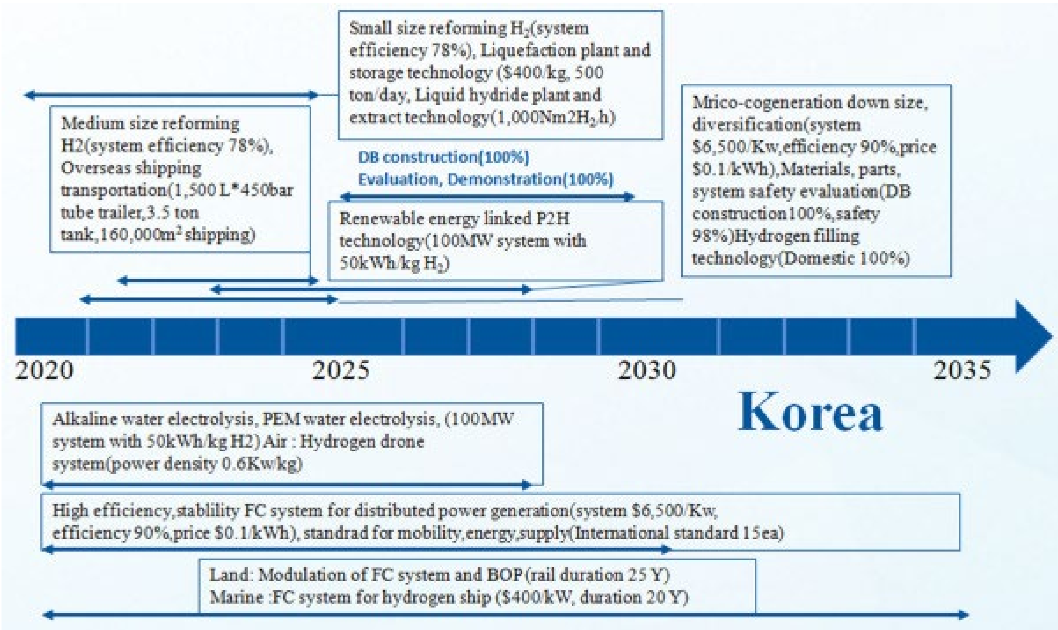



Figure 32 Strategy and roadmap of Korea for hydrogen and fuel cells from 2020 to 2035 [56]

## 3.5 Adaption of hydrogen policy and regulation based on Thailand's scenarios

Looking at case studies associated with the national policies, regulations and strategies for moving forward with a hydrogen economy in the aforementioned countries, it is likely that Thailand would require a comprehensive approach to formulating a unique strategy to promote the usage of hydrogen in rail transit. The proposed strategy has to consider various perspectives, including the specific energy landscape, economic priorities, and regulatory frameworks peculiar to Thailand. The approach from those countries to incentivize the growth of a hydrogen economy, including financial support and regulatory frameworks, can serve as a model for Thailand. To encourage the development of hydrogen infrastructure, Thailand may consider implementing financial incentives, subsidies, and supportive policies that attract in-cash and in-kind investment from both the public and private sectors. Additionally, the establishment of hydrogen refuelling stations and distribution networks is also necessary for initiatives involving a hydrogen-powered railway project in Thailand. Ultimately, tailoring these global best practices to Thailand's context involves a careful balance between economic priorities, environmental considerations, and collaboration across sectors to ensure the successful integration of hydrogen into the country's energy landscape.

# 4 SAFETY PERSPECTIVES AND STANDARD OF THE HYDROGEN-POWERED RAILWAY

Safety is a paramount consideration in the utilization of hydrogen-powered railway systems. As the rail industry transitions towards sustainable energy sources such as hydrogen fuel cells, ensuring rigorous safety perspectives and adherence to standards becomes imperative. This chapter explores the safety considerations associated with hydrogen-powered railways, addressing the concerns related to hydrogen's unique properties and potential hazards. The discussion will focus on the established safety standards and regulations governing the development, operation, and maintenance of hydrogen-based technology applied to railways.

## 4.1 Basic knowledge of hydrogen properties

Hydrogen, with its atomic structure comprising a lone proton and electron, holds the distinction of being the simplest element in the periodic table. Due to the lowest atomic weight at 1.008 g/mol, hydrogen primarily exists as a stable diatomic molecule ($H_2$) under ambient temperature and atmospheric pressure. Hydrogen is the lightest and most prevalent element in the universe, constituting approximately 75% of its total elemental mass. Regarding its diatomic form, hydrogen manifests as a colourless, odourless and tasteless gas. It has high flammability when combined with air [89, 90].

Due to the smaller size of hydrogen molecules compared to those of known odorants, hydrogen can easily leak through the openings. Hydrogen tends to move away from the source of a leak faster than odorants because of its buoyancy/high dispersion coefficient. Hydrogen is the lightest gas, which is 14 times lighter than air. Although it is not toxic, a health hazard may be caused by thermal burns. Hydrogen is flammable or explosive under a mixture of air. In addition to gaseous hydrogen ($GH_2$), liquid hydrogen ($LH_2$) is frequently found in some applications due to convenient transportation, which will rapidly boil or flash to a gas phase if exposed to the environment at normal temperature. The volumetric ratio of $LH_2$ to $GH_2$ is 1:848. This means that $LH_2$ expands approximately 850 times upon conversion to its gas phase at normal temperature and pressure (NTP). The phase diagram of hydrogen is shown in **Figure 33**. Hydrogen can be in gaseous, liquid, or slush forms depending on temperature and pressure. The slush hydrogen is a mixture of solid and liquid phases at the triple point temperature. Hydrogen may react violently if combined with oxidizers, such as air, oxygen, and halogens. However, hydrogen has safely been used in the industrial sector, e.g. in oil refineries, petrochemicals, steel, fertilizer, for many years [91].

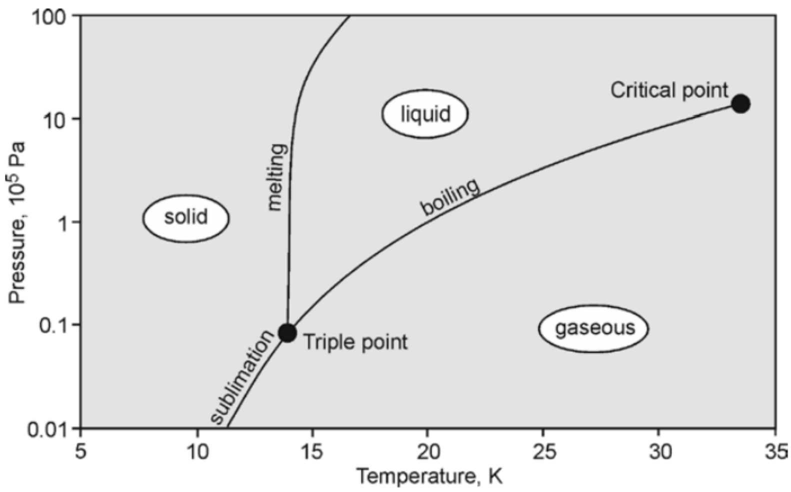



**Figure 33 Phase diagram of hydrogen [91]**

### 4.1.1 Physical properties of hydrogen

In terms of buoyancy characteristics, the density of gaseous hydrogen is 0.08375 $kg/m^3$ at NTP, while that of air is 1.205 $kg/m^3$ (hydrogen is 14 times lighter than air). Compared with other fossil fuels, gasoline (petrol) vapour and propane are heavier than air. Methane is lighter than air but still 8 times heavier than hydrogen gas, as shown in **Figure 34** [91]. This indicates that hydrogen gas is very buoyant, resulting in a decrease of safety concerns when it is released into the atmosphere. The heavier hydrocarbon-based fuels are capable of forming large combustible clouds, resulting in more severe fire and explosion hazards than hydrogen [92].

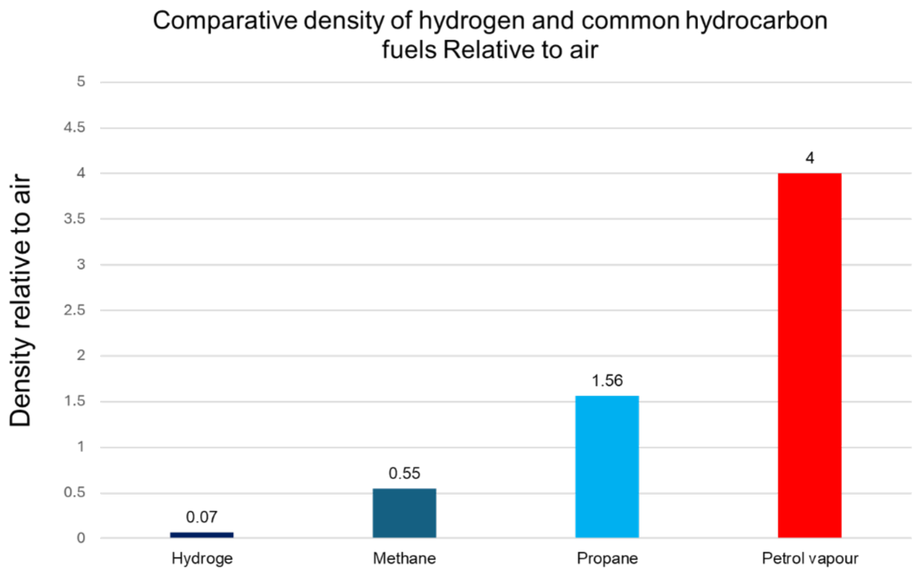



**Figure 34 Relative density of hydrogen and common hydrocarbon-based fuels with respect to air [91]**

In general, hydrogen, which possesses the smallest relative molecular mass, exhibits a heightened susceptibility to leakage or permeation from high-pressure environments when compared to natural gas. In the event of a hydrogen leak, three potential jet-flow states are obtained: 1) subsonic jet flow, 2) critical jet flow, and 3) supersonic jet flow [93],. Leaked hydrogen travels in the direction of the leak due to initial momentum and rises upward through aerostatic buoyancy. In confined spaces, a hydrogen-air mixture accumulates at the top, and under suitable conditions, ignition occurs in the presence of a heat source. However, the ignition is unlikely to occur if the mixture spreads into an unrestricted area with a hydrogen volume fraction lower than 4%. Hydrogen's extensive flammable range, rapid flame propagation speed, and low ignition energy present challenges for safe utilization. Additionally, its small molecular volume enables significant diffusion into metals, causing hydrogen-induced cracking of those metals. Hydrogen leakage can lead to jet formation, transforming into a plume rising swiftly under buoyancy, forming a combustible hydrogen-air mixture. When the mixture reaches a combustible concentration and encounters minimal ignition energy, hydrogen ignition takes place, often accelerating into Deflagration-to-Detonation Transition (DDT) within a few seconds. While minor leaks may spread rapidly without immediate danger, a substantial leak might lead to the risk of jet flames and explosions [94].

### 4.1.2 Ignition property

The ignition of hydrogen in the presence of air occurs within a specific flammable range, where the air content is between the Upper Flammable Limit (UFL) and the Lower Flammable Limit (LFL), given the presence of an effective ignition source. Hydrogen's flammability range is notably broader than hydrocarbons, ranging from 4 to 77 vol% in a mixture with air at NTP. When burned in pure oxygen, the flammability range widens further, ranging from 4.1 to 94 vol% in a mixture with $O_2$ at NTP. Hydrogen is highly susceptible to ignition from various sources, including mechanical sparks, electrostatic discharge, electrical equipment, catalyst particles, and atmospheric discharge. Proper elimination or isolation of ignition sources is crucial. The auto-ignition temperature, which indicates the minimum temperature required for combustion without an external ignition source, is relatively standard. Hydrogen, propane, and natural gas (methane) all have similar auto-ignition temperatures. As illustrated in **Figure 35**, the auto-ignition temperatures of these fuels are at least twice as high as that of gasoline vapour [91].

