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UNIVERSIDAD PONTIFICIA
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BACHELOR’S DEGREE IN INDUSTRIAL ENGINEERING

FINAL UNDERGRADUATE PROJECT

Optimization model of a Hydrogen Refueling Station network for heavy vehicles in Spain

Autor: Ana Sanz García

Director: Marta Galdós Ispizua

Co-Director: María Luisa Serrano Irurzun

Madrid, July 2023

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título Optimization model of a Hydrogen Refueling Station network for heavy vehicles in Spain en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el curso académico 2023 es de mi autoría, original e inédito y no ha sido presentado con anterioridad a otros efectos.

El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada de otros documentos está debidamente referenciada.

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Acknowledgements

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OPTIMIZATION MODEL OF A HYDROGEN REFUELING STATION NETWORK FOR HEAVY VEHICLES IN SPAIN

Autor: Sanz García, Ana.

Director: Galdós Ispizua, Marta.

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Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

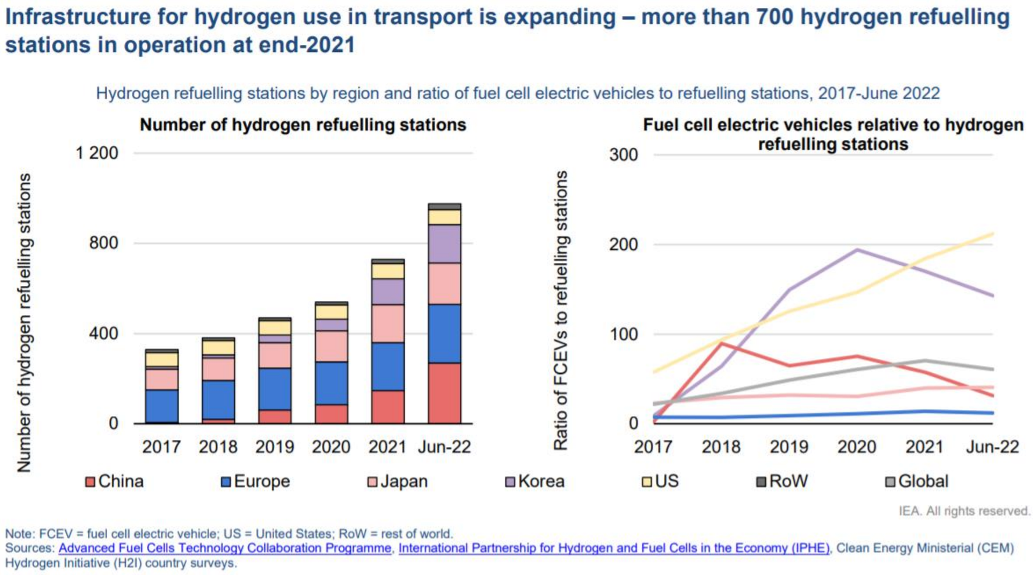
RESUMEN DEL PROYECTO

El sector del transporte contribuye actualmente a casi una cuarta parte de las emisiones mundiales de gases de efecto invernadero, lo que subraya la importancia de descarbonizar esta industria. El hidrógeno se perfila como una alternativa destacada a los combustibles convencionales, ya que promete reducir las emisiones de CO2, en consonancia con los objetivos esbozados en el Acuerdo de París. Por lo tanto, el objetivo final de este proyecto es evaluar el papel fundamental del hidrógeno en la transición del transporte pesado y el establecimiento de una sólida red de estaciones de servicio, contribuyendo así a soluciones sostenibles que apoyen el objetivo general de lograr cero emisiones netas de CO2 para 2050.

Palabras clave: Hidrógeno, vehículos pesados, estaciones de repostaje de hidrógeno, despliegue de infraestructura de hidrógeno, sostenibilidad.

El sector del transporte representa actualmente el 23% de las emisiones mundiales de gases de efecto invernadero. Dentro de este sector, los vehículos pesados contribuyen de forma significativa, representando el 6% de las emisiones totales de la UE [a]. Para alinearse con el ambicioso objetivo de lograr cero emisiones netas de CO2 para 2050, como se indica en el Pacto Verde Europeo, es imperativo promover la transición a vehículos de cero emisiones [b].

Diversas alternativas, como los vehículos eléctricos, los vehículos de pila de combustible y los biocombustibles, han surgido como posibles facilitadores de la transición energética. Mientras que la electrificación ha demostrado ser un éxito para los vehículos ligeros, su viabilidad para los vehículos pesados se ve obstaculizada por su elevado coste y sus inalcanzables requisitos energéticos, lo que la convierte en un enfoque menos práctico. Por ello, los vehículos de pila de combustible se perfilan como una solución prometedora para los vehículos pesados, ya que ofrecen una gran cantidad de ventajas, como cero emisiones de CO2, alta densidad energética, mayor autonomía y capacidad de repostaje rápido. Además, el hidrógeno tiene el potencial de abatir sectores difíciles de descarbonizar y presenta una oportunidad única para el almacenamiento de energía a gran escala. Esto brinda la oportunidad de fomentar el acceso a los recursos renovables, reforzando la seguridad energética y la autosuficiencia de las naciones; por lo tanto, tiene poder para remodelar el panorama geopolítico [c].



Infrastructure for hydrogen use in transport is expanding – more than 700 hydrogen refuelling stations in operation at end-2021

Hydrogen refuelling stations by region and ratio of fuel cell electric vehicles to refuelling stations, 2017-June 2022

Note: FCEV = fuel cell electric vehicle; US = United States; RoW = rest of world.
Sources: Advanced Fuel Cells Technology Collaboration Programme, International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Clean Energy Ministerial (CEM) Hydrogen Initiative (H2I) country surveys.

Figura 1. Infraestructura de Hidrógeno [c]

El objetivo de este estudio es abordar el reto crucial que supone la insuficiencia de infraestructuras de hidrógeno para satisfacer la futura demanda de vehículos eléctricos de pila de combustible (FCEV). Para lograr este objetivo, se desarrolla un modelo de optimización utilizando el software GAMS, diseñado para estimar el número óptimo y las ubicaciones estratégicas de las estaciones de repostaje de hidrógeno en función del flujo proyectado de vehículos pesados de hidrógeno y sus características únicas, minimizando al mismo tiempo los costes. A continuación, el modelo se evalúa para los horizontes temporales de 2030 y 2050, incorporando diversos escenarios para evaluar exhaustivamente los requisitos de infraestructura necesarios para atender la futura demanda de vehículos.

Para el año 2030, el modelo prevé una demanda de 105 estaciones de repostaje de hidrógeno distribuidas estratégicamente, con un coste estimado de 200 millones de euros, lo que representa una importante reducción del 40% de los gastos actuales. Estos resultados coinciden con la Hoja de Ruta del Hidrógeno del Gobierno español, que hace hincapié en la necesidad de instalar entre 100 y 105 estaciones para 2030 [d]. Para alcanzar este objetivo, sería esencial un ritmo de construcción anual de 21 estaciones a partir del año próximo, considerando un plazo de construcción de dos años.

De cara a 2050, el modelo revela un aumento sustancial de la demanda, que requerirá 935 estaciones de repostaje debido a una tasa de penetración prevista del 20%. Aunque existe una reducción aproximada del 80% de los costes a lo largo de la cadena de valor del hidrógeno, la viabilidad práctica de estos resultados puede verse influida por los avances tecnológicos de aquí a 2050. Se examinaron dos escenarios adicionales, proponiendo el segundo un enfoque más factible, reduciendo el número de estaciones necesarias a 471, con un coste de 200 millones de euros. Este plan, ambicioso pero viable, incluye 366 estaciones adicionales que se instalarán junto a las 105 previstas para 2030, lo que requiere una inversión adicional de 60 millones de euros para 2050, además de los 140 millones iniciales para 2030.

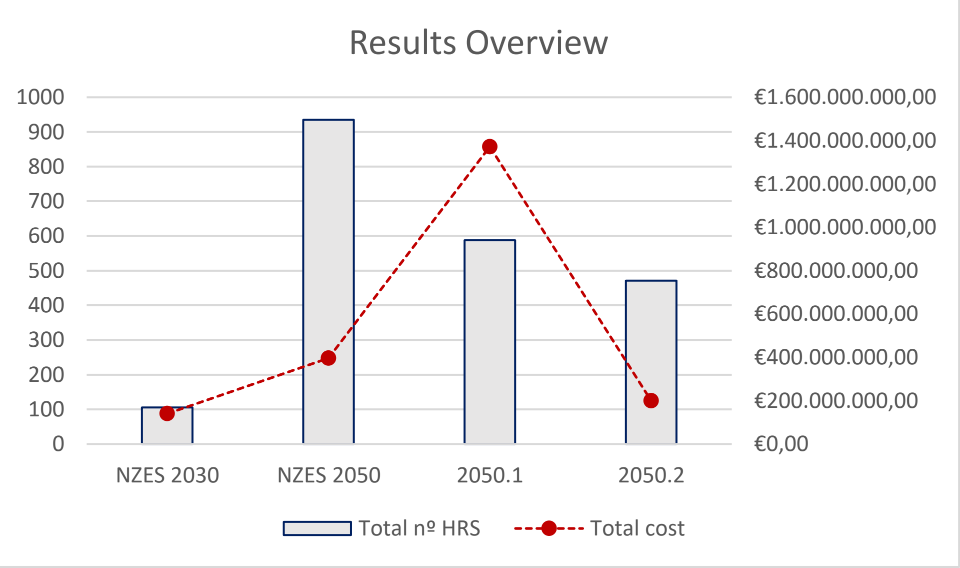


Figura 2. Resumen de Resultados [Elaboración propia]

En conclusión, el hidrógeno se ha revelado como una alternativa viable y prometedora para descarbonizar el sector del transporte, especialmente en zonas difíciles de descarbonizar. Sin embargo, aún quedan algunos retos por abordar, como el establecimiento de una infraestructura de recarga sólida y la reducción de costes, para garantizar su adopción generalizada. Los resultados obtenidos en el estudio indican claramente la necesidad inminente de iniciar el despliegue de infraestructuras de hidrógeno para satisfacer la demanda futura y avanzar hacia el ambicioso objetivo de lograr cero emisiones netas en 2050.

Referencias

[a] Agencia Internacional de la Energía (AIE), «Emisiones de CO2 en 2022,» 2022.

[b] Unión Europea, «European Green Deal,» 2019.

[c] Agencia Internacional de la Energía (AIE), «Global Hydrogen Review,» 2022.

[d] Gobierno de España, «Hoja de ruta del hidrógeno en España,» 2020.

OPTIMIZATION MODEL OF A HYDROGEN REFUELING STATION NETWORK FOR HEAVY VEHICLES IN SPAIN

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ABSTRACT

The transportation sector currently contributes nearly a quarter of global greenhouse gas emissions, underscoring the importance of decarbonizing this industry. Hydrogen is emerging as a leading alternative to conventional fuels, as it promises to reduce CO2 emissions, in line with the goals outlined in the Paris Agreement. Therefore, the ultimate goal of this project is to assess the pivotal role of hydrogen in the transition of heavy transport and the establishment of a robust refueling station network, thus contributing to sustainable solutions that support the overall goal of achieving net zero CO2 emissions by 2050.

Keywords: Hydrogen, heavy-duty vehicles, hydrogen refueling stations, hydrogen infrastructure deployment, sustainability.

The transportation sector currently accounts for 23% of global greenhouse gas emissions. Within this sector, heavy-duty vehicles (HDVs) contribute significantly, representing 6% of total EU emissions [a]. To align with the ambitious goal of achieving net zero CO_2 emissions by 2050, as outlined in the European Green Deal, the imperative is to promote the transition to zero-emission vehicles [b].

Various alternatives, including electric vehicles, fuel cell vehicles, and biofuels, have emerged as potential enablers of the energy transition. While electrification has proven successful for light-duty vehicles, the feasibility for HDVs is hindered by their elevated cost and unattainable energy requirements, making it a less practical approach. Hence, fuel cell vehicles emerge as a promising solution for HDVs, offering a plethora of advantages, such as zero CO2 emissions, high energy density, extended range, and rapid refueling capabilities. Additionally, hydrogen holds the potential to decarbonize hard to abate sectors and presents a unique opportunity for large-scale energy storage. This provides an opportunity to foster access to renewable resources, bolstering energy security and self-sufficiency for nations; thus, holding power to reshape the geopolitical landscape [c].

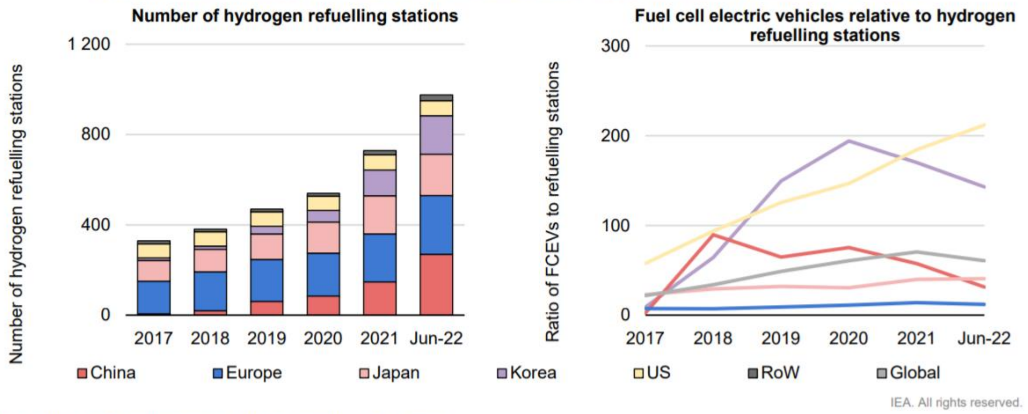

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Figure 1. Hydrogen Infrastructure [c]

This study aimed to address the crucial challenge of insufficient hydrogen infrastructure to meet the future demand for fuel cell electric vehicles (FCEVs). To achieve this objective, an optimization model is developed using the GAMS software, designed to estimate the optimal number and strategic locations of hydrogen refueling stations based on projected heavy-duty hydrogen vehicle flow and their unique characteristics, while minimizing costs. The model is then evaluated for the timeframes of 2030 and 2050, incorporating diverse scenarios to comprehensively assess the infrastructure requirements necessary to cater to future vehicle demand.

For the year 2030, the model forecasts a demand for 105 strategically distributed hydrogen refueling stations, at an estimated cost of 200 million euros, representing a significant 40% reduction in current expenses. These findings align with the Spanish government's Hydrogen Roadmap, emphasizing the necessity of installing 100-105 stations by 2030 [d]. To achieve this objective, an annual construction rate of 21 stations from the upcoming year would be essential, considering a two-year construction timeframe.

Looking ahead to 2050, the model reveals a substantial surge in demand, requiring 935 refueling stations due to an anticipated 20% penetration rate. While there is an approximate 80% cost reduction along the hydrogen value chain, the practical viability of these outcomes may be influenced by technological advancements by 2050. Two additional scenarios were examined, with the second sub-scenario proposing a more feasible approach, reducing the number of required stations to 471, at a cost of 200 million euros. This ambitious yet viable plan includes an additional 366 stations to be installed alongside the 105 stations planned for deployment by 2030, necessitating an additional 60 million euros investment for 2050, in addition to the initial 140 million euros for 2030.

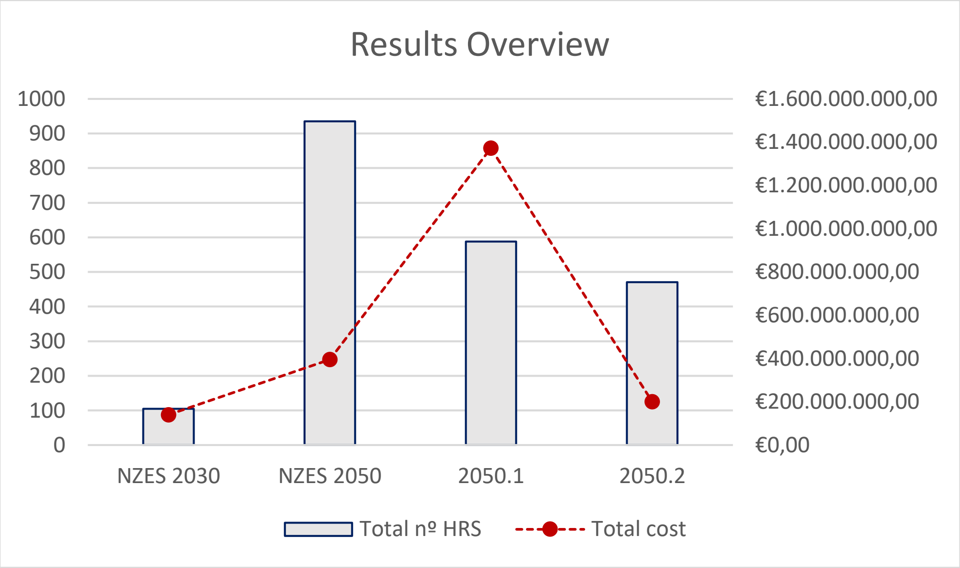

Figure 2. Results Overview [Self-elaborated]

The results obtained highlight the need for the sector's advancement to focus on enhancing fuel cell vehicle technology, particularly by increasing vehicle autonomy as demonstrated in the second sub-scenario. This approach not only enhances feasibility and profitability but also paves the way for significant advancements within the industry.

