Task 5.1 – Limitations, constraints and barriers to Hydrogen Mobility

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Task 5.1– The case of the Medio Tejo Region

WP: Work Package 5: Mobility Use of Hydrogen

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Task 5.1- Medio Tejo

Introduction:

Médio Tejo is a sub-region of Central Portugal, associating 13 urban and rural municipalities. The geographical area of intervention covers 3344 km^2 in the centre of the country and integrates the municipalities of Abrantes, Alcanena, Constância, Entroncamento, Ferreira do Zêzere, Mação, Ourém Sardoal, Sertã, Tomar, Torres Novas, Vila de Rei e Vila Nova da Barquinha, connected by the biggest Iberian River –Tejo, with a total of 247,330 inhabitants.

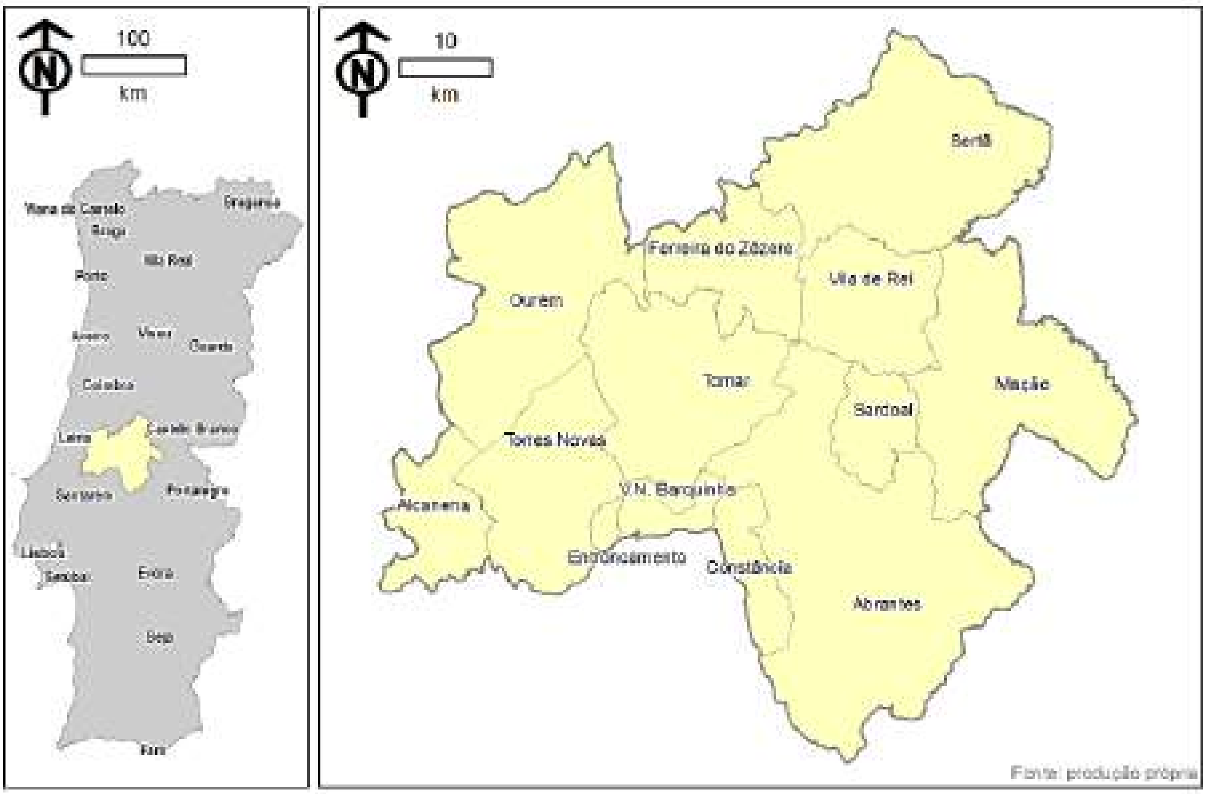


Figure 1. Map of Médio Tejo and its municipalities (FCHJU).

The region is characterized by diversity and quality of endogenous resources as a decisive factor in the installation of industries that have as one of their competitive advantages the proximity of access to raw materials. The concentration of business activities and, in particular, activities linked to logistics and large-scale distribution, in the vicinity of the A1-A23 Road junction, with activities and functions of global logistics intermediation in the Spain-Portugal distribution circuits - through the existing International Routes, with interconnection to ports, reinforces the strategic added value of the region. Médio Tejo Region also has a high potential for endogenous renewable energy production. Renewable energy production in the region represents around 6% of the national total (FCHJU).

Energy use in the region is approximately 4,000GWh/year, resulting in emissions of 900ktCO_2/year. The transport sector is responsible for 40% of energy consumptions and 35% of CO_2 emissions.

Médio Tejo Region is served by a set of road and railroad infrastructures of significant importance, making it strategically located within the national context with heavy logistic traffic and opportunities for refuelling stations corridor. Public transportation plays a crucial role in connecting the medium-sized cities within the region, while simultaneously reducing reliance on private cars. Médio Tejo territory has a relatively low population density, which results in certain areas lacking sufficient services. As a result, residents often need to travel to local cities using either private vehicles or public transportation.

The transport sector heavily relies on fossil fuels. Recognizing this, Médio Tejo Region aims to promote the use of energy alternatives with the potential to decarbonize the sector and reduce operational costs.

As part of Médio Tejo Mobility Plan and SmarTejo initiative, hydrogen is seen as a solution to facilitate the transition across various sectors, particularly in transport and industry. Thus, an integrated use of FCH technologies is being designed in Médio Tejo, building up of local and regional H2 value chain and valuing regional surplus renewable energy: the Hytagus Valley.

Hytagus Valley aims to build a Hydrogen Value Chain in the Middle Tagus Region, promoting the integrated use of hydrogen and fuel cell technologies (FCH) in different sectors and applications, particularly in transport and buildings. The Valley involves the components of production, distribution, storage, supply and final consumption, as well as the component of innovation and knowledge, being this transversal to the entire value chain.

The hydrogen sector interconnection will allow the green energy of the electric sector to be used for the decarbonization of other sectors such as transport, buildings or industry, integrating the different FCH technologies within this ecosystem. This integration will induce the increase of renewable energies in the local energy mix and, simultaneously, contribute to the balance of the electric grid.

This regional value chain developed with Hytagus Valley will have an integrated approach, linking individual sub-projects to each other, showing their systemic interaction in a distinct regional or local configuration, so that hydrogen production, storage and use projects are interconnected.

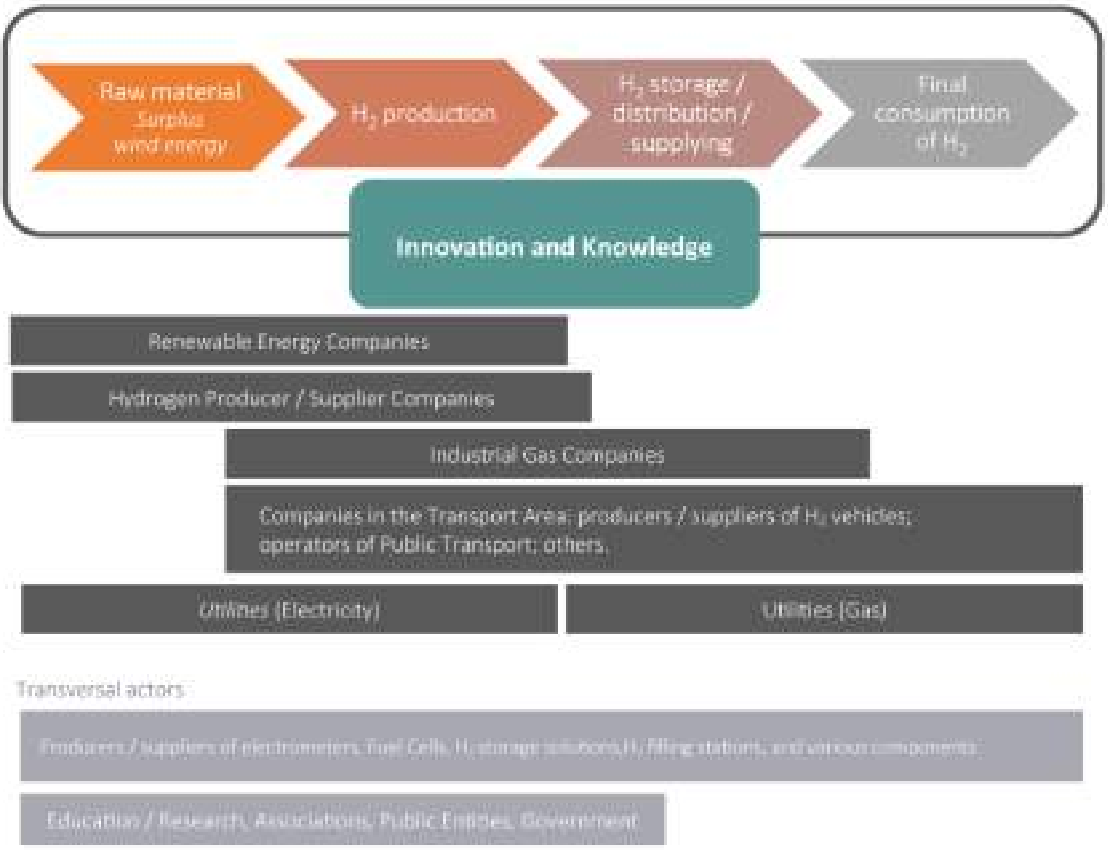


Figure 2. Hytagus Valley - Hydrogen Chain Value in Médio Tejo Region

Hydrogen could use the untapped capacity of renewable electricity that still exists, thereby enabling the integration of new renewable production units.in the area. Moreover, hydrogen offers an opportunity to develop a low-carbon transportation system that meets the region's specific needs and its population. This includes providing a better connection service between the various hubs in the region, improving access to essential services and employment opportunities, and simultaneously achieving a reduction in the carbon footprint of transport and alignment with the commitment to achieve carbon neutrality by 2030[3].

I. Logistics and Services (Light Vehicles and Long Distances Trucks)

Overview of the logistics sector with a breakdown/benchmark of the different logistics subsectors

Médio Tejo Region is distinguished by its geostrategic position in the heart of Portugal, being traversed by key land transportation routes used for the movement of goods. It is also home to major railway hubs, notably located in Entroncamento, facilitating internal multimodal connections to the rest of Europe. This unique positioning makes the region a strategic point for the supply of hydrogen at both the national and European levels. The Multimodal Terminal in Entroncamento is connected to the main road and rail axes of Portugal and Spain, ensuring reduced transit times on connections to Europe (FCHJU).

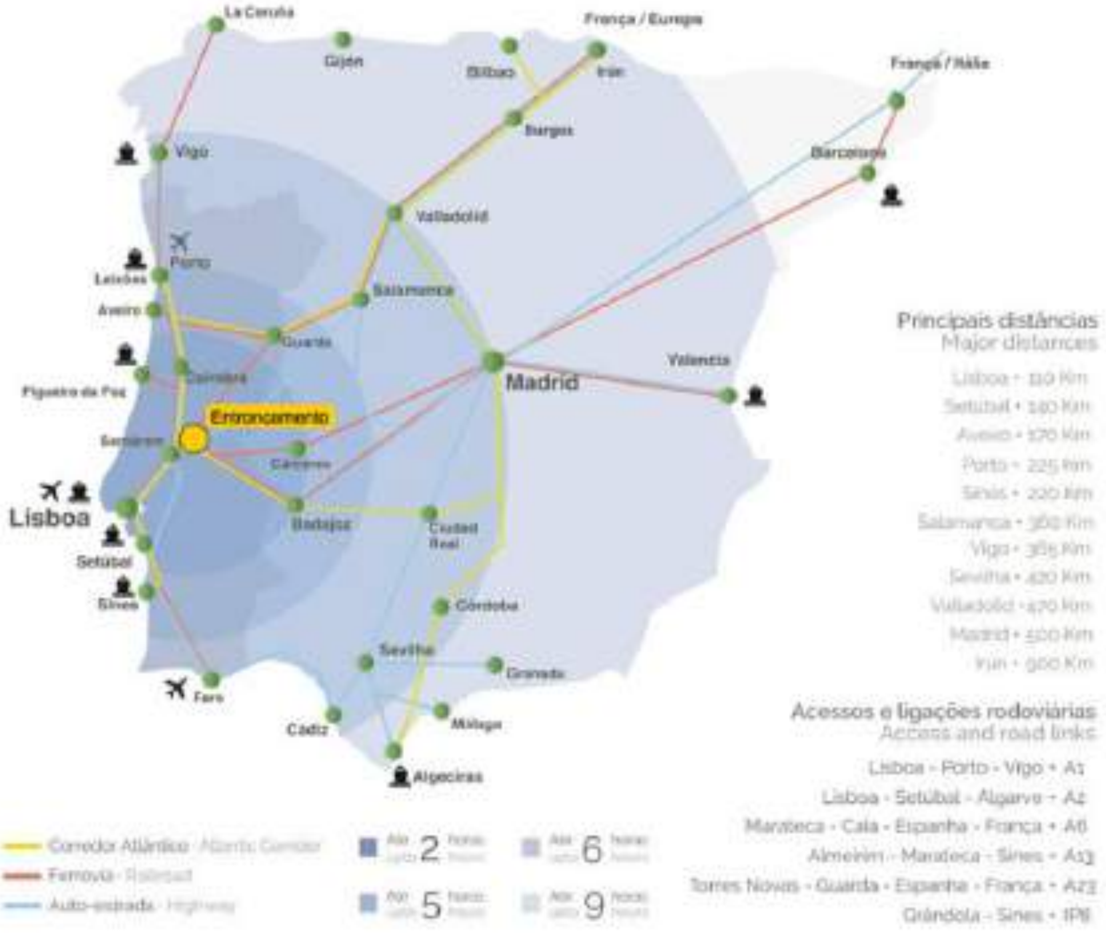


Figure 3. Intermodal Road-Rail Transfer Zone in Médio-Tejo (Medway Iberia)

In terms of road infrastructure, Médio Tejo Region is well-connected with major North-South and Lisbon-Spain communication routes. These roads serve as vital corridors for the movement of both freight and passenger vehicles, making them significant potential consumers of hydrogen as a substitute for diesel. The region's road network is primarily supported by the most important roads of the national network, featuring numerous connections to the whole country. Notably, there are twenty-three access points to the A1, A13, and A23 highways. Travel across the region also involves complementary itineraries (IC3, IC8, and IC9), national roads (with N1, N2, and N3 standing out), as well as various regional and municipal roads.