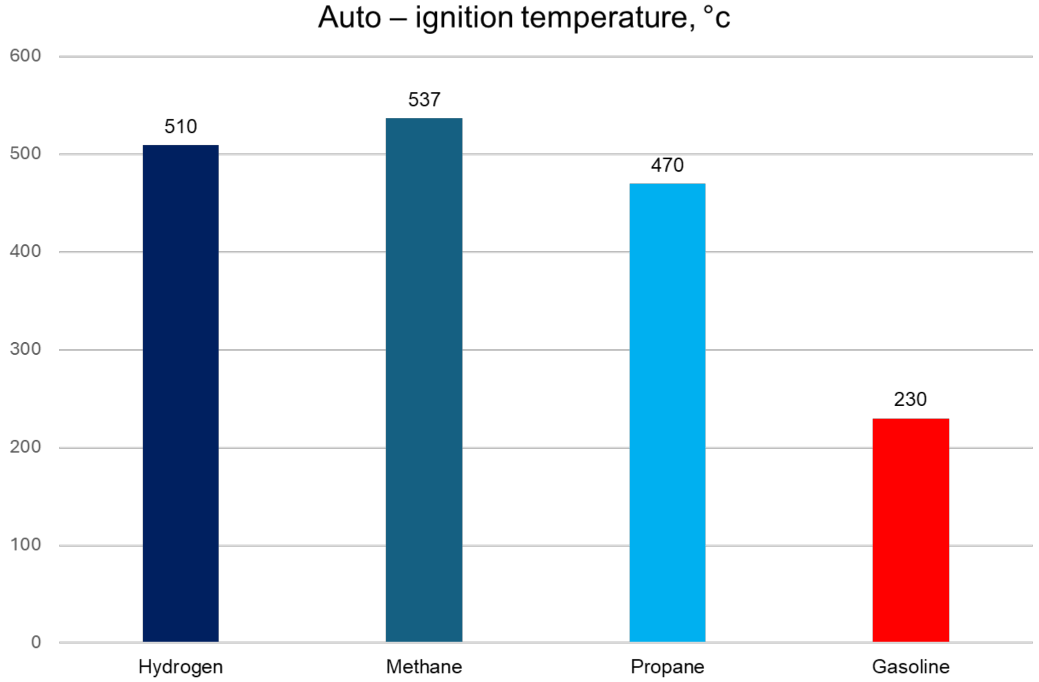



**Figure 35 Temperatures at which hydrogen and various other fuels undergo auto-ignition [91]**

### 4.1.3 Flame radiation

Hydrogen combustion is characterized by very pale blue flames that do not emit visible light during the daytime because sunlight can overshadow the flame's visibility. Moreover, hydrogen flames do not produce smoke, generating only water when burned in air, unless sodium-containing or dust particles are present. In contrast to hydrocarbon combustion, hydrogen flames emit significantly less heat, and the human sensation of this heat is only felt upon direct contact with the flame. A distinctive feature is that fire caused by hydrogen is difficult to notice, which propagates despite human monitoring in an area prone to hydrogen leaks (spills or accumulation) leading to potentially combustible mixtures. Consequently, convective and radiative heat fluxes from hydrogen combustion become crucial for safeguarding life, property and the environment [91].

### 4.1.4 Detonability limits

In the context of accidents, hydrogen detonation is the most severe outcome. Hydrogen's detonability range surpasses that of other fuels, as outlined in **Table 8**, which provides a comparison of explosion-related properties for hydrogen, methane, propane, and gasoline. Notably, the laminar flame speed of a hydrogen-air mixture far exceeds that of common hydrocarbon gases, with hydrogen's laminar burning velocity being approximately 8 times and 6 times greater than methane/gasoline and propane, respectively. Additionally, the heat release per unit mass for hydrogen is the highest among other hydrocarbon fuels [95].

**Table 8 Explosion properties compared between hydrogen, methane, propane and gasoline [91]**

| | Hydrogen | Methane | Propane | Gasoline |
|---|---|---|---|---|
| Explosion limits [vol.%] and maximum laminar burning velocity in air [m/s] | | | | |
| Lower limit | 13.0 – 18.3 | 6.3 | 3.1 | 1.1 |
| Upper limit | 59.0 | 13.5 | 7.0 | 3.3 |
| Burning velocity | 270 | 37 | 47 | 30 |
| Heat of combustion [kJ/g] and experimental maximum safety gap [cm] | | | | |
| Combustion heat | 135.4 | 52.8 | 40.3 | 46.0 |
| Max safety gap | 0.008 | 0.12 | – | 0.074 |

## 4.2 Safety concerns of hydrogen utilization

Green hydrogen is recognized as a future energy carrier for decarbonizing many activities in the transportation sector. Fuel cells, being electric in nature, share common electric motors and various components with other technologies. The core operational principle involves fuel cells which are employed for on-board electricity generation through an electrochemical process that extracts electrons from hydrogen and combines them with oxygen purged into the system. This technology offers numerous advantages, making it an appealing choice for zero-emission medium- and heavy-duty transportation vehicles. Notably, it features rapid refuelling capabilities, a high gravimetric storage density, and enables long-distance transportation and intensive usage [96].

### 4.2.1 Hazards and safety of hydrogen

The risks associated with any fuel are closely connected to its physical characteristics, where some properties affect the likelihood of incidents, while others determine the severity of consequences. Key properties, like the flammability range, are associated with probability, while the heat of combustion is linked to consequences. Moreover, certain attributes, such as vapour pressure and flash point, are relevant to liquids, whereas the properties, such as flammability limits, ignition energy, and maximum pressure during combustion, are related to gases or their vapour. This should highlight the importance of recognizing the diverse nature of safety considerations across different states of fuels.

Gaseous hydrogen, distinct from hydrocarbon fuels, requires tailored safety procedures due to its unique properties, including low density, high diffusivity, low ignition temperature, low ignition energy, and a wide detonation range (4% – 75% by Vol.), as mentioned previously in **Section 5.1**. The buoyant effects of hydrogen, exemplified by its notably higher rising velocity in comparison to methane, emphasize the imperative for thorough safety measures. Under normal conditions, the rising velocity for a release of 1,200 kg of hydrogen is measured at 27.92 m/s, significantly surpassing the rate of 13.93 m/s observed for methane. This highlights the significance of buoyancy considerations when dealing with hydrogen. With its low ignition temperature and energy but high latent heat of combustion, hydrogen can lead to distinct safety challenges, including the potential for detonation across a broad concentration range [97, 98]. The physical properties of hydrogen compared with methane at 1 atm and 298 K are shown in **Table 9**.

**Table 9 Physical properties of hydrogen and methane at 1 atm and 298 K [97]**

| Property | Unit | Methane | Hydrogen |
|---|---|---|---|
| Physical state | | Gas | Gas |
| Flammability limits | Vol. % fuel in air | 5.3 – 15% | 4.0 – 75% |
| Auto-ignition temperature | °C | 632 | 572 |
| Ignition energy | mJ | 0.280 | 0.018 |
| Heat of combustion | kJ/mol | 890.3 | 285.8 |
| Max. pressure during combustion | Bar gauge | 7.1 | 6.8 |
| Deflagration index | Bar m/s | 55 | 550 |
| Stoichiometric air requirement | $kg_{air}/kg_{fuel}$ | 17.2 | 34.3 |
| Lower volumetric energy density 350 bar, 25°C) | $MJ/dm^3$ | 11.6 | 2.8 |
| Laminar flame speed (in air at 1 bar, 25°C, λ=1) | cm/s | 42 | 230 |

In considering hydrogen safety, the Safety Diamond for Hydrogen offers a succinct representation of key safety aspects associated with the use of hydrogen. This visual tool incorporates four colour-coded quadrants to convey specific information as shown in **Figure 36**. The red quadrant denotes a flammability rating of 4, classifying hydrogen as an extremely flammable gas. In the yellow quadrant, a stability rating of 0 signifies that hydrogen is normally stable and does not react with water. The white quadrant indicates the absence of specific hazards. Lastly, the blue quadrant highlights a health rating of 3, emphasizing a serious level of concern regarding health impacts. This comprehensive and intuitive graphical representation serves as a valuable reference for quickly assessing the safety characteristics of hydrogen, aiding in the implementation of necessary precautions and protocols across various applications, from manufacturing and transportation to storage and use. This colour-coded system provides a concise overview, highlighting hydrogen's substantial flammability, overall stability, lack of specific hazards, and the significant health risks associated with its use [99].

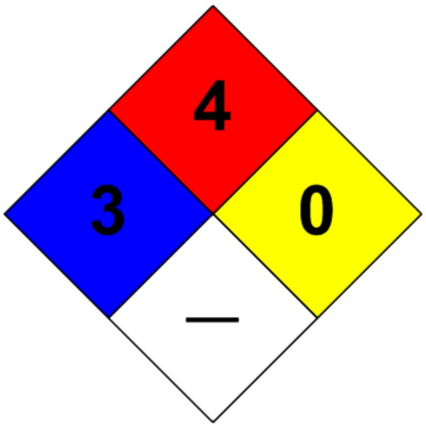



**Figure 36 Safety diamond for hydrogen [99]**

### 4.2.2 Safety concerns of hydrogen utilization in the transportation sector

The utilization of hydrogen as a fuel in transportation activities holds great promise, necessitating a comprehensive examination of associated hazards. This scrutiny is essential across various operational scenarios, encompassing instances of vehicle inoperability, routine operation, and collision scenarios. The potential risks typically revolve around fire, explosion, or toxicity, with the latter being negligible due to the non-toxic nature of both hydrogen and its combustion byproducts. Fire and explosion risks in the hydrogen-powered transportation sector can arise from the vehicle's fuel storage, fuel supply lines, or fuel cell system. It is worth noting that the fuel cell presents the least hazardous option based on the current technology commercially available. A summary of pertinent hazards associated with hydrogen vehicles is listed in **Table 10**.

**Table 10 Summary of the hazards pertinent to hydrogen-powered vehicles [100]**

| **Potential hazards** | |
|---|---|
| Toxicity | Ignored, as combustion products are non-toxic |
| Fire explosion | Due to storage on vehicles, fuel supply lines or from the fuel cell (the least hazardous, where H2& O2 are separated by a thin polymer membrane 20–30 μm) |
| Membrane rupture | $H_2$ and $O_2$ combine → fuel cell loss of potential (detected by control → system supply line should be disconnected. |
| **Failure modes in the fuel-gas tank in normal operation and collision** | |
| Catastrophic rupture of the tank | Due to manufacturing defect, abusive handling stress fracture, puncture by a sharp object, and failure of pressure relief valve to open. |
| Massive leak | Due to similar reasons |
| Slow leak | Due to stress cracking of tank liner, faulty pressure relief valve and feed line. |

Comprehensive risk assessments, based on identified failure modes, have been conducted in various studies, such as in a publication cited as [101], to analyze the most probable or severe scenarios for hydrogen-related accidents. These scenarios encompass fuel tank fire or explosion in both open spaces and tunnels, fuel line leaks in unconfined spaces and garages, and accidents at refuelling stations. Hydrogen, known for its high volatility and rapid dispersion in the environment, is challenging to ignite except within highly confined spaces. Notably, hydrogen dissipates quickly in the air, reducing the risk of lingering in the event of a leak. As reported in the literature, a comparative study was conducted to assess the fire accidents occurring with hydrogen fuel cell and gasoline-powered internal combustion engine vehicles. The study results revealed that in case of a fuel leak, the fire on the hydrogen fuel cell vehicle was significantly less severe than that on the gasoline vehicle. The timeline of the incidents showed that the jet fire from the fuel cell vehicle diminished rapidly as hydrogen was consumed, resulting in minimal damage. In contrast, the fire on the gasoline vehicle escalated, eventually leading to total destruction as shown in **Figure 37**. Safety measures for hydrogen tanks, including structural strength and secure fixation, are crucial to prevent danger in collision accidents [102].

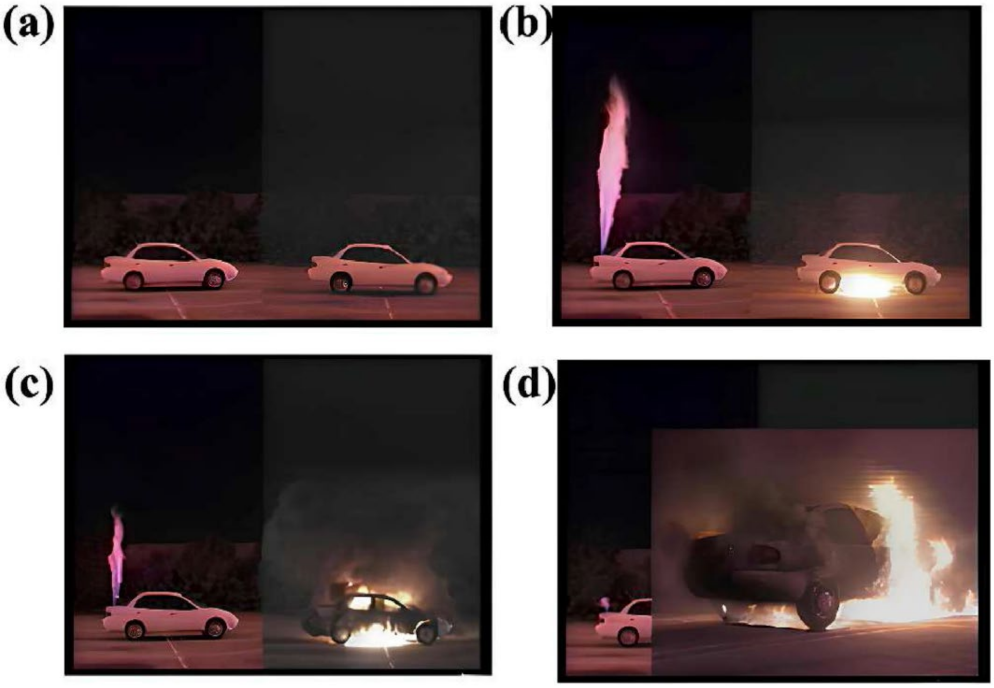



**Figure 37 Development of fire on fuel cell vehicles (left) and the gasoline vehicle (right) in case of fuel leakage with time at (a) 0 s, (b) 30 s, (c) 60 s, and (d) 90 s [102]**

In tandem with physical safety measures, safety control systems complement these efforts by relying on various sensors to detect potentially hazardous concentrations of hydrogen in the air. These commercially available sensors, including catalytic beads, electrochemical, and Metal-Oxide-Semiconductor sensors, operate based on distinct hydrogen detection principles. They continuously monitor the surrounding environment for any signs of hydrogen leakage. If a potentially dangerous concentration is detected, these sensors trigger safety protocols, such as activating ventilation systems or initiating emergency shutdown procedures. The integration of both physical safety measures and advanced sensor-based control systems contributes to a comprehensive approach to ensuring effective safety measures throughout the hydrogen infrastructure and applications [103].