In conclusion, hydrogen has emerged as a viable and promising alternative to decarbonize the transportation sector, particularly in challenging-to-decarbonize areas. However, certain challenges remain to be addressed, such as the establishment of a robust recharging infrastructure and cost reduction, to ensure its widespread adoption. The results obtained from the study strongly indicate an imminent need to initiate the deployment of hydrogen infrastructure to meet future demands and advance towards the ambitious goal of achieving net zero emissions by 2050.

References

[a] International Energy Agency (IEA), «CO2 Emissions in 2022,» 2022.

[b] European Union, «European Green Deal,» 2019.

[c] International Energy Agency (IEA), «Global Hydrogen Review,» 2022.

[d] Spanish Government, «Hydrogen Roadmap in Spain,» 2020.

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Chapter 1. INTRODUCTION

The transportation sector represented 23% of the global greenhouse gas emissions in 2022, where heavy-duty vehicles were responsible for 28% (6% of total EU emissions) [1]. Thus, it is imperative to stimulate the transition to zero-emission vehicles to achieve net zero CO_2 emissions by 2050 as the European Green Deal states [2].

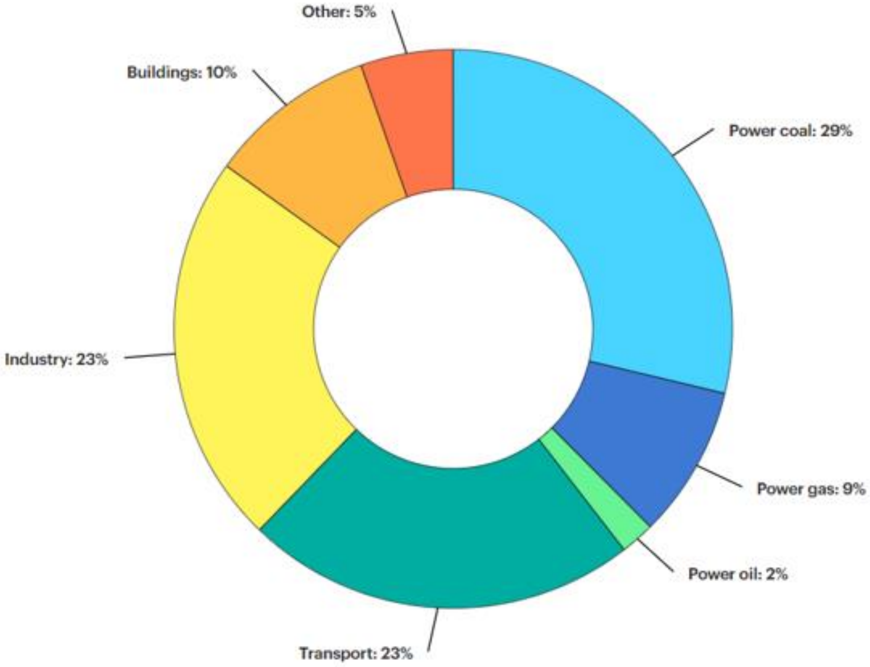


Figure 1. Global energy-related CO2 emissions by sector [1]

The need to reduce greenhouse gas emissions to mitigate climate change's effects has made decarbonization a global priority. Alternatives such as electric vehicles, fuel cell vehicles and the use of biofuels have been emerging as possible catalyzers for the energy transition. However, while the electrification of light-duty vehicles has been a viable strategy for reducing carbon dioxide emissions, heavy-duty vehicles' high cost and energy requirements make this approach less practical.

Hydrogen fuel presents an alternative solution. These vehicles, powered by clean and renewable fuel, emit only water vapor as a by-product and the capability to generate this fuel from low carbon sources, solar or wind energy, ensures a fully clean and eco-friendly production process. They also have the potential to have a longer range than electric vehicles and have a faster refueling time, making hydrogen a competent alternative for long-distance travel and heavy-duty transport.

The technology's development is being hindered by several challenges, such as its high cost and the lack of infrastructure for recharge stations. Hence, this project aims to conduct a comprehensive analysis of hydrogen as an energy vector for heavy-duty vehicles and develop an optimization model for the deployment of hydrogen refueling station network on the main Spanish highways. The study targets to address one of the major handicaps in the industry, being a catalyst for the transition to hydrogen-powered heavy-duty vehicles, taking a step towards the decarbonization of transport.

The research component of the project will be conducted to establish the technical feasibility of hydrogen as a fuel. It will encompass various aspects of hydrogen as an energy vector, including production methods, transportation and storage options and will analyze the obstacles this technology is currently facing. Moreover, the technical and economic requirements of a hydrogen refueling station installation will be assessed and a general overview of the transport sector regarding hydrogen as a fuel will be reviewed.

On the other hand, the optimization model aims to be a tool to analyze the deployment of a station network along the primary highways in Spain contributing to the energy transition. The model operates by using projected daily vehicular flow data as input parameters, enabling it to determine the optimal number of refueling stations to be installed and their strategic locations by minimizing investment costs.

Subsequently, the model is evaluated across two distinct scenarios, 2030 and 2050. These scenarios encompass progressive increases in the penetration ratio of fuel cell vehicles, thereby inducing a decline in costs through economies of scale. Two additional sub-scenarios are considered conducting a sensitivity analysis regarding the effect of changes in the stations or vehicle's technology, on the estimate of stations required by 2050. The data collected through this process will serve as a foundation to gain insights into the evolution of the hydrogen industry. Thus, the overall objective is to provide an overview of the infrastructure deployment required to cater to the needs for the decarbonization of heavy-duty transport.

It is important to note that while hydrogen holds significant potential for decarbonizing transport and reducing greenhouse gas emissions, a comprehensive examination is necessary to establish its practical feasibility. Thus, this project attempts to contribute to this examination and provide sustainable solutions aligned with the net zero-emissions by 2050 goal, studying the viability of a proposal, key to the hydrogenation of heavy-duty transport, and the deployment of a recharge station network.

1.1 SUSTAINABLE DEVELOPMENT GOALS (SDG)

This project aligns with several Sustainable Development Goals (SDGs) outlined by the United Nations [3], including:

1. **SDG 7 & SDG 13:** Affordable and Clean Energy & Climate Action– The development of a hydrogen refueling station network proposal, aims to promote the use of clean and renewable energy sources, such as hydrogen, which can help to reduce dependence on fossil fuels and increase access to affordable and clean energy. Thus, contributing to the decarbonization of the transportation sector and combat climate change, by reducing greenhouse gas emissions.

2. **SDG 9:** Industry, Innovation, and Infrastructure – The project aims to support the growth of the hydrogen industry and infrastructure in the country, promoting innovation and economic growth.

3. **SDG 11:** Sustainable Cities and Communities – The choice of hydrogen as a fuel, improves air quality in urban areas, which can have a positive impact on public health and well-being, supporting the sustainable development of cities and communities.

Figure 2. Sustainable development goals [3]

Chapter 2. STATE OF THE ART

Heavy-duty Vehicles (HDVs) used in the long haul and freight transportation sectors account for an extensive portion of greenhouse gas emissions. Hydrogen has emerged as a potential alternative to conventional fuels, offering advantages such as zero CO_2 emissions, high energy density, longer ranges and faster refueling. Hence, the transition to hydrogen-fueled HDVs can play a pivotal role in decarbonizing transportation and meeting climate change objectives.

As an energy vector, hydrogen can store and transport energy; however, despite being one of the world's most abundant elements, in nature, it is always found jointly with other elements, so it must undergo certain production and conversion processes. It has a high energy density by weight, meaning a small amount can hold a lot of energy; however, its volumetric energy density is low, meaning a large volume is necessary to store significant amounts of energy. This presents a challenge to both storage and transportation that needs the development of efficient yet cost-effective methods for doing so.

Hence, an in-depth analysis of the technology and industry advancements related to hydrogen fuel for heavy-duty vehicles and the available network of hydrogen refueling stations (HRS), is presented; setting the foundation, for further analysis of hydrogen's energy transition based on the refueling infrastructure capabilities and hydrogen's penetration rate forecast up to 2050.

2.1 HYDROGEN'S POTENTIAL

In today's context, the issue of emissions has gained paramount importance due to the urgent need for mitigating climate change. The Net Zero Emissions by 2050 Scenario sets ambitious targets for emission reduction, emphasizing the imperative to curb greenhouse gas emissions across various sectors. Among these sectors, transportation emerges as a significant contributor, with heavy-duty transportation accounting for over a quarter of total emissions [1]. Consequently, decarbonizing the transportation sector becomes a critical priority.

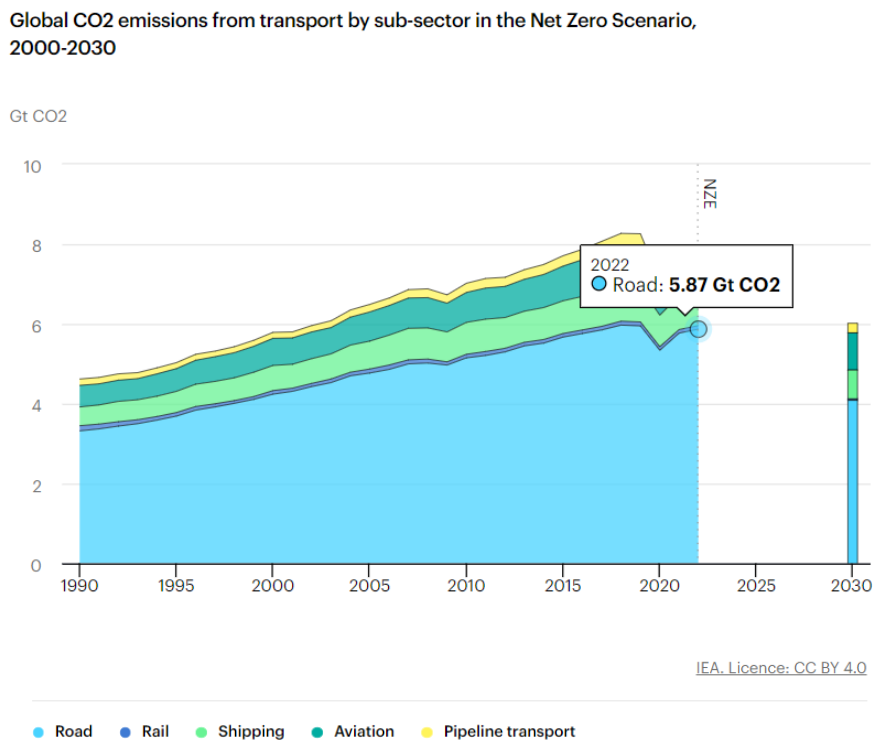


Figure 3. Global CO2 emissions from transport [1]

While electric vehicles (EVs) have gained considerable attention as alternatives to fossil fuels, hydrogen has emerged as a fuel with significant traction in recent years. Hydrogen serves as an alternative when electrification is not feasible due to technical and economic constraints. It offers several advantages, such as being a non-polluting and filtrating substance, providing greater range and shorter refueling time. However, it is essential to acknowledge that the current costs associated with hydrogen production, storage, and infrastructure development are relatively high.

The potential of hydrogen as an alternative fuel source stems from various factors:

- **Addressing Hard to Abate Sectors:** Hydrogen holds promise in tackling sectors that are particularly challenging to decarbonize solely with electricity. These sectors encompass one-third of today's global emissions, including heavy-duty transportation (trucks, trains, ships, and airplanes) and energy-intensive industrial processes in the chemical and metallurgical industries that rely on high-temperature heat. Moreover, the inherent constraint in the existing electric grid, currently remains ill-prepared to adequately cater to and withstand the supplementary demand entailed by the electrification of the entire transportation sector.

- **Enabling Large-Scale Energy Storage:** Hydrogen overcomes one of the limitations of electricity by facilitating efficient storage and transport on a large scale. This characteristic opens up the possibility of establishing international energy markets for the storage and transportation of energy, akin to the existing markets for coal, oil, and natural gas.

- **Expanding Access to Renewable Resources:** Hydrogen can be produced using renewable resources such as water, wind, and solar power. This presents a transformative opportunity for many countries, as it enables them to tap into their domestic renewable energy sources and reduce dependence on external energy powers. For instance, the European Union, which currently relies on other energy-supplying nations like Russia and the United States, could enhance its energy security and achieve greater self-sufficiency through hydrogen utilization. Thus, the adoption of hydrogen as an energy carrier could lead to a significant shift in the geopolitical landscape where, by leveraging their renewable resources, countries could achieve the energy trilemma: ensuring energy security, promoting sustainable energy, and achieving competitive energy costs.

While the widespread adoption of hydrogen as an alternative fuel does face challenges, such as cost reduction, infrastructure development, and establishing supportive policies, it offers a viable pathway to decarbonize sectors that prove difficult to address through electrification alone. By recognizing its potential as an alternative fuel source, stakeholders can strategically invest in research, development, and infrastructure to unlock its benefits fully. Hence, embracing hydrogen as part of a diversified energy portfolio has the potential to revolutionize the transportation sector, enable cleaner industrial processes, and contribute significantly to achieving global emission reduction targets, thus paving the way for a sustainable and secure energy future.

2.2 HYDROGEN VALUE CHAIN

2.2.1 PRODUCTION METHODS AND TYPES OF HYDROGEN

Hydrogen is an energy carrier, meaning it must be produced from a primary energy source through various transformation processes. There are different methods for producing it, each with major differences depending on the starting feedstock used, the production process itself or the technology maturity associated with it. It is also important to note that depending on the source, hydrogen is classified into different colors to identify the types and eco-friendliness of each.

2.2.1.1 TYPES OF HYDROGEN

- **Grey hydrogen:** Produced from reformed natural gas through the process of steam methane reforming (SMR), which involves heating natural gas with steam to generate hydrogen and carbon dioxide as a by-product.
- **Brown hydrogen:** Produced from natural gas through a process called gasification, which involves heating coal or other carbon-rich materials to form a mixture of hydrogen and CO2.
- **Blue hydrogen:** Hydrogen produced from any fossil fuel with CO2 capture.
- **Turquoise hydrogen:** Produced through pyrolysis of natural gas without using water vapour and leaving behind a solid carbonaceous residue which is easier to manage than CO2.
- **Golden hydrogen:** Produced from natural gas using carbon capture and storage (CCS) technologies, but in a more efficient manner than blue hydrogen production. The captured carbon can then be utilized for industrial purposes or stored permanently.
- **Green hydrogen:** Produced through electrolysis processes that use renewable electricity (such as from wind or solar power) to split water molecules into

hydrogen and oxygen atoms. Since no carbon emissions are created during production, this fuel source can be considered carbon-free.

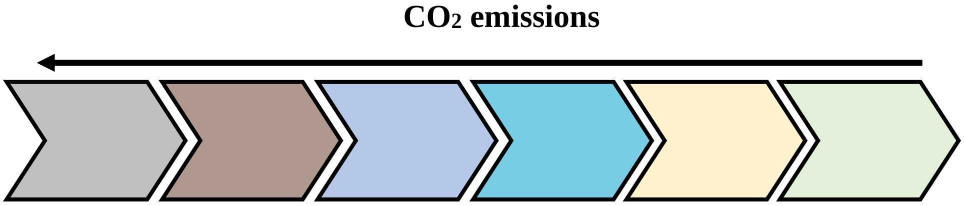


Figure 4. Types of hydrogen [Self elaborated]

At present, much of the hydrogen used in industry is grey hydrogen which is characterized by its low cost but remains unappealing due to CO_2 emissions. Green hydrogen on the other hand is more costly but holds great promise for a low-carbon economy. Future solutions could include improving carbon capture technologies, cutting emissions from natural gas supply chains, and expanding renewable energy sources to lower costs and boost green hydrogen availability. Meanwhile, golden hydrogen is becoming an increasingly popular option as it presents an opportunity to reduce carbon emissions.

2.2.1.2 PRODUCTION METHODS

2.2.1.2.1 Reforming

SMR (Steam Methane Reforming):

Steam methane reforming (SMR) is the most widely used method for producing hydrogen. In SMR, natural gas is reacted with steam in the presence of a catalyst to produce hydrogen and carbon monoxide by following this chemical equation:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Equation 1. Steam Methane Reforming Chemical Reaction

The hydrogen produced is purified and compressed for use. SMR typically operates at high temperatures (700-1100 ºC) and pressures (15-30 bar), requiring large amounts of natural gas and water. While this mature method has many advantages, it also generates significant greenhouse gas emissions as well as other pollutants like carbon monoxide or nitrogen oxides.

POX (Partial Oxidation):

Partial Oxidation (POX) is an incomplete oxidation of a hydrocarbon, in which carbon is only reduced to CO and the hydrogen remains unreacted. High temperatures (1300-1500 degrees Celsius) are necessary for this process to reduce coke formation during combustion. CO_2 can then be removed by either oxidizing it into CO_2 or reacting it with water for hydrogen and CO_2. For natural gas, efficiency levels up to 70% have been achieved via partial oxidation; however, less hydrogen is produced than through reformers; hence POX methods tend to be employed when dealing with liquid hydrocarbons.

ATR (Autothermal Reforming):

Auto-Thermal Reforming (ATR) is a method that utilizes both SMR and POX, so the heat released during partial oxidation is used for reforming, creating a net zero energy balance. Carbon dioxide produced during partial oxidation is displaced with water to generate hydrogen and CO_2, giving similar efficiency levels as partial oxidation. ATR's main advantage over steam reforming lies in its quick start-up time as well as larger amounts of hydrogen produced than POX processes can generate, but still produces a significant amount of greenhouse gas emissions.