As the transport sector is currently among the largest consumers of energy and relies heavily on fossil fuels, accounting for more than 40% of total energy consumption in the region, it is crucial to promote the use of H2 in Médio Tejo area, in particular, by implementing hydrogen refuelling stations that serves the main road corridors, creating a supply of this green energy source (currently still non-existent). This effort is essential to create a continuous transcontinental availability of hydrogen technology throughout Europe and thus promote/allow the use of H2 in mobility, particularly in sectors such as logistics and long-distance transportation.

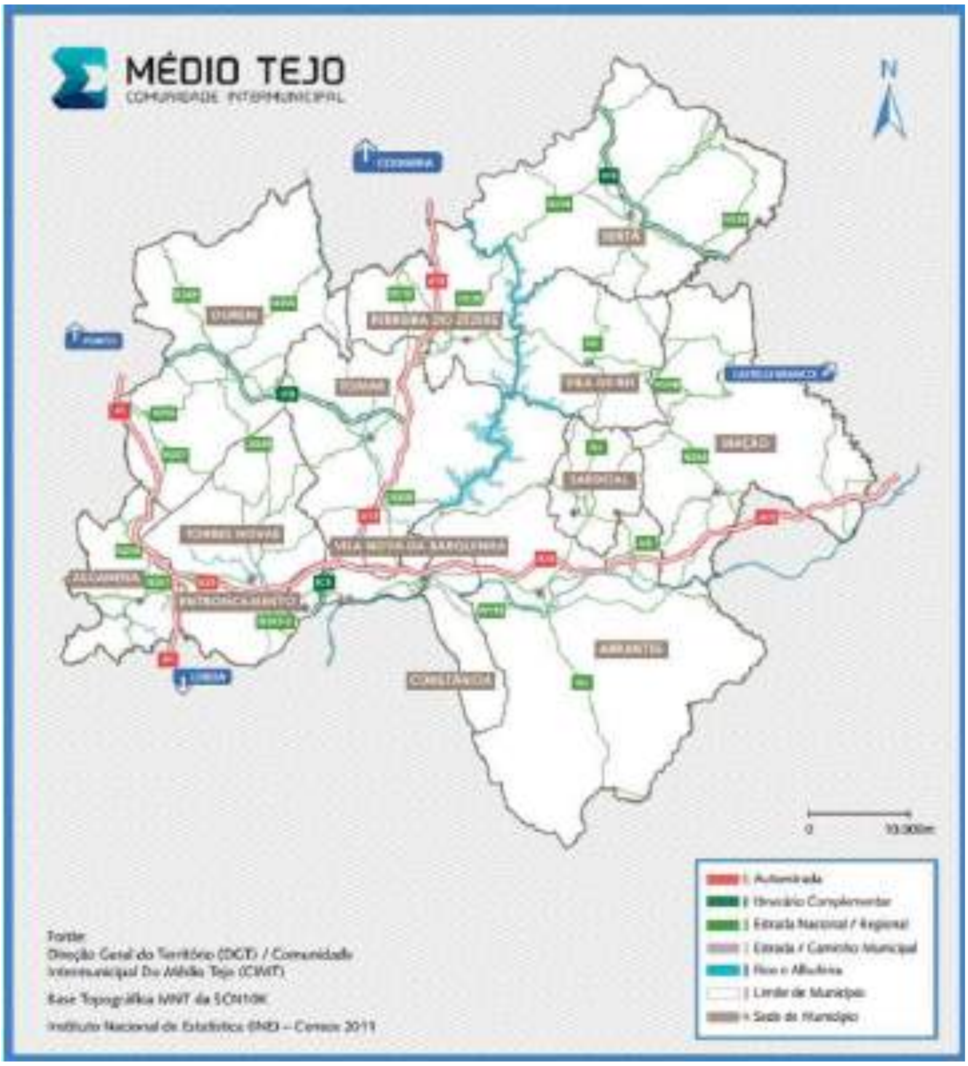


Figure 4. Road network of Médio Tejo (Médio Tejo Intermunicipal Community)

On one of the main road networks (South-North, A1), there is an average daily traffic of 20,000 light vehicles and 2,000 heavy vehicles, while on the connecting road (Portugal-Spain, A23) there is an average daily traffic of 15,000-10,000 light vehicles and 1,500-1,000 heavy vehicles.

Médio Tejo region, in line with national and European targets, has committed itself to a strategy of decarbonizing the territory and, in particular, the transport sector. In this context, the need to explore alternative energy sources has become increasingly evident, with a specific focus on hydrogen. In addition, the region has a relatively low population density, which often forces the use of private cars for transportation. This underlines the imperative of introducing more sustainable transport alternatives, such as hydrogen, to mitigate the carbon footprint of transportation and improve access to services and employment opportunities. The region is currently undergoing an energy transition, marked by the closure of the Pego coal-fired power plant in 2021. This transition requires the integration of renewable energy sources and the use of dormant renewable electricity capacity, making hydrogen a valuable option.

Médio Tejo Region is actively involved in initiatives such as the HyTagus project and collaborates in various European networks, including Hydrogen Europe and S3 European Hydrogen Valley, among others. These efforts reflect a collective commitment to advancing hydrogen technology.

The following figure illustrates the load diagrams of light and heavy vehicles on the road network of the Médio Tejo Region. The analysis of the figures shows that the load diagram of light and heavy vehicles exhibits a very similar structure, despite the difference in scale (approximately 1 to 10).

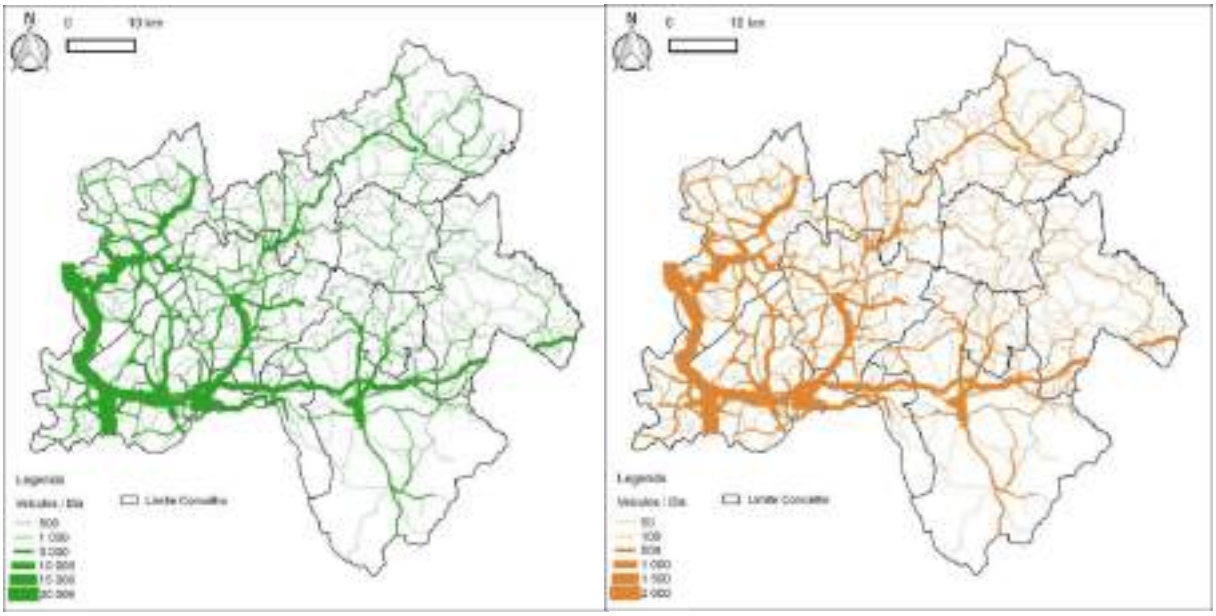


Figure 5. Load diagram of light vehicles and heavy vehicles on an average annual day, respectively (Médio Tejo Intermunicipal Mobility and Transport Plan).

In general, Médio Tejo Region has 50 % of its population within a 5-minute drive of an industrial hub, with only 10 % residing more than 10 minutes away. This indicates a region with high road accessibility to industrial areas, with only the municipalities of Sertã, Mação, Ourém, Tomar, and Abrantes showing lower accessibility to these spaces. The increase in the use of alternative energy sources and energy-efficient, clean mobility, as well as their integration into urban transport systems, constitutes a key strategy for improving sustainability and urban quality of life, as well as reducing dependence on fossil fuels. This transition towards a cleaner mobility is not only critical for passenger transportation but also for the transportation of goods.

Regarding the Logistics and Mobility Services sectors, 564 establishments are located in the region, with a turnover of 260 M€ (Table 1).

	Logistics and Mobility Services Establishments (n.º)
Freight transport via railways	2
Urban and suburban passenger land transport	4
Taxi operation	192
Inter-urban passenger transportation by bus	11
Other miscellaneous land passenger transport, n.e.c.	16
Freight transport by road and removal services	242
Air transport	1
Warehousing and support activities for transportation (include cargo handling)	32
Postal and courier activities	64

Table 1. Logistics and mobility services establishments, 2021 (Statistics of Portugal) .

The main transport companies in Medio Tejo region have a turnover of around 154 M€, with Road Freight Transport predominating (Table 2).

Rank	**Municipality**	**Field of Activity**	**Turnover M€/year**
1	Ourém	Road Freight Transport	47
2	Alcanena	Road Freight Transport	45
3	Torres Novas	Refrigerated Transport and Warehousing	21
4	Torres Novas	Interurban Bus Transportation	15
5	Entroncamento	Railroad Transport and Logistics	14
6	Santarém	Road Freight Transport	12

Table 2: Main transport companies in Médio Tejo Region (Ribatejo Invest Magazine).

Importance of a robust logistics infrastructure for hydrogen mobility

For hydrogen mobility in Médio Tejo to truly thrive and contribute significantly to a sustainable transportation system, a robust logistics infrastructure is essential. Unlike conventional fossil fuels, hydrogen requires specialized storage, handling, and distribution mechanisms due to its unique properties. Although its production can occur virtually anywhere, establishing an efficient and extensive logistics network is crucial for ensuring a seamless supply chain, from hydrogen production to its delivery to refuelling stations. Thus, establishing an efficient and extensive logistics network is crucial for ensuring a seamless supply chain, from hydrogen production to its delivery to refuelling stations.

The creation of this infrastructure is essential to the creation of a value chain for hydrogen in the Médio Tejo Region, contributing to the production of renewable hydrogen in the region and leveraging the acquisition of hydrogen-powered vehicles, among other innovative technologies that are essential and integral to the value chain to be created.

It will also support the regional strategy of acquiring hydrogen-powered public transport vehicles to connect the region's main cities, as well as renewing the fleet of hydrogen-powered MSW collection vehicles.

Likewise, the availability of a robust logistics infrastructure for hydrogen mobility will make it possible to overcome the main current barriers to private investment in hydrogen mobility.

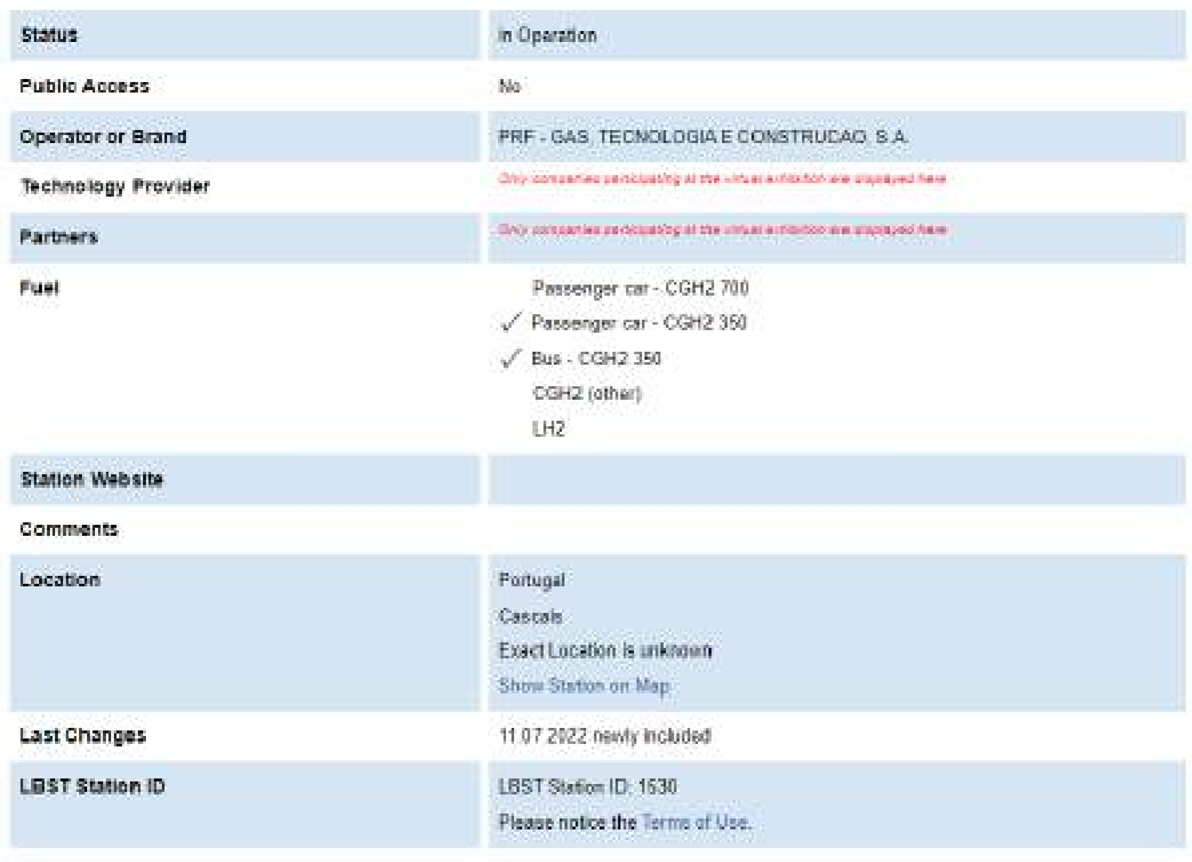
Finally, this infrastructure will also boost the development of innovation and knowledge in the region, fostering the creation of skilled jobs and industrial innovation, among other things. The contribution to job creation is particularly important for the region in this period of energy transition, in which the closure of the coal-fired power generation activity at the Pego Thermoelectric Power Station at the end of 2021 has led to the loss of several jobs.