Hence, the safety profile of hydrogen fuel in transportation exhibits both similarities and distinctions from other fuels, with certain factors indicating the potential for more severe accidents and others suggesting the possibility of less severe incidents. Consequently, determining whether hydrogen is inherently more or less risky in transportation remains unclear. Notably, the commendable safety records of trucks transporting compressed and liquefied hydrogen on U.S. roads provide reassurance, indicating that significant, undisclosed risks associated with hydrogen fuel usage are unlikely [100].

## 4.3 Standardization activities of hydrogen applications to railways

Currently, there is a notable absence of dedicated and specific regulations and standards governing the utilization of rail applications as shown in Figure 38. Nevertheless, by integrating existing regulations from other sectors involving hydrogen usage, in conjunction with the established standards specific to railway operations, most associated hazards can be effectively mitigated [104].


**Figure 38 Current status of hydrogen standardization of mobility cluster [104]**

In terms of pressure technology, the current state-of-the-art refuelling method for railways is the technology based on gaseous hydrogen pressure of 350 bar (35 MPa), which is employed in the ongoing development of hydrogen-powered trains worldwide. As of now, $LH_2$ and $CcH_2$ refuelling technologies and corresponding nozzles are not utilized in rail vehicles but are being developed for trucks. It is worth noting that there is currently no hydrogen refuelling technology available that matches the refuelling speed of diesel trains. Furthermore, it has been shown that the on-board hydrogen storage options for railway applications are mainly based on compressed gaseous hydrogen ($CGH_2$) at various pressure levels (350, 500, 700 bar), while cryo-compressed hydrogen ($CcH_2$) and liquid hydrogen ($LH_2$) technologies are being explored for their potential implementation in trains [105].

### 4.3.1 Standards relevant to hydrogen refuelling stations in railway applications

At present, a notable absence of comprehensive standards exists concerning hydrogen refuelling protocols for high-flow (HF) heavy-duty vehicles. While SAE J2601-2 sets the parameters for refuelling heavy-duty vehicles equipped with over 10 kg of hydrogen storage and/or mass flow rates of up to 7.2 kg/min, it falls short in providing the requisite practical intricacies needed for a fully comprehensive standard. The capacity for railway applications is expected to surpass the scope covered by current protocols. ISO 19885-3, a high-flow hydrogen refuelling protocol currently under development under the auspices of ISO/TC 197, represents a promising option for meeting the unique requirements of trains. Additionally, EN 17127 delineates the overarching requirements for the refuelling protocol [105].

In the context of fueling Fuel Cell Electric Multiple Units (FCEMUs), there is also a lack of directly applicable standards and regulations. To bridge this gap, a practical approach is taken, combining regulations from other industries with established specific standards for railway applications. Standardization efforts for hydrogen refuelling used for railway vehicles are ongoing within CEN/TC 256/WG 43 "Railway applications – Ground-based services – Hydrogen refuelling equipment". An analysis of interface requirements for hydrogen refuelling was conducted, taking into account different hydrogen forms, including compressed gas hydrogen ($CGH_2$), cryo-compressed hydrogen ($CcH_2$), and liquid hydrogen ($LH_2$). This analysis identified key components (nozzles, receptacles, hoses, breakaway systems, and communication interfaces) crucial for ensuring compatibility during refuelling across various methods. Notably, there are currently no dedicated nozzles and receptacles developed specifically for refuelling railway vehicles [4, 105].

When addressing the compatibility of the Hydrogen Refuelling Station (HRS) with train systems, it is imperative to align it with a designated standard for rail vehicles. In this regard, ISO 19880-1 (Gaseous hydrogen – Fuelling stations – Part 1: General requirements) and EN 17127 (with a specific focus on the refuelling point) serve as essential references within this delivery. These standards establish the fundamental criteria encompassing design, installation, commissioning, operation, inspection, and maintenance, with a primary emphasis on safety.

The hydrogen refuelling equipment consists of nozzles and receptacles, hose and breakaway. Nozzles and receptacles play a crucial role in establishing the connection between the refuelling station and the vehicle. The choice of these components for railway applications is contingent upon the form of hydrogen used, which includes compressed gaseous, liquid, and cryo-compressed hydrogen. Currently, there are no dedicated nozzles and receptacles tailored for refuelling railway vehicles. However, the FCH JU Project PRHYDE has compiled relevant standards governing the specifications for nozzles and receptacles used with trucks and other heavy-duty transport systems for $CGH_2$. These standards, ISO 17268 and SAE J2600, provide comprehensive guidelines for ensuring compatibility between nozzles and receptacles, accounting for factors such as the nominal operating pressure, and, in the case of 350 bar vehicles, the mass flow rate.

At the present time, there are no specific nozzles and receptacles designed explicitly for refuelling rail vehicles. In general, the typical operating pressure for heavy-duty vehicles (HDVs), including buses, trucks, and current hydrogen trains, is 350 bar. Consequently, the compatibility options for WEH nozzle-receptacle combinations suitable for heavy-duty road vehicles are as follows:

- High flow nozzle TK16 H2, available with and without communications, along with the corresponding receptacle TN1 H2 (in compliance with ISO 17268).
- Fast-filling nozzle TK25 H2, available without communication, and the corresponding receptacle TN5 H2.

It is important to consider the characteristics and technical specifications when selecting the appropriate receptacle and nozzle. Both receptacles are recommended for refuelling railway vehicles, with the primary distinction between them being the presence of a data interface. Specifically, TN1-H35HF supports communication, whereas TN5-H35 does not offer this capability.

For the hose, ISO 19880-1 establishes comprehensive safety and performance criteria for refuelling stations dispensing gaseous hydrogen to light-duty land vehicles. However, it serves as a valuable reference that can also provide guidance for refueling HDVs.

A breakaway serves as a critical safety component within the hose assembly, designed to reduce potential damage to the dispenser in case a vehicle is inadvertently driven away while the dispenser nozzle remains connected. This safety device is engineered to disconnect when exposed to a maximum force of 1000 N, irrespective of the operational pressure within the device. It incorporates double shut-off valves, effectively isolating both connection sides when disengaged. In addition, NFPA2 – Hydrogen Technology Codes also provide the safety requirements for the production, piping, storage, installation, utilization, and handling in all cryogenic liquid or compressed gas forms. **Figure 39** shows the key standards potentially applied to railway applications associated with hydrogen refuelling stations.

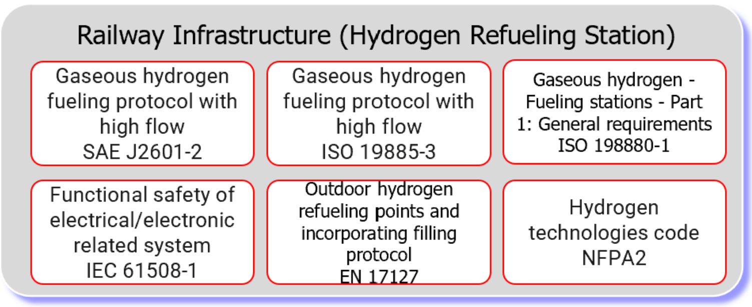



**Figure 39 Key standards potentially applied for hydrogen refuelling stations of railway transportation**

### 4.3.2 Standards of Hydrogen-powered Railway Vehicles

Currently, there are no specific regulations and standards applicable to the use of hydrogen storage systems (HSS) in railway vehicles (rolling stocks). To address potential hazards, an approach is taken where existing regulations from other hydrogen usage sectors are combined with established railway-specific standards. This method effectively manages the high potential risks. For instance, hydrogen pressure storage systems in hydrogen-powered motor vehicles must adhere to type approval regulations specified in regulation (EC) No. 79/2009 of the European Parliament and the Council of the European Union, which will be succeeded by R134 after July 2022. However, it is important to note that the corresponding procedure for managing these risks is not yet universally regulated [104].

Furthermore, in the international standardization domain, the PNW 9-2697 ED1: Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 2: Hydrogen storage system project is underway [106]. Regarding the standards proposed for hydrogen-powered railway vehicles, the IEC (International Electrotechnical Commission) has drafted the standard, IEC 63341, to ensure safety operations of railway vehicles at both the sub-system and system levels, while ISO17268-4, ISO19881-2 and ISO19887-2 provide the specific recommendations for safety operations of hydrogen-powered railway vehicles in the component level as shown in Figure 40.

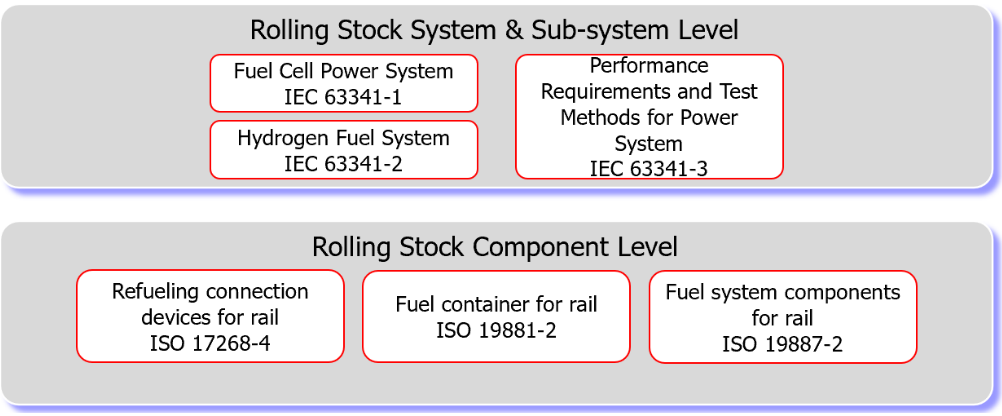



**Figure 40 IEC and ISO standards available for considering safety operation of hydrogen-powered rolling stocks**

# 5 ECONOMIC IMPACTS

The economic impacts of integrating green hydrogen-powered railway systems are multifaceted and play an important role in shaping the future of the transportation sector. This introduction explores the economic dimensions associated with the adoption of green hydrogen technology in railways, emphasizing its potential to bolster innovation. As the global focus shifts towards sustainable energy solutions, green hydrogen-powered railways offer a pathway to reduce operational costs, enhance energy efficiency, and contribute to environmental sustainability. The discussion in this chapter will focus on the economic benefits and challenges of implementing green hydrogen technology while considering such factors as initial investment, operational savings, and the broader economic ecosystem.

## 5.1 Hydrogen supply chain

The Hydrogen Supply Chain (HSC) is a complex network which includes the production facility, intermediate storage hubs, and diverse transportation modes. This intricate system is visualized as a network with nodes representing potential sites for hydrogen production, storage, or consumption, and edges illustrating the pathways for hydrogen transportation as shown in **Figure 41**. The HSC involves interconnected components such as production plants, storage facilities, transportation routes, and points of demand. By comprehensively considering the entire HSC network, a holistic understanding of hydrogen pathways from production to consumption is achieved. The hydrogen supply chain processes start with the procurement of initial fuels and conclude with hydrogen sales at fuel stations. The network consists of various levels, including fuel procurement, manufacturing plants, distribution, storage terminals, and fuel stations, with options for implementation at each level. Liquid hydrogen is normally transported using truck, rail, and ship, whereas truck, rail, and pipeline transportation modes are employed for gaseous hydrogen. Storage infrastructure enhances the responsiveness to hydrogen demand. Depending on the physical form of hydrogen, storage methods of hydrogen are different. Fuel stations, the final stage, offer standard and on-site options for hydrogen refuelling, catering to customer needs [107, 108].

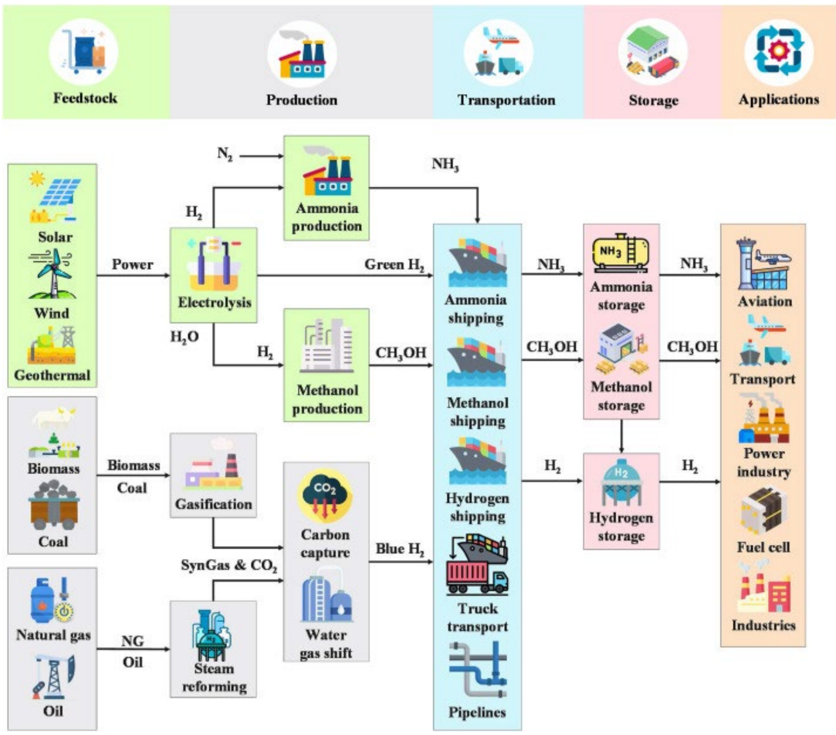



**Figure 41 Hydrogen supply chain [109]**

Recognizing key hydrogen markets is essential for the hydrogen economy which consists of various sectors, such as fuel cell vehicles, combined heat and power systems, power generation, industrial feedstock, ammonia production, refining, methanol production, and steel production [110]. Market penetration has the potential to diminish expenses linked to incorporating hydrogen into the energy sector, leading to enhanced cost competitiveness. As the demand for green hydrogen rises, economies of scale become influential, as larger production volumes contribute to cost reductions through improved efficiency and optimized production processes [6].