2.2.1.2.2 Biomass Gasification

Biomass gasification is the process of heating biomass, such as wood chips or agricultural waste, in a low-oxygen environment to create hydrogen, carbon monoxide, and other gases.

$$C_6H_{12}O_6 \rightarrow 2CH_4 + 2CO + 2CO_2 + 2H_2$$

Equation 2. Biomass Gasification Chemical Reaction

The gas mixture can then be purified and compressed for use as hydrogen fuel. Biomass gasification offers the advantage of using waste materials as a feedstock while reducing greenhouse gas emissions. Unfortunately, it remains an emerging technology with high capital and operating costs. Biomass gasification operates at low to high pressures (1-30 bar) and high temperatures ranging from 700-1000 ºC.

2.2.1.2.3 Pyrolysis

Pyrolysis is a method through which hydrogen is produced by thermally decomposing hydrocarbon-based feedstocks, such as natural gas or biomass, without the presence of oxygen. Its flexibility in terms of feedstock selection enables the attainment of substantial hydrogen yields. Additionally, the process allows for the co-production of value-added byproducts, including carbon black or biochar. However, challenges arise, including the emission of carbon unless carbon capture and storage (CCS) technologies are incorporated, substantial energy requirements, and the availability and cost considerations about suitable feedstocks.

2.2.1.2.4 Thermolysis and Thermochemical Cycles

Thermolysis is a process in which hydrogen is extracted from molecules containing it (such as hydrocarbon or water) through the direct application of heat that comes from an external source (concentrated solar energy or nuclear energy) rather than from within the fuel itself.

The most straightforward method for hydrogen production is direct thermolysis of water, which requires temperatures above 2500 ºC. However, due to both its need for a heat source and the stability of materials used, this high temperature makes the process impractical. The solution lies in using thermochemical cycles, which use a series of intermediate reactions that keep the process' temperature below 1000 ºC.

2.2.1.2.5 Electrolytic processes

Water Electrolysis

Electrolysis of water is an electrochemical process that allows for the clean production of hydrogen when its energy source comes from non-polluting sources. The process involves passing an electric current through a solution of water and an electrolyte, which causes the water molecules to break down into hydrogen and oxygen gas. The hydrogen gas is collected at the cathode, while the oxygen gas is collected at the anode.

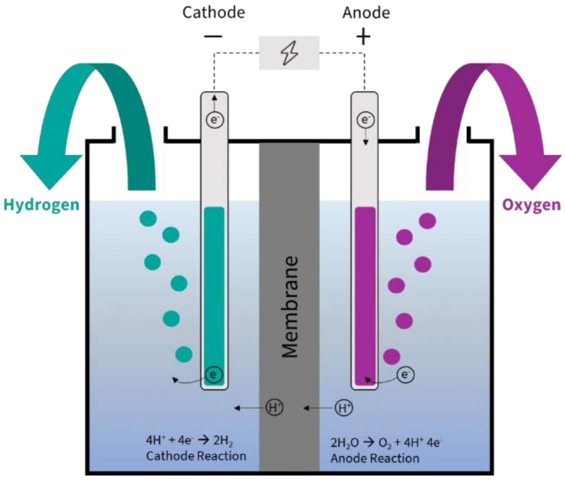


Figure 5. Water Electrolysis for hydrogen production [4]

Electrolysis of water is currently the main pathway for producing hydrogen using renewable resources. Its growing global significance can be attributed to its primary energy source - electricity - for breaking water molecules. Furthermore, modular systems enable easy integration with various forms of renewable production sources and the flexibility to operate under variable conditions. Electrolysis can be conducted at various temperatures depending on the desired result:

- At low temperatures: using alkaline or proton exchange membrane (PEM) electrolysers.
- At elevated temperatures: using solid oxide electrolysers.

Photo Electrolysis:

Photo electrolysis is an innovative approach for the production of hydrogen that utilizes sunlight and specialized semiconducting materials to split water into hydrogen and oxygen. Unlike conventional electrolysis, which requires external electricity, photo electrolysis capitalizes on the intrinsic properties of specialized semiconducting materials, known as photoelectrodes. These materials absorb sunlight and initiate chemical reactions that facilitate water splitting. Through this process, photons from sunlight generate electron-hole pairs, resulting in an electron flow that facilitates the electrolysis of water. The distinctive advantage of photo electrolysis lies in its utilization of abundant solar energy, obviating the need for external electrical power. However, research must continue to enhance efficiency, stability, and cost-effectiveness.

2.2.1.3 COMPARATIVE ANALYSIS AND SECTION OVERVIEW

In summary, hydrogen production encompasses various methods that yield different types of hydrogen, which are classified into distinct colors based on their respective sources. These color classifications provide insights into the production process and can aid in understanding the sustainability and environmental impact associated with each method.

At present, steam methane reforming is the most cost-effective method for hydrogen production in heavy-duty transport. However, this method has high greenhouse gas emissions which make it unsustainable. With the increasing focus on sustainability in transportation, there is an increasing interest in using more eco-friendly methods for hydrogen production, such as electrolysis or biomass gasification. These methods have the potential for greater sustainability but are currently more expensive than steam methane reforming. When selecting a hydrogen production method for heavy-duty transportation, factors like cost, sustainability and resources must be taken into consideration.

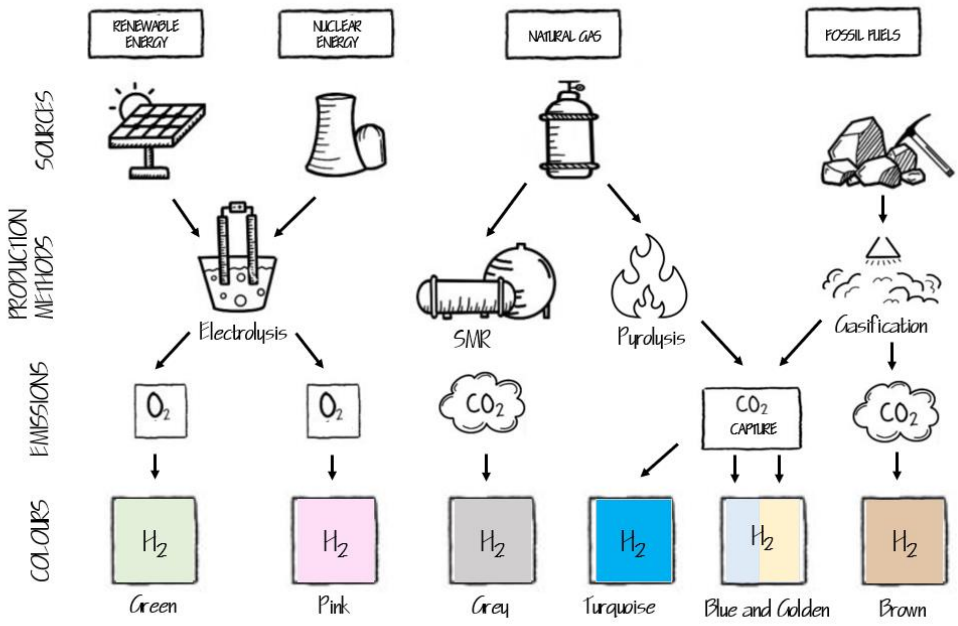


Figure 6. Hydrogen Production Methods and Colors [Self-elaborated]

The following table presents a comparative analysis of the production methods described above.

Production Method	Level of Maturity	CO_2 emissions	Efficiency (%)	Cost (€/kg)
SRM	Mature	High	70 - 80	1.5 - 2
POX	Mature	High	60 - 70	1.5 - 2
ATR	Mature	Medium	70 - 80	1.5 - 2
Pyrolysis	Emerging	Low	30 - 40	4 - 6
Biomass Gasification	Emerging	Low	30 - 40	4 - 6
Thermolysis	Emerging	Low	20 - 30	5 - 8
Water Electrolysis	Mature	Zero	70 - 80	5 - 6
Photo electrolysis	Emerging	Zero	10 - 20	10 - 15

Table 1. Comparative analysis of production methods (Self-elaborated, based on [5]

2.2.2 STORAGE

The storage of hydrogen is a critical aspect of harnessing its potential as a clean and sustainable energy source. The low energy density of hydrogen requires large volumes to be stored to meet energy demands effectively. Additionally, hydrogen's small molecular size enables it to permeate through certain materials, demanding specialized storage containers and pipelines to prevent unwanted leakage. Safety considerations are paramount, given hydrogen's highly flammable nature, requiring strict adherence to safety protocols and infrastructure design. Taking into consideration the aforementioned factors, there are several options for hydrogen storage currently.

- **Compressed hydrogen storage** involves compressing the gas to high pressures, typically above 100-200 bars. This technique increases its energy density, facilitating its storage and transportation. Compressed hydrogen can be transported through pipelines at a low cost. However, one of the challenges it presents is the need for high-pressure storage vessels, which must be carefully designed, constructed, and maintained to ensure safety. Additionally, when used in vehicles these increase both cost and weight.

- **Liquid hydrogen storage** entails liquefying the gas at cryogenic temperatures around -253 °C. Liquid hydrogen has approximately ten times the energy density of hydrogen compressed at 100 bars. This allows for more efficient storage and transportation, especially for large quantities of hydrogen. However, the liquefaction of hydrogen is a complex and energetically costly process. Additionally, cryogenic systems and vacuum techniques are required to maintain low temperatures and prevent losses.

- **Hydrogen carriers**, such as ammonia (NH3) and methane (CH4), provide an alternative for hydrogen storage and transportation. These molecules possess higher energy densities and may be easier to handle and transport than pure hydrogen. Ammonia and methane can make use of existing infrastructure, including tanks and pipelines, which facilitates their implementation. However, it is important to consider the NOx emissions associated with ammonia use and the long-term availability of methane.

Transporting compressed hydrogen as a gas through pipelines is the most cost-effective choice for distances of up to approximately 1,500 km. However, for longer distances, alternative methods like transmission as ammonia or LOHC (Liquid Organic Hydrogen Carriers) may prove more economically viable, particularly when moving hydrogen overseas, despite the conversion costs associated with the process. When it comes to local distribution, pipelines are a cost-effective solution for efficiently distributing large volumes of hydrogen over extended distances. Conversely, for shorter distances or lower volumes, trucks are likely to be the more economical option.

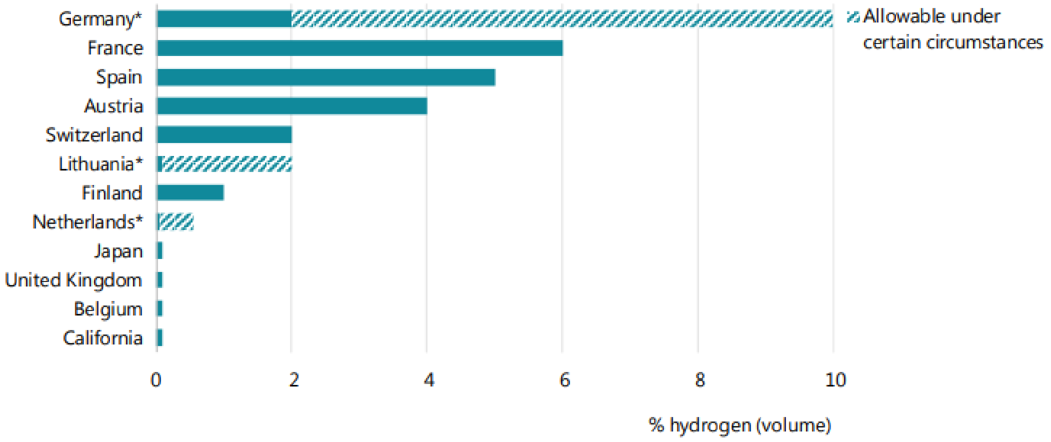
2.2.3 TRANSPORT AND DISTRIBUTION

Transportation also poses a challenge in the hydrogen value chain, due to the element's intrinsic properties described in previous sections. The main distribution options are pipeline distribution and truck transportation which operate with both compressed hydrogen gas and liquid hydrogen. Liquid-phase hydrogen transportation provides significant advantages, particularly for intercontinental transport, due to its capacity for carrying much larger quantities. Hydrogen transporting trucks, for instance, can transport up to four times more hydrogen in liquid form compared to the gaseous phase. Nevertheless, the whole value chain has to be taken into consideration since the liquefaction of hydrogen has substantial costs.

- **Transportation by road involves the use of trucks**, which carry tanks operating at high pressures ranging from 200 to 700 bar. However, this method is suitable primarily when the hydrogen source and destination are nearby. A notable drawback is the need to transport small quantities of hydrogen at high pressures, which poses potential safety hazards.

- **Pipeline distribution** offers the option of blending the natural gas pipeline network with hydrogen transportation or using dedicated pipelines for hydrogen transport. It proves cost-effective for long distances, up to approximately 5000 km, with estimated costs ranging from 0.1 to 0.17 €/kg H_2/1000 km. Hydrogen pipelines connect major production and consumption points, ensuring efficient delivery of compressed hydrogen and reducing overall costs.

Ensuring harmonized blend limits for natural gas on an international level is vital to facilitate the widespread adoption of hydrogen blending. It is crucial to develop standards that accommodate potential variations in hydrogen blending levels over time. Currently, national regulations for gas quality are typically determined by the elements in the gas value chain that have the lowest tolerance for blending. In many regions, the maximum allowable blending is set at 2%, while a few areas allow for blending levels between 4% and 6% (as illustrated in Figure 7) [6].



* Higher limit for Germany applies if there are no CNG filling stations connected to the network; higher limit for the Netherlands applies to high-calorific gas; higher limit for Lithuania applies when pipeline pressure is greater than 16 bar pressure.

Sources: Dolci et al. (2019), "Incentives and legal barriers for Power-to-Hydrogen pathways: An international snapshot", *International Journal of Hydrogen*; HyLaw (n.d.), *Online Database*; Staffell et al. (2019) "The role of hydrogen and fuel cells in the global energy system", *Energy and Environmental Science*.

Figure 7. Current limits on hydrogen blending in natural gas networks [6].

2.2.4 FINAL APPLICATIONS: FUEL CELL TECHNOLOGY

Fuel cell technology is a final use of hydrogen and is the key for H_2 batteries. It offers a clean and efficient alternative to traditional combustion engines for powering vehicles. Fuel cells produce electricity through an electrochemical reaction between hydrogen and oxygen, with water vapor as the only by-product. This means they produce zero emissions, making them ideal for cutting greenhouse gas emissions and improving air quality.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{electrical energy}$$

Equation 3. Fuel-cell chemical reaction

Fuel cells come in many varieties, but the proton exchange membrane (PEM) fuel cell is the most popular for transportation applications. PEM fuel cells consist of an anode and cathode separated by a proton exchange membrane with hydrogen supplied to the anode and oxygen supplied to the cathode. At the anode, hydrogen is split into protons and electrons; protons pass through the membrane while electrons generate an electric current which powers the vehicle.

One major benefit of fuel cell technology is its high efficiency. Fuel cells can convert up to 60% of hydrogen energy into usable electricity, compared to only 20% efficiency for gasoline engines. This enables vehicles with longer driving ranges and faster refueling times than battery electric counterparts.

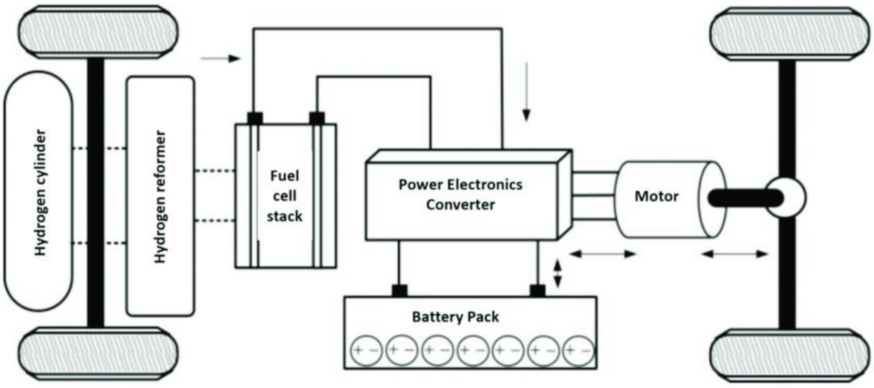


Figure 8. Fuel Cell Vehicle [7]

However, there are still challenges to be overcome in terms of the cost and availability of fuel cell technology. Fuel cells are currently more expensive than traditional combustion engines and batteries, although costs are expected to decrease as production scales up and technology improves. Additionally, hydrogen fueling infrastructure is still limited, particularly for heavy-duty vehicles that require larger amounts of hydrogen. Hence the scope of this project is to provide an overview hydrogen refueling network based on the current and forecasted demand.

Despite these challenges, as technology improves and costs decrease, fuel cell vehicles are expected to become an increasingly important part of a sustainable and low-carbon transportation system.

2.3 HYDROGEN REFUELING STATIONS

A hydrogen refueling station (HRS) is a facility designed to provide hydrogen gas for refueling hydrogen-powered vehicles. HRSs play a critical role in enabling the adoption and use of hydrogen fuel cell vehicles. They involve various components working together in synergy to release hydrogen fuel. Proper sizing and selection of components are crucial to ensure efficient and safe operations.