Identification of logistics limitations

According to the National Hydrogen Strategy (EN-H2), approved in July 2020, Portugal will have 50 - 100 hydrogen refuelling stations (HRS) by 2030. However, currently, no public HRs operating in Portugal were identified, according to HRS in Europe, both for 350bar and 700bar.

Figure 6: HRS Availability Map (HRS in Europe).

However, there is one private hydrogen refuelling station operating in Portugal, located in Cascais. This refuelling station is dedicated to supplying urban public transport vehicles in the municipality of Cascais.



Status	In Operation
Public Access	No
Operator or Brand	PRF - GAS, TECNOLOGIA E CONSTRUCAO, S.A.
Technology Provider	Only companies participating at the virtual exhibition are displayed here
Partners	Only companies participating at the virtual exhibition are displayed here
Fuel	Passenger car - CGH2 700 ✓ Passenger car - CGH2 350 ✓ Bus - CGH2 350 CGH2 (other) LH2
Station Website	
Comments	
Location	Portugal Cascais Exact Location is unknown Show Station on Map
Last Changes	11.07.2022 newly included
LBST Station ID	LBST Station ID: 1530 Please notice the Terms of Use.

Figure 7. Cascais HRS characteristics (H2 Stations Map).

This limitation constrains the expansion of fuel cell mobility solutions. The lack of production and distribution of green H_2 delays the growth of this market in Médio Tejo Region and throughout Portugal.

In terms of end-user accessibility, it is crucial to strategically locate refuelling stations and ensure their immediate availability and a well-stocked inventory for user convenience, promoting the adoption of hydrogen-powered vehicles. In Médio Tejo Region, the main roads and distribution centres are clear and easily accessible.

Mention of service-related barriers

The strategic document Hydrogen in the Portuguese Energy System: Integration Challenges identifies the main challenges to the implementation of a robust logistics infrastructure for hydrogen mobility in Portugal, namely (DGEG):

- Resistance to decentralisation of the energy sector
- Regulatory and normative framework
- Low H_2 literacy (citizens, decision-makers and financiers)
- Lack of demonstration projects
- Lack of sectoral policy instruments

- Low technological diffusion and competition
- Guarantees of origin mechanism
- Complexity of use
- High cost-benefit and investment
- Low supply and demand

Investments in hydrogen infrastructure and logistics are essential for encouraging businesses and freight operators to embrace hydrogen-powered transportation solutions. A well-connected network of hydrogen refuelling stations along major transportation routes is essential for long-haul trucking, freight shipping, and delivery services, enhancing the practicality and attractiveness of hydrogen mobility for goods transportation.

II. Public Transportation (Intercity and Interregional)

Presentation of the relevance of hydrogen-powered public transportation in reducing GHE

The decarbonization of mobility and transportation takes on a special focus, as this is one of the sectors with the greatest importance in terms of national greenhouse gas emissions.

The coverage area of MédioTejo21 extends over an approximately 4,211 km^2 area with a population of 240,679 inhabitants. Public transportation served over 1,178,740 passengers in 2022, which presents a considerable amount of CO_2 potential to mitigate (Calculations of CO_2 emitted at point IV).

Figure 8. Map of regular passenger transport network routes Médio Tejo (Médio Tejo Intermunicipal Community)

Indicator		RMTejo	Rodoviária da Beira Interior
Km total of vehicles	2021	2 329 865	417 532
	2022	2 680 743	426 221
Passengers	2021	891 072	87 659
	2022	1 032 486	146 257

Table 3. Passenger and distance data for public transportation in Médio Tejo Region (Médio Tejo Intermunicipal Community)

Hydrogen-powered public transportation presents a compelling and major solution for decarbonizing the transport sector in Médio Tejo Region, where 52,73% of greenhouse gas emissions come from the transportation system, while the average in Portugal is 25,8% GHG emissions.

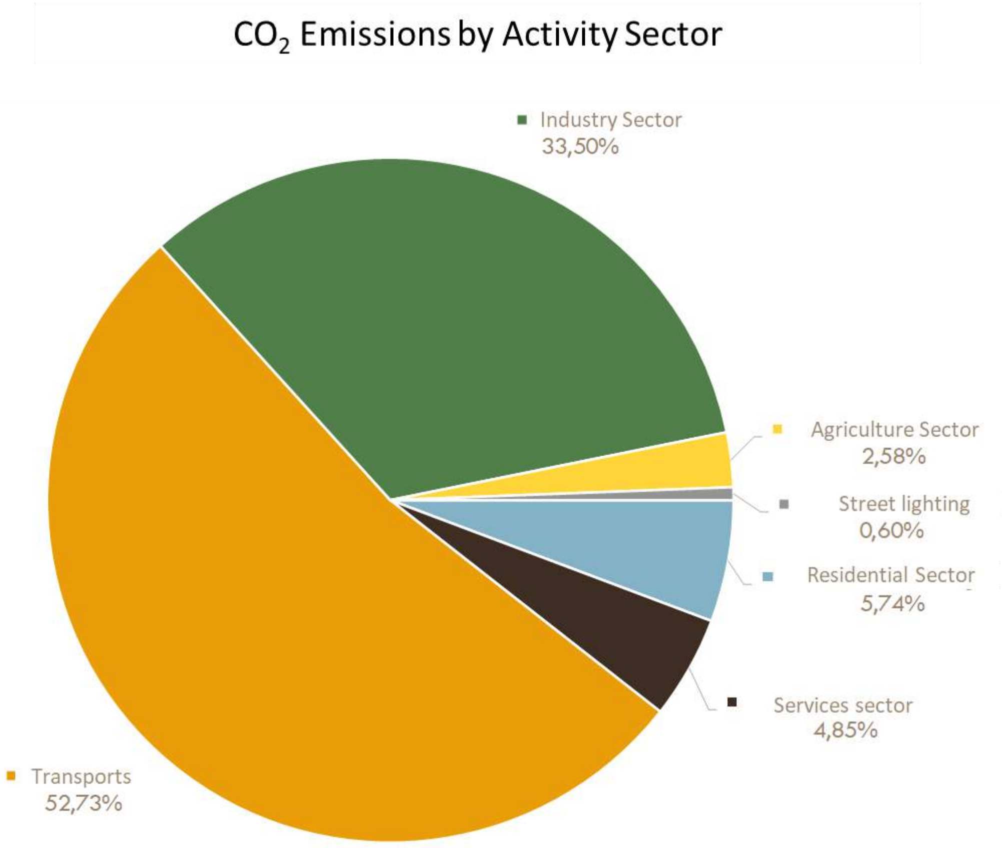


Figure 9. Sectoral CO_2e emissions in Médio Tejo Region (MédioTejo21)

By using fuel cell technology, hydrogen vehicles emit only water as a byproduct, providing an emission-free alternative to conventional fossil fuel-powered vehicles. The widespread adoption of hydrogen-powered buses, taxis, and other public transport options holds significant potential to substantially reduce greenhouse gas emissions in the region, contributing to global efforts to combat climate change.

The current bus fleet operating in the country has an estimated average age of 16 years, which significantly contributes to the increase in greenhouse gas emissions and notably worsens air quality in urban areas. Therefore, it is crucial to continue promoting the renewal of fleets by co-financing "clean buses," particularly those powered by electricity and hydrogen.

Achieving decarbonization in the transportation sector is vital to meet the energy and climate objectives for 2030 and 2050. Portugal has set a target of a 20% share of energy from renewable sources in the transport sector for the next decade (DGEG.gov).

The challenges faced by society require a collaborative approach between energy and climate policies. This is the only way to outline a viable path toward a carbon-neutral economy and society that simultaneously promotes economic growth and an improved quality of life.

Ensuring the maintenance of a resilient and flexible system, with diversification of energy sources and origins, reinforcing, modernizing, and optimizing energy infrastructure, developing interconnections, and promoting the integration, reconfiguration, and digitization of the energy market, thus maximizing its flexibility.

Decarbonizing the transportation sector, promoting modal shifts, and improving the operation of public transport networks, as well as encouraging electric and active mobility and the use of clean alternative fuels. Ensuring the decarbonization of the transport sector requires the strategic, legal and financial support of national authorities, as well as the European Commission. Their support plays a key role in driving a significant change in the transition to green fuels and the use of clean and efficient mobility solutions, in particular to enable and drive the implementation of innovative and effective actions that respond to the challenges associated with creating a carbon-neutral economy and a just transition.

Identification of limitations in hydrogen-powered public transportation. Overview of the specific regulatory framework for hydrogen vehicles at regional and national level

Hydrogen-powered transport systems often involve substantial initial implementation costs. These costs encompass the production, storage and distribution of hydrogen. When examining the Regional Hydrogen Roadmap, it can be seen that approximately 56% to 66% of the overall budget is allocated to the purchase of vehicles alone, compounded by the fact that fuel cell vehicles cost significantly more than conventional internal combustion engine vehicles. **These cost barriers represent a significant constraint for public transport agencies and governments when considering the adoption of hydrogen-powered fleets.**

In Portugal, the implementation of hydrogen technologies in mobility still **faces challenges related to the lack of specific regulations for production by private entities**. Currently, hydrogen is imported from other countries due to the lack of a solid legal framework. To get around this gap, companies in partnership with government institutions are using the European directive as a basis to start pilot hydrogen production, with plans to establish permanent production facilities soon. The lack of regulation is holding back the development of the sector in Portugal.

Another crucial limitation is the need for public investment in refuelling networks. Although sustainable mobility is a priority, the development and widespread adoption of hydrogen-powered vehicles hinge on a robust infrastructure for refuelling. This aspect underscores the key role hydrogen can play in reducing greenhouse gas emissions in the transportation sector.

The Portuguese government has also expressed its intention to promote scientific research applied to clean technologies and new methods of producing electricity from renewable sources. It stresses the importance of flexibility in the energy system by supporting innovative research and demonstration projects, particularly those involving the use of hydrogen for energy storage and conversion into electricity, direct injection into the gas grid, renewable gas production, carbon substitution in industrial processes and electrification using fuel cells to support electric mobility. **However, despite these intentions, the financing and implementation of many of these plans are at an early stage and some projects that have already been approved are being postponed due to the economic uncertainties that have marked recent years.** Overcoming these barriers will be crucial to the successful achievement of the stated objectives (DGEG.GOV).Finally, **another crucial aspect that demands immediate attention is the lack of standardization in hydrogen logistics.** The development and implementation of hydrogen fuelling infrastructure, storage, and distribution systems require adherence to established standards to ensure safety, efficiency, and compatibility across various stakeholders. Without standardized guidelines, there is a risk of fragmented and inconsistent practices, hindering the widespread adoption of hydrogen-powered transportation in the region.

Addressing these barriers requires a well-defined and consistent regulatory framework[1], adjusted

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[1] Portugal has made significant progress on the national agenda for renewable energies and the hydrogen economy. The Basic Climate Law (Law no. 98/2021), approved on December 31, 2021, consolidates objectives, principles and obligations for the different levels of governance for climate action, establishing that the State must promote the replacement of fossil fuels, as an energy source, with electricity supply or renewable gases. Decree-Law 84/2022, approved on December 9, sets ambitious targets for the consumption of energy from renewable sources, going beyond the commitments made in the National Energy and Climate Plan 2030 and the roadmap to Carbon Neutrality 2050. This law reflects Portugal's commitment to reducing

through continuous market analysis, aiming to render regulatory principles practical without discouraging investments. Governments should strive to streamline licensing and permitting procedures and enhance collaboration among various involved authorities, with the goal of minimizing their substantial influence on project timelines. This is especially crucial for specific infrastructure projects like new pipelines, underground storage, and import/export terminals.

Mention of infrastructure-related barriers

Hydrogen powertrain Fuel Cell Vehicles (FCVs) represent a promising clean energy solution. However, the availability of specialized refuelling infrastructure possesses a significant challenge in Médio Tejo Region. At present, there are no hydrogen refuelling stations in the region, and only one in Portugal with private access. This lack of infrastructure hinders the widespread adoption of hydrogen-powered transportation, including buses, trains, and other public vehicles.

To facilitate the transition to low-emission hydrogen transportation, it is essential to establish a robust and extensive refuelling network. This network not only connects areas where low-emission hydrogen can be produced cost-effectively with urban centers but also manages fluctuations in both production and demand. Additionally, it ensures the system's resilience in case of supply disruptions.

Several barriers must be overcome to achieve this goal, including:

1. Insufficient development of very large-scale hydrogen supply and transport to hydrogen refuelling stations (HRS).

2. The absence of a connected national and international network of hydrogen infrastructure.

3. Limited solutions for automated communication between hydrogen trucks and HRS.

4. The lack of standardized refuelling protocols optimized for fast refuelling.

Addressing these challenges is crucial to make hydrogen-powered transportation a viable and environmentally friendly option in Médio Tejo Region and beyond. It requires coordinated efforts in infrastructure development and technology standardization to create a sustainable hydrogen ecosystem.