However, the main obstacles to using green hydrogen are due to its elevated expenses [6, 110]. Currently, the global green hydrogen market is in the initial nascent phase and is not yet economically viable in comparison to hydrogen derived from alternative sources. The overall pricing is influenced by many factors such as the cost of electrolyzers, their scale, and the accessibility of renewable electricity, etc. Industries are exploring strategies to enhance the direct utilization of hydrogen or its conversion into more cost-effective and readily distributable raw materials like ammonia, synthetic fuels, or methane. The utilization of existing natural gas infrastructure is considered a cost-reducing measure. Additionally, hydrogen encounters efficiency losses that contribute to increased costs, posing challenges to its competitiveness relative to other energy sources [111].

Hence, reducing the expenses associated with renewable energy, particularly solar and wind, directly impacts the cost-effectiveness of producing green hydrogen. Through the widespread deployment of electrolyzers and the availability of affordable renewable electricity, green hydrogen may become more economically viable compared to low-carbon alternatives, potentially achieving competitiveness by 2040 or even earlier. This development enhances its attractiveness as a viable option for decarbonization efforts. In addition, government policies and incentives play a pivotal role in reducing the cost of green hydrogen through mechanisms like subsidies, grants, tax incentives, and regulatory frameworks. Collaborative initiatives involving industry stakeholders, research institutions, and governments can expedite the advancement and commercialization of green hydrogen technologies. The exchange of knowledge, resources, and best practices among these entities can foster quicker reductions in costs, enhancing overall cost competitiveness. Governments, by promoting investment in research and development across green hydrogen production, logistics, storage, and utilization, can significantly improve the efficiency and cost-effectiveness of crucial components in the green hydrogen sector. Hydrogen has emerged as a notable energy carrier, garnering widespread interest and demonstrating diverse applications in multiple sectors. Although the shift towards a hydrogen-based economy is in its initial phases, a mounting body of evidence and practical case studies is substantiating the economic feasibility and versatile applications of hydrogen across various industries [6].

## 5.2 Forthcoming structures & applications

Hydrogen fuel cells (HFCs) serve as viable alternative energy sources across various transportation, portable, and stationary applications. Scientific and research findings affirm the increasing prevalence of HFCs in the foreseeable future. **Figure 42** illustrates the potential future applications of HFCs, categorized into four main areas: stationary, portable, transportation, and space applications. Within stationary applications, a notable rise is anticipated in residential implementations, particularly in addressing local energy demands through the utilization of hydrogen energy [55].

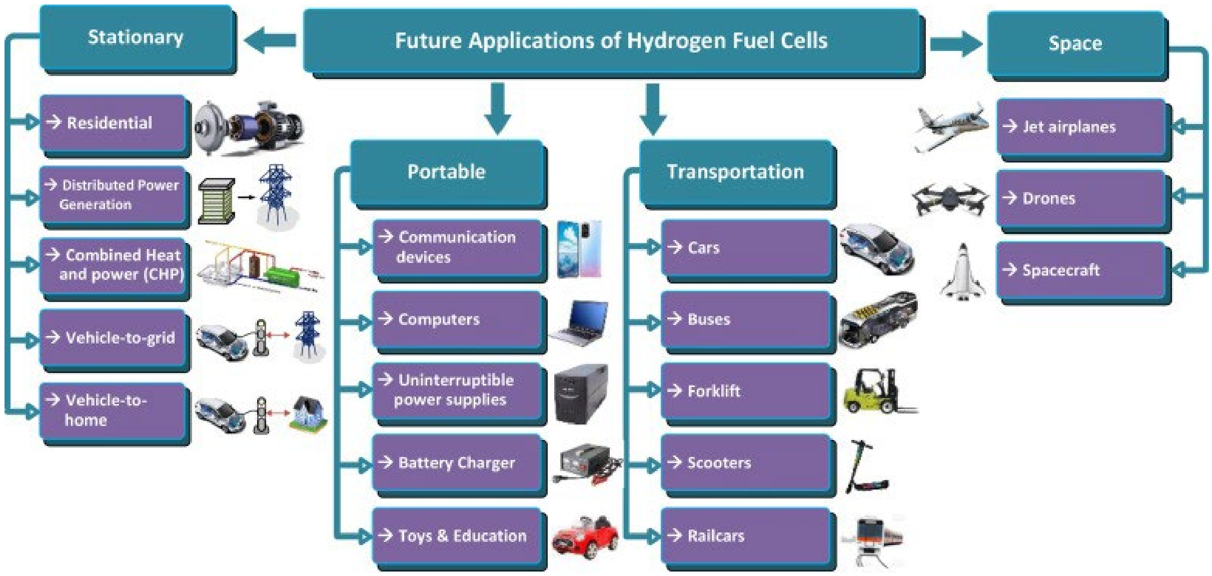



**Figure 42 Prospective uses of hydrogen fuel cells in various domains [55]**

Research in the transportation sector indicates the commercialization of hydrogen fuel cells, with major automobile manufacturers producing commercially available hydrogen fuel cell-based cars. The study not only highlights the current commercialization but also provides a comprehensive future perspective and structural concepts for the ongoing and future utilization of hydrogen fuel cells in the transportation sector [65]. Beyond cars, potential modes of transportation explored in the study encompass forklifts, scooters, and railcars [112].

Moreover, hydrogen technology experiences are finding applications in various sectors, with ongoing studies aimed at widespread implementation and commercialization. Transportation, heating and electricity generation are identified as potential applications on the brink of commercial viability. The Hydrogen Roadmap Europe report (see **Figure 43**) revealed the implementation trends in diverse areas such as transportation, heating, industrial heat, industrial feedstock and power generation. Hydrogen-fuelled vehicles catering to different segments like automobiles, forklifts, and buses are available, and their commercialization is imminent. Projections have indicated that the fuel-cell vehicles are expected to reach a market share of 1% by 2025, with approximately 5,500 hydrogen-powered trains and one-third of total truck sales incorporating fuel cells by 2050 [55, 113].

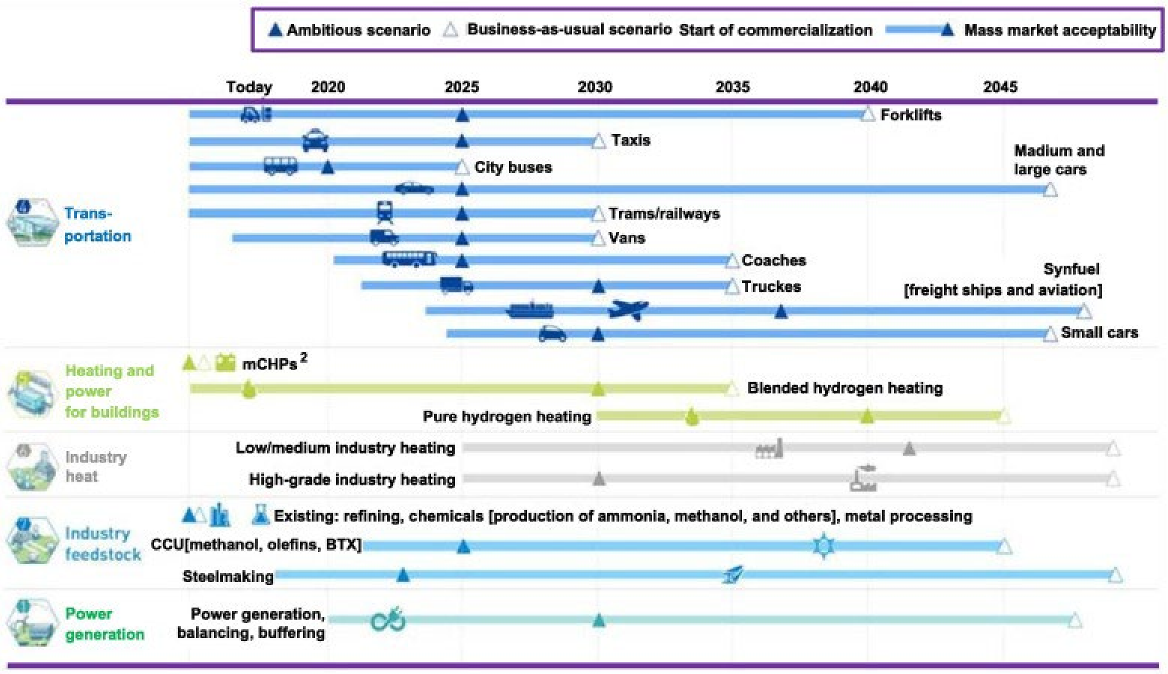



**Figure 43 Trends in the implementation of hydrogen technology across various sectors [55]**

## 5.3 Total cost of ownership analysis for hydrogen applications to the railway

In this section, the business viability of fuel cell hydrogen railway technologies is discussed. In fact, the new technologies often involve additional costs compared to existing market options. In order to obtain comparative information, an analysis of the total cost of ownership (TCO) for the relevant railway applications was conducted. The assessment indicated that the introduction of fuel cell hydrogen trains is not anticipated to negatively impact the revenue aspects of the business case. Instead, the potential upside to the business case was derived from the monetization of externalities, particularly in terms of mitigating environmental costs. The model of TOC for fuel cell hydrogen railway application is shown in **Figure 44**.

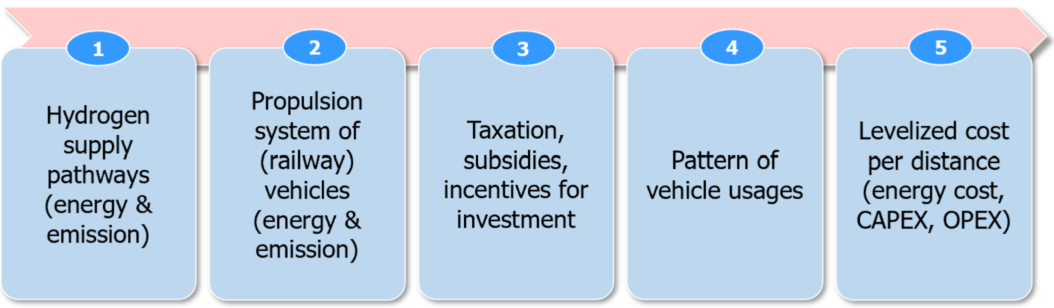



**Figure 44 Keys inputs (1-4) and outputs of TCO (total cost of ownership) model for hydrogen applications to railways**

The TCO for fuel cell hydrogen trains is primarily influenced by the operational expenditure (OPEX) associated with energy, specifically the electricity price for on-site hydrogen production or the external costs of purchasing trucked-in hydrogen fuel. Additionally, the capital expenditure (CAPEX) for fuel cell hydrogen refuelling infrastructure, on-site hydrogen production facilities, and the fuel cell hydrogen trains themselves play a crucial role in determining competitive TCO [114]. To evaluate the commercial viability of FCH train solutions, we analyzed the TCO in contrast to existing technology alternatives, primarily diesel combustion engine trains, battery trains, and overhead catenary systems.

In general, all the applications suggested a route to achieving commercial competitiveness under certain conditions. These conditions primarily included achieving low energy sourcing costs and maximizing asset utilization, particularly in the case of FCH trains and hydrogen refuelling infrastructure.

According to the European Union, electrical multiple units are already in service on major transportation routes across all European countries, shuttling passengers from the primary to secondary stations. However, diesel-electric multiple units are still available for services, particularly in the regions where remote cities need to be connected. For instance, these trains are deployed in mountainous terrain or rural areas. In addition, powertrains based on fuel cell hydrogen technology for multiple units exhibit promising economic and environmental benefits. This is particularly true for routes connected to a primary traffic hub, which typically possesses the necessary infrastructure for on-site hydrogen production. Furthermore, as trains often traverse densely populated regions and make stops in environmentally sensitive areas like mountains or scenic spots, the need to minimize emissions is quite necessary. Hence, the successful introduction of fuel cell hydrogen multiple units relies on three key factors. Firstly, it is advantageous to consider an overarching system from the outset, aiming to create multiple routes emanating from a central point utilizing hydrogen trains wherever feasible. Secondly, ensuring that the trains are sized beyond the specifications of the specific line allows for flexible deployment on various routes. Finally, the utilization of hydrogen as both a fuel and electricity storage medium enables the optimization of overall operating costs by leveraging fluctuating energy prices and taking advantage of periods of low-cost hydrogen production.