2.3.1 TYPES OF REFUELING STATIONS

In terms of hydrogen production:

- **Onsite Production:** These stations generate hydrogen on-site using methods such as the previously studied. It allows for better control over hydrogen supply and can be tailored to specific demands at the cost of requiring a significantly bigger initial investment.
- **Offsite Production:** In this type, hydrogen is produced at a centralized location and transported to the refueling station. Offsite production requires a reliable supply chain for hydrogen delivery, which involves transportation via trucks or pipelines.

In terms of operation pressure:

- **350 bar** stations are designed to dispense hydrogen at a 350-bar pressure into the vehicle's tank. Mainly used for heavy-duty vehicles where storage space is not a concern.

- **700 bar** stations are designed to dispense hydrogen at 700 bar pressure into the vehicle's tank. Compressing hydrogen to a higher pressure reduces the need for more storage space making this option the better one for light vehicles. However, the technical requirements are significantly complex compared to 350 bar stations to ensure safety.

In terms of storage systems:

- **Back-to-back systems** are design configurations that cater for the continuous refueling of multiple vehicles in quick succession, often seen in scenarios like refueling a fleet of buses. This design requires larger storage tanks and higher capacity equipment to meet the increased demand for hydrogen during a concentrated period, with the subsequent increase in cost.
- **Without back-to-back** the refueling operations are designed to cater to vehicles' needs throughout the day rather than focusing on continuous, consecutive refueling of multiple vehicles. These stations are typically designed to handle a steady flow of vehicles with intermittent refueling requirements; thus, storage tanks are dimensioned accordingly.

Dimensioning and ratio are of utmost importance in the context of hydrogen refueling stations (HRS). Sizing the stations and selecting the appropriate type considering the requirements demanded from the fuel cell industry, is essential for ensuring profitability and the deployment of an efficient network. For instance, for bus refueling stations, profitability can be achieved without subsidies when there is a significant number of trucks involved. These are self-sustaining HRSs without hydrogen generation. However, when an electrolyzer is included, its cost matches that of the HRS itself. Hence, highlighting the importance of sizing stations aligned with the industry's demand, not incurring unnecessary costs.

2.3.2 COMPONENTS OF A REFUELING STATION:

A hydrogen refueling station (HRS) comprises various essential components that work together to enable the efficient storage and dispensing of hydrogen gas for refueling hydrogen-powered vehicles. When considering compressed hydrogen:

A. Hydrogen Generation or Distribution: When considering a station with onsite production, this component involves the production of hydrogen gas. On the other hand, it considers the arrival of gaseous hydrogen or liquid hydrogen, via trucks or pipelines.

B. Compression: The generated hydrogen gas is compressed to increase its density and facilitate efficient storage. Compression is achieved using hydrogen compressors capable of reaching high pressures.

C. Cascade Storage: Compressed hydrogen is stored in high-pressure storage tanks. Cascade storage is a method of storing compressed hydrogen, at different pressure levels using a series of interconnected storage vessels. Each stage operates at a lower pressure than the previous stage, typically determined by the pressure differential required for efficient and controlled transfer between stages, which is based on pressure equalization. Cascade storage offers several advantages:

- It optimizes pressure levels to match the specific requirements of different vehicles, eliminating the need for extensive pressure regulation and enabling efficient fuelling.
- Maximizes space utilization by utilizing multiple pressure stages, reducing the reliance on large, single-pressure storage tanks.
- Enhances safety and reliability by containing hydrogen within affected stages in case of leaks or failures, ensuring the overall integrity of the storage system.
- Provides a cost-effective solution by utilizing lower-cost storage tanks operating at lower pressure levels, reducing infrastructure expenses compared to a single high-pressure storage system.

The type of tanks used depends on factors such as pressure requirements, safety regulations, and station design. Common tank types include Type I, Type II, Type III, and Type IV, each with specific characteristics and construction materials.

i. Type I: Typically made of steel, thus the heaviest among the four types. They rely on the strength of the material to contain hydrogen gas at high pressures. These tanks are commonly used for stationary storage applications and are known for their robustness and durability.

ii. Type II: These tanks have a metal liner, usually made of steel, covered with a composite material, such as fiberglass or carbon fiber. The composite material provides additional strength and helps reduce the overall weight of the tank. Mainly used in HRS due to their favorable strength-to-weight ratio.

iii. Type III: They feature a composite liner wrapped with high-strength carbon fiber over a metal liner. The composite material provides both strength and stiffness, while the metal liner offers additional gas containment properties while ensuring lightweight, making them suitable for applications where weight reduction is a priority.

iv. Type IV: Type IV storage tanks are entirely constructed of lightweight composite materials, such as carbon fiber-reinforced polymers. These tanks offer the highest strength-to-weight ratio among the four types. The composite structure provides exceptional gas containment properties while minimizing weight, making them the better option for hydrogen fuel cell vehicles due to their lightweight nature, contributing to improved vehicle efficiency.

D. Dispenser: The dispenser unit is responsible for delivering hydrogen gas to vehicles. It regulates pressure, initiates, and halts the fueling process, and provides a secure connection between the refueling station and the vehicle's filling point, through verified valves.

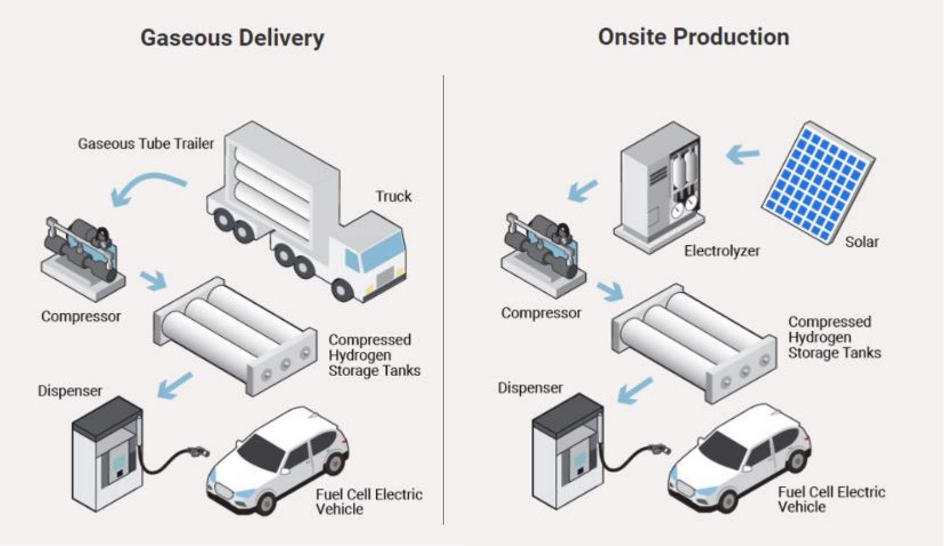


Figure 9. Hydrogen Refueling Station Components [8]

Hydrogen refueling stations (HRS) for compressed hydrogen differ from those intended for liquid hydrogen due to the distinct physical properties and storage requirements of the two forms. Compressed hydrogen stations primarily focus on high-pressure storage and compression technologies to accommodate the gaseous nature of hydrogen. They feature specialized compressors, high-pressure storage tanks, and cascading systems to ensure efficient gas storage and delivery. In contrast, HRS for liquid hydrogen incorporate cryogenic storage tanks that maintain extremely low temperatures to store hydrogen in its liquid state, and the handling and transfer of liquid hydrogen require specific equipment (chiller) and safety protocols.

- **Cryogenic Storage tank:** The cryogenic tank in a HRS for liquid hydrogen plays a critical role in ensuring the availability and controlled dispensing. The tank's function is to maintain the liquid hydrogen in a stable state, preventing it from evaporating or boiling off while minimizing losses due to heat ingress, and maintaining the temperature of the liquid at -253 ºC.

- **Chiller:** Both during compression and expansion, hydrogen experiences a significant temperature increase. Without the chiller, the temperature of the hydrogen inside the tank could exceed 65ºC, potentially causing damage. Particularly in high-pressure systems operating at 700 bar, without the chiller, the hydrogen would reach excessively high temperatures, posing a risk of tank rupture. The chiller's function in a hydrogen refueling station (HRS) for liquid hydrogen is to cool the hydrogen to approximately -40ºC (as per regulations) before introducing it into the vehicle. This is done to mitigate the abrupt temperature change and prevent damage to the vehicle's hydrogen tank.

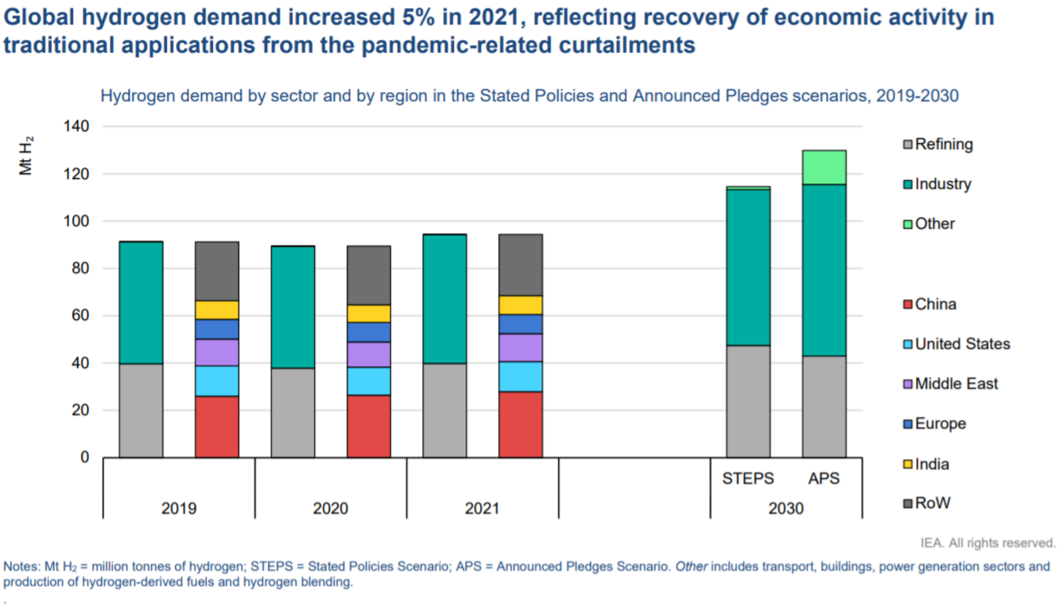
The use of liquid hydrogen in a cryogenic state requires energy expenditure during liquefaction and generation. However, it offers cost savings and significantly facilitates the subsequent value chain. Despite HRS operating with liquid hydrogen being more compact and occupies less space, they must address the challenge with liquid hydrogen's boil-off, where liquefied and cryogenic gases tend to vaporize and release, thus requiring a continuous consumption system. Therefore, the utilization of liquid hydrogen in hydrogen refueling stations is not a viable option. However, it holds promise for future implementation, particularly when a substantial number of fuel cell vehicles (FCVs) are present, and continuous consumption can be assured.

Considering all of the above, the current market situation and the scope of this project (heavy-duty vehicles) the model considers refueling stations with offsite production and without a back-to-back system, dispensing compressed gaseous hydrogen at 350 bars for its current viability and cost-efficiency.

2.4 SECTOR OVERVIEW

2.4.1 HYDROGEN DEMAND

According to current policies and procedures, it is projected that hydrogen demand could reach 115 million tons by 2030. The majority of this demand is driven by its traditional usage in refining and industry. However, there has been a significant increase in emerging applications, which witnessed a growth of 60% from 2020 totaling around 40 thousand tons. To meet existing climate targets, governments around the world must create 130 million tons of hydrogen by 2030, with 25% coming from new applications, followed by roughly 200 million tons by 2030 to achieve net zero emissions by 2050 [9].


Global hydrogen demand increased 5% in 2021, reflecting recovery of economic activity in traditional applications from the pandemic-related curtailments

Hydrogen demand by sector and by region in the Stated Policies and Announced Pledges scenarios, 2019-2030

IEA. All rights reserved.

Notes: Mt H_2 = million tonnes of hydrogen; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. *Other* includes transport, buildings, power generation sectors and production of hydrogen-derived fuels and hydrogen blending.

Figure 10. Global hydrogen demand [9]

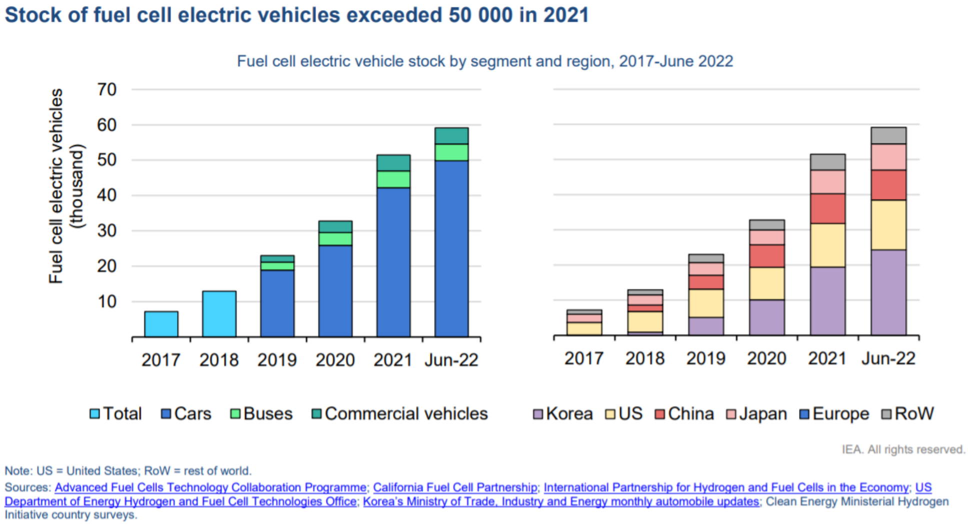
In 2021, plants employing fossil fuels with carbon capture, utilization, and storage (CCUS) produced less than 1 million tons of low-emission hydrogen. Even though the number of projects for manufacturing low-emission hydrogen is fast increasing, governments must enact ambitious regulations to meet their climate obligations and dramatically reduce their use of natural gas, coal, and oil by 2030 [5].

Heavy industrial, heavy-duty road transport, and shipping, according to IEA estimates, offer the biggest potential savings in fossil fuel consumption and emissions. In terms of hydrogen transportation, one of the most promising opportunities is repurposing natural gas pipelines for hydrogen transmission. According to estimates, it can cut investment costs by 50-80% when compared to building new pipelines [10]. Another alternative being explored currently is blending natural gas with hydrogen to benefit from the available infrastructure, but practical experience is limited, and extensive reconfiguration and adaption will be necessary.

2.4.2 HYDROGEN IN TRANSPORT

In 2021, global demand for hydrogen in transport reached 30 kt, a 60% increase over 2020. This, however, accounts for only 0.03% of overall hydrogen demand and 0.003% of total transportation energy use [9]. Road vehicles, including heavy-duty trucks and buses, were the dominant source of hydrogen demand in transportation; their numbers climbed dramatically in 2021, with commercial vehicle estimates exceeding those from buses for the first time.

In 2021, the global stock of fuel cell electric cars (FCEVs) hit 51,000 units, with Korea nearly doubling their existing stock with over 9,200 new units added. China leads the globe in hydrogen utilization for heavy-duty vehicle transportation, accounting for more than 85% of all fuel-cell buses and 95% of all fuel-cell trucks. Policies such as California's Advanced Clean Truck legislation and the Global Memorandum of Understanding on Zero Emission Medium- and Heavy-Duty Vehicles, on the other hand, are putting pressure on truck manufacturers to expand their supply of zero-emission trucks. H2Accelerate was launched in Europe as an initiative to enable the use of hydrogen in long-haul heavy-duty trucking across the continent [9].


Stock of fuel cell electric vehicles exceeded 50 000 in 2021

Fuel cell electric vehicle stock by segment and region, 2017-June 2022

IEA. All rights reserved.

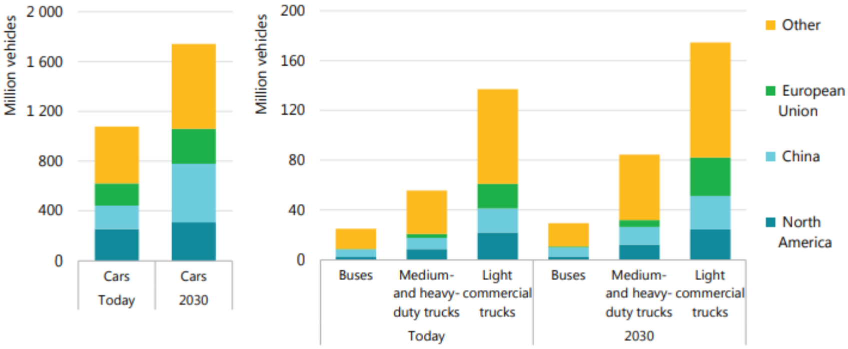
Note: US = United States; RoW = rest of world.

Sources: Advanced Fuel Cells Technology Collaboration Programme; California Fuel Cell Partnership; International Partnership for Hydrogen and Fuel Cells in the Economy; US Department of Energy Hydrogen and Fuel Cell Technologies Office; Korea's Ministry of Trade, Industry and Energy monthly automobile updates; Clean Energy Ministerial Hydrogen Initiative country surveys.