Regarding infrastructure, it plays a pivotal role in advancing the internal energy market by ensuring the interconnections of energy. These connections are essential for securing the energy supply, improving the functionality of energy systems, enhancing competition and stability in energy markets, facilitating market integration, promoting fairness and balance in setting energy costs and prices, and contributing to the achievement of the EU's energy, climate, and competitiveness objectives. It's also vital to emphasize the importance of regional cooperation, which should be strengthened to bring Member States, particularly Spain and France, closer together. The goal is to monitor and assess interconnection projects that address the connectivity needs of energy markets and systems.

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greenhouse gas emissions, with the global renewable energy target rising to 49% by 2030. Additionally, Decree-Law no. 72/2022, published on October 19, introduces exceptional administrative simplification measures for renewable energy projects, with specific conditions for municipal approval. Furthermore, Ministerial Order 15/2023, published on January 4, defines a system for the centralized purchase of biomethane and hydrogen, known as energy auctions, contributing to the injection of specific quantities into the national gas network.

III. Hydrogen Supply Stations (HRS)

Overview of the importance of HRS in ensuring a reliable and accessible supply infrastructure

HRS is a critical component of the infrastructure required to support the widespread adoption of hydrogen as a clean and sustainable energy carrier. HRS plays a vital role in ensuring a reliable and accessible supply infrastructure for hydrogen-powered vehicles and various industrial applications. This endpoint of the logistical H_2 market will enable hydrogen mobility, Along the hydrogen transport routes, strategic dispatch stations can be established. These stations function similarly to vehicle refuelling stations but are designed to handle larger volumes of hydrogen and may have specific connections for tanker truck loading. These Dispatch Stations play a crucial role in optimizing the distribution process, ensuring that larger quantities of hydrogen can be efficiently transported to various locations. As the world moves toward a more sustainable energy future, hydrogen is expected to play a crucial role in sectors such as transportation, industry, and energy storage. HRS serves as a bridge during the transition from fossil fuels to renewable hydrogen, facilitating the integration of hydrogen-based solutions into existing infrastructure. Hydrogen is not only used in transportation but also finds applications in various industrial sectors, including chemical production, steelmaking, and power generation. HRS and strategically placed Dispatch Stations ensures a reliable supply of hydrogen to these industries, promoting the use of clean hydrogen in their processes. It also promotes Energy Security, since H_2 can be produced from diverse sources, including renewable energy, natural gas with carbon capture and storage (CCS), and nuclear power. Diversifying the hydrogen supply through various production methods and geographic locations enhances energy security and reduces dependency on fossil fuels.

Identification of HRS limitations

There is currently one hydrogen service station open in Portugal, DRHYVE, an infrastructure installed by PRF Gas Solutions in Cascais, working solely for the Cascais Municipality, although the strategic plan approved by the Portuguese government foresees the opening of at least 50 hydrogen stations by 2030 in the country.

The limited availability of hydrogen infrastructure poses a significant obstacle to the widespread adoption of hydrogen mobility and industrial use, hindering the interest and investment potential of various stakeholders in the sector. To instigate positive change, concerted efforts are needed to accelerate the deployment of hydrogen stations as well as green hydrogen production across the country. This involves ensuring strategic locations and accessibility to the public, encouraging private investment, collaborating with key industry players, promoting public awareness campaigns, and streamlining regulatory processes.

Mention of safety-related barriers, such as negative public perception and the need for clear safety standards

The potential of hydrogen as a clean energy source in Portugal is significant. However, the safety-related challenges intrinsic to hydrogen usage present substantial barriers to its widespread adoption. These barriers are mostly technical or logistical but also revolve around public perception and regulatory standards.

The adoption and implementation of new technologies or initiatives always bring negative perceptions, and the public perception of hydrogen safety forms a critical barrier to its acceptance.

Hydrogen has a highly flammable nature[2], coupled with incidents in the past associated with its use, contributing to a sense of unease among the public. This concern often outweighs the potential environmental benefits and the fact that when handled correctly, hydrogen is as safe as other fuels. To address negative public perception its fundamental to develop targeted, effective communication and dissemination tools, to educate the public about hydrogen's safety features, environmental benefits, and safety risks management.

Regulatory standards, or the lack thereof, form another significant barrier to hydrogen. Like many other countries, Portugal is grappling with the need to update and adapt the safety standards and regulations to account for the use of hydrogen in different sectors. These regulations need to be clear, robust and are essential to guide the safe production, storage, transportation, and use of hydrogen and to provide the framework within which public utilities, transportation providers, and other potential hydrogen users can confidently develop their hydrogen capabilities[3].

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[2] Hydrogen does have several safety advantages compared to conventional fuels, but it also requires specific safety measures due to its unique properties. Since hydrogen is a gas under high pressure, similar precautions to those applied for liquefied petroleum gas (LPG) are necessary. Therefore, safety standards and precautions are crucial.

[3] In terms of safety standards, the current practice in the region of Medio Tejo aligns with the recommendations provided by PRF (hydrogen gas solutions company and owner of the portable HRS): using only steel crowd safety barriers around the portable HRS. Additionally, a protocol similar to that of LPG is followed for refuelling the FCEBus.

IV. Volumes of Hydrogen production required

How many hydrogen tons must be produced and at what breakeven price to empower a real hydrogen mobility model to be implemented[4]?

In 2022, Médio Tejo public transport system had a total of 1,178,743 passengers with 3,106,964 km travel between all fleet. In recent years, there has been a decline in the total sales of diesel, coloured diesel (diesel used for specific purposes with lower taxes), and fuel oil. The decrease in sales may be attributed to various factors, but it is worth nothing that the impact of the pandemic could be a contributing factor to these numbers.

	Diesel (tons)			**Coloured-Diesel (tons)**			**Fuel-oil (tons)**		
Year	2019	2020	2021	2019	2020	2021	2019	2020	2021
Médio Tejo	292,975	250,004	246,777	14,826	14,810	11,097	11,329	7,188	5,108

Table 4. Fuel Sold in Médio Tejo Region 2019-2022. (Statistics of Portugal)

According to Hussein and Felipe (2022) (Felipe e Hussein), fuel consumption of a Fuel Cell Electric Truck will reach 6.7 kg/100 km at worst case and with 20% increase max cargo compared to the diesel-powered trucks. Diesel powered trucks have an average of 30 L/100 km (assuming between mid and heavy size trucks) (Solutions). Buses diesel consumption range between 19-24 L/100 km and Fuel Cell Electric Buses from 4-7 kg/100 km (Ivkovic, Kaplanović e Milovanović).

Assumptions:

- Fuel Cell Electric Truck (FCET): 6.7 kg/100 km
- Fuel Cell Electric Bus (FCEB): 5 kg/100 km
- Fuel Cell Electric Vehicles (light) (FCEV): 0.79 kg/100 km (Toyota Mirai)
- Diesel Truck: 30 L/100 km
- Diesel Bus: 19 L/100 km
- Diesel Car: 6 L/100 km

- CO_2 emissions:

One litre of diesel weighs 835 grams and contains 86.2% carbon, which is equivalent to 720 grams of carbon in each litre of diesel. It takes 1,920 grams of oxygen to burn 1 litre of diesel. The carbon dioxide produced is therefore equal to the sum of 720 grams of carbon and 1,920 grams of oxygen. That's 2,640 g/L CO_2 produced per 1 liter of diesel burned.

Therefore for 1 kg of diesel: 2.640 kg_{CO_2} / 0.835 kg_{Diesel} = **3.162 kg CO_2 per kg diesel burnt.**

Emission of CO_2 for diesel, coloured-diesel and fuel-oil sold at Médio Tejo Region (2021):

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[4] Preliminary information: this topic is being worked on to collect real data from logistics companies in Médio Tejo Region and may be subject to updates.

262,982,000 kg_{Diesel} x 3.162 kg_{CO_2} = **831,549 tons of CO_2** emitted.

Emission of CO_2 for the public transportation system of Médio Tejo Region (2022):

3,106,964 km travelled *19 L/100 km = 590,323 L Diesel used

590,323 L * 2.64 kg/L = 1,558,453 kg CO_2, **1,558.45 tons of CO_2** emitted.

- H_2 Production Required:

H_2 in Médio Tejo requirement to replace Diesel assuming it was used fully on diesel cars:

FCEV: 246,777,000 kg Fuel / 0.0500 kg/km[5] = 4,935,540,000 km

FCEV: 0.0079 kg/km * 4,935,540,000km = 38,990,766 kg, 38,991 tons H_2 needed.

H_2 in Médio Tejo requirement to replace Diesel assuming it was used fully on diesel trucks:

FCET: 246,777,000 kg Fuel / 0.2505[6] kg/km = 985,137,725 km

FCET: 0.067 kg/km * 985,137,725 km = 66,004,228 kg, 66,004 tons H_2 needed.

H_2 in Médio Tejo requirement to replace Coloured-Diesel and Fuel-oil, used fully on diesel trucks[7]:

16,205,000 kg Fuel / 0.2505 kg/km = 64,690,619 km travelled (equivalent)

FCET: 0.067 kg/km * 64,690,619 km = 4,334,271.5 kg, 4,334 tons H_2 needed.

H_2 in Médio Tejo requirement to replace Public Transportation system:

FCEB: 3,106,964 km travelled * 0.0500 kg/km = 155,348 kg, 155 tons H_2 needed.

H_2 requirement to replace 100% diesel, coloured-diesel and fuel-oil: 38,991 to 66,004 tons of H_2, 4,334 tons of H_2 and 155 tons H_2 for public transportation system of Médio Tejo Region, respectably.

Assumptions:

- Diesel Price reference: 1.60 €/L
- Diesel Used: 246,777,000 kg / 0.835 kg/L = 295,541,317.36 L

(295,541,317.36 L * 1.60 €/L = 472,866,108 €/year)

-Public transportation system: 590,323 L *1.60 €/L = 944,517.06 €/year)

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[5] 0.05 kg/km was calculated by taking the diesel car average consumption in liters and multiplying it by the diesel density: (6 L/100 km * 0.835 kg/L).

[6] 0.2505 kg/km was calculated by taking the diesel truck average consumption in liters and multiplying it by the diesel density: (30 L/100 km * 0.835 kg/L).

[7] Here is the equivalent calculation for the truck, but under the assumption that the company benefits from a tax incentive for its operations, leading to a decreased diesel cost. It's important to note that only a limited number of activities in Portugal qualify for this tax reduction on diesel prices.

- Coloured Diesel price reference: 1.25 €/L (19,407,185.63 L[8] * 1.25 €/L = 24,258,982 €/year)

Target price for H_2 for FCEV: 472,866,108 € / 38,990,766 kg = **12.13 €/kg H_2**

Target price for H_2 for FCET: 472,866,108 € / 66,004,228 kg = **7.16 €/kg H_2**

Target price for H_2 for FCET: 24,258,982 € / 4,334,272 kg = **5.60 €/kg H_2**

Target price for H_2 for FCEB in public transportation system: 944,517.06 € / 155,348 kg = **6,08 €/kg H_2**

These results were obtained considering that all diesel/colored-diesel sold was 100% dedicated to each type of vehicle:

-The price of hydrogen per kilogram to be on par with the price of diesel for light vehicles, considering only the energy necessary to cover the same distance, would be **12,13 €/kg H_2**. Below this price, FC starts to get cheaper than using diesel powered engines.

-The price of hydrogen per kilogram to be on par with the price of diesel for Heavy trucks, considering only the energy necessary to cover the same distance, would be **7.16 €/kg H_2**. Below this price, FC starts to get cheaper than using diesel powered engines.

-The price of hydrogen per kilogram to be on par with the price of coloured diesel, considering only the energy necessary to cover the same distance, would be **5.60 €/kg H_2**. Below this price, H_2 starts to get cheaper than using diesel powered engines.

The price of hydrogen per kilogram to be on par with the price of diesel for the public transportation system of Médio Tejo, considering only the energy necessary to cover the same distance, would be **6.08 €/kg H_2**. Below this price, H_2 starts to get cheaper than using diesel powered engines.

The study report on Fuel Cells Hydrogen Trucks – Heavy-duty's High Performance Green Solution, published in December 2020, presented data on specifics routes these trucks operate on to explore potential opportunities for Fuel Cell Hydrogen (FCH) technology in these operations and business cases. To conduct these case studies, a balanced geographical distribution across Europe was ensured to provide a varied perspective on the application potential of FCH technology in various national contexts. The report achieved the following results regarding Fuel and Energy Costs:

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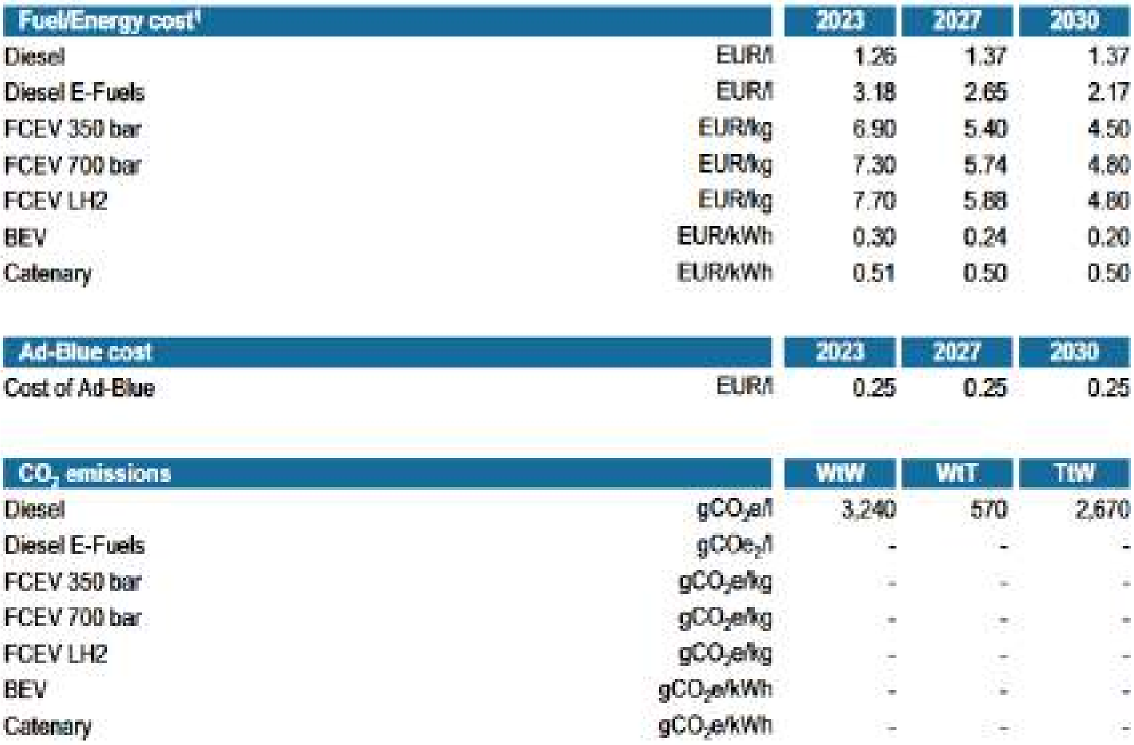
[8] Fuel-oil and coloured-diesel used in 2021 under 7 reference condition (16,205,000 kg / 0.835 kg/L) =19,407,185.63 L.