In Thailand's case, the State Railway of Thailand (SRT) is totally responsible for the national railway system, covering four primary lines: Northern, Eastern, North-eastern, and Southern, and presently operates on a non-electrified system by using diesel propulsion for both passenger and freight transportation. A case study in Thailand examines a rail service extension from Bangkok to Pattaya - Ban Phlu Ta Luang - Chuk Samet with a total distance of 196 km. This line plays a crucial role in the economic landscape, connecting significant industrial zones (Map Ta Phut Industrial Estate), the Laem Chabang Port, and tourist destinations like Pattaya city, as shown in **Figure 45**.

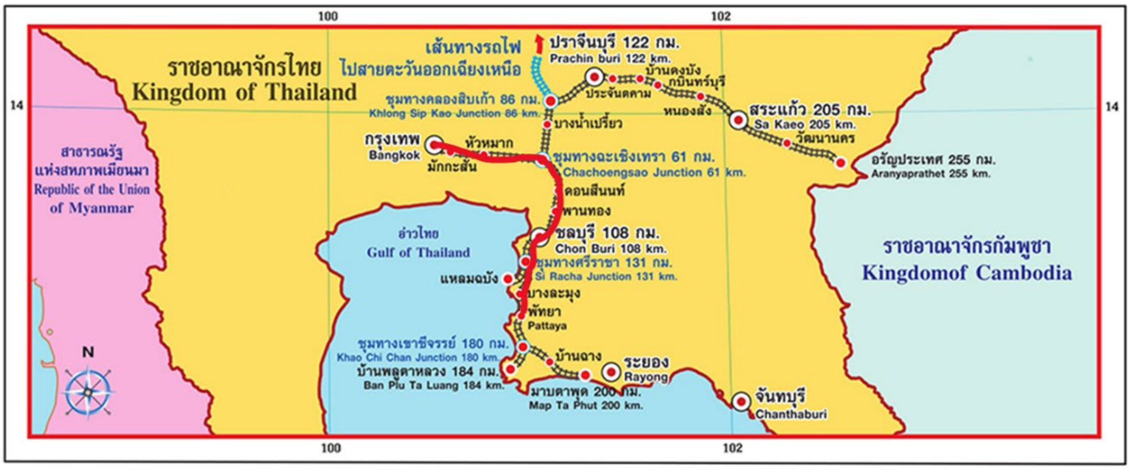



**Figure 45 A proposed railway route for TCO examination based on the Thailand scenario**

The TCO for fuel cell hydrogen trains was divided into the hydrogen infrastructure domain and hydrogen-powered trains. In addition, efficient asset utilization is crucial for both fuel cell hydrogen trains and associated hydrogen refuelling infrastructure. The degradation of the fuel cell system is contingent on utilization, particularly in terms of full-load hours performed. Higher utilization of the fuel cell system resulted in reduced service and maintenance intervals, consequently increasing costs. This factor was significantly important for applications of heavy-duty fuel cell hydrogen trains, offering the potential for further TCO reduction if the operational lifetime of the fuel cell stack can be prolonged before refurbishment becomes necessary. On the other hand, the fuel supply infrastructure ideally operated with consistent utilization by the trains, minimizing inefficient overcapacity in the hydrogen refuelling station (HRS) system.

Hence, the TCO model competitively outlines the characteristics of multiple-unit trains using a hydrogen-powered traction system compared with those using diesel-powered, battery-powered, and overhead catenary (OCS) systems. The detailed parameters for CAPEX pertaining to the infrastructure include refuelling station, electrification system, and the train's specifications such as power rating, maximum speed, price, energy consumption, lifetime, and route length. Additionally, the parameters for OPEX in association with operational and maintenance costs, encompass metrics like trips per day, energy cost, staff cost, and maintenance cost as shown in **Table 11**.

**Table 11 Key parameters considered for TOC model of hydrogen-powered train**

| Parameter | Quantity | Unit |
|---|---|---|
| Multiple unit | 1 train set | 3 cars with hybrid system |
| Total power rating of train | 1,000 | kW |
| Max speed | 150 | km/h |
| H2 consumption | 0.25 | $kgH_2/km$ |
| Fuel cell capacity | 400 | kW |
| Battery power | 100 | kWh |
| $H_2$ storage capacity | 130 | kg at 350 bar |
| Route length | 200 | km |
| Round trip | 400 | km |
| Trip/day | 2 | Trip |

To assess the ownership costs associated with the utilization of green hydrogen energy under a specific condition of Thailand's railway operation, three types of low-emission energy technology employed in a railway's traction, including OCS, battery, and hydrogen, were examined. The various costs taken into account were obtained through a comprehensive survey.

Based on the information and data obtained from the experts' review, it was estimated that the price of a new multiple-unit train set (3 cars) powered by OCS would be 230.0 million THB. The price of lithium-ion battery was approximately 19.6 million THB, while that of hydrogen fuel cell integrated with low-capacity lithium-ion battery, was set at 44.0 million THB. These prices were considered as additional costs when the traction system of the train set switched.

The infrastructure costs for the proposed rail system were comparable to those of traditional railway systems. However, certain components contributed to increased expenses. For instance, the inclusion of electrical substations for delivering on-demand electricity can lead to cost addition to the electrification system infrastructure. The total investment cost for the construction of an overhead power line system was estimated to be approximately 33.8 million THB per km.

In the context of battery-powered train systems, the construction of large facilities for battery charging is inevitably required. These battery charging facilities come at a price of 10.0 million THB. Regarding the hydrogen-powered trains, the additional costs came from the set-up of hydrogen gas refuelling facilities. The investments in construction of each hydrogen refuelling station requested a budget in the amount of

50.0 million THB. These variations in infrastructure costs reflect the specific requirements and technologies associated with each individual type of railway system.

Based on the energy consumption characteristics of each type of train, the calculations of power required for train operation have yielded the following results: 1) 4.5 kW/km for OCS trains, 2) 5.175 kW/km for battery-powered trains, and 3) 0.25 $kgH_2$/km for hydrogen-powered trains. Moreover, the energy loss in battery-powered trains due to charging is approximately 15% higher than that of OCS trains which are directly connected to high-voltage transmission lines.

Maintenance costs have been divided into two categories: 1) rolling stocks and 2) infrastructure. For all three train systems, maintenance expenses are set at 3% of the respective initial prices of purchasing the trains, as well as 3% of total investment in the construction of their infrastructure. The total lifespan for both trains and infrastructure in this study was assumed to be 30 years.

Energy prices for the three train types are computed based on electricity and hydrogen gas costs. Electricity costs are determined using Time-of-Use (TOU) meter rates and service charges specified by the Metropolitan Electricity Authority of Thailand (MEA). The calculated rate stands at 4.12 THB/kWh. Since there is no reference price of green hydrogen commercially available in Thailand, the actual price of commercial green hydrogen in China has been used in the current study. The price of green hydrogen in China in November 2023 was 81.80 RMB which equalled 409.24 THB (RMT-to-THB exchange rate of 5.0029).

From the TCO analysis based on the aforementioned parameters, it was clear that the most significant factors to influence TCO were related to infrastructure and personnel expenses. The analysis results revealed that the OCS trains, marked by overhead transmission infrastructure, possessed the highest prices with respect to other forms of train traction systems. Consequently, both the initial infrastructure investment and routine maintenance expenses for the OCS surpassed those of other systems as shown in **Figure 46**.

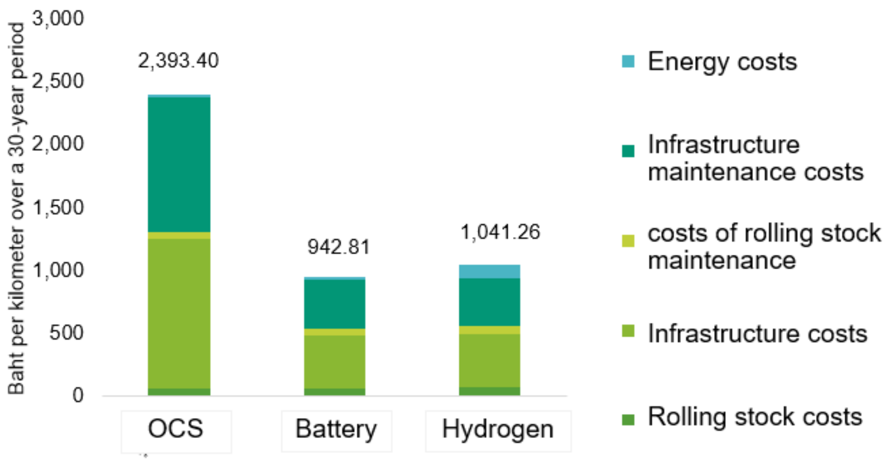



**Figure 46 TCO diagram compares three types of trains: hydrogen-powered, battery-powered, and OCS-powered trains**

The study on ownership costs for all three types of trains revealed that infrastructure has the greatest impact, with OCS trains being the most expensive due to overhead transmission infrastructure costs, which also affect maintenance expenses. Interestingly, both battery-powered trains and hydrogen-powered trains showed similar pricing. However, the higher cost of hydrogen-powered trains is attributed to the higher price of green hydrogen compared to battery-powered trains. If the cost of green hydrogen were to decrease, hydrogen-powered trains could potentially become competitive with battery-powered trains.

# 6 THAILAND'S SCENARIOS DEALING WITH (GREEN) HYDROGEN APPLICATIONS TO RAILWAY

Thailand's scenarios dealing with green hydrogen applications to railways were examined in order to undertake a comprehensive exploration of the nation's strategic framework for integrating environmentally sustainable technologies into its rail transportation sector. By examining the various scenarios and potential pathways, this chapter elucidates Thailand's visions for potential implementation of green hydrogen in the railway transportation sector. It emphasizes the distinctive considerations and challenges inherent in applying hydrogen technology to Thailand's context, encompassing the aspects of production, transportation, and specific applications within the railway industry. Additionally, the enabling mechanisms, policies, and regulatory frameworks based on the foundation of Thailand's approach are discussed to foster the adoption of green hydrogen in its railway sector.

## 6.1 Hydrogen production

Currently, the hydrogen gas production capacity in Thailand is dedicated to the production of grey hydrogen. This is attributed to the cost advantage of grey hydrogen produced through steam methane reformation, as it has proved to be more economical than the production costs incurred for other varieties of hydrogen gas. However, Thailand has elevated its aim to reduce GHG emissions, raising the target from 20% to 30% by 2030 when compared to the business-as-usual scenario. Affirming its commitment, Thailand has put a great deal of effort into achieving the overarching objective of carbon neutrality by 2050, culminating in net-zero GHG emissions by 2065 [115].

Hence, the utilization of green hydrogen will become an optimum option for Thailand to achieve its ambitious carbon neutrality target. Thailand's tropical climate, characterized by year-round productivity in renewables such as solar energy, creates favourable conditions for the sustainable production of green hydrogen. There might be a concern regarding the reliability of electrical power generated from renewable sources, particularly solar PV which effectively produces electricity at a maximum of 6 hours per day. This intermittent nature of renewable energy in Thailand presents challenges for green hydrogen production, prompting a practical shift toward considering blue hydrogen derived from natural gas with the aid of a carbon capture system (CCS). Beyond using solar energy as a feedstock, emerging technologies are exploring the utilization of methane from municipal and agricultural waste facilities, potentially forming the basis for a blue and/or turquoise hydrogen production industry in Thailand [116]. Additionally, carbon capture technology is being considered as an alternative to the transition from blue hydrogen to green hydrogen production, although it involves higher costs. Therefore, Thailand has the potential to develop a low-carbon hydrogen sector for both domestic use and international export, with a preference for blue hydrogen due to the limited availability of green hydrogen in commercial markets. Leveraging existing natural gas infrastructure, blue hydrogen emerges as the most competitive option in the Thai market for hydrogen-related activities.

The hydrogen production sector in Thailand is marked by the presence of key industry players, including Linde (Thailand) Public Co., Ltd., Air Liquide (Thailand) Co., Ltd., Praxair (Thailand) Co Ltd, and Bangkok Industrial Gas Co., Ltd. (BIG). Notably, BIG is a joint venture between Thai investors, led by Bangkok Bank, and Air Products and Chemicals Inc. They are major contributors to daily hydrogen production, producing approximately 70 tons. The ratio of hydrogen production in Thailand by key industrial players is illustrated in **Figure 47**. These companies play crucial roles in producing a sufficient quantity of hydrogen to serve the domestic demand across various industries.