Figure 11. The stock of fuel-cell electric vehicles [9]

Although demand for hydrogen in transportation is now low, it is predicted to skyrocket in the future years as countries attempt to decarbonize and reduce emissions in the transportation sector. To illustrate the scale of this market, if all the 1 billion cars, 190 million trucks, and 25 million buses currently in use worldwide were replaced with Fuel Cell Electric Vehicles (FCEVs), the demand for hydrogen would reach up to 300 MtH2/yr. This amount is more than four times the current global demand for pure hydrogen (as shown in Figure 12).

Looking ahead to the next decade until 2030, without significant efforts to meet the Paris Agreement goals, the demand for oil in road transport is projected to increase by 10% [6]. This growth would primarily be driven by the demand for trucks in emerging economies and the increasing number of cars owned globally. Especially, being the heavy vehicle sector, a difficult sector to tackle in terms of decarbonization, where hydrogen is emerging as one of the best alternatives. Overall, the increasing demand for hydrogen represents an exciting opportunity for the hydrogen industry, as it plays a critical part in the transition to a low-carbon economy.



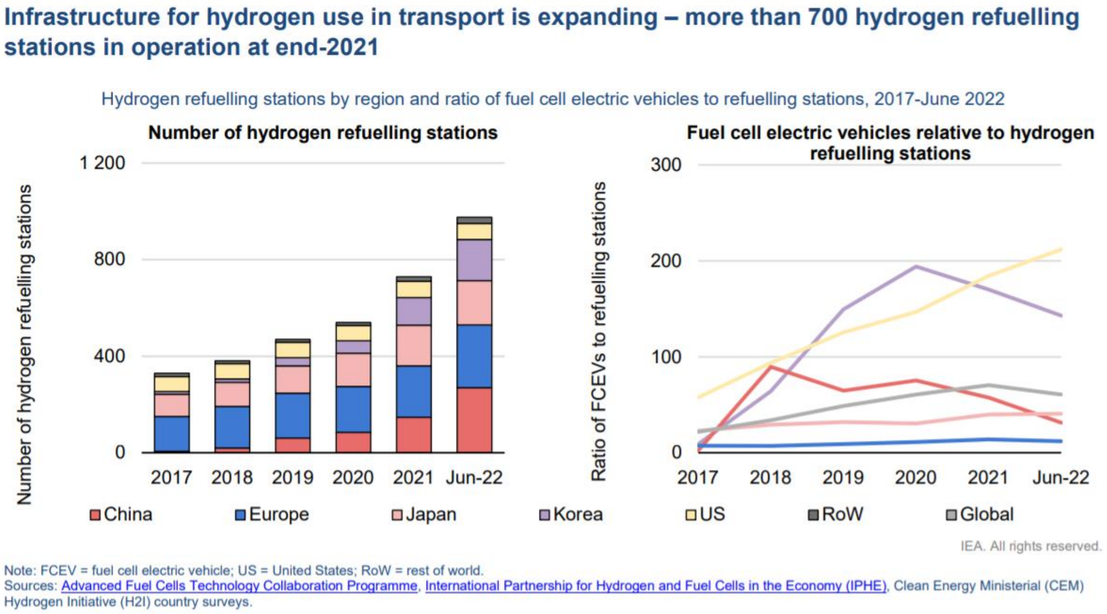
Source: IEA 2019. All rights reserved.

Figure 12. Road vehicle fleet growth to 2030 under current trends [6]

Although there have been substantial cost reductions in fuel cell technology over the past decade, its high cost and limited production volumes remain as challenges. The potential for cost reduction in on-board storage tanks is expected to be slower compared to fuel cells. Hydrogen storage for fuel cell electric vehicles (FCEVs) involves expensive composite materials and high-pressure compression (350-700 bar). It is currently established as an expensive technology but has the potential of experiencing a significant cost reduction through the scaling of production and future innovation in the technology. Nevertheless, attaining these cost reductions must consider the challenge of simultaneously enhancing fuel cell performance and durability [6].

2.4.3 REFUELING STATION NETWORK

There were 975 hydrogen refueling stations (HRSs) globally as of June 2022, with the bulk of them equipped to distribute hydrogen at 700 bar for passenger light-duty cars [10]. However, as the use of hydrogen trucks grows, there is a demand for refueling stations that can dispense hydrogen at quicker flow rates than present light-duty vehicle refueling stations. To fulfil this need, both the government and industry are attempting to create high-throughput heavy-duty hydrogen refueling methods and protocols.


Infrastructure for hydrogen use in transport is expanding – more than 700 hydrogen refuelling stations in operation at end-2021

Hydrogen refuelling stations by region and ratio of fuel cell electric vehicles to refuelling stations, 2017-June 2022

Note: FCEV = fuel cell electric vehicle; US = United States; RoW = rest of world.
Sources: Advanced Fuel Cells Technology Collaboration Programme, International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Clean Energy Ministerial (CEM) Hydrogen Initiative (H2I) country surveys.

Figure 13. Refueling stations network [9].

Despite the rapid growth of HRSs, the ratio of fuel cell electric vehicles (FCEVs) per HRS differs by country, as shown in Figure 13. In terms of the infrastructure required based on future forecasts, the European Partnership claims the need for a rapid expansion, giving the pressing need to follow through the road to net zero. By 2030, Europe would need to install approximately 52 million charging points and nearly 5,000 Hydrogen Refueling Stations (HRS) to support the increasing number of xEVs[1] on the roads. This is a substantial increase compared to the current infrastructure, which consists of around 270,000 chargers and approximately 200 HRS. Looking ahead to 2050, the future landscape of road transportation becomes more uncertain, especially concerning the roles that BEVs and FCEVs will play in the overall ecosystem.

Whilst electric vehicles remain the primary alternative to fossil fuels, hydrogen powered vehicles are gaining importance and already represent 5% of the market forecasts for 2030 (Figure 14). Nevertheless, despite their potential, there are still challenges to overcome [11].

1. Lack of awareness among government authorities responsible for granting permits, as they often apply restrictions and regulations more suited to significantly larger industrial chemical plants. Authorities need to familiarize themselves with the specific requirements of hydrogen refueling stations.

2. The complexity of the filling standard at 700 bar makes it challenging to homologate and maintain compliance, with various parameters requiring constant review. Moreover, frequent technological advancements may cause the standard to become outdated.

3. Stringent and inflexible restrictions pose challenges to the long-term viability and adaptability of hydrogen refueling stations.

4. The high costs of the industry. However, cost reduction will come with technical innovation and advancements in the design of compressors, the improvement of storage systems and the presence of economies of scale.

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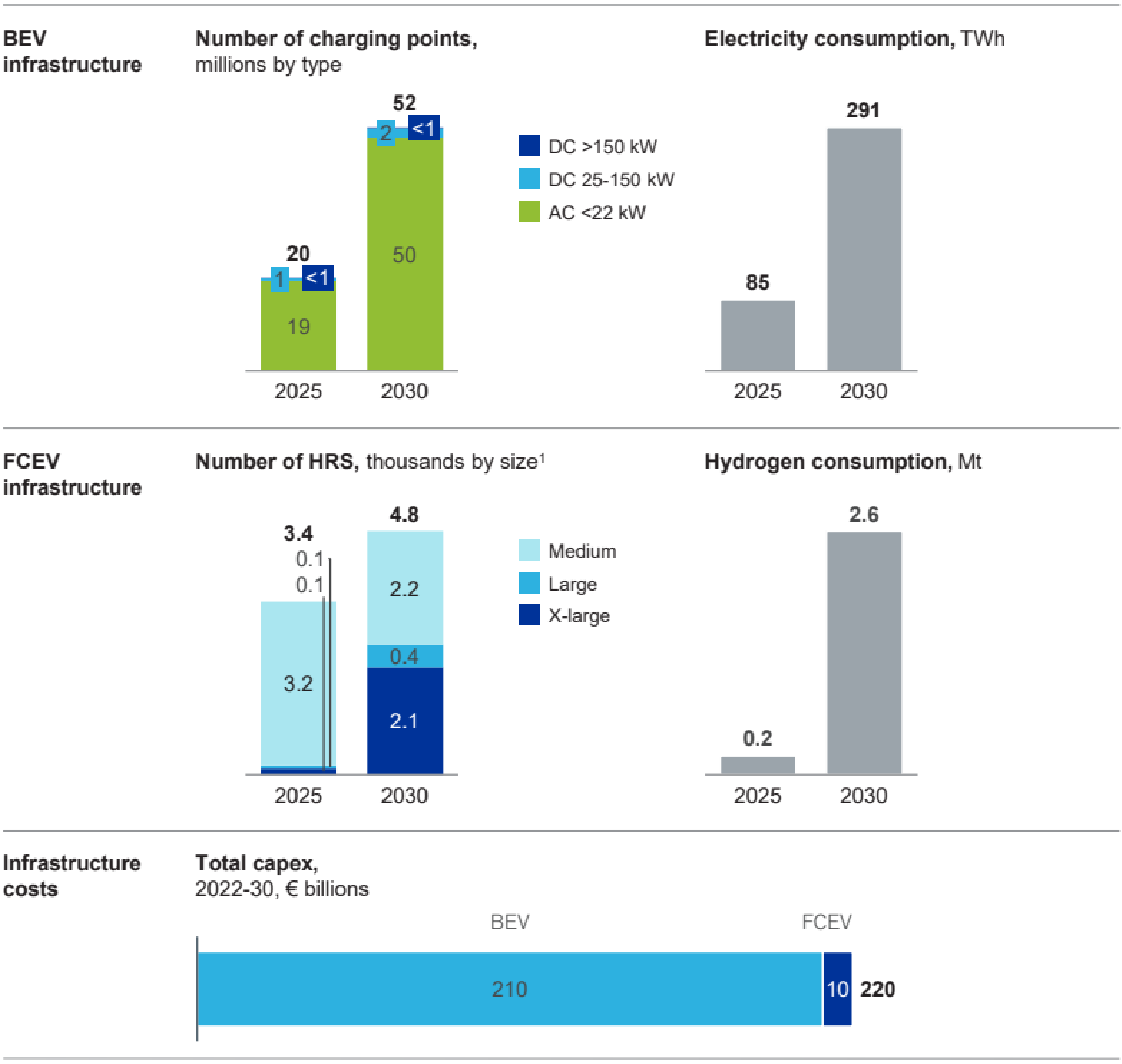
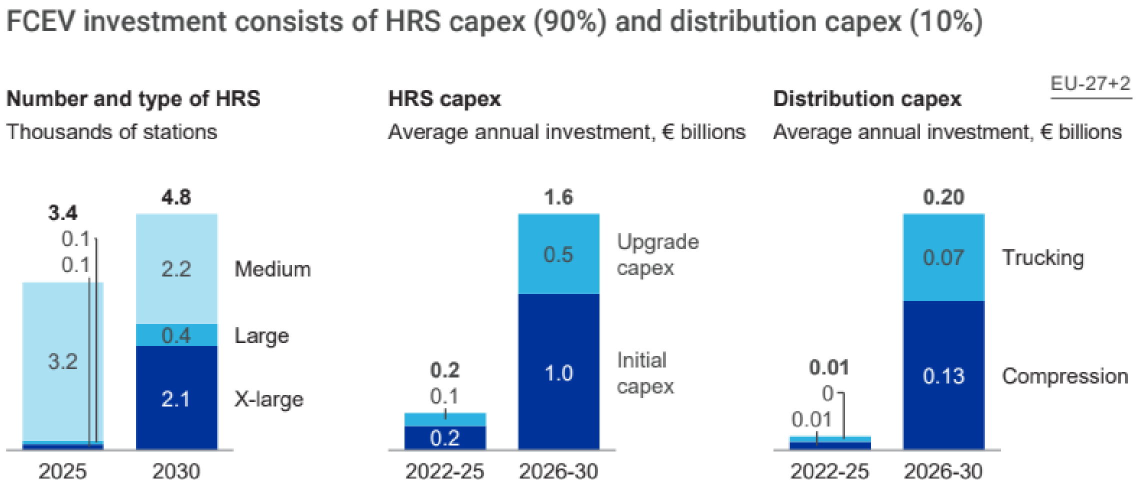
[1] FCEVs, BEVs and PHEVs



[1] Medium station = 480 kg/day capacity; large station = 1,000 kg/day capacity; x-large = 4,000 kg/day capacity.

Source: McKinsey Center for Future Mobility

Figure 14. BEVs and FCEVs infrastructure deployment [12]


FCEV investment consists of HRS capex (90%) and distribution capex (10%)

Note: The cost of hydrogen dispensed by HRS varies depending on the country it is built in, the pressure it operates at, and the efficiency of station technology. Small HRS in the EU are estimated to dispense hydrogen at a cost of between €3 to €5 in 2030 and €3 to €4 per kilogram in 2050, medium HRS at a cost of between €3 to €5 in 2030 and €2 to €3 in 2050, large HRS at a cost of between €3 to €5 in 2030 and €2 to €3 in 2050, and extra-large HRS at a cost of between €3 to €4 in 2030 and €2 t0 €3 in 2050. Converted from dollars (exchange rate €1.18/$1.00).

Source: McKinsey Center for Future Mobility; McKinsey Hydrogen Insights FCEV infrastructure model; McKinsey Hydrogen Insights hydrogen demand model

Figure 15. FCEV infrastructure and investment forecast to 2030 [12].

2.4.4 SITUATION IN SPAIN

An assessment of the market share of zero emissions vehicles reveals a significant surge in recent years, with projections indicating continued growth in the future. Europe has outpaced the United States in this domain, showcasing its leading position in the global market. As one of Europe's primary influential nations, Spain holds a crucial role that, if effectively harnessed, could elevate the country as a frontrunner in renewable energy utilization, given its abundant resources and potential for further advancement.

Hydrogen emerges as a substantial catalyst for Spain's economic and technological advancement. It assumes a strategic role in the energy transition towards achieving climate neutrality, facilitating enhanced integration of Renewable Energy Resources (EERR) within the energy landscape. The versatility of hydrogen extends across multiple sectors, rendering it instrumental in decarbonizing transportation, industry, electricity generation, and buildings. This pivotal function drives sector coupling and fosters circular economy practices. Spain's strategic geographical positioning confers immense potential for renewable hydrogen production, ensuring both domestic sufficiency and opportunities for exporting renewable hydrogen [14].

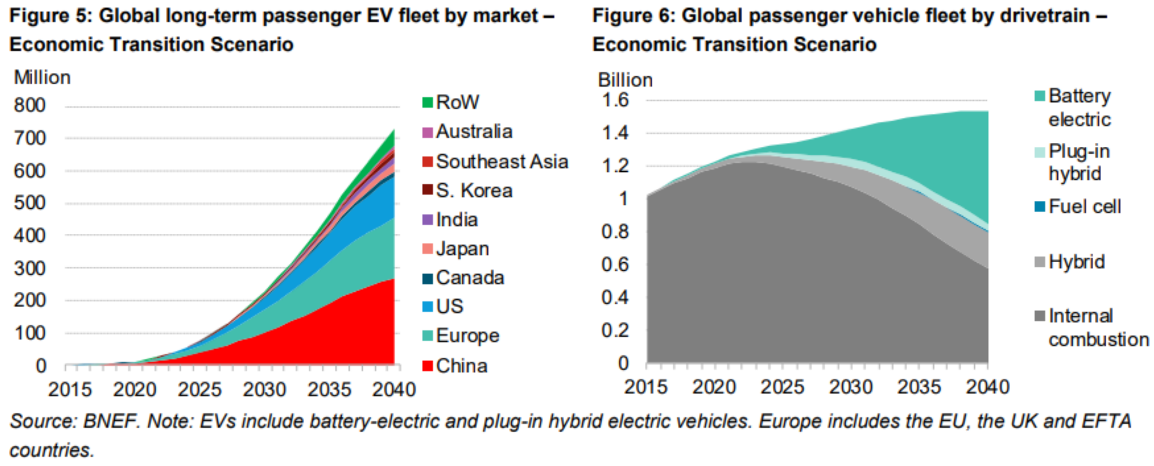


Figure 5: Global long-term passenger EV fleet by market – Economic Transition Scenario

Figure 6: Global passenger vehicle fleet by drivetrain – Economic Transition Scenario

Source: BNEF. Note: EVs include battery-electric and plug-in hybrid electric vehicles. Europe includes the EU, the UK and EFTA countries.

Figure 16. EV Market Share Overview [13]

The Spanish government has committed EUR1.5 billion in hydrogen technology investment over the next decade, to build a domestic supply chain and growing hydrogen use in industry, transportation, and power generation [15]. Furthermore, Spain is a member of the European Clean Hydrogen Alliance, which aims to establish a globally competitive hydrogen economy across Europe.

In Spain, the transportation sector, particularly fuel cell electric vehicles (FCEVs), drives hydrogen consumption. Spain had 10 hydrogen refueling stations (HRSs) active as of June 2022, with intentions to increase this number to 40 by 2023 and 150 FCEVs on the road in 2020, with ambitions to expand that number to 5,000 by 2030 [16]. The Spanish government has undertaken a variety of strategies to encourage FCEV adoption, including tax breaks, subsidies for HRS implementation, and public procurement programs. Within them, it has created a Hydrogen Roadmap, a strategic strategy to promote and support the use of hydrogen as an efficient and renewable energy source. Its goal, announced in September 2020, is to attain 4 GW of manufacturing capacity by 2030, which is expected to generate 50,000 jobs and attract 8.9 billion euros in investment.