Fuel/Energy cost[1]		2023	2027	2030
Diesel	EUR/l	1.26	1.37	1.37
Diesel E-Fuels	EUR/l	3.18	2.65	2.17
FCEV 350 bar	EUR/kg	6.90	5.40	4.50
FCEV 700 bar	EUR/kg	7.30	5.74	4.80
FCEV LH2	EUR/kg	7.70	5.88	4.80
BEV	EUR/kWh	0.30	0.24	0.20
Catenary	EUR/kWh	0.51	0.50	0.50

Ad-Blue cost		2023	2027	2030
Cost of Ad-Blue	EUR/l	0.25	0.25	0.25

CO_2 emissions		WtW	WtT	TtW
Diesel	gCO$_2$e/l	3,240	570	2,670
Diesel E-Fuels	gCOe$_2$/l	-	-	-
FCEV 350 bar	gCO$_2$e/kg	-	-	-
FCEV 700 bar	gCO$_2$e/kg	-	-	-
FCEV LH2	gCO$_2$e/kg	-	-	-
BEV	gCO$_2$e/kWh	-	-	-
Catenary	gCO$_2$e/kWh	-	-	-

Figure 10. Energy/Fuel cost and emission - Case study (FCH2JU e Berger)

> Cost of energy includes infrastructure surcharges and taxes.

> Diesel and Diesel E-Fuels including taxation at the pump.

> BEV charging electricity based on base electricity price, grid fees, tariffs and surcharges for fast charging infrastructure – Prices ultimately depend on the utilisation.

> Catenary charging includes utilisation charges for catenary infrastructure (e.g., substation, grid connection, catenary wires).

<u>- Electrolyser capacity required:</u>

To produce 1 kg of H_2 is needed 33.32 kWh/kg, but the efficiency is 65 % (average reference) the real necessity of electricity is 51,26 kWh/kg (33.32/0.65).

Power needed with μ = 65 % and 12 h a day working:

FCEB: 155,348 kg/year * 51.26 kWh/kg = 7,963,138.5 kWh/year / 12*365 h/year = 1,818 kW, **1.8 MW electrolyser capacity needed.**

FCEV: 38,990,766 kg/year * 51.26 kWh/kg = 1,998,666,665 kWh/year / 12*365 h/year = 456,316.6 kW, **456 MW electrolyser capacity needed.**

FCET: 66,004,200 kg/year * 51.26 kWh/kg = 3,383,375,292 kWh/year / 12*365 h/year = 772,460 kW, **772.46 MW electrolyser capacity needed.**

To replace coloured diesel and fuel oil: 4,334,200 kg/year * 51.26 kWh/kg = 222,171,092 kWh/year / 12*365 h/year = 50,723.99 kW, **50,724 MW electrolyser capacity needed.**

In summary, a 1.8 MW electrolyser is needed to power the public transportation system in Médio Tejo Region, a 51 MW electrolyser(s) to power the activities which have special tax deduction (like agro and train transportation of goods) and a 456 to 773 MW electrolyser(s) to replace all normal diesel sold in the Médio Tejo Region between light vehicles and heavy trucks.

The prices of H_2 vary between different activities, but to breakeven the prices of fossil fuel the kg of H_2 can be for **FCEV - 12.13 €/kg H_2, FCET - 7.16 €/kg, FCEB - 6.00 €/kg and 5.60 €/kg** to replace the tax incentive activities (coloured-diesel and fuel-oil).

Mapping of the most important long distance logistics companies regionally/nationally[9]:

Top 8 companies ranking in the sector H49410 - Road freight transport in Portugal in an overall of 345.635 main companies in Portugal.

National Long-Distance Logistics Companies:

1. **Doctrans - Transportes Rodoviários De Mercadorias, Lda:** Doctrans is a road freight transportation company operating in Portugal, specializing in the delivery of goods by road. Location: Lisbon, Rank: 149 Overall Nationally
2. **TJA - Transportes J. Amaral, S.A.:** TJA is a transportation company that provides road transportation and logistics solutions, catering to various cargo transportation needs. Location: Aveiro, Rank: 314 Overall Nationally
3. **Luís Simões - Logística Integrada, S.A.:** Luís Simões is an integrated logistics company that offers comprehensive services, including road transportation, warehousing, and distribution. Location: Lisbon, Rank: 315 Overall Nationally
4. **Lamision - Sociedade De Transportes, Lda:** Lamision is a cargo transportation company operating in Portugal, specialized in road freight transportation. Location: Lisbon Rank: 324 Overall Nationally
5. **LASO - Transportes, S.A.:** LASO is a transportation company with a wide range of services, including road transportation and logistics for various industries. Location. Lisbon, Rank: 338 Overall Nationally
6. **Patinter - Portuguesa De Automóveis Transportadores, S.A.:** Patinter is a company specializing in automobile and heavy cargo transportation. They focus on specialized transportation solutions. Location: Viseu, Rank: 384 Overall Nationally
7. **Dachser Portugal, Sociedade Unipessoal, Lda:** Dachser is a global logistics company operating in Portugal. They offer road, air, and sea transportation services, as well as logistics solutions. Location: Oporto, Rank: 481 Overall Nationally

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[9] Preliminary information: this topic is being worked on in order to collect real data from logistics companies in the Médio Tejo Region, and may be subject to updates.

8. **Transportes Paulo Duarte, Lda:** Transportes Paulo Duarte is a transportation company dedicated to road freight services. They provide transportation solutions for various needs. Location: Lisbon, Rank: 677 Overall Nationally

Logistics Sector Nacional Rank	District	Company Name	Overall National Rank
1	Lisbon	Doctrans - Transportes Rodoviários De Mercadorias, Lda	149
2	Aveiro	TJA - Transportes J. Amaral, S.A.	314
3	Lisbon	Luís Simões - Logística Integrada, S.A.	315
4	Lisbon	Lamision - Sociedade De Transportes, Lda	324
5	Lisbon	LASO - Transportes, S.A.	338
6	Viseu	Patinter - Portuguesa De Automóveis Transportadores, S.A.	384
7	Oporto	Dachser Portugal, Sociedade Unipessoal, Lda	481
8	Lisbon	Transportes Paulo Duarte, Lda	677

Table 5. Top 8 Companies in the Logistics Sector in Portugal (Ranking)

Top 5 companies ranking in the sector H49410 - Road freight transport and H52213 - Other land transport auxiliary activities in Portugal – Médio Tejo Region.

Regional Long-Distance Logistics Companies (Médio Tejo Region):

1. **Transportes Broliveira, Lda:** Transportes Broliveira is a transportation company that specializes in road freight services. They offer solutions for the transportation of goods by road. Rank: 742 Overall Nationally
2. **Transbase - Transporte e Logística, S.A.:** Transbase is a company that offers both transportation and logistics services. They provide a range of logistical solutions, including road transportation. Rank: 896 Overall Nationally
3. **Greenyard Logistics Portugal, S.A.:** Greenyard Logistics is involved in logistics and transportation related to the food industry. They handle the transportation of fresh produce and other food products. Rank: 1394 Overall Nationally
4. **Medway Logistics Services, S.A.:** Medway Logistics Services is a subsidiary or division of Medway, a major railway and logistics company in Portugal. They likely focus on logistics solutions, potentially including road transportation. Rank: 1565 Overall Nationally
5. **Transporte Vieira Vacas, Lda**: Transporte Vieira Vacas is a transportation company specialized in road freight services. They likely provide transportation solutions for various cargo needs. Rank: 2951 Overall Nationally

Logistical Sector Region Rank	Municipality	Company Name	Overall National Rank
1	Ourém	Transportes Broliveira, Lda	742
2	Alcanena	Transbase - Transporte e Logística, S.A.	896
3	Torres Novas	Greenyard Logistics Portugal, S.A.	1394
4	Entroncamento	Medway Logistics Services, S.A.	1565
5	Santarém	Transporte Vieira Vacas, Lda	2951

Table 6. Top 5 Companies in the Logistics Sector in Médio Tejo Region (Ranking)

Breakeven purchase[10] price per company (what is the max price/kilo a company will be willing to pay in order to decarbonise)[11]

Looking solely at fuel costs, any price below **7.17 €/kg** of H_2 would serve as an incentive for any company with a fossil-fuelled vehicle fleet. Since hydrogen is a clean energy source, there would be no carbon taxes or other taxes associated with fossil fuels. Additionally, when transitioning from diesel-powered trucks or vehicles, a maximum of 20% more load capacity can be achieved, reducing the need for one new truck for every five diesel powertrains, if feasible for the same route.

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[10] For heavy transport.

11 Preliminary information: this topic is being worked on in order to collect real data from logistics companies in Médio Tejo regionMédio Tejo Region and may be subject to updates.

V. OMS and business model for decarbonization

Potential business models that would accelerate decarbonization considering the hydrogen price

- **Overview:**

As part of its energy transition strategy, Médio Tejo Region intends to develop a comprehensive hydrogen ecosystem in its territory. This ecosystem encompasses the entire value chain, from green hydrogen production and transportation/distribution to its utilization in the transport sector and injection into the gas grid. It's this synergy that propels us towards a future less reliant on fossil fuels.

Within the framework of Médio Tejo Mobility Plan and SmarTejo, hydrogen emerges as a viable solution for the transition of multiple sectors. Initially, hydrogen presents an avenue to harness surplus renewable electricity capacity, thereby facilitating the incorporation of additional capacity in the region. Moreover, hydrogen represents a promising opportunity to cultivate a sustainable, low-carbon transportation solution that caters to the distinctive demands of the region and its residents. This initiative aims not only to diminish the carbon footprint of the transportation sector, aligning with the commitment to achieve carbon neutrality by 2030 but also to enhance intercity connectivity, providing improved access to services and employment opportunities.

- **Implementation Plan:**

A plan designed to reduce reliance on fossil fuels by promoting the adoption of fuel cell-powered vehicles, incorporating green hydrogen in the industrial sector, and injecting green hydrogen into the natural gas grid. This plan is guided in mind with the principles of sustainability and clean energy.

Decentralized Modular Green Hydrogen Production: Decentralized hydrogen production using renewable energy sources such as wind or solar power ensures a clean and sustainable source of hydrogen. This method helps reduce the carbon intensity of hydrogen production.

Transition to Fuel Cell-Powered Vehicles: This aligns with the goal of reducing the carbon footprint in transportation. Fuel cell vehicles, especially those powered by green hydrogen, can significantly reduce emissions, making them a sustainable choice for the future.

HRS (Hydrogen Refuelling Stations): Establishing HRSs is a key step to support the adoption of fuel cell vehicles. This infrastructure development is crucial for providing convenient refuelling options and promoting the use of fuel cell vehicles.

Distribution to the Natural Gas Grid: Injecting green hydrogen into the natural gas grid is a way to decarbonize the gas supply using already existing infrastructure. It can serve as an energy carrier, allowing the broader use of renewable energy in various sectors.

Use in Industry: The utilization of green hydrogen in industrial processes can lead to a significant reduction in greenhouse gas emissions. It aligns with the goal of promoting cleaner and more sustainable industrial practices.

- **Market:**

First Phase: Focuses on replacing fossil fuel-powered vehicles with fuel cell-powered vehicles in public transportation companies and private logistics companies within the region. This can significantly contribute to reducing pollutant emissions and promoting cleaner technologies.

Second Phase: Injecting hydrogen into the natural gas grid or using hydrogen directly in the industry is an interesting approach to diversify the energy matrix and reduce dependence on fossil fuels, especially fossil methane. This can contribute to decarbonizing the industry and energy generation.

Third Phase: Extending the use of fuel cell vehicles to the private transportation sector is an important step in promoting sustainable mobility. This can be facilitated by establishing hydrogen refuelling infrastructure and providing incentives for the acquisition of fuel cell vehicles.

- **Financial:**

The plan originates from the 'Médio Tejo Hydrogen Project: Options Report Deployment of Fuel Cell Vehicles, Supporting Infrastructure, and Injection of Hydrogen in the Gas Grid in Médio Tejo Region,' developed in 2021 as part of the Project Development Assistance program by FCHJU. Considering this report, we present the following options:

This plan considers the installation of a hydrogen production (electrolysers modules) site at Pego Power Plant. It can include the acquisition of 30 fuel cell coaches for public transport between cities, 15 fuel cell trucks for biomass transportation to the power plant, 10 urban buses, 5 refuse trucks and 25 vans are deployed, which are supplied by a distributed network of hydrogen refuelling stations, also includes the injection of hydrogen into the gas distribution grid.