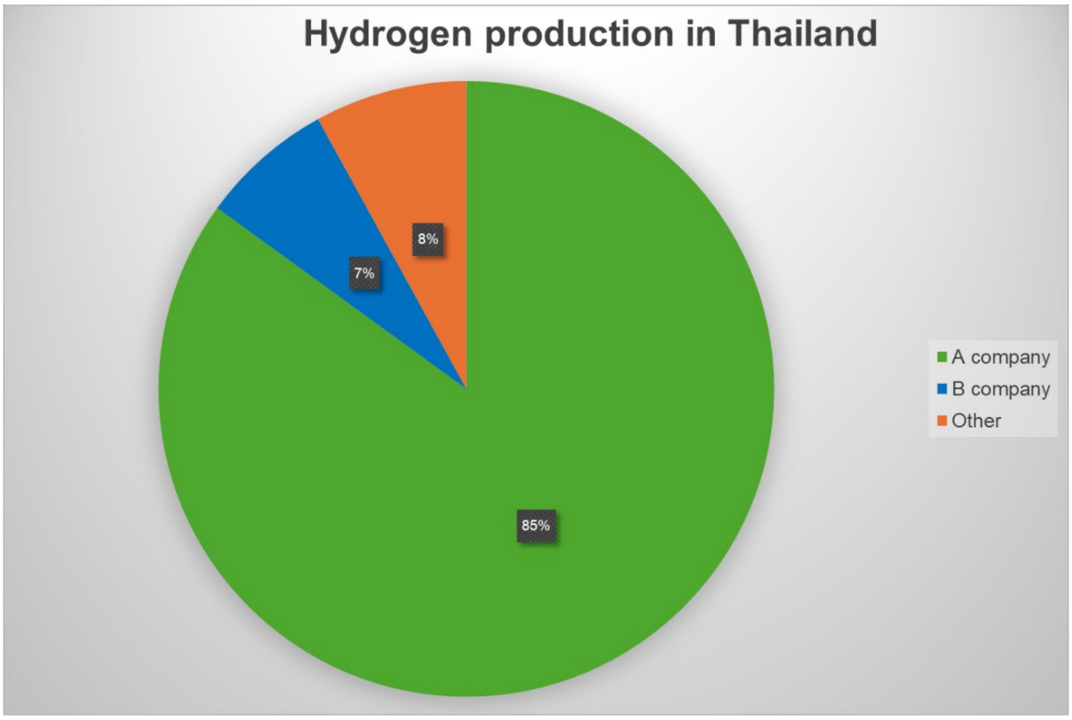



**Figure 47 The ratio of hydrogen production in Thailand market**

Green hydrogen has been facing economic challenges compared to grey and blue hydrogen. The production cost of grey hydrogen, derived from natural gas, has been reported to be in a range of $0.98 to $2.93 per kg, while that of blue hydrogen has ranged between $1.8 - $4.7 per kg. In contrast, green hydrogen has been more expensive, with a production cost ranging between $4.5 - $12.0 per kg. In the case of Thailand, the production cost of green hydrogen has been estimated to be around $8.30 per kg, which is far above that of grey and blue hydrogen as shown in **Figure 48** [117].

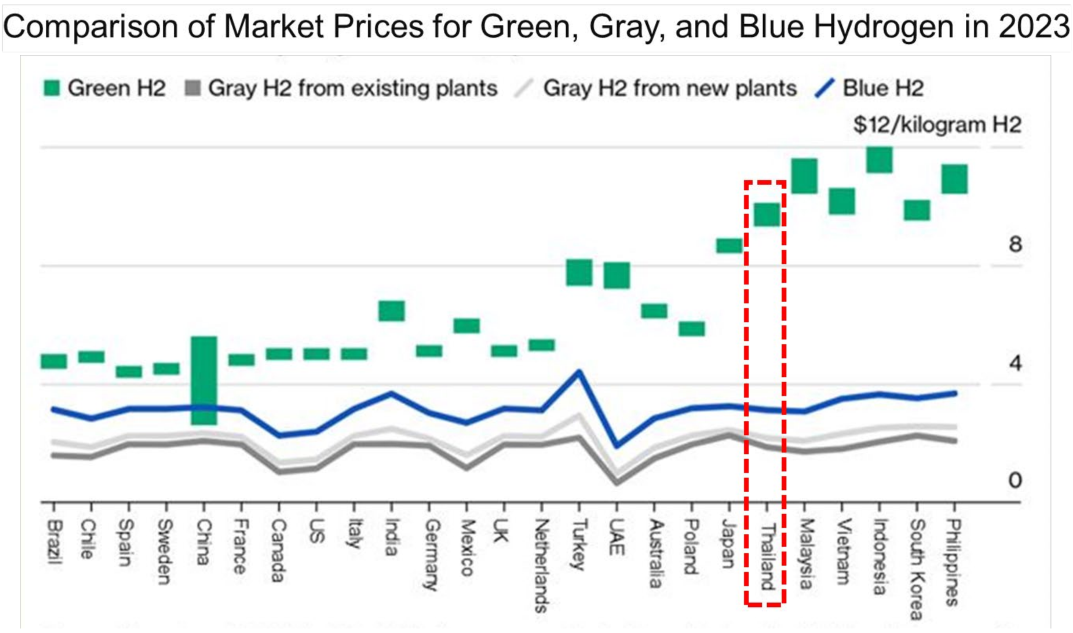



**Figure 48 Hydrogen production cost reported in 2023 for each country [117]**

## 6.2 Hydrogen transportation and delivery

The comprehensive infrastructure of Thailand's 4,255-kilometre natural gas pipeline network, managed by the Petroleum Authority of Thailand (PTT), provides a strategic advantage for hydrogen gas transmission and distribution. The pipeline system, detailed in Section 3.4.1, not only facilitates widespread hydrogen gas distribution to meet commercial demands but also offers flexibility. It allows seamless blending of hydrogen gas at 5 – 10 vol% into the existing gas delivery pipeline, with the capability to separate hydrogen gas at its destination for various industrial applications. However, hydrogen, being the smallest molecule, can diffuse through pipeline materials, especially metals, leading to embrittlement and hydrogen-induced cracking in the pipeline, particularly those made of high-strength steel. To mitigate these risks, pipeline engineers and experts have conducted some engineering tasks and employed measures such as applying coatings or linings to reduce hydrogen permeation and maintaining proper operation pressure levels. On-going monitoring, inspection and research for improved materials and technologies are crucial for ensuring the safe and efficient use of hydrogen transmitted through gas pipeline facilities. In addition to pipelines, specialized transportation methods such as tube trailers and trucks have also played distinct roles in hydrogen gas transportation. Tube trailers are normally dedicated to transporting compressed hydrogen for short to medium distances, serving applications like hydrogen fuel cell vehicle refuelling stations and industrial needs. Specialized trucks, each with a capacity of 1.5 to 3 tons of hydrogen, provide an alternative means of hydrogen transportation in Thailand.

Moreover, the economic assessment of hydrogen transportation modes has emphasized the superiority of rail and pipelines for point-to-point transport, with rail being optimal for distances over 200 km when the daily hydrogen transportation requirement is below approximately 70 tons. Pipelines become the most efficient option for larger flow rates due to their capacity to handle increasing hydrogen demands without additional intermodal containers. Despite initial concerns about pipeline specifications, they prove adaptable to rising demand. Conversely, truck transport exhibits poor economic viability for point-to-point hydrogen transportation, except in specific cases of minimal demand and distance. However, trucks show their potential for hydrogen distribution, particularly for smaller demands and shorter distances, such as distributing hydrogen within cities. Nevertheless, for transportation needs exceeding approximately 70 tons per day, pipelines have emerged as the most cost-effective option, emphasizing the importance of selecting transportation modes based on demand, distance, and economic efficiency in the hydrogen transport sector [118].

## 6.3 Hydrogen applications to railways

The potential adoption of fuel cell hybrid technology has led to overhauling the existing trains or procuring the advanced fuel cell hybrid trains deployed for the State Railway of Thailand (SRT). This pioneering technology has the capacity to redefine the contours of Thailand's railway infrastructure. Based on experts' opinions received during the expert meeting, it was recommended that commencing the initial phase of testing with Diesel Multiple Units (DMU) should focus on the Nakhon Pathom - Krung Thon Buri and Mahachai-Wong Wien Yai routes. The selection of those routes is a key strategic consideration, as they feature maintenance depots capable of supporting refuelling activities, making them well-suited for testing clean energy trains. This approach ensures that the feasibility and effectiveness of hydrogen-powered locomotives are thoroughly evaluated in practical operating conditions. Additionally, the eastern region, particularly in Map Ta Phut, with its abundant sources of hydrogen directly supplied from the region, has been considered an ideal area for conducting comprehensive tests and studies related to technology demonstration of hydrogen-powered trains. However, the absence of specific safety regulations for hydrogen-powered train technology has been acknowledged, highlighting the necessity to establish these regulations in the future. Leveraging international practices and insights from case studies in other countries is deemed advantageous in formulating a comprehensive set of safety standards, taking account of Thailand's specific constraints. It is worth noting that Thailand has a dedicated department for rail technology, known as the Rail Technology Research and Development Agency (RTRDA). This agency is playing a key role in conducting studies, emphasizing the significance of a strong regulatory framework to ensure the safety of hydrogen-powered train operations nationwide. Additionally, the fuel cell hybrid technology proposed for Thailand railway applications has specified that hydrogen should be stored at high pressures, specifically at 300 or 350 bar, utilizing compressed gaseous storage methods. This storage method has been selected for its anticipated efficiency and safety, ensuring the ready availability of hydrogen fuel for use in hydrogen-powered trains. However, an alternative advantageous option might be liquid hydrogen, particularly in scenarios involving heavy railway traffic Typically, liquid hydrogen can be stored at pressures of 350 bar and raised to 700 bar, providing a practical and effective alternative. Importantly, there have been no reported accidents associated with the utilization of liquid hydrogen.

## 6.4 Enabling mechanisms

Thailand is actively considering the adoption of hydrogen as an energy carrier, particularly in the transportation sector, with a specific focus on long-haul trucks. The private sector is currently in the process of estimating costs and constructing hydrogen refueling stations to support the Energy Policy and Planning Office (EPPO) initiative on hydrogen.

Furthermore, the Department of Energy Business (DOEB) is actively formulating policy plans for the future use of hydrogen in the energy sector. Establishing safety regulations for hydrogen transportation, storage, and refuelling stations is deemed significant for determining the viability of hydrogen utilization. Therefore, it is crucial to have clarity in designating the purpose of hydrogen, whether for energy production or as an industrial feedstock. If intended for transportation, hydrogen must undergo official registration as a type of fuel/energy by the DOEB, which will also be responsible for monitoring hydrogen energy prices to ensure fair consumer pricing. Additionally, Thailand has a plan to promote hydrogen as a clean energy source across various transportation modes, encompassing cars, railways, and aeroplanes through the Office of Transport and Traffic Policy and Planning (OTP). The plan has included a commitment to establishing hydrogen refuelling stations. OTP has set carbon emissions reduction targets at 30 - 40% reduction by 2023. It has also aimed that the implementation of carbon capture technology will occur between 2030 - 2040. Their long-term objective is to achieve net-zero emissions by 2065.

The TCO analysis in Section 6.3 revealed that the pricing for hydrogen-powered and battery-powered trains was closely aligned despite variations in infrastructure costs. This convergence was primarily attributed to the higher cost of green hydrogen production compared to the expenses associated with battery-powered trains. Consequently, in the context of Thailand’s conditions, the initial stage indicated that blue hydrogen might be a more viable option for railway applications. Thailand's abundance of natural gas resources provides a potential avenue for blue hydrogen production, especially when coupled with efforts to develop green hydrogen, aiming to reduce overall costs and secure a stable renewable source. The importance of governmental support has been highlighted to drive the demands for hydrogen utilization, particularly during the initial phase, playing a pivotal role in facilitating the ramp-up of the hydrogen market in Thailand. Additionally, imposing taxes on $CO_2$ emissions becomes crucial for enhancing hydrogen competitiveness as a more environmentally friendly alternative to other fossil fuels.

Analyzing the enabling mechanisms of hydrogen-powered trains in Thailand through a SWOT analysis offers a holistic perspective on their feasibility and impact within the country's rail transportation sector as shown in **Figure 49**. The hydrogen railway industry has demonstrated a variety of internal and external factors when analyzed through a SWOT (Strengths, Weaknesses, Opportunities, Threats) framework. In terms of strengths (S), the government plays a crucial role by actively promoting robust policy and regulation mechanisms that support the industry's development. This proactive stance has created a favourable policy environment for the hydrogen railway sector, providing a clear framework and guidelines for its growth. Additionally, the presence of promotion plans, likely endorsed or facilitated by the government, has served to encourage research and innovation within the industry. The commitment to multi-level nationwide cooperation is another strength, showcasing collaboration between various hydrogen technology stakeholders across the country, including foreign countries. This collaborative approach will contribute to the internal strength and resilience of the hydrogen railway sector, positioning it for sustainable technology, innovation, and support. Additionally, the hydrogen-powered railway sector reveals promising opportunities (O) for growth and development. Firstly, there is the potential for new business creation, positioning the hydrogen railway industry as a catalyst for establishing specialized companies focused on hydrogen technologies, infrastructure development and related services. This not only stimulates economic growth but also encourages diversification. In addition, the advancement of technology will emerge as a key opportunity, allowing for the incubation of cutting-edge technologies related to hydrogen-powered trains and associated systems. Furthermore, the opportunity to enhance domestic industries suggests that the growth of the hydrogen-powered railway sector can positively impact and strengthen various industries within the country, fostering the development of supply chains, manufacturing capabilities, and specialized skills. Lastly, the potential for initiatives aimed at establishing a new techno-economic ecosystem highlights collaborative efforts, policies, or projects that can create a supportive environment for technological innovation, economic growth, and sustainability within the hydrogen railway sector.