The roadmap emphasizes four important areas for hydrogen sector development: production, transportation, storage, and usage. It aims to promote a whole hydrogen value chain from manufacturing to consumption, with a particular emphasis on transportation. To that end, it aims to have at least 150 hydrogen refueling stations by 2030, with a focus on heavy-duty vehicles. As a comparison, Spain has the target of achieving a stock of 2.7 million to 3.6 million electric vehicles by 2030, representing 50% to 70% of all passenger car sales during that time, and an estimated 205,000 to 263,000 charging stations [17].

To achieve these goals, the Spanish government has launched several measures and incentives to encourage development in the hydrogen sector. These include R&D funding, tax benefits for corporations investing in hydrogen, and legislative reforms to stimulate its usage in transportation applications. Furthermore, they developed The Hydrogen Platform, a public-private partnership, to coordinate efforts and stimulate growth in this industry.

Overall, the Hydrogen Roadmap marks a significant commitment by the Spanish government to foster the growth of the hydrogen economy in Spain, notably in transportation. If executed successfully, this plan has the potential to generate significant economic and environmental benefits while also increasing Spain's energy security and competitiveness.

Figure 17. Hydrogen Roadmap in Spain [16]

Chapter 3. OPTIMIZATION MODEL

A prominent impediment hindering the advancement of fuel cell vehicles lies in the scarcity of accessible hydrogen refueling infrastructure. For this purpose, an optimization model has been developed aiming to serve as a basis for the analysis of the deployment of a hydrogen network on the main Spanish roads. It seeks to offer effective solutions and establish the necessary groundwork to effectively accommodate the forthcoming growth and expansion of hydrogen-related initiatives.

The model uses a forecast of daily flows of vehicles as inputs to determine the number of hydrogen refueling stations to install and the strategic locations of these, whilst minimizing installation costs. The model is then evaluated in two different scenarios (2030 and 2050), considering fuel cell vehicles penetration ratio increase and the consequent cost reduction due to economies of scale. Subsequently, two additional sub-scenarios are considered by carrying out a sensitivity analysis on the impact of changes in the station's storage capacity or the vehicles technology on the number of stations estimated. The data collected will then serve as a basis to create an overview and provide solutions to the hydrogen industry's evolution in the near future.

The model has been solved using the GAMS (General Algebraic Modelling System), a backend software and optimization package designed for mathematical programming and optimization tasks, by employing mixed integer non-linear programming (MINLP). The model output for each scenario is then collected in an Excel file to analyze the whole and draw the corresponding conclusions.

In line with the established framework, the primary objective is to provide a comprehensive understanding of the model's structure, design, and underlying assumptions laying the foundation for the subsequent analysis of results.

3.1 MODEL DESCRIPTION

The development of the model is focused on determining the installation of a hydrogen refueling station (HRS) network for heavy vehicles. Thus, the model identifies the quantity and location of HRS to be installed in the six main Spanish highways (A1, A2, A3, A4, A5, A6) while minimizing total costs.

The HRS to be installed are intended to serve heavy hydrogen vehicles because of their viability in the near future compared to light vehicles, which will allow for accelerating the return on the investment made. Since the sizing of storage tanks changes depending on the pressure at which the hydrogen must be dispensed, it must also be defined as a primary characteristic, in this case being the stations considered work with 350 bar hydrogen. In addition, the refueling stations considered have the following characteristics, in order to lower costs and improve efficiency.

- HRS without on-site production capacity. Hence, hydrogen transportation to the stations will also have to be considered.
- HRS designed without a back-to-back system, meaning their capacity (kg of hydrogen) is to be dispensed throughout the day, not in a continuous way.

For this preliminary analysis the following simplifications have also been considered. Subsequently, after the successful implementation of the model, incorporating enhancements would not pose any difficulties.

- Only the six main highways are considered (A1, A2, A3, A4, A5, A6)
- No traffic or irregularities in roads are considered.
- Only one model of heavy-duty vehicle, and thus its characteristics, is evaluated as if all vehicles on the road were a fleet based on the same vehicle model (Hyundai XCIENT)
- Distance between HRS has a 0,1% error over the value determined by the model.

3.2 MODEL DESIGN

The design of the model, divided into sets, parameters, variables, constraints, and objective functions, is described below and the source code can be found in Exhibit 1. It aims to determine the optimal number and locations of hydrogen refueling stations (HRS) based on the daily flow of vehicles on the six main roads in Spain (A1, A2, A3, A4, A5, A6). For this purpose, the inputs taken into consideration are the following: the daily flow of fuel cell heavy-duty vehicles, the characteristics of these vehicles, three types of HRS with different capacities (400, 800, 1200 kg of H_2 per day) and the costs associated with each type of HRS.

The model is responsible for determining the optimal number of HRS of each type to be installed on each road, so that the hydrogen refueling demand is satisfied and the total installation costs are minimized. To achieve this, an optimization approach is employed that considers both the refueling needs of the vehicles and the costs involved in the HRS infrastructure.

The outputs yielded bear significant relevance for strategic decision-making in the deployment of a Hydrogen Refueling Station (HRS) network. These outputs encompass the allocation of hydrogen stations of varying types along specific road segments, the spatial distribution between these stations, and the overall installation expenditure. Through the determination of the optimal quantity of HRSs and their strategically chosen locations, the model facilitates the maximization of efficiency and coverage within the hydrogen refueling infrastructure, while simultaneously minimizing the incurred costs.

It is essential to consider that the model is highly flexible, making it a valuable tool for finding solutions. Moreover, it exhibits significant sensitivity to input variations; thus, if these change, i.e., the hydrogen growth predictions either increase or decrease, it allows for straightforward results extraction.

The model is based on the following equations 1 and 2 as principles, where the number of HRS to be installed (equation 6, pg. 14) is proportional to the number of vehicles in the fleet divided by their refueling periodicity and inversely proportional to the capacity of the station. Such capacity is calculated as the maximum kilograms of hydrogen a station can provide, divided by the kilograms needed per vehicle when refueling. The refueling periodicity is calculated through equation 1 as the vehicle's range divided by the kilometers the vehicle travels per day.

- $Refueling\ Periodicity = \frac{Range}{km\ per\ day}$
- $N^{\underline{o}}\ of\ HRS\ to\ install = \frac{\frac{n^{\underline{o}}\ vehicles}{Refueling\ Periodicity}}{\frac{Capacity\ of\ HRS\ in\ KgH2}{KgH2\ per\ refuel}}$

3.2.1 MATHEMATICAL FORMULATION

3.2.1.1 Sets

Sets are used to represent the different elements or categories of the model, allowing for the modeling and analysis of systems with multiple dimensions and relationships. For this model, two sets were defined:

- **Roads, r:** Six main highways in Spain, [A1, A2, A3, A4, A5, A6].
- **HRS, h:** Types of HRS to be installed, [1, 2, 3].

3.2.1.2 Parameters

Parameters are the known values that can be estimated from data, providing the input to the model. The following parameters are defined:

<u>Vehicle's characteristics:</u>

✓ **A**	Vehicle's range [km]
✓ **D**	Average distance to be traveled [km]
✓ **SC**	Vehicle's storage capacity [kg of Hydrogen]

<u>Vehicle's flow to be satisfied:</u>

✓	**F (r)**	Flow of FCV per day in each road r [number of vehicles]

<u>Road characteristics:</u>

✓	**RoadDis (r)**	Road length [km]

<u>HRS characteristics:</u>

✓	**CAP (h)**	Maximum capacity of each HRS type [kg]
✓	**C (h)**	Total cost of each HRS type [Millions of €]

3.2.1.3 Variables

Variables represent quantities that the model seeks to find optimal values for. Therefore, the following have been defined:

- **N(r,h):** This variable represents the number of hydrogen refueling stations (HRS) that should be installed on each road r and of each type h. Its optimal value is determined by the model through equation 5 to satisfy the vehicle demand on each specific road.
- **NDef(r,h):** This is an auxiliary integer variable that represents the final number of HRS stations to be installed on each road r and of each type h. It is used to round the number of HRS stations to be installed on each specific road. It is used to round the number of HRS to the biggest integer value, ensuring a realistic installation.
- **Flow(r,h):** This variable indicates the flow of vehicles that is assigned to each type of HRS on each road. It represents the number of vehicles expected to use each type of hydrogen refueling station on a specific road.
- **DHRS(r):** Represents the distance between hydrogen refueling stations on each road r. Its value is calculated in the model to determine the optimal distance between HRS stations installed on the same road.
- **x(r):** This variable indicates the number of HRS to be installed per road.

- **y(h):** This represents the number of HRS to be installed per type.
- **RP:** Represents the hydrogen refueling periodicity, i.e., the frequency with which vehicles must stop at HRS stations to refuel.
- **AuxRP:** This is an auxiliary integer variable used to approximate the hydrogen refueling periodicity (RP) to the nearest biggest integer, ensuring the realistic planning of vehicle refueling stops.
- **Q(h):** the cost associated with each type of hydrogen refueling station.
- **TotalQ:** This variable represents the total cost of installing hydrogen refueling stations. Its value is obtained by summing the costs associated with each type of HRS station installed.

3.2.1.4 Constraints

To establish constraints and derive relevant variables for future analysis, the model utilizes a comprehensive mixed-integer non-linear programming approach. These constraints play a vital role in shaping the model's behavior and extracting valuable insights.

- **<u>Refueling Periodicity:</u>** This equation calculates the refueling periodicity (RP), which represents the number of refueling stops required for each vehicle during its travel. It ensures that vehicles can complete their journeys without running out of fuel. The RP is determined by dividing the total distance to be traveled (D) by the vehicle's range (A).

$$Refueling\ Periodicity, RP = \frac{Range}{km\ per\ day}$$

Equation 4. Refueling Periodicity

- **<u>Constraint 1:</u>** Equation that rounds up the value of the refueling periodicity (RP) to the nearest highest integer. This ensures the coherence of results where refueling stops are scheduled at appropriate intervals, avoiding fractional refueling stops, and guaranteeing the vehicles technical requirements are met.

$$Final\ Refuelling\ Periodicity, AuxRP = ceil(RP)$$

Equation 5. Final Refueling Periodicity

- **Number of HRS to install:** This equation determines the number of hydrogen refueling stations (HRS) of type h to be installed on road r. It is calculated by multiplying the flow of vehicles assigned to each type of HRS (Flow) on road r by the auxiliary variable (AuxRP) and dividing it by the ratio of the HRS capacity (CAP) to the vehicle storage capacity (SC). It ensures that the number of HRS is sufficient to cater to the vehicle flow and meet the refueling needs.

$$Number\ of\ HRS\ to\ install, N(r,h) = \frac{\frac{nº\ vehicles}{Refueling\ Periodicity}}{\frac{Capacity\ of\ HRS\ in\ KgH2}{KgH2\ per\ refuel}}$$

Equation 6. Number of HRS to install

- **Constraint 2:** This auxiliary equation ensures that the number of HRS (N) to be installed on road r and of each type h is rounded up to the nearest highest integer. It guarantees that partial HRS installations are not considered, as only complete HRS can be installed.

$$Final\ number\ of\ HRS\ to\ install, NDef(r,h) = ceil\ (N(r,h))$$

Equation 7. Final number of HRS

- **Constraint 3:** This constraint ensures that the flow assigned to each type of HRS on road r adds up to the total flow of vehicles (F) on that road. It guarantees that all vehicles are allocated to the corresponding HRS types, avoiding any discrepancies or incomplete assignments.

$$Flow\ of\ vehicles\ in\ road\ r, F(r) = \sum_{h} Flow(r,h)$$

Equation 8. Vehicle flow in road r

- **Number of HRS to be installed in each road:** Determines the total number of HRS to be installed on road r. It is obtained by summing the definite number of HRS (NDef (r,h)) of each type h. It provides a comprehensive count of the HRS installations required on a particular road.

$$x(r) = \sum_{h} NDef\ (r,h)$$

Equation 9. Number of HRS per road

- **Number of HRS to be installed of each type:** Calculates the total number of HRS of each type h. The value is obtained by summing the definite number of HRS (NDef (r, h)) on all roads r. It provides an overall count of the HRS installations required for each type.

$$y(h) = \sum_{r} NDef\ (r,h)$$

Equation 10. Number of HRS per type

- **Distance between HRS:** This equation calculates the distance between HRS on road r. It is obtained by dividing the road length (RoadDis) by the number of HRS (x) installed on that road. Since this is a basic model, traffic density measures are not considered and thus, distance between HRS is determined as equitable and constant. A small positive value (0.001) is added to the denominator to avoid division by zero and ensure a meaningful distance calculation. Such preventive measures result in an error of one meter over the final value of distance (measured in km) determined by the model.

$$Distance\ between\ HRS, DHRS(r) = \frac{Road\ Length(r)}{x(r) + 0{,}001}$$

Equation 11. Distance between stations

- **Cost per HRS Type:** This equation calculates the total cost (Q) of infrastructure deployment for each type of HRS. It is obtained by multiplying the cost per HRS type (C) by the number of HRS per type (y).

$$Cost\ per\ type\ of\ HRS, Q(h) = C(h) \cdot y(h)$$

Equation 12. Cost per type

3.2.1.5 Objective Function

The objective function holds the variable that is optimized by the model, whilst respecting the constraints previously considered. In this case, it is defined as the sum of all costs associated with each HRS type. Hence, it represents the total cost of the HRS network installation providing an overall estimate of the investment required for the infrastructure deployment.

$$Total\ cost, TotalQ = \sum_h Q(h)$$

Equation 13. Total cost

The following diagram shows a visual representation of the model:

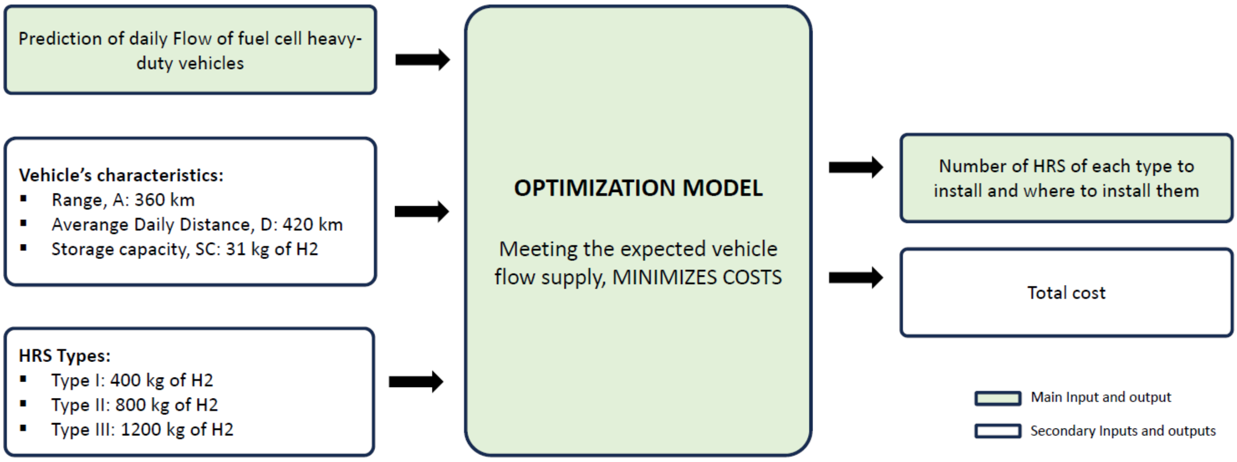


Figure 18. Visual representation of the optimization model [Self-elaborated]

3.2.2 DATA IMPLEMENTATION

3.2.2.1 Vehicle characteristics

The vehicle's parameters have been established based on the technical characteristics of the Hyundai XCIENT Fuel Cell truck [18]. Hyundai's selection over other manufacturers offering fuel cell heavy-duty vehicles is justified by several key factors. Firstly, Hyundai has established itself as a global leader in hydrogen-powered vehicles, demonstrating a long-term commitment to fuel cell technology and investing significantly in research and development in advance their fuel cell stack technology. Additionally, Hyundai possesses extensive experience and a proven track record in the production and commercialization of hydrogen vehicles, having pioneered their development for over a decade. This experience has allowed Hyundai to refine their design, engineering, and manufacturing processes, earning them recognition and credibility in the industry. Lastly, Hyundai's proactive approach includes actively collaborating with governments and industry partners to expand the hydrogen infrastructure network. By establishing strategic partnerships and promoting hydrogen supply chains, Hyundai is helping to build a robust hydrogen infrastructure, which can be advantageous for the successful implementation of hydrogen refueling infrastructure projects. Overall, these factors position Hyundai as a compelling choice for fuel cell heavy-duty vehicles due to their leadership, experience, and commitment to hydrogen technology and infrastructure development.

The parameters used by the model are the following:

Maximum Speed [km/h]	Range, A [km]	Storage capacity [kg of H_2]
85	400	31

Table 2. Technical characteristics of Hyundai XCIENT Fuel Cell truck [18].

The range introduced in the model differs from Hyundai's technical data set by 60 km, considered as a safety factor, as a result of a 15% of the original value.

$$Range, A = 400 \cdot 0{,}85 = 340\ km$$

Equation 14. Range Data

The maximum speed reached by the truck is used as a basis for calculating the average daily distance travelled by each vehicle. According to the law, trucks circulate at a maximum speed of 80km/h on highways and taking into account that the speed will not be constant due to the stops made, an average speed of 50 km/h is considered. Being the working day of a worker is 8 hours, with stops of 15 minutes every 2 hours, a 7-hour workday is considered. Therefore, the average daily distance travelled by each vehicle is calculated as follows:

$$Averange\ daily\ distance, D = 50\ km/h\ \cdot 7\ h = 350\ km$$

Equation 15. Average Daily Distance (D) Data

3.2.2.2 Hydrogen Refueling Station Characteristics

Three types of HRS are considered in the model, each with a different capacity of hydrogen available to refuel vehicles without a back-to-back system (throughout the day).