Considering the identified usages and the hydrogen demand associated to them, the dimensioning of the production site leads to the following characteristics:

- Power of the electrolyser: ~9 MW
- Power efficiency: ~60,6 %
- Estimated number of hours operated per year: ~6,200 h/year
- Hydrogen production per year: 1 020 tH_2/year

Based on the current natural gas demand in Médio Tejo, estimated that having 5% of hydrogen in the Médio Tejo natural gas distribution grid represents a demand of 500 tH_2/year. Green hydrogen injection in the gas grid brings several opportunities:

- It couples the electricity and the gas sectors.

- It helps decarbonising the gas grid and thus decarbonising end-user activities (heat generation, etc.).

- It enables energy storage as excess renewable electricity can be used to produce green hydrogen injected in the grid.

Category	Cost Item
Hydrogen production	• ~9 MW (nominal capacity of 3.5 tH_2/day) of electrolyser installed at the former coal power plant of Pego • 1,020 tH_2 produced per year
Hydrogen Distribution	Distribution at two different sites: • One HRS (capacity 1,400 kgH_2/day) at the production site. This HRS will refuel the 12 fuel cell coaches (new line) and the fuel cell trucks. • One HRS (capacity of 500 kgH_2/day). This HRS will refuel the additional usages, such as the 17 coaches which will operate on the existing lines, the refuse trucks and the cars and vans. • As one HRS will not be located at the production site: delivery of hydrogen via tube trailers
Hydrogen Injection	• Injection station in gas distribution grid
Hydrogen Use	• Mobility: 12 fuel cell coaches (196.9 tH_2/year), 15 trucks for forest residues transport (196 tH_2/year), 5 refuse trucks (26 tH_2/year), 10 urban minibuses (11 tH_2/year), 16 fuel cell coaches (existing lines) (80 tH_2/year), vans for private local companies (9,1 tH_2/year)[12]. • Hydrogen injection: in natural gas distribution grid (500 tH_2/year) • Industry: no demand identified at this stage

Table 7. Estimated Budget for phase 1 and 2. (FCH BM)

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[12] During the Project Development Assistance program, the intermunicipal community of Médio Tejo CIMT (*Comunidade Intermunicipal do Médio Tejo*) was supported in the development of a hydrogen ecosystem that includes a complete value chain, including green hydrogen production, transport, distribution, use in the transport sector (including a new circular fuel cell coach lines linking 6 cities in Médio Tejo) and injection into the gas grid. Several options have been derived depending on the hydrogen demand and production opportunities identified in the region.

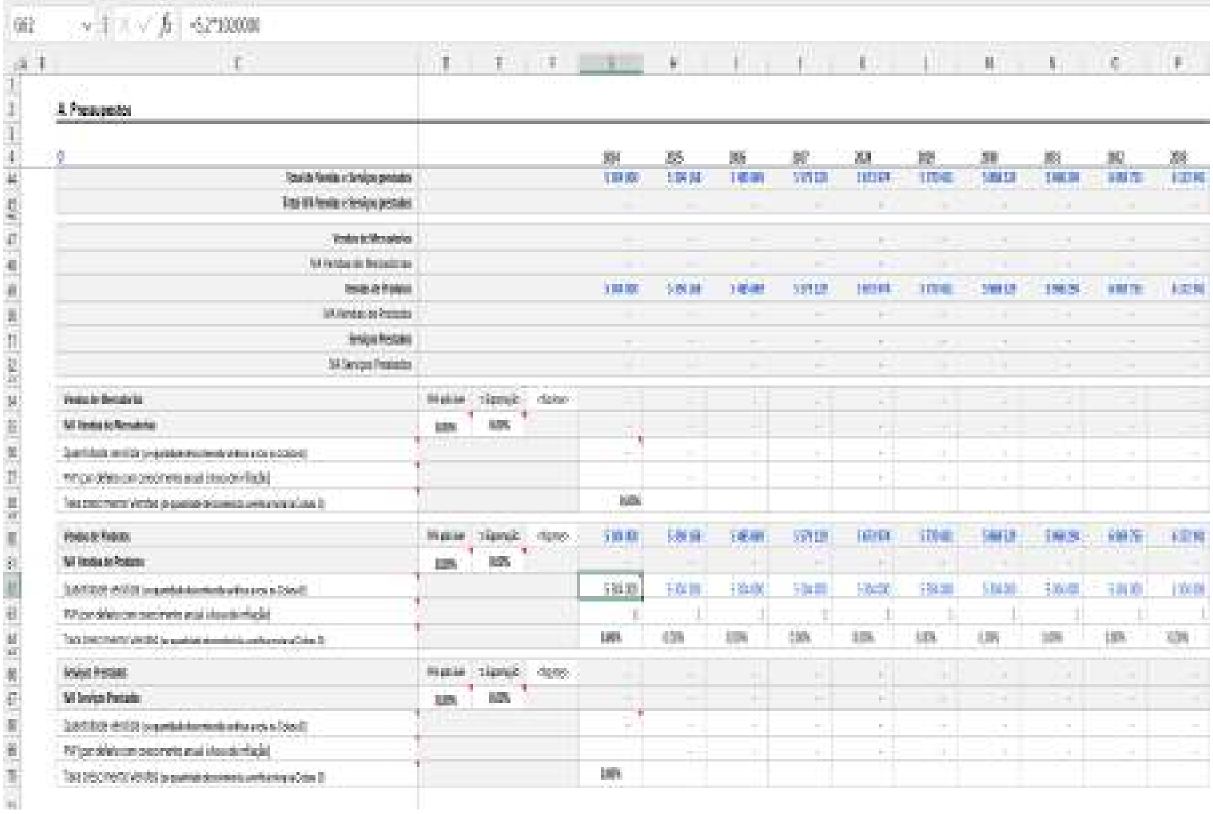
Category	Cost Item	Total Capital Cost (€) *
Infrastructure	Modular Electrolysers, 9 MW (including filling center and tube trailers)	~ 20M
	Refuelling stations (capacity 1400 kgH_2/day and 500 kgH_2/day, 350 bar)	~ 4.5M (3.25M and 1.3M for the two HRS)
	Injection station	~ 500k
Vehicles	30 x Fuel cell coaches	14.5M
	15 x Fuel cell trucks	~ 7,5M
	10 x Fuel cell urban buses	~ 6M
	5 x Fuel cell refuse trucks	~ 3M
	25 x Fuel cell vans	~ 630k
	TOTAL	~ 56.63M

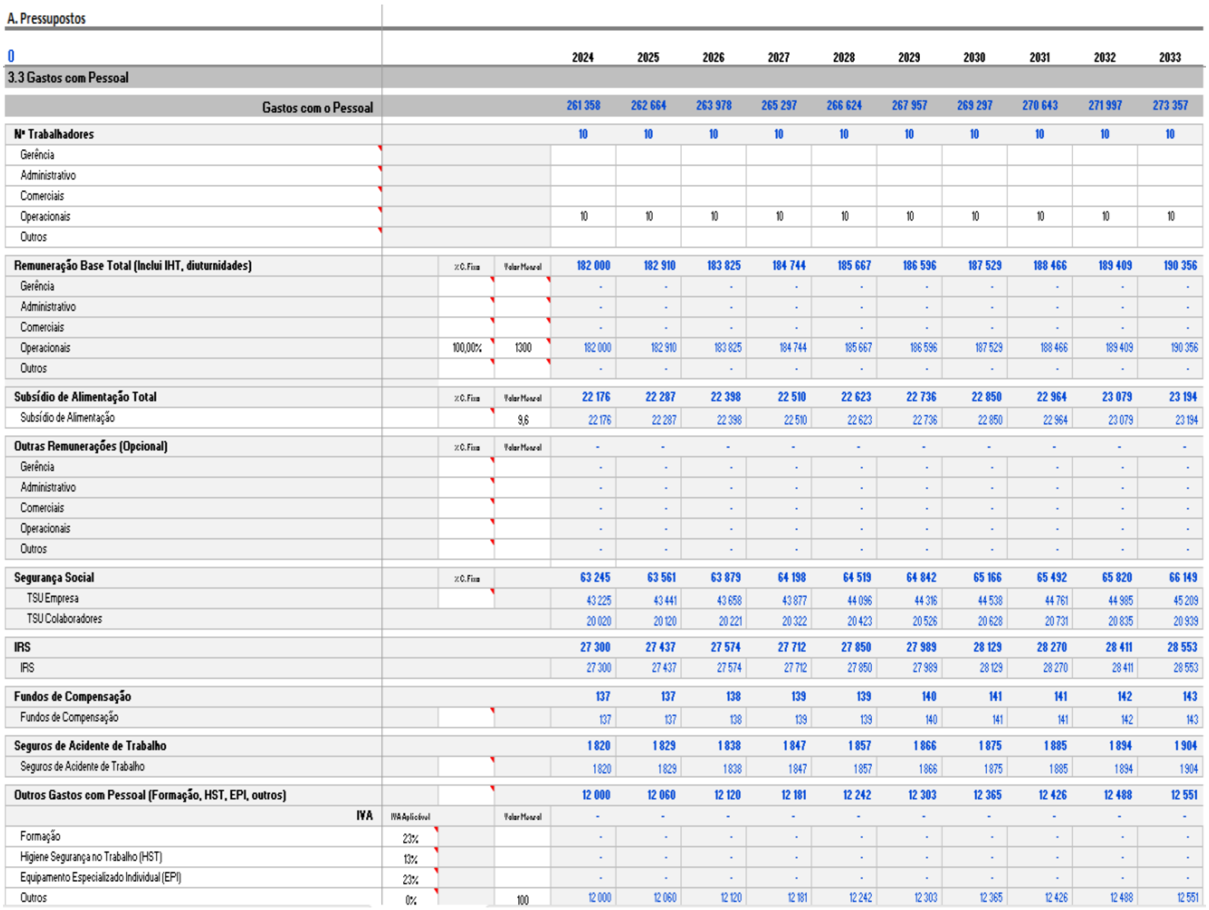
Table 8. Summary of the Plan

* Estimations based on the data of the FCH JU

Using a 10-year Investment Project Evaluation Tool we can observe a payback of 9.72 years and a TIR of 4.92 % with the follow assumptions:

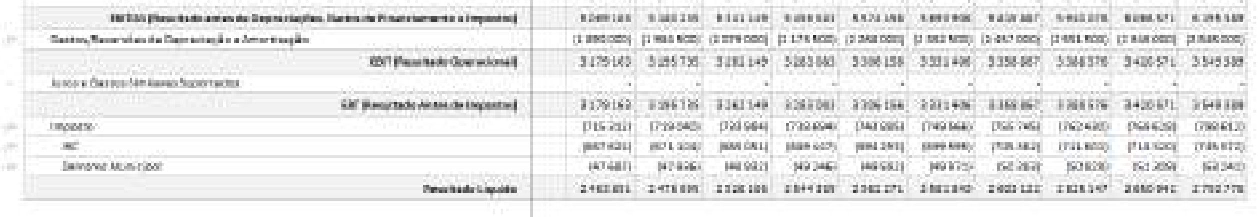
- Selling price/value kgH_2: 5.2 €/Kg (Clean Hydrogen Partnership)
- Green H_2 Production: 1,020 tH_2/year
- Total Base Remuneration per Year for Employees (10 Technicians/ 2 shifts): 261 358€/year (1300€/month per worker)
- CAPEX: 56,700,000 €
- 5% maintenance cost/year and other residual OPEX





A. Pressupostos

0				2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
3.3 Gastos com Pessoal													
Gastos com o Pessoal				261 358	262 664	263 978	265 297	266 624	267 957	269 297	270 643	271 997	273 357
Nº Trabalhadores				10	10	10	10	10	10	10	10	10	10
Gerência													
Administrativo													
Comerciais													
Operacionais				10	10	10	10	10	10	10	10	10	10
Outros													
Remuneração Base Total (Inclui IHT, diuturnidades)		%C.Fixa	Valor Mensal	182 000	182 910	183 825	184 744	185 667	186 596	187 529	188 466	189 409	190 356
Gerência				-	-	-	-	-	-	-	-	-	-
Administrativo				-	-	-	-	-	-	-	-	-	-
Comerciais				-	-	-	-	-	-	-	-	-	-
Operacionais		100,00%	1300	182 000	182 910	183 825	184 744	185 667	186 596	187 529	188 466	189 409	190 356
Outros				-	-	-	-	-	-	-	-	-	-
Subsídio de Alimentação Total		%C.Fixa	Valor Mensal	22 176	22 287	22 398	22 510	22 623	22 736	22 850	22 964	23 079	23 194
Subsídio de Alimentação			9,6	22 176	22 287	22 398	22 510	22 623	22 736	22 850	22 964	23 079	23 194
Outras Remunerações (Opcional)		%C.Fixa	Valor Mensal	-	-	-	-	-	-	-	-	-	-
Gerência				-	-	-	-	-	-	-	-	-	-
Administrativo				-	-	-	-	-	-	-	-	-	-
Comerciais				-	-	-	-	-	-	-	-	-	-
Operacionais				-	-	-	-	-	-	-	-	-	-
Outros				-	-	-	-	-	-	-	-	-	-
Segurança Social		%C.Fixa		63 245	63 561	63 879	64 198	64 519	64 842	65 166	65 492	65 820	66 149
TSU Empresa				43 225	43 441	43 658	43 877	44 096	44 316	44 538	44 761	44 985	45 209
TSU Colaboradores				20 020	20 120	20 221	20 322	20 423	20 526	20 628	20 731	20 835	20 939
IRS				27 300	27 437	27 574	27 712	27 850	27 989	28 129	28 270	28 411	28 553
IRS				27 300	27 437	27 574	27 712	27 850	27 989	28 129	28 270	28 411	28 553
Fundos de Compensação				137	137	138	139	139	140	141	141	142	143
Fundos de Compensação				137	137	138	139	139	140	141	141	142	143
Seguros de Acidente de Trabalho				1 820	1 829	1 838	1 847	1 857	1 866	1 875	1 885	1 894	1 904
Seguros de Acidente de Trabalho				1820	1829	1838	1847	1857	1866	1875	1885	1894	1904
Outros Gastos com Pessoal (Formação, HST, EPI, outros)				12 000	12 060	12 120	12 181	12 242	12 303	12 365	12 426	12 488	12 551
IVA	IVA Aplicável		Valor Mensal	-	-	-	-	-	-	-	-	-	-
Formação	23%			-	-	-	-	-	-	-	-	-	-
Higiene Segurança no Trabalho (HST)	13%			-	-	-	-	-	-	-	-	-	-
Equipamento Especializado Individual (EPI)	23%			-	-	-	-	-	-	-	-	-	-
Outros	0%		100	12 000	12 060	12 120	12 181	12 242	12 303	12 365	12 426	12 488	12 551