However, the weaknesses (W) identified in the SWOT analysis for the hydrogen railway sector have highlighted internal challenges that the industry must navigate. A significant learning curve in the development and implementation of hydrogen-powered railway technology will cause potential delays and inefficiencies, requiring focused efforts on acquiring the necessary knowledge and expertise. Social acceptance challenges underscore resistance or skepticism, stemming from concerns about safety and environmental impact, hindering widespread adoption. Budget constraints have presented limitations in financial resources for infrastructure development, impeding crucial investments in research and deployment. A shortage of technical stakeholders and experts can result in a risk to progress and innovation, necessitating efforts to address skills gaps. Policy instability, vulnerable to changes in government regulations, adds uncertainty, demanding strategic planning for the long term. The external threats (T) identified the underscored challenges and risks that the industry is encountering. The costly and import-dependent nature of hydrogen railway technology will pose a vulnerability to economic fluctuations and supply chain disruptions. Potential issues with techno-economic partnerships highlight challenges in collaborating with other industries, including disagreements on economic terms and coordination complications, hindering effective technology development and deployment. Concerns about the sustainability of financial cooperation have emphasized uncertainties and changing circumstances in financial support or collaborations, impacting the industry's ability to secure consistent funding for essential projects.

Hence, the SWOT analysis of hydrogen trains in Thailand provides a comprehensive evaluation of their feasibility and impact on the country's rail transportation sector. The government's proactive role in promoting robust policies and regulations emerges as a strength, creating a favourable environment for the hydrogen railway sector. Multi-level nationwide cooperation strengthens the industry's internal resilience, fostering sustainable technology and innovation. Opportunities for growth include the potential for new business creation, technological advancement, and positive impacts on domestic industries. However, internal weaknesses, such as a significant learning curve, social acceptance challenges, budget constraints, a shortage of expertise and policy instability, pose challenges that demand strategic navigation. External threats, including the costly and import-dependent nature of technology and potential issues with partnerships, underline the risks that need careful consideration. Addressing these aspects is crucial for ensuring the long-term success and sustainability of hydrogen trains in Thailand's rail transportation sector.

| | Positive | Negative |
|---|---|---|
| Internal | **Strength (S)**<br>▪ Policy and regulation mechanisms to support<br>▪ Availability of promotion plans for investigators<br>▪ Multi-level nationwide cooperation | **Weakness (W)**<br>▪ Large learning-curve<br>▪ Social acceptance and safety concerns<br>▪ Budget availability for investment<br>▪ Lack of technical stakeholders and experts<br>▪ Policy instability |
| External | **Opportunity (O)**<br>▪ New business creation<br>▪ Advanced technology incubation<br>▪ Technology enhancement of domestic industries involved<br>▪ New techno-economic ecosystem initiative | **Threat (T)**<br>▪ Expensive & import technology<br>▪ Techno-economic partnership<br>▪ Financial cooperation sustainability |

Figure 49 SWOT analysis of hydrogen-powered trains dedicated for Thailand

# 7 CONCLUSIONS & RECOMMENDATIONS

This chapter synthesizes the various scenarios and potential pathways discussed throughout the report, offering a comprehensive overview of the implications and outcomes for the application of green hydrogen to railways in the Thailand context. The conclusions draw attention to the unique considerations, challenges, and opportunities specific to Thailand, providing valuable insights for policymakers, industry stakeholders and researchers involved in advancing sustainable and innovative solutions within the country's railway sector.

## 7.1 Conclusions

The integration of green hydrogen is heralded as a revolutionary and environmentally sustainable solution poised to transform the landscape of a future energy sector. In response to the global emphasis on carbon emission reduction and the shift towards cleaner energy alternatives, green hydrogen emerges as an important player in fostering sustainability within transport operations. Green hydrogen is produced through a process known as electrolysis, where renewable energy sources, such as wind or solar power, are used to split water into hydrogen and oxygen. The resulting hydrogen is considered "green" as it is produced without generating carbon emissions, making it a clean and sustainable energy carrier. When utilized in fuel cells, green hydrogen can be converted back into electricity, emitting only water vapour as a byproduct, thus offering a renewable and environmentally friendly alternative to traditional energy sources, contributing to a more sustainable and eco-friendly mode of transportation.

The application of hydrogen-powered propulsion technology to railways represents a revolutionary and sustainable solution for the transportation sector. The integration of hydrogen fuel cells in trains serves as a clean and efficient alternative to traditional diesel-powered locomotives, resulting in reduced carbon emissions and environmental impact. This technology involves converting hydrogen gas into electricity through fuel cells, which then power electric traction motors to drive the train. A significant advantage lies in the onboard production of electricity, eliminating the need for external power sources. Particularly noteworthy is the Proton Exchange Membrane Fuel Cell (PEMFC), which is attractive for vehicle use due to its simplicity, quick start-up, high power density, long life cycle, and efficient operation at lower temperatures. To enhance the fuel cell system's performance, a hybrid system is integrated, addressing the drawbacks of fuel cell technology by incorporating a secondary energy storage system to assist with start-up, acceleration, or climbing. In addition, the ongoing implementation of hydrogen technology in railway applications is in the developmental phase, demanding the creation of a robust infrastructure that includes refuelling stations, efficient hydrogen transportation systems, and the incorporation of stringent safety measures. Similar safety measures, as seen in hydrogen technology for vehicles, are applicable.

In Germany, hydrogen has been gaining traction in the railway sector with the development of hydrogen-powered trains. Companies like Alstom have introduced hydrogen fuel cell trains, known as "Coradia iLints". China has also been making strides in hydrogen railway applications, with ongoing projects exploring hydrogen fuel cell technology for trains. Foshan's groundbreaking initiatives, including the world's first hydrogen energy modern tram in March 2015 and the subsequent introduction of an 11-metre hydrogen fuel cell electric bus prototype in October 2015, highlighted China's leadership in hydrogen technology. Meanwhile, Indonesia has initiated a pilot project to explore the feasibility of hydrogen-powered trains by PT Industri Kereta Api (INKA) in Madiun, East Java. These global initiatives have demonstrated the increasing recognition and adoption of hydrogen technology in the railway sector as the nation’s responsibilities towards reducing its carbon footprint and promoting greener transportation alternatives.

Analyzing the TCO, the impacts of hydrogen technology in railway applications have involved a thorough assessment of economic factors beyond initial acquisition costs. The model of TCO was evaluated based on a hypothesis that the trains will be operated from Bangkok to Pattaya - Ban Phlu Ta Luang - Chuk Samet totalling 196 km. An examination of the costs associated with three types of energy trains has underscored the significance of infrastructure and personnel expenses in influencing the study's outcomes. The overhead contact system (OCS), characterized by its overhead transmission infrastructure, has revealed the highest costs, reflecting the inherently elevated expenses associated with such infrastructure. The pricing of battery-powered trains has closely aligned with that of hydrogen-powered trains, despite differences in infrastructure costs. This pricing parity has been attributed to the higher cost of green hydrogen compared to battery-powered trains. Despite differing infrastructure dynamics, both battery- and hydrogen-powered trains have presented comparable overall expenses in the study. However, the model in this route has considered the distance for one-time refuelling or charging, suggesting that for long distances, hydrogen-powered trains may have an opportunity to outperform battery-powered trains in terms of charging time efficiency. Investments in hydrogen infrastructure, including production facilities and refuelling stations, were weighed against long-term operational efficiency. This comprehensive perspective, considering both initial investments and ongoing operational expenses, has played a crucial role in determining the economic viability and sustainability of integrating hydrogen technology into railway applications. Moreover, it will propel the potential for job creation, economic growth, and innovation in the clean energy sector.

The integration of hydrogen technology in railway applications under Thailand's conditions has represented a transformative shift towards sustainable and innovative transportation. While acknowledging potential challenges like initial costs, the adoption of hybrid fuel cell designs promises enhanced efficiency and performance for hydrogen-powered trains. Government support has played a key role in offsetting initial expenses, fostering private investment, and further affirming the economic viability of hydrogen technology in the railway sector. This concerted effort has aligned with Thailand's commitment to sustainable transportation, marking a transformative leap towards a greener and technologically advanced railway infrastructure.

## 7.2 Suggestions for future work

The suggestions for future work in the hydrogen technology demonstration phase in Thailand revolve around comprehensive strategies to maximize success and pave the way for widespread adoption. Firstly, continued collaboration and partnership-building among government agencies, private sector firms, and research institutions are essential. Strengthening ties with international organizations and countries with advanced hydrogen technologies can facilitate knowledge exchange and technology transfer. Moreover, ongoing research and development efforts should focus on refining hydrogen production methods, storage solutions, and fuel cell technologies to enhance efficiency and reduce costs. Then, implementing pilot projects and expanding the scale of demonstration initiatives can provide valuable data and insights for scaling up hydrogen applications in the railway sector.

Additionally, fostering public awareness and education campaigns to promote the benefits of hydrogen technology is vital for gaining public acceptance and support. Lastly, the formulation of clear and supportive regulatory frameworks, including incentives for private sector investment, will be critical to creating an enabling environment for the sustainable growth of hydrogen technology in Thailand.

### 7.2.1 Potential stakeholders of technology demonstration phase

The potential stakeholders in the hydrogen technology demonstration phase in Thailand are diverse and encompass various sectors crucial for the successful implementation of this initiative. Among the primary stakeholders are government bodies, including the Ministry of Energy and the Ministry of Transport, responsible for setting policies, regulations, and providing financial support to drive the hydrogen technology agenda. Energy and transportation companies, both public and private such as in the hydrogen production and distribution sector, play a vital role as stakeholders, contributing to infrastructure development, hydrogen production, and integrating the technology into existing transportation systems. Research institutions and universities are pivotal stakeholders, engaging in research and development activities, providing expertise and fostering innovation in hydrogen technology. Industry associations and advocacy groups can act as facilitators, promoting awareness, collaboration and advocating for favourable policies. Finally, railway operators in Thailand hold significant potential as key stakeholders in the hydrogen technology demonstration phase production. These operators play a crucial role in the successful integration of hydrogen technology into the country's railway infrastructure. Their involvement includes adopting hydrogen-powered trains, investing in necessary infrastructure such as refuelling stations, and collaborating with technology providers for the deployment of hydrogen fuel cell systems. Railway operators are quite important in showcasing the viability, effectiveness, and safety of hydrogen-powered trains.

International collaborations with foreign governments and organizations may also be key stakeholders, bringing global expertise, technological partnerships, and potential investment. Local communities and the general public are essential stakeholders, as their acceptance and engagement are crucial for the success of hydrogen technology integration. Overall, a collaborative effort among these diverse stakeholders is imperative for the successful demonstration and production of hydrogen technology in Thailand.

### 7.2.2 Suggestions of non-technical issues

Regarding the German case study, a well-defined governance structure has been crucial for the effective implementation and development of the National Hydrogen Strategy, as depicted in **Figure 24**. Similarly, for the successful deployment of hydrogen technology in railway applications in Thailand, a strategic and comprehensive approach is imperative. Establishing a robust regulatory framework becomes paramount, encompassing safety standards, licensing procedures, and environmental regulations to govern the deployment of hydrogen-powered trains. The proposed hydrogen administration model for Thailand is illustrated in **Figure 50**. Key stakeholders in the hydrogen technology for railway applications in Thailand include government agencies such as the Ministry of Energy and the Ministry of Transport, responsible for formulating hydrogen policies and overseeing energy-related aspects. Siemens can play a pivotal role in preparing the rolling stock, while the State Railway of Thailand (SRT) can manage its infrastructure suitable for the technology demonstration of hydrogen-powered trains. In the hydrogen production sector, companies like Linde and Big are potential stakeholders, contributing to hydrogen production, while Linde, Big, and PTT have the capability to handle hydrogen delivery. Research and development in hydrogen technology for railway applications under Thailand's constraints can be spearheaded by organizations like NSTDA and RTRDA.

Furthermore, public awareness campaigns are essential to acquaint the general population with the benefits and safety measures associated with hydrogen technology, addressing potential concerns and fostering public acceptance. Formulating long-term policies and strategies aligned with Thailand's economic and environmental goals is crucial, providing a stable foundation for sustained investment and growth in the hydrogen-powered railway sector.

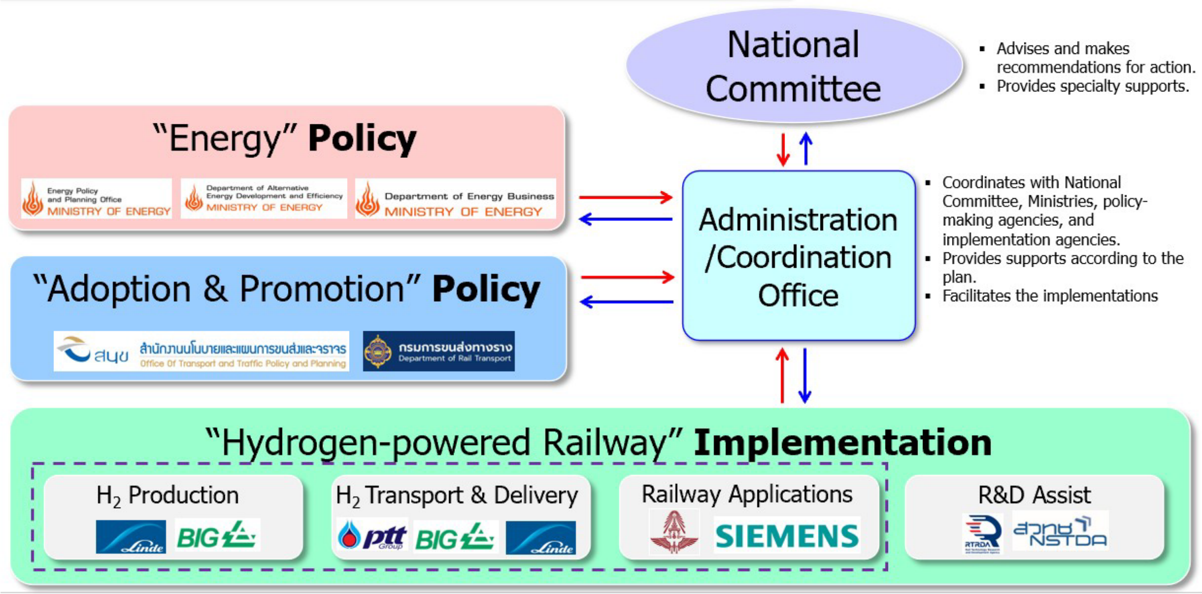



Figure 50 A proposed model integrated with relevant agencies and administrative offices as key stakeholders to drive green hydrogen applications to railways in Thailand.