1. Type I HRS: 400 kg of hydrogen available, capacity of fully refueling 12 vehicles throughout the day, with a cost of 156.667 € per vehicle.
2. Type II HRS: 800 kg of hydrogen available, capacity of fully refueling 25 vehicles throughout the day, with a cost of 110.000 € per vehicle.
3. Type III HRS: 1200 kg of hydrogen available, capacity of fully refueling 38 vehicles throughout the day, with a cost of 63.330 € per vehicle.

The number of vehicles each station can cater is determined with the following equation, being the storage capacity of each vehicle, 31 kg as established previously:

$$Number\ of\ vehicles\ catered = \frac{Capacity\ of\ HRS}{Storage\ capacity\ of\ each\ vehicle}$$

Equation 16. Number of catered vehicles

The selection of specific capacities for each hydrogen refueling station (HRS) is justified by considering the global landscape, current market options, and technological advancements. The chosen capacities consider the evolving needs of hydrogen-powered vehicles, ensuring efficient refueling operations and optimal utilization of resources. This selection of capacities aligns with the advancements being made in fuel cell technology, such as improved fuel cell efficiency and extended driving ranges. These developments indicate a growing demand for higher-capacity HRSs to support longer journeys and faster refueling times. The costs incurred by each type of station were taken from an interview to Rafael Calvera, Vice President of the Calvera Group, one of the companies currently at the forefront of the hydrogen sector [11]. As the station's capacity increases, a notable trend is observed wherein the cost per vehicle decreases, despite the overall cost witnessing an increment.

3.2.2.3 Road Characteristics

To calculate the distance between stations, the road length is an essential parameter. Thus, according to Spanish General Traffic Management ('Dirección General de Tráfico, DGT') [19]:

	A1	A2	A3	A4	A5	A6
Road Length [km]	371	504	355	660	408	590

Table 3. Road Length in km of the six main Spanish highways [19]

3.2.2.4 Forecast of daily flow of fuel cell heavy-duty vehicles

The prediction of the daily flow of fuel cell heavy-duty vehicles is based on the estimation of the ratio of hydrogen-powered heavy-duty vehicles to the total number of vehicles.

This penetration ratio is applied to the Average Daily Traffic (ADT) for heavy-duty vehicles, which measures the daily flow of heavy-duty vehicles. The ADT is derived from the data collected by the primary and secondary traffic monitoring stations installed along each of the six main roads [19]. By aggregating the vehicle counts recorded by each station, an average ADT is calculated for each road, considering both the primary and secondary stations. This provides a distribution of vehicle flows across the different roads.

ROAD	ADT	% ADT OVER TOTAL
A1	3.753,70	12,45%
A2	7.580,43	25,14%
A3	7.565,86	25,09%
A4	5.088,88	16,88%
A5	2.883,00	9,56%
A6	3.279,33	10,88%
TOTAL	30.151,20	100,00%

Table 4. Average Daily Traffic from primary and secondary stations [Self-elaborated based on [19]]

The European Commission forecasted a penetration rate of 3% for 2030, which increases to 20% by 2050 of the hydrogen technology, considering the expected increase in the adoption of hydrogen technology over time [20]. This prediction is then applied to the total Average Daily Traffic (ADT), resulting in the estimation of the daily flow of hydrogen-powered heavy-duty vehicles for each road.

Year	Total number of vehicles (Spain)	FCV Penetration Rate	Total Heavy-Duty FCV	**Total Heavy-Duty FCV ADT**
NZE 2030	687.594,18	3,0%	20.628	1.013
NZE 2050	884.372,00	20,0%	176.874	8.684

Table 5. Total Heavy-Duty FCV Penetration Rate and ADT [Self-elaborated]

The total number of vehicles forecasted for both scenarios have been calculated creating a trend line exponential equation, using the available data on the current heavy-duty vehicles in Spain [21] and the estimated projection of an increase in 44% of the heavy-duty sector activity for 2050 [22].

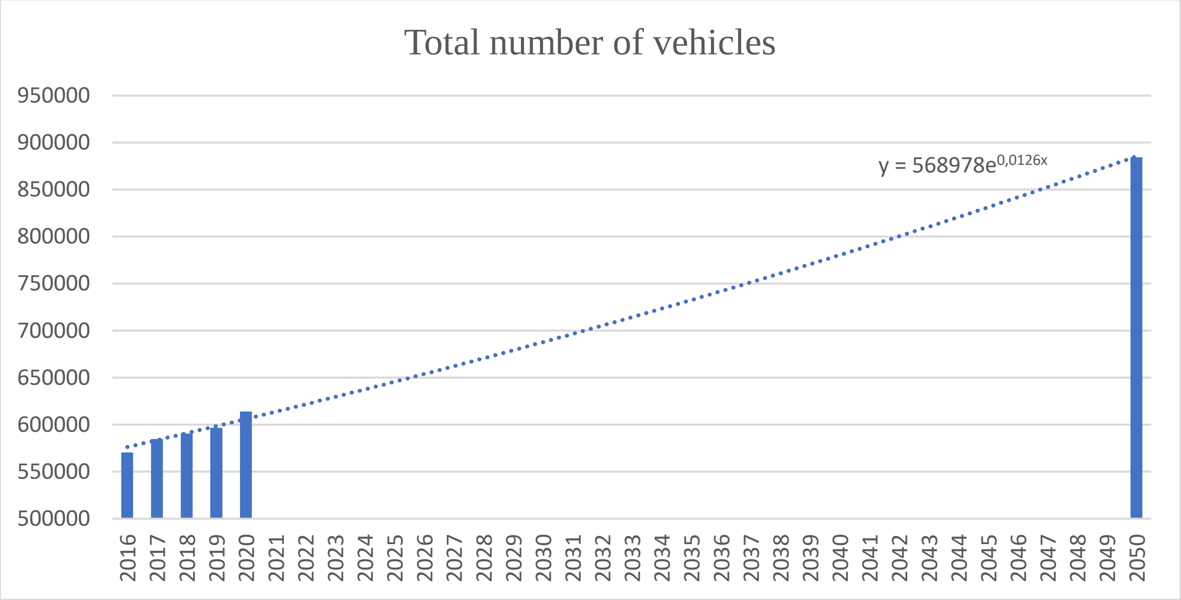


Figure 19. Total number of vehicles forecast [Self-elaborated]

The available data is then used as a validation set to establish a correction factor in other to provide an accurate estimate for 2030.

Year	Real Value	Obtained Value (E+16)	Error
2016	570315	6,122	9,31583E-12
2017	584733	6,200	9,43118E-12
2018	590674	6,278	9,40863E-12
2019	596599	6,358	9,38344E-12
2020	614147	6,438	9,53941E-12

Mean Error	9,4157E-12

Table 6. Validation of trend line for number of vehicles to 2030 forecast [Self-elaborated]

Combining the distribution of vehicle flows obtained from the ADT with the predicted penetration ratio, the average daily flow of hydrogen-powered heavy-duty vehicles for each road is calculated. This flow serves as a crucial input for the model, enabling accurate analysis and planning of the hydrogen infrastructure needs.

Year	Total Heavy-Duty FCV ADT	A1	A2	A3	A4	A5	A6
		12,45%	25,14%	25,09%	16,88%	9,56%	10,88%
NZE 2030	1013	126	255	254	171	97	110
NZE 2050	8684	1081	2183	2179	1466	830	944

Table 7. Forecast of Daily Flow of Heavy-Duty FCV in each road [Self-elaborated]

Last but not least, in terms of costs, cost reduction ratios of 40% for 2030 and 80% for 2050 are considered to account for economies of scale and technological advancements [24]. This ratio reflects the expected reduction in costs over time as the hydrogen infrastructure develops and matures. By incorporating this cost reduction ratio into the model, we can assess the long-term cost implications and project the financial feasibility of the hydrogen refueling infrastructure.

	Cost Reduction	Type I HRS	Type II HRS	Type III HRS
Current costs (2021)		1.880.000,04 €	2.750.000,00 €	2.406.559,00 €
NZE 2030	40%	1.128.000,02 €	1.650.000,00 €	1.443.935,40 €
NZE 2050	80%	376.000,01 €	550.000,00 €	481.311,80 €

Table 8. Cost Reduction Rates [Self-elaborated]

Chapter 4. ANALYSIS OF RESULTS

The model resolution using mixed integer non-linear programming has had a feasible outcome making it possible to determine the optimal number of HRS to be installed on Spanish roads to meet the supply needs of the trucks in the fleet analyzed.

The model has undergone evaluation under two distinct scenarios: 2030 and 2050, aligning with the net zero emissions trajectory for 2050. Building upon the results obtained from the 2050 scenario, two additional sub-scenarios have been introduced to conduct a sensitivity analysis. One sub-scenario explores parameter variations pertaining to the station, while the other examines modifications in vehicle-related parameters. The objective is to gain valuable insights into the technological advancements required by the sector and to ascertain the current landscape's adaptability towards embracing this technology.

In addition, a scalability perspective has been considered, enabling the model to be applied on a broader scale. This feature facilitates the incorporation of a broader range of data, encompassing the introduction of diverse vehicle fleets and traffic data. As a result, more accurate estimations can be derived, leading to valuable insights for future conclusions.

4.1 SCENARIO 1 (2030)

The input to this scenario reflects a hydrogen penetration rate of 3%, i.e., with a predicted daily flow of 1013 heavy-duty hydrogen vehicles by 2030. The increase in the number of fuel cell vehicles would indirectly result in an estimated cost reduction of 40% for the installation of refueling stations for the year 2030 in relation to actual costs.

Equation 5, (pg. 42) estimates the number of hydrogen refueling stations of each type to supply the flow of vehicles on each road, while the variables x and y computed through equations 11 and 12 (pg. 46) represent the total to be installed per road and the total per type. Thus, in this scenario, the results are as follows:

	Type I HRS	Type II HRS	Type III HRS	Total per road
A1	7	4	3	**14**
A2	14	7	5	**26**
A3	14	7	5	**26**
A4	9	5	3	**17**
A5	6	3	2	**11**
A6	6	3	2	**11**
Total per type	**56**	**29**	**20**	**105**

Table 9.Scenario 1 Results (2030) [Self-elaborated]

The demand can be verified by taking the A4 road as an example, where the estimated vehicle flow for 2030 is 171 (ADT heavy-duty). According to the results shown in Table 9.

- 9 Type I HRS: This type of station has a capacity of 400 kg of hydrogen throughout the day, so if each vehicle requires 31 kg, it can accommodate 12 vehicles. In this case, with 9 stations, 108 fillings of hydrogen tanks.
- 5 Type II HRS: Similarly, the number of tank fillings that can be achieved for type II stations type is calculated, resulting in 25 fillings per station. Therefore, this type caters 125 fillings.
- 3 Type III HRS: Likewise, with a 1200 kg of dispensed hydrogen, type III stations can cater to 38 fillings per day and per station, resulting in a total of 114 fillings.

Thus, with this distribution, a total of 347 fillings can be performed daily. Since the refueling periodicity ratio is 2 (equation 4), meaning each vehicle must make two stops in every journey, the number of vehicles per road is half the fillings made: 173 vehicles. The factor of 2 is considered based on the vehicle's range and the distance to be covered, where it is calculated that the filling ratio is 1.42 times per journey (ratio represented by variable refueling periodicity, calculated through equation 4 (pg. 42)). The fulfillment of the demand, which amounts to 171 vehicles requiring refilling daily along highway A4, is satisfied with a surplus idle capacity of 1.16%. An equivalent verification process is carried out for all road networks.

It can be observed that, as a result of their lower cost, a greater number of Type I hydrogen refueling stations are installed in all cases, while the minimum possible number of Type III stations is chosen. Specifically, a total of 56 Type I stations, 29 Type II stations, and 20 Type III stations are to be installed. Despite Type III stations being the most expensive, it has been previously noted that they offer a lower cost per supplied vehicle, making them more financially viable in the long term.

The number of stations per road is entirely reliant on the volume of vehicle traffic. Consequently, roads with higher daily vehicle flow need a greater number of stations situated at closer intervals (with distances between them calculated according to equation 13, pg. 46).

	Total Heavy-Duty FCV ADT	**Number of HRS per road**	**Distance between them [Km]**
A1	126	14	26,50
A2	255	26	19,38
A3	254	26	13,65
A4	171	17	38,82
A5	97	11	37,08
A6	110	11	53,63

Table 10. Distribution of HRS [Self-elaborated]

In the given data, the first column represents the input for the model, while the last two columns illustrate the distribution of the refueling station network. It should be noted that although the number of stations to be installed on the A2 and A3 roads is the same (26 stations), the spacing between them varies depending on factors such as vehicle density and flow per kilometer of the road, similar to the situation observed on the A5 and A6 roads.

To provide a general overview, this scenario estimates the need for a total of 105 hydrogen refueling stations to be installed in 2030, entailing a cost of approximately 140 million euros.

TOTAL Nº HRS	105
TOTAL COST	139.898.000,00 €

Table 11. Results Overview [Self-elaborated]

This is an ambitious goal for 2030, considering that it takes an average of 2 years to build a station [25]. To achieve the target of 105 stations by 2030 and meet the estimated vehicle demand, a total of 21 stations per year must be built, starting from the upcoming year. It is important to note that, despite the existence of 11 private trial stations in Spain currently [26], these do not meet the specified requirements to cater the needs of the estimated hydrogen heavy-duty ADT in 2030. Hence, it is necessary to construct 21 stations adhering to the outlined specifications in order to achieve the goal of 105 stations by 2030, thereby satisfying the estimated vehicle demand.

A substantial investment of approximately 140 million euros is required to accomplish this task. This insight allows for a comprehensive understanding of the market landscape and the pressing need to pursue financial resources, initiate funding for projects, and promptly commence construction activities.

Furthermore, it is worth highlighting that this outcome is aligned with the Spanish government's strategic plan to reduce emissions, as outlined in the hydrogen roadmap [16]. Spain, in line with its commitment to the Paris Agreement, acknowledges the importance of contributing to the development of new technologies and renewable fuels, such as hydrogen. Specifically, for the year 2030, the hydrogen roadmap insists on the installation of 100 to 150 hydrogen refueling stations. Thus, the model output of installing 105 HRS is deemed necessary and coherent.

4.2 SCENARIO 2 (2050)

The provided input in this scenario reflects an increase in the hydrogen penetration rate to 20% and a subsequent cost reduction of 80% compared to the current situation. Likewise, when considering the input of vehicle flow on the roads, a more irregular distribution with higher values of HRS needed is observed compared to the 2030 scenario. This pattern arises due to the sector's growth, which reflects the percentage of hydrogen vehicle penetration and the imperative to reduce emissions to ensure the attainment of net-zero emissions by 2050. Consequently, this scenario underscores the need for ambitious and proactive advancements within the sector.

	Type I HRS	**Type II HRS**	**Type III HRS**	**Total per road**
A1	56	28	19	**103**
A2	113	57	38	**208**
A3	113	57	38	**208**
A4	76	38	26	**140**
A5	129	-	-	**129**
A6	147	-	-	**147**
Total per type	**634**	**180**	**121**	**935**

Table 12. Scenario 2 Results (2050) [Self-elaborated]

The fulfillment of demand is confirmed to be in line with the previous scenario, thus validating the attainment of optimal results. Notably, on the A5 and A6 roads, the optimal solution entails exclusively installing Type I stations. This strategic decision is driven by the projected cost reduction anticipated by 2050, in conjunction with the projected surge in road vehicles. The distribution of stations per road remains unaltered throughout all four scenarios, as the proportion of vehicles relative to the total daily flow on each road, as determined in section 4.2.2.4., remains constant.

	Total Heavy-Duty FCV ADT	**Number of HRS per road**	**Distance between them [Km]**
A1	1081	103	3,60
A2	2183	208	2,42
A3	2179	208	1,70
A4	1466	140	4,71
A5	830	129	3,16
A6	944	147	4,01

Table 13. HRS Distribution [Self-elaborated]

In a broader perspective, this scenario highlights the need to install 935 hydrogen refueling stations (HRS) as outlined in Table 12 by 2050, incurring a total cost of approximately 400 million euros.

TOTAL HRS	935
TOTAL COST	395.585.000,00 €

Table 14. Overview [Self-elaborated]

The installation of such a substantial number of stations necessitates maintaining a minimum distance between them. Consequently, conducting an analysis of the 2050 scenario under identical conditions as in 2030 would lack practical relevance. Accordingly, two additional sub-scenarios are considered in order to assess the effect of variations in HRS storage capacity and vehicle range on the optimal number of stations required. These two sub-scenarios anticipate advancements in technology by 2050, including enhanced vehicle range, increased storage capacity at hydrogen refueling stations, and an expanded road network.

4.2.1 SCENARIO 2.1: CHANGE IN STORAGE CAPACITY

In this scenario, a 60% enhancement in storage capacity of HRS tanks has been considered. As these costs are intricately linked to the capacity, the analysis incorporates the regression line, depicted in the current cost calculation which showcases the cost reduction per vehicle.