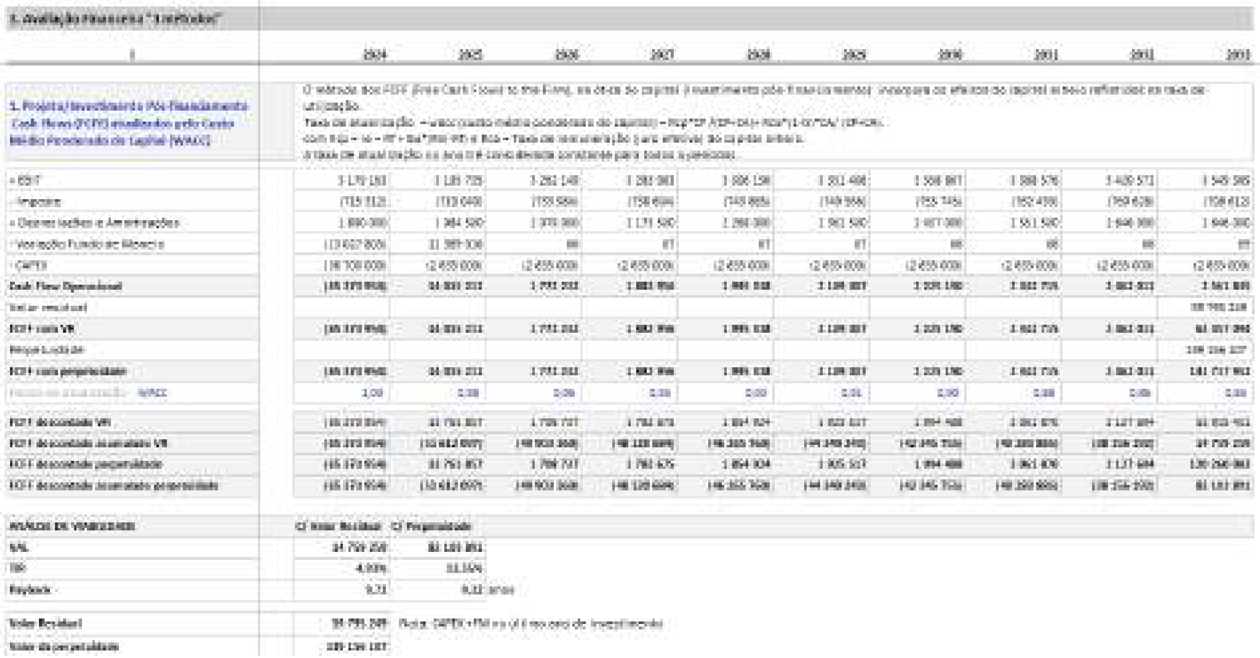


Figure 11. Sales, Personal Spendings and Financial Evaluation of the Business Plan (IAPMEI)

The demand for hydrogen originates from both the transportation sector and the injection of hydrogen into the gas grid. This dual application holds great potential for reducing CO_2 emissions, benefiting not only the transport industry but also all consumers linked to the gas distribution grid, including industrial and residential users.

This comprehensive strategy not only serves as a means to curtail emissions but also lays the groundwork for a versatile distribution and scaling model within the hydrogen value chain. It incorporates the use of modular electrolysers and the strategic deployment of two hydrogen refuelling stations (HRS) in Médio Tejo. These HRS locations offer enhanced flexibility for vehicles, making refuelling more convenient and accessible.

Furthermore, by placing HRS facilities not only at the production site but also in municipalities where fuel cell vehicles such as refuse trucks and coaches are in operation, this plan maximizes the utility of hydrogen as a fuel source. This not only benefits local residents but also contributes to the broader environmental goals. As the TRL and know-how increases the third phase would be easier to spread for the general public.

Overall, this plan addresses multiple aspects of the hydrogen economy, from production to distribution and utilization. It not only offers the reduced carbon emissions but also positions Médio Tejo as a regional leader in sustainable hydrogen production and distribution in the Center of Portugal.

VI. Subsidies/ aids/ support from local and regional governments that will support the implementation of the hydrogen model

All sectors will be called upon to contribute to the decarbonization of the economy, but in the next decade, it will be in mobility and transportation, as well as in the production and consumption of energy from renewable sources, where it will be necessary to impose a faster pace of transformation. Therefore, a greater concentration of investment needs to be directed towards these areas.

Fiscal policy can also play an important role in the energy transition by reflecting and incorporating the main social and environmental costs, internalizing externalities, and influencing behaviour change as a determining factor for competition and equity.

In this context, we can observe a significant reorientation of financial flows towards energy transition and decarbonization, along with the growth of new forms of financing using technological innovation (crowdfunding, local investment cooperatives, among others) that will support this transition.

Within the Hydrogen Value Chain, the following programs feature calls:

1. The “Plano de Recuperação e Resiliência”, Recovery and Resilience Plan (RRP) funded by NextGeneration EU instrument, is a nationally applied program with an execution period until 2026. It aims to implement a set of reforms and investments aimed at restoring sustained economic growth after the pandemic. This plan strengthens the objective of convergence with Europe over the next decade.
    a. “C14-Hydrogen and Renewables”: The investments planned in this context, to be promoted by the Environmental Fund, can take various forms. This includes supporting projects to produce hydrogen and biomethane from renewable sources, as well as technologies that have been tested but are not yet widely distributed in the national territory. Both aspects aim at self-consumption and/or injection into the grid. The goal is to achieve a production capacity of 264 MW for renewable gases. The production of renewable gases, such as hydrogen or biomethane, is exclusively from renewable energy sources. (PRR.GOV)
2. The “Centro2030 - Fundo da Transição Justa” (Center2030 - Just Transition Fund) Intended to mitigate the socio-economic impacts of the transition to carbon neutrality in the Médio Tejo Region resulting from the closure of the Pego Thermal Power Plant in Abrantes. This is achieved through support for the diversification of economic activities, which includes renewable energies value chain in the region. (Centro2030.GOV)
3. The Environmental Fund (Fundo Ambiental) was created to enhance the effectiveness of environmental policy by consolidating resources from various existing funds. It provides a more adaptable and financially capable instrument to address environmental challenges. This initiative was established through Decree-Law No. 42-A/2016, effective from January 1, 2017. The fund's rules for allocation, management, monitoring, and revenue utilization were defined in this legislation. It led to the discontinuation of several other environmental funds. In 2021, additional changes were made with Decree-Law No. 114/2021, which included the integration of the Permanent Forestry Fund, Innovation Support Fund, Energy Efficiency Fund, and Systemic Sustainability Fund for the Energy Sector into the Environmental Fund. Within this Fund the Calls we can encounter to support the implementation of hydrogen model is:

City/intercity mobility buses

Call Decarbonization of Public Transportation (Descarbonização Transportes Públicos) (Fundo Ambiental DTP): the main objective is to support the acquisition of efficient buses that use clean energy sources, i.e., with better environmental performance, through the purchase of new buses powered exclusively by electricity (batteries) or hydrogen (fuel cells), with no emissions of PM, NO_x, CO, and UHC, and the installation of hydrogen refuelling stations and electric charging infrastructure for use by the vehicles to be acquired, through a competitive bidding process based on objective, transparent, and non-discriminatory criteria. This program was endowed with 48,000,000 € in 2022.

City/intercity mobility vehicles

No aids/support are in order on this point regionally or nationally.

Long distance trucks

No aids/support are in order on this point regionally or nationally.

Last mile vans

No aids/support are in order on this point regionally or nationally.

VII. Scouting of innovating solutions on hydrogen mobilities

Aviation

French startup Turbotech designs hybrid-electric propulsion systems for airplanes and electric-vertical take-off and landing (E-VTOL) vehicles. TG-R55 and TG-R90 are the startup’s turbogenerators that produce electric power onboard, presented in flight in 2023. When used in conjunction with batteries, they offer up to 10 times more range, compared to full-electric plane systems. The turbogenerators combine electric generators and turbines, fitted with integrated annular exchangers which enable exhaust gas energy recovery. The startup’s turbogenerators allow for lower weight expenditure on the vehicle, increasing efficiency of travel. The startup also designs a low emission turboprop engine, TP-R90. (Startus Insights)

Railway

Rail is also adding to hydrogen consumption as hydrogen trains are being trialled and adopted along more routes. In addition, several fuel cell ferries are beginning operation in 2023, which will further diversify hydrogen use for transport applications. Orders for ammonia- and methanol15 ready vessels could also result in additional hydrogen use for shipping in the coming years if these technologies reach commercial maturity. (IEA)

Roadway

NamX, a Moroccan start-up, has presented a prototype fuel cell SUV that can be fuelled in part by replaceable hydrogen capsules, with plans to launch in 2026. (IEA)

Activity is also increasing with respect to hydrogen combustion, which allows for retrofitting of diesel engines, as done by Technocarb and CMB.TECH. The latter anticipate converting up to 20 trucks per month. (IEA)

PRF Gas Solutions has officially introduced the first portable hydrogen refuelling station in Portugal, named DRHYVE. It currently supplies vehicles at 350 bar, with future plans to accommodate 700 bar for light vehicles. Developed entirely by PRF, the station marks a step towards autonomous solutions, with upcoming units designed for local hydrogen production. (PRF)

Conclusions:

The integration of hydrogen mobility in Médio Tejo Region is a strategic response to the imperative of decarbonizing the transport sector and achieving regional sustainability goals, establishing a southern hydrogen corridor linking Portugal to Europe. However, several limitations, constraints, and barriers must be addressed to ensure the successful development and adoption of hydrogen mobility in the region.

As we move towards a decarbonized future, diversifying our power sources becomes crucial since relying on only one, like fossil fuel, is no longer feasible. Hydrogen emerges as a key player in the green transition, offering a versatile alternative to replace fossil fuels in various applications. Beyond its role in industrial processes such as ammonia and methanol production, as well as the metallurgical industry for steel production, electronics for material purification, and the food industry for the hydrogenation of oils, hydrogen proves indispensable across diverse industrial processes to a pivotal role in mobility, serving as a sustainable solution when electrification is not reliable. Hydrogen provides capabilities ranging from short to long distances, 24/7 fast response, heavy cargo transport, fast refuelling, to intensive use scenarios. Hydrogen has, among other advantages, the following main benefits:

(i) in complementarity with the electrification strategy, it allows for reducing the costs of decarbonization.

(ii) substantially reinforces supply security in the context of decarbonization, as hydrogen enables the storage of renewable electricity for long periods.

(iii) reduces energy dependence by using endogenous sources in its production.

(iv) decreases greenhouse gas emissions in various sectors of the economy since it facilitates the easier replacement of fossil fuels (e.g., refining, chemical, metallurgical, cement, extractive, ceramic, and glass industries).

(v) promotes efficiency in energy production and consumption by allowing scalable solutions tailored to needs, close to the point of consumption and distributed throughout the national territory.

(vi) fosters economic growth and employment through the development of new industries and associated services.

(vii) Hydrogen value chain inserts in a economies of scale, this easy and fast scalable approach not only improves economic efficiency but also contributes to making hydrogen a more cost-effective option.

The lack of Hydrogen Refuelling Stations (HRS), the absence of operational hydrogen refuelling stations in Portugal, especially in Médio Tejo Region, poses a significant challenge. The dearth of infrastructure hinders the growth of hydrogen-powered transportation, including buses, trains, and other public vehicles.

Safety concerns and negative public perception regarding the safety of hydrogen persist, although it's a small obstacle. Addressing this minor challenge requires targeted communication to educate the public about the safety features and environmental benefits of hydrogen, highlighting its safe usage when handled correctly.

The absence of infrastructure development on an extensive and efficient distribution network for hydrogen limits the expansion of fuel cell mobility solutions. The lack of interconnected national and international hydrogen infrastructure impedes the seamless integration of hydrogen-powered transportation.

A clear regulatory framework and adapted safety standards and regulations for hydrogen usage in Portugal pose a significant hurdle. A well-defined regulatory framework is essential to guide the safe production, storage, transportation, and use of hydrogen, instilling confidence in investors and stakeholders.

The substantial initial costs associated with implementing hydrogen technologies in mobility, including the purchase of vehicles and the development of refuelling networks, present financial challenges for public transport agencies and governments.

Addressing these limitations is crucial for the successful implementation of hydrogen mobility in Médio Tejo Region and subsequent spread. Hydrogen, as a clean and sustainable energy carrier, holds the potential to significantly contribute to the decarbonization of the transport sector. Overcoming these barriers is vital for the following reasons:

1. Environmental Impact: Hydrogen-powered transportation offers a clean and emission-free alternative to conventional fossil fuel-powered vehicles. This will contribute to reducing greenhouse gas emissions and combating climate change.
2. Economic Development: The establishment of a robust hydrogen mobility infrastructure will stimulate economic development by creating skilled jobs, fostering industrial innovation, and attracting private investments.
3. Commitment to Decarbonization: The Médio Tejo Region's commitment to decarbonization aligns with national and European targets. Overcoming barriers is essential for realizing these commitments and contributing to a sustainable and resilient energy future.