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# Appendix

**The 1st Expert Meeting on the Feasibility Study for the Applications of Green Hydrogen in Thailand's Railway Sector**

**Date:** 23 August 2023 (09:30 – 12:30) **Venue:** NSTDA Rama VI Road Office, Bangkok

**Attendees:**

**NSTDA:**

1. Dr Ing. Ekkarut Viyanut
2. Dr Kullachet Korpattanachaijaroen
3. Mr Somrit Buddhanbut

**GIZ TH (H2Uppp):**

4. Dr Chulaluck Pratthana

**Public Sectors (Ministry of Energy):**

5. Representatives from the Energy Policy and Planning Office (EPPO)
6. Representatives from the Department of Energy Business (DOEB)
7. Representatives from the Department of Alternative Energy Development and Efficiency (DEDE)

**Private Sector:**

8. Representatives from PTT
9. Representatives from Linde
10. Representative from Siemens Energy
11. Representative from BIG

**Meeting Agenda**

**Part I: Policy and Hydrogen Production Technology**

**Energy Policy and Planning Office (EPPO):**

- EPPO discussed the use of hydrogen in Thailand and highlighted the absence of a carbon neutrality summary. EPPO is planning to adopt hydrogen as an energy carrier in the transport sector, especially for long-haul trucks. This is in the process of cost estimation and construction of hydrogen refuelling stations.
- EPPO is conducting the study of hydrogen policy in the power sector with progress currently standing at around 80%. It will be presented to EPPO's board committees in the future.

**Department of Energy Business (DOEB):**

- DOEB is responsible for overseeing the energy business sector. Hydrogen energy has not been regulated because it has been categorized out of the energy scope. However, DOEB has initiated policy plans for its future use.
- DOEB emphasized the necessity of establishing safety regulations for hydrogen transportation, storage, and refuelling stations, for example.
- It should be clearly designated whether hydrogen is intended for use in energy production or as a feedstock in the industrial sector. Furthermore, if hydrogen is to be used within the transportation system, it must firstly be registered as a kind of fuel/energy. DOEB will closely monitor the price of hydrogen energy to ensure fair pricing for consumers.

**Department of Alternative Energy Development and Efficiency (DEDE):**

- DEDE has a plan to employ hydrogen as fuel for electricity generation. A study focusing on comparison between battery electric vehicles and hydrogen-powered vehicles is currently ongoing.

**Part II: Policy and Transportation Technology and Hydrogen Refueling Station**

**Bangkok Industrial Gas (BIG):**

- BIG emphasized the importance of governmental support to increase demand of hydrogen utilization in industrial sectors. The support at the initial phase of promoting hydrogen utilization is necessary for hydrogen market ramp-up in Thailand.
- They also mentioned that taxation of $CO_2$ emissions is another factor to leverage hydrogen competitiveness as compared to other fossil fuels.

**Linde Thailand:**

- Linde expressed its preference for using blue hydrogen for launching hydrogen-related activities because it will take a while for green hydrogen to be commercially available on the Thai market. The reason to support this is that continuity and stability of electrical power generated from renewable sources, such as PV solar, is a key concern in the production of green hydrogen in Thailand. A maximum duration of 6 hours is obtained for PV solar electricity generation in a day, making green hydrogen less viable than blue hydrogen under the current constraints of hydrogen production infrastructure in Thailand.
- Linde highlighted the potential for reducing green hydrogen production costs through increased capacity of energy production from renewable sources.
- In the context of Thailand, hydrogen can be transported using two main methods: 1) tube trailers and 2) gas line networks. Tube trailer is capable of transporting hydrogen at a quantity of 1.5 to 3 tons per trip.

**PTT PCL:**

- PTT PCL discussed the production of hydrogen-powered vehicles in Thailand and the important role of carbon emission taxation for promotion of hydrogen-related activities.
- It was also noted that green hydrogen production is costly due to the intermittency of renewable energy sources in Thailand. Blue hydrogen produced through any process using natural gas is more practical for Thailand's current state. There are some existing facilities at PTT PLC available for the production of blue hydrogen.
- In addition to utilizing renewable energy sources, the application of carbon capture technology represents an alternative means for producing green hydrogen. However, a notable drawback is that this approach comes with a relatively high cost.

**GIZ:**

- GIZ provided an overview of the H2Uppp project, which aims to promote green H2/PtX projects in developing and emerging (ODA) countries to further develop markets for green H2/PtX technologies through on-site cooperation.

**Discussion:**

- Linde proposed conducting a hydrogen rail demonstration in the EEC zone. BIG suggested that investment in hydrogen refuelling stations and infrastructure should be avoided due to its high cost. They could replace the hydrogen tank at Map Ta Phut, with consideration given to its location.
- Examining the feasibility of integrating hydrogen energy in trains involves assessing the scale of implementation, categorized into three sizes:
    1. Trial runs for 1-2 trains.

2. Trials encompassing 2-10 trains.
3. Trials involving more than 15 trains.

For trial runs of 2-15 trains or more, the estimated cost is approximately 200 million baht. In the case of a prototype scenario, where 1-2 trains can be refuelled using hydrogen tube trailer at a designated location (e.g., in a trial run at 2 stations with hydrogen tube trailers, the cost is approximately 50 million baht), or hydrogen can be compressed into tanks that are trailed alongside the trains.

- The meeting summarized that a demonstration project should be established to create social awareness and test the feasibility of hydrogen-powered trains in Thailand. The support from BOI is also crucial. The previous research conducted by the Office of Transport and Traffic Policy and Planning (OTP), the Ministry of Transport, Thailand might be used as the guidelines in the current project.




**The 2nd Expert Meeting on Feasibility Study on Applications of Green Hydrogen in Railways in Thailand**

**Date** 29 September 2023 **Time:**, 09:30 – 12:30 (GMT+7)

**Venue:** NSTDA Rama VI Road Office, Bangkok

**Attendees:**

**NSTDA:**

1. Dr Ing. Ekkarut Viyanut
2. Dr Kullachet Korpattanachaijaroen
3. Mr Somrit Buddhanbut

**GIZ TH (H2Uppp):**

4. Dr Chulaluck Pratthana
5. Dr Pramote Puengjinda

**Public Sector:**

6. Representative from the State Railway of Thailand (SRT)
7. Representative from the Rail Technology Research and Development Agency (RTRDA)
8. Representative from the Office of Transport and Traffic Policy and Planning (OTP)
9. Representative from the Department of Rail Transport (DRT)

**Private Sector:**

10. Representative from PTT PCL

**Part 1: Hydrogen Transport and Refueling**

**PTT PCL:**

- PTT PCL emphasized the importance of exploring the utilization of hydrogen combustion engines in railway applications. They explained that hydrogen combustion engines could serve as a supplementary power source during acceleration, contributing to energy efficiency. PTT PCL expressed strong support for hybrid energy solutions, combining hydrogen with other power sources for improved performance and sustainability.

**OTP:**

- OTP has presented a comprehensive plan aimed at promoting hydrogen as a clean energy source across various modes of transportation, including cars, railways, and aircrafts. They have outlined their commitment to establishing hydrogen refuelling stations. OTP has also outlined their carbon emissions reduction targets, with specific milestones for 2023, aiming for a 30-40% reduction in carbon emissions, and for 2030-2040, they plan to achieve carbon capture utilization. Their ultimate goal is to reach net-zero emissions between 2050 and 2065. Additionally, OTP expressed a strong support for the development of fuel cell technologies to facilitate the widespread use of hydrogen as a clean energy source.

**DRT:**

- DRT acknowledged the limitations associated with retrofitting existing trains used by the State Railway of Thailand (SRT). They pointed out that factors such as assembly area constraints and load capacities posed challenges. To address these limitations, DRT recommended procuring new fuel cell hybrid trains as a more practical and efficient solution. DRT also emphasized the need to establish hydrogen refuelling stations at maintenance depots, ensuring that fuelling infrastructure is in place to support hydrogen-powered trains.

**SRT:**

- SRT expressed support for fuel cell hybrid technology for railway applications and specified that hydrogen should be stored at high pressures, specifically 300 or 350 bar, with compressed gaseous storage methods. This choice of storage method is expected to provide efficient and safe storage for hydrogen fuel, ensuring that it's readily available for use in hydrogen-powered trains.

**GIZ:**

- GIZ initiated a discussion on the potential impact of hydrogen trains on railroad tracks. They drew a comparison between traditional railroad tracks, which typically bear a load of 20 tons, and Diesel Multiple Units (DMU) that currently support loads of up to 16 tons. GIZ highlighted the importance of understanding how the introduction of hydrogen trains might affect the existing railway infrastructure.

**Part 2: On-Board Hydrogen Technology**

**PTT PCL:**

- PTT PCL discussed the advantages of using liquid hydrogen, especially in situations where there is heavy railway traffic. They emphasized that liquid hydrogen can be stored at normal pressures of 350 bar and then expanded to 700 bar, making it a viable and efficient option. While highlighting the safety aspects of using liquid hydrogen, PTT PCL noted that there have been no reported accidents related to its use. They emphasized the need for standardization to ensure the safe and confident use of hydrogen energy.

**DRT:**

- DRT discussed the current absence of safety regulations specific to hydrogen train technology. However, they recognized the necessity of establishing such regulations in the future. They recommended drawing on international best practices and case studies from other countries to develop a comprehensive set of safety standards. DRT mentioned that the Rail Technology Research and Development Agency (RTRDA) will be responsible for conducting these studies.

**SRT:**

- SRT proposed a testing plan for hydrogen trains, suggesting that the initial testing phase should involve Diesel Multiple Units (DMU). They identified two potential testing routes: Nakhon Pathom-Krung Thon Buri and Mahachai-Wong Wien Yai. These routes were chosen due to the presence of maintenance depots that could support refuelling, making them suitable for testing clean energy trains.

**DRT:**

- DRT concurred with OTP regarding the introduction of hydrogen-powered trains, highlighting that such an endeavour is more complex and challenging than electric train alternatives. Their agreement reflects the shared recognition of the potential and difficulties associated with transitioning to hydrogen-based railway transportation.

**PTT PCL:**

- PTT PCL suggested a specific testing route in the eastern area, particularly in Map Ta Phut, an area that possesses readily available hydrogen sources. They considered this location optimal for conducting comprehensive tests and studies related to hydrogen train technology.

**Part 3: Other Considerations**

**PTT PCL:**

- PTT PCL provided valuable information on the operational advantages of hydrogen trains. They highlighted that a single hydrogen fill can enable these trains to cover a distance of 600-1,000 kilometers, making them a highly efficient and cost-effective choice. In addition, PTT PCL discussed the cost comparisons with the Overhead Catenary System (OCS) for railway electrification, emphasizing that OCS systems become economically viable when there is a consistent and substantial ridership of at least 60 passengers per day, considering both passenger and freight trains. They also explored two methods for transporting hydrogen: establishing hydrogen stations and implementing hydrogen gas pipelines. To reach a break-even point for hydrogen gas pipelines, the distance should exceed 200 kilometres.

**SRT:**

- SRT suggested the importance of calculating maintenance costs, especially in relation to the distance between OCS trains and hydrogen trains. They also encouraged a study of how vibrations from hydrogen-powered trains might affect railway infrastructure.

**OTP:**

- The implementation of hydrogen energy should commence with goods freight trains, potentially by incorporating hydrogen refuelling points at ICD or CY locations. It is important to highlight the key advantage of hydrogen, which allows for longer travel distances compared to electric battery vehicles. Initially, hydrogen trucks may utilize various refuelling points to meet their requirements.
- OTP put forward a proposal to study the effects of hydrogen energy in various modes of transportation beyond railways. This expanded perspective aims to explore the broader potential and benefits of hydrogen as a clean energy source.

**RTRDA:**

- RTRDA highlighted the necessity of government support in regulating the pricing of hydrogen energy to enhance its competitiveness in the market. They emphasized the importance of fuel cell technology achieving lower costs and higher efficiency to encourage its widespread adoption.

**GIZ:**

- In Germany, hydrogen has been found to have a cost 35% lower than diesel and results in a 30% lower TOC. They stressed the need to revise regulations concerning the storage pressure of hydrogen gas, which is currently limited to 350 bar.


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