	Capacity	Vehicles	Cost
TYPE I HRS	640	20	2.573.294,00 €
TYEP II HRS	1280	41	2.213.831,90 €
TYPE III HRS	1920	61	1.261.046,90 €

Table 15. Parameters for Sub-Scenario 2.1. [Self-elaborated]

Taking into account these characteristics, the model estimated a demand for 588 stations by 2050, resulting in a cost of 1.372.286.000, 00 €.

There is an observed reduction in the number of required HRS by 37,11%. It is noteworthy that despite the higher cost per vehicle, the prevalence of Type I stations continues due to their lower overall cost. However, this approach would entail a 246,90% increase following current cost reduction estimations. Consequently, this alternative is not entirely economically viable when compared to the base scenario for 2050. Although it establishes a more realistic objective by reducing the required number of stations, which would need a highly aggressive cost reduction.

	Type I HRS	Type II HRS	Type III HRS	Total per road
A1	35	18	12	65
A2	71	36	24	131
A3	71	36	24	131
A4	48	24	16	88
A5	81	-	-	81
A6	92	-	-	92
Total per type	398	114	76	588

Table 16. Results Scenario 2.1 [Self-elaborated]

4.2.2 SCENARIO 2.2: CHANGE IN RANGE

Considering the market options currently available, in this scenario, a 60% enhancement in vehicle range has been considered. The model input now stands at 640, adjusted by a safety factor of 15%, resulting in a calculated range of 544 km. All other model parameters remain consistent with the 2050 base case.

In this instance, the model estimates the need of installing 471 hydrogen refueling stations by 2050 with an incurred cost of 199.335.000,00 €.

	Type I HRS	Type II HRS	Type III HRS	Total per road
A1	28	14	10	52
A2	57	29	19	105
A3	57	29	19	105
A4	38	19	13	70
A5	65	-	-	65
A6	74	-	-	74
Total per type	319	91	61	471

Table 17. Results Scenario 2.2 [Self-elaborated]

A notable decrease in the necessary number of HRS is observed compared to the 2050 base case, 49,63%, even lower than the previous scenario. These stations are distributed according to the specifications outlined in Table 15. Additionally, a favorable reduction of 49,61% in costs compared to the base 2050 scenario is observed.

This results in the need for 366 additional stations to the existing 105 installed in 2030, that would incur only an additional investment of approximately 60 million euros. Such findings reinforce the importance of optimizing infrastructure deployment and cost-efficiency to achieve the sector's goals effectively.

4.3 COMPARATIVE ANALYSIS

Following a comprehensive analysis of each scenario in isolation, it is deemed pertinent to juxtapose and compare them to derive conclusive insights. This comparative examination allows for the synthesis of final observations and recommendations.

	NZES 2030	NZES 2050		
		Base Case	**Case 1**	**Case 2**
Total nº HRS	105	935	588	471
Total cost	139.898.000,00 €	395.585.000,00 €	1.372.286.000,00 €	199.335.000,00 €

Table 18. Final overview [Self-elaborated]

In the analysis of the 2050 base scenario, it becomes apparent that the model provides a significantly high estimate for the number of stations required. However, from a technical perspective, it is unrealistic to deploy 800 stations within a 20-year timeframe. Despite the relatively modest increase in capital investment compared to 2030, this approach lacks practicality.

By comparing the results of the first sub-scenario in 2030, where the storage capacity of station tanks is expanded, a reduction in the number of required stations for the 2050 base case is observed, leading to a more feasible number. However, this reduction is accompanied by a significant cost escalation. Although the cost per vehicle decreases due to economies of scale resulting from increased capacity and the ability to serve more vehicles per station, the overall cost (cost per vehicle multiplied by the number of vehicles) is higher. Consequently, this alternative also suffers from feasibility concerns.

In contrast, the second sub-scenario achieves a further reduction in the required number of stations for 2050 without a disproportionate cost increase compared to 2030. Therefore, this option, which focuses on the development of hydrogen vehicle technology by extending their range by 60%, emerges as the most viable choice. In conclusion, upon the results observed, the optimal direction for technological progress in the sector lies in enhancing vehicle autonomy.

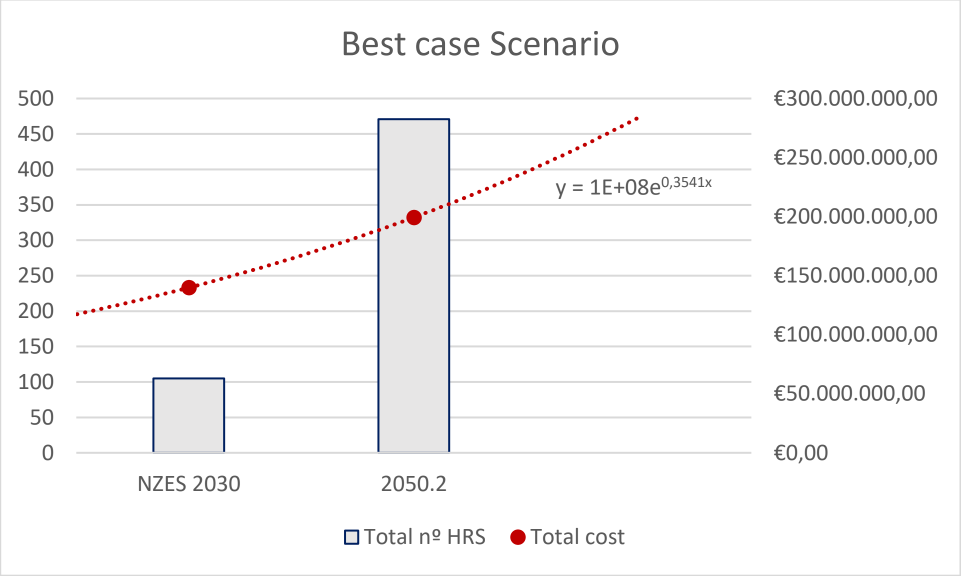


Figure 20. Best Case Scenario [Self-elaborated]

4.4 SCALABILITY OF THE MODEL AND FUTURE STUDIES

The developed optimization model sets the basis of an approach to tackling the problem of the lack of hydrogen infrastructure. It exhibits a solid level of flexibility and adaptability, making it suitable for tackling complex and realistic problems. Therefore, two proposals are made to further enhance its versatility, enabling it to handle diverse datasets and address a wide range of related scenarios.

- The main focus would be on improving the data input process to the model, allowing it to automatically determine the optimal number of HRS to be installed based on updated traffic flows on Spanish roads. This involves incorporating detailed information on traffic volumes, busiest routes, and vehicle mobility patterns in different regions.

- To attain a more pragmatic outcome, a consideration could be to expand the model parameter input, encompassing diverse types of stations with on-site or off-site production, while also taking into account various distribution options such as trucks or pipelines. Moreover, incorporating considerations for secondary roads and other fuel cell vehicle models, beyond the current single model, would enhance the model's comprehensiveness and accuracy.

- The model exhibits a high degree of sensitivity to inputs, and given the dynamic nature of the burgeoning sector, the current forecasts lack precision. Consequently, the results yielded by this project will progressively improve in accuracy as the quality of data increases. The objective is to continually refine the model by evaluating it over extended time horizons, thereby generating a more precise sector curve that can serve as a robust basis for future research endeavors.

On the whole, the currently available model lays a solid foundation that could be further enhanced through the integration of more comprehensive data on updated traffic flows and the implementation of more accurate estimates. These proposed improvements aim to enhance the adaptability of the model to the specific traffic conditions and requirements observed on Spanish roads, thereby yielding realistic and dependable outcomes. These would result in more informed and accurate decision-making, thus enabling more efficient planning of the hydrogen refueling infrastructure and the necessary investment required for its deployment.

Chapter 5. CONCLUSIONS

Heavy-duty vehicles account for 28% of greenhouse gas emissions from road transport (6% of total EU emissions) [1]. Therefore, to fulfill the objectives of the Paris Agreement [26] it is essential to reduce greenhouse gas emissions. Given the significant contribution of the transportation sector to global emissions, it is imperative that this industry becomes a leader for energy transition.

In light of the aforementioned background, a range of alternatives have been developed, encompassing electric vehicles (BEVs and PHEVs), hydrogen fuel cell vehicles (FCVs), and biofuels. While electric vehicles have garnered significant attention, fuel cell vehicles are emerging as a prominent choice, particularly within the heavy-duty vehicle sector, due to their notable advantages over EVs. These advantages encompass extended range, expedited refueling times conducive to long-distance travel, and more lightweight and compact storage systems that allow for increased design adaptability. Nonetheless, it is crucial to acknowledge the challenges inherent in this technology, such as the limited availability of refueling infrastructure and the higher costs associated with production and distribution.

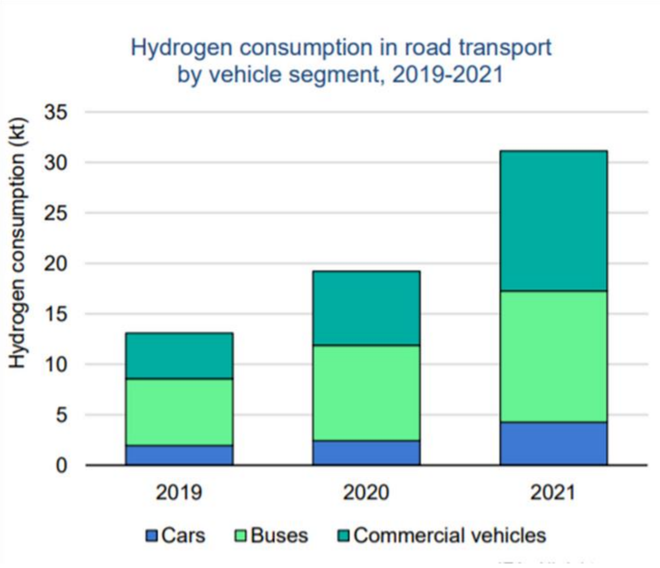


Figure 21. Hydrogen Consumption in road transport [9]

Consequently, the primary objective of this study was to offer valuable insights into addressing a key challenge pertaining to hydrogen technology: the insufficiency of infrastructure. To obtain a comprehensive understanding of the infrastructure needed to meet the demand for vehicles, an optimization model was developed, which estimates the optimal number and locations of hydrogen refueling stations based on projected heavy-duty hydrogen vehicle flow and their distinctive features. The model has undergone evaluation for the timeframes of 2030 and 2050, encompassing diverse scenarios that enable a comprehensive assessment of the infrastructure requirements to cater to future vehicle demand.

In order to meet the future demand for FCEVs, the model indicates a requirement of 105 hydrogen refueling stations for the year 2030. These stations should be strategically distributed as outlined in Table 9. The estimated cost for establishing this network amounts to 200 million euros, which reflects a significant 40% reduction compared to current expenses related to equipment, installation, and operations. These findings align closely with the Hydrogen Roadmap devised by the Spanish government, which also emphasizes the necessity of installing 100-105 hydrogen refueling stations by the year 2030 [16]. To achieve this objective, an annual construction rate of 21 stations commencing from the upcoming year would be imperative.

When considering the year 2050, the model reveals a notable surge in the demand for refueling stations, with an estimated total of 935 stations required. This represents a significant increase compared to the figures projected for 2030, driven by an anticipated 17% penetration rate. While there is an approximate 80% reduction in costs along the hydrogen value chain, it is important to acknowledge that these outcomes may lack practical viability due to the expected technological advancements in the sector by 2050. In light of this, two additional scenarios have been carefully examined, accounting for a substantial 60% augmentation in vehicle autonomy and a corresponding 60% increase in storage tank capacity.

In the initial sub-scenario, a decrease in the estimated quantity of necessary stations to a more feasible number, namely 588, is evident. Nevertheless, the associated costs undergo a substantial increase, rendering this scenario less practicable. Conversely, the second sub-scenario showcases an even greater reduction in the number of required stations by 2050, with an estimate of 471 stations at a cost of 200 million. This alternative involves the installation of an additional 366 stations in addition to the 105 stations planned for deployment by 2030, thereby presenting an ambitious yet viable approach. Accomplishing this objective would require an additional investment of 60 million for 2050, in addition to the initial 140 million required for 2030.

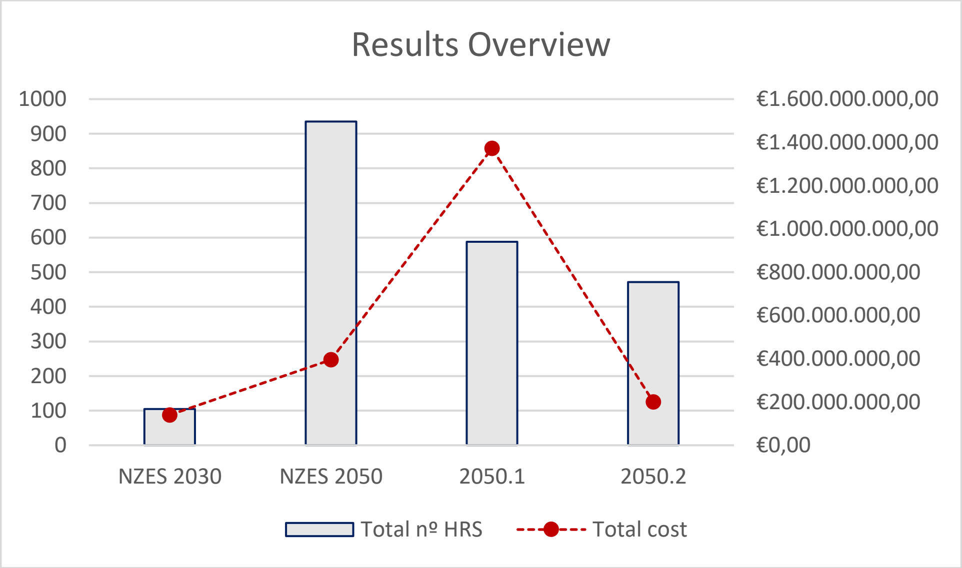


Figure 22. Results Overview [Self-elaborated]

Given these findings, it is clear that the progress of the sector should center around enhancing fuel cell vehicle technology, specifically by extending vehicle autonomy. This strategic approach not only ensures greater feasibility and profitability but also facilitates notable advancements within the industry. However, it is essential to acknowledge the considerable number of refueling stations still required and the limited timeframe available for their construction. Hence, immediate action is crucial to effectively mitigate emissions and achieve meaningful progress.

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ANEXO I. GAMS CODE

```
*OPTIMIZATION MODEL TFG*

SETS

   r    road                    /A1, A2, A3, A4, A5, A6/
   h    capacity type HRS       /1, 2, 3/;


PARAMETERS

   A              vehicle's range [km] /340/
   D              average distanced to be travelled per day [km] /350/
   SC             vehicle's storage capacity [kg of hydrogen] /31/
   F(r)           flow of fuelcell vehicles per day in each road r [vehicles]
                  /A1 126, A2 255, A3 254, A4 171, A5 97, A6 110/
   RoadDis(r)     road length [km]
                  /A1 371, A2 504, A3 355, A4 660, A5 408, A6 590/
   C(h)           Total cost of each HRS type [M€] /1 1.128, 2 1.650, 3 1.444/
   CAP(h)         capacity of each HRS [kg] /1 400, 2 800, 3 1200/;



POSITIVE VARIABLES

   N(r,h)         number of HRS to be installed
   Flow(r,h)      Flow of vehicles assigned to each type of HRS in each road
   DHRS(r)        Distance between HRS
   x(r)           number of HRS per road
   y(h)           number of HRS per type;

VARIABLE

   Q(h)           cost per type
   RP             Refueling periodicity
   TotalQ         Total cost;

INTEGER VARIABLE

   AuxRP           auxiliar refueling periodicity
   NDef(r,h)       auxiliar number of HRS to be installed;


EQUATIONS

   RefuelingPeriodicity        number of stops a vehicle must make
   Cons1                        auxiliary equation to round RP to the nearest
                                higher integer number
```

```
   NumberHRS(r,h)             number of HRS of type h to be installed in road r
   Cons2(r,h)                 auxiliary equation to round up the number of HRS to
                              be installed
   Cons3(r)                   flow assigned to each HRS type must add up to flow
                              in road r
   NumberHRSRoad(r)           number of HRS per road
   NumberHRSType(h)           number of HRS per type
   DistanceHRS(r)             distance between HRS
   Costpertype(h)             Total cost per type og HRS to be installed
   TotalCost                  total cost of infrastructure deployment;



RefuelingPeriodicity         .. RP =G= D/A;
Cons1                         .. AuxRP =E= ceil(RP);
NumberHRS(r,h)                .. N(r,h) =E= (Flow(r,h)*AuxRP)/(CAP(h)/SC);
Cons2(r,h)                    .. NDef(r,h) =E= ceil(N(r,h));
Cons3(r)                      .. F(r) =E= sum(h,Flow(r,h));
NumberHRSRoad(r)              .. x(r) =E= sum(h, NDef(r,h));
NumberHRSType(h)              .. y(h) =E= sum(r, NDef(r,h));
DistanceHRS(r)                .. DHRS(r) =E= (RoadDis(r)/(x(r)+0.001));
Costpertype(h)                .. Q(h) =E= C(h)*y(h);
TotalCost                     .. TotalQ =E= sum(h, Q(h));



MODEL HRSInfrastructure /all/;


SOLVE HRSInfrastructure USING MINLP MINIMIZING TotalQ;
```