Stakeholders, including government entities, private businesses, research institutions and European Commission should collaborate to address infrastructure and regulatory challenges. Shared efforts can accelerate the development of hydrogen mobility in the region. Strategic investments in hydrogen infrastructure, including production, refuelling stations, and transportation fleets, are crucial. For this, public-private partnerships can provide the necessary financial support for the development of these initiatives. Governments at both regional and national levels should implement supportive policies, including regulatory frameworks, incentives, and subsidies, to encourage the adoption of hydrogen technologies and facilitate the growth of hydrogen mobility.

Collaboration with the European Commission is not only relevant but almost mandatory to overcome the challenges associated with the hydrogen value chain. Its pivotal role in shaping policies and frameworks that can harmonize efforts across member states and drive a unified approach towards sustainable energy solutions is essential. The European Commission’s indispensable assistance can provide a standardized regulatory environment and streamline incentives on a broader scale, ensuring consistency and coherence in the transition to hydrogen mobility. Collaborating with local governments is equally vital, as they possess valuable insights into the region-specific challenges and can contribute to tailoring initiatives that align with local needs. The synergy between the EU Commission and local governments is essential for creating a comprehensive and effective strategy that promotes the widespread adoption of hydrogen technologies and fosters the growth of sustainable mobility initiatives throughout the region.

In summary, overcoming the identified limitations and barriers requires a concerted effort from all stakeholders. The successful development and adoption of hydrogen mobility in the Médio Tejo Region will not only contribute to the region's sustainability goals but also serve as a model for clean and efficient transportation systems on a broader scale, including the connection of the hydrogen corridor to the southern part of Europe.

Task 5.1– The case of the Northern Netherlands Region

WP: Work Package 5: Mobility Use of Hydrogen

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Task 5.1 – Northern Netherlands

Introduction:

The Northern Netherlands comprises of the three northern-most provinces of the Netherlands, including Friesland, Groningen, and Drenthe. The map of the Netherlands can be seen below in **Figure 12** in which all three provinces are located along the North Sea. The geographical area of the Northern Netherlands covers roughly 11,380 km^2 and comprises of the three municipalities within the provinces: the municipality of Friesland, the municipality of Groningen, and the municipality of Drenthe. The population within the region consists of around 1,729,702 inhabitants.

Figure 12. Map of the Netherlands (htt).

The largest natural gas field in Europe is located in the province of Groningen, known as the Groningen gas field, and has an estimated 2,740 billion cubic meters of recoverable natural gas. Since the discovery of the gas field in the late 1950s, the energy infrastructure and supply in the Netherlands was strongly linked to the extraction and use of natural gas. In later decades however, the natural gas extraction resulted in subsequent earthquakes within the area which caused damage to residential houses. It was therefore decided by the Dutch government to not only phase out the extraction of natural gas starting in the mid 2010s, but also to stop all production of natural gas by 2030 (Potter, 2018). This commitment started around the same time when countries adopted the universal, global climate deal, *The Paris Agreement,* to limit the increase of the global temperature as well as limit greenhouse gas emissions.

Outlined in The Netherland’s National Climate Agreement, participating sectors such as industry, electricity, built environment, mobility, and agriculture have created agreements that highlight the actions that will be taken per sector to reach the national climate targets (httGo). One key cross-sectorial theme that has been identified to help decarbonize the energy system, is the application of hydrogen. More specifically, new opportunities for the application of hydrogen have presented themselves, including the mobility sector for transportation.

Since the Netherlands is the leader in the European gas industry, it is “favourably positioned to build on its position and heritage of natural gas excellence to accelerate hydrogen developments and lead this emerging industry” (The Northern Netherlands Hydrogen Investment Plan 2020: Expanding the Northern Netherlands Hydrogen Valley, 2020). To elaborate, the Netherlands ‘has access to the assets needed to develop a robust hydrogen ecosystem: potential for at-scale offshore wind, hydrogen infrastructure (dense high-quality gas infrastructure, hydrogen storage in salt caverns, port availability), talent and knowledge institutions, chemicals trading, and hydrogen offtake markets” (The Northern Netherlands Hydrogen Investment Plan 2020: Expanding the Northern Netherlands Hydrogen Valley, 2020). During the period 2020 to 2025, the Northern Netherlands hydrogen ecosystem will be scaled up, and specifically in the mobility sector, the hydrogen demand will be kick-started by “introducing various hydrogen vehicles, such as long-distance buses, trucks, trains, ships, and drones, with the required hydrogen refuelling stations in place” (The Northern Netherlands Hydrogen Investment Plan 2020: Expanding the Northern Netherlands Hydrogen Valley, 2020).

As a part of these hydrogen developments, New Energy Coalition, is leading the project management for the HEAVENN project (H2 Energy Applications in Valley Environment for Northern Netherlands). The Northern Netherlands is the first region to receive a subsidy for their so-called Hydrogen Valley and has been approved by the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership). This subsidy is intended for the development of a fully functioning green hydrogen value chain in the Northern Netherlands between the years 2020-2026. Furthermore, the program facilitates the deployment of a variety of hydrogen fuel cell end-user applications across the project clusters, while ensuring the interconnection between them. This will be delivered by facilitating the deployment of key transport and distribution gas infrastructure to deliver green hydrogen from supply to the end-user sits across the entire Northern Netherlands region (HEAVENN, n.d.). The green mobility plan applies to the entire HEAVENN region, and therefore the entire Northern Netherlands region. More specifically, four hydrogen refuelling stations are being built in Groningen and Delfzijl, among other places, at 350 bar (suitable for heavy transport) and 700 bar (suitable for passenger transport). Together with the bus filling station in Emmen, this brings the number of hydrogen filling points to five. In addition, a vehicle fleet consisting of 105 passenger vehicles, 8 light duty trucks, 8 heavy duty trucks, 4 waste collection trucks, 2 long-distance buses (Qliners) and 2 eight-seater vans will be created. These vehicles will provide an initial impetus for the development of hydrogen mobility in the region, thus driving the autonomous growth of zero-emission mobility (HEAVENN, n.d.).

I. Logistics and Services (Light Vehicles and Long Distances Trucks)

Overview of the logistics sector with a breakdown/benchmark of the different logistics subsectors

The Northern Netherlands' logistics sector plays an important role in the region's economic development. Based on the region's strategic location, it has access to major European markets, including the Ruhr area in Germany, Scandinavia, and the United Kingdom. The region's proximity to major seaports and highways makes it a crucial transportation and logistics hub.

Furthermore, the three provinces of the Northern Netherlands, Friesland, Groningen, and Drenthe have heavily invested in their transportation infrastructure. This includes modern highways, railways, and well-connected waterways, making it easy to transport goods via road, rail, and water.

The different logistics subsectors in the Northern Netherlands include seaports and maritime logistics, inland and rail transport, agribusiness logistics, energy and sustainability logistics, high-tech manufacturing and aerospace logistics, warehousing and distribution, and cross-border and E-commerce logistics. To elaborate on the seaports and maritime logistics, the ports of Groningen, Delfzijl, and Harlingen are essential for cargo and container shipping and connects the region to international trade routes. In addition, the inland waterways facilitate the transportation of goods by water with barges, and the rail networks connect the Northern Netherlands to the rest of Europe, making it an ideal location for rail freight transport. **Table 7** below shows the breakdown of logistics companies by industry.

Logistics Companies	**Industry**
Green Logistics Groningen BV	Road Transport
Nijdam Expeditiebedrijf	Road Transport
Bolk Transport	Road Transport
Simon Loos	Road Transport
De Rijke Group	Road Transport
DB Cargo	Rail Transport
Nederlandse Spoorwegen (NS)	Rail Transport
ProRail	Rail Transport
Groningen Seaports	Maritime and Port Logistics
Royal Wagenborg	Maritime and Port Logistics
Niestern Sander Ship Repair	Maritime and Port Logistics

Table 7. Logistics Companies by industry

To conclude, the Northern Netherland's logistics sector is diverse and dynamic which caters to a wide range of industries. The region's strategic location, focus on sustainability, and investment in infrastructure make it an attractive destination for logistics companies looking to tap into the European market. Furthermore, collaboration and innovation, including the development of hydrogen in mobility, offers a unique opportunity to continue driving the economic growth in the logistics sector.

Explanation of the importance of a robust logistics infrastructure for hydrogen mobility

A robust logistics infrastructure is essential for the development and success of hydrogen mobility. The infrastructure is designed to distribute the production and supply of hydrogen to the end-users within the hydrogen supply chain and can also be critically linked to storage facilities. It is therefore vital that there is a robust logistics infrastructure in place to properly transport and distribute hydrogen to the necessary demand-side locations, including hydrogen fuelling stations.

The infrastructure company in the Netherlands, Gasunie, “operates and owns a gas network of approximately 11,700 kilometres. In June 2021, Gasunie received a formal mandate from the Ministry of Economic Affairs and Climate Policy to develop a national hydrogen transport network; the ‘Dutch hydrogen backbone’ and could be in place as early as 2027” (European Hydrogen Backbone: A European Hydrogen Infrastructure Vision Covering 28 Countries, 2022). **Figure 13** below, shows the Netherlands’ national hydrogen transport and infrastructure network.

Figure 13. Map of the Netherlands hydrogen backbone and infrastructure by 2040 (European Hydrogen Backbone: A European Hydrogen Infrastructure Vision Covering 28 Countries, 2022).

The positioning of the Northern Netherlands region will serve as a corridor for the North Sea region where the integration of large offshore wind energy will be deployed. The production of renewable hydrogen will therefore be used and linked to the infrastructure of the Netherlands hydrogen backbone and distributed to end-users, including hydrogen mobility.

Identification of logistics limitations

There can be limitations and challenges in the logistics infrastructure which can impact the widespread adoption of hydrogen as a fuel source, including the use of hydrogen in mobility. One limitation is the lack of an efficient and extensive distribution network which can limit the uptake of potential users of hydrogen fuel cell vehicles and can make it difficult to find convenient refuelling stations.

Other limitations and challenges include high infrastructure costs, safety concerns, transportation challenges across country borders, public acceptance, as well as regulatory and policy challenges.

These limitations are already being addressed to help overcome these challenges through government incentives, private sector investments, and international cooperation. Therefore, the goal should be to develop a robust and efficient hydrogen infrastructure that can support the growth of hydrogen mobility and promote its use in a variety of transportation applications.

Mention of service-related barriers

As the development of hydrogen mobility progresses, there are service-related barriers that impact the adoption of hydrogen fuel cell vehicles. First, there is this “chicken-and-egg” dilemma in which there is a challenge between having a sufficient amount of hydrogen refuelling stations (hydrogen supply) and having a sufficient amount of hydrogen fuel cell vehicles available. Customers are unwilling to purchase hydrogen-fuelled vehicles if there are not enough hydrogen refuelling stations conveniently located and vice-a-versa, companies or authorities are hesitant to develop hydrogen refuelling stations if there is not enough hydrogen-demand coming from the mobility sector. This heavily effects the business model of both hydrogen-suppliers as well as hydrogen-vehicle uptakers; therefore, it is crucial that local businesses, authorities, and stakeholders work together in the simultaneous development of both the supply and demand side.

Another service-related barrier includes the lack of funding in the developments of hydrogen mobility. For instance, “most hydrogen projects are financed by subsidies from governmental authorities. For hydrogen refuelling stations this is necessary at this point in time to compensate for both high initial capital costs and high recurring operation and maintenance costs. Opposed to that, banks are reluctant to finance hydrogen-themed projects due to existing insecurities on the future of hydrogen. Another reason hydrogen usage in the transport sector is negligible at this point in time is the high prices for the few options in hydrogen-based transport. At this moment fuel cell vehicles are significantly more expensive in current capital costs, fuel costs, and infrastructure costs compared to fossil fuel vehicles and electric vehicles. However, due to technological innovations, these prices are expected to drop significantly” (Hydrogen Applications in Heavy-Duty Transportation: A study on the potential benefits and barriers of hydrogen applications in inland cargo ships, trains, and heavy-duty trucks, HEAVENN Report Green Planet, 2021).

Furthermore, another service-related barrier relates to the scarcity of green hydrogen. For example, “hydrogen can come as grey, blue, or green hydrogen which have different prices. Green hydrogen is scarce and substantially more expensive compared to grey and blue hydrogen. An important reason for this is that it is expensive to mass-produce green hydrogen. Due to the higher production costs, the costs for customers are higher. However, in some industries, potential customers are willing to pay more for a more sustainable fuel source” (Hydrogen Applications in Heavy-Duty Transportation: A study on the potential benefits and barriers of hydrogen applications in inland cargo ships, trains, and heavy-duty trucks, HEAVENN Report Green Planet, 2021).

In the case of the Northern Netherlands, “global businesses (e.g., Engie, Equinor, RWE, Shell and Vattenfall) have increasingly committed to the Northern Netherlands as their hydrogen ecosystem of choice, and regional governments have increased their commitments to realise the Northern Netherlands hydrogen ecosystem. Close collaboration with the surrounding countries will add to its development. This increased momentum has brought about the next phase in the realization of the Dutch hydrogen opportunity, moving from pilots and demos to maturing and scaling up the Northern Netherlands hydrogen ecosystem” (The Northern Netherlands Hydrogen Investment Plan 2020: Expanding the Northern Netherlands Hydrogen Valley, 2020).

II. Public Transportation (Intercity and Interregional):

Presentation of the relevance of hydrogen-powered public transportation in reducing GHE

The transportation sector within the EU accounts for 25% of greenhouse gas emissions, while road transport accounts for 71% of those emissions (E. Council, Fit for 55: Towards a more sustainable transport). For the Netherlands, recent GHG emissions statistics from 2022 show that the mobility sector emitted approximately 30 Mt CO_2eq in 2022. This contribution is shown in green in **Figure 14** among emissions from other sectors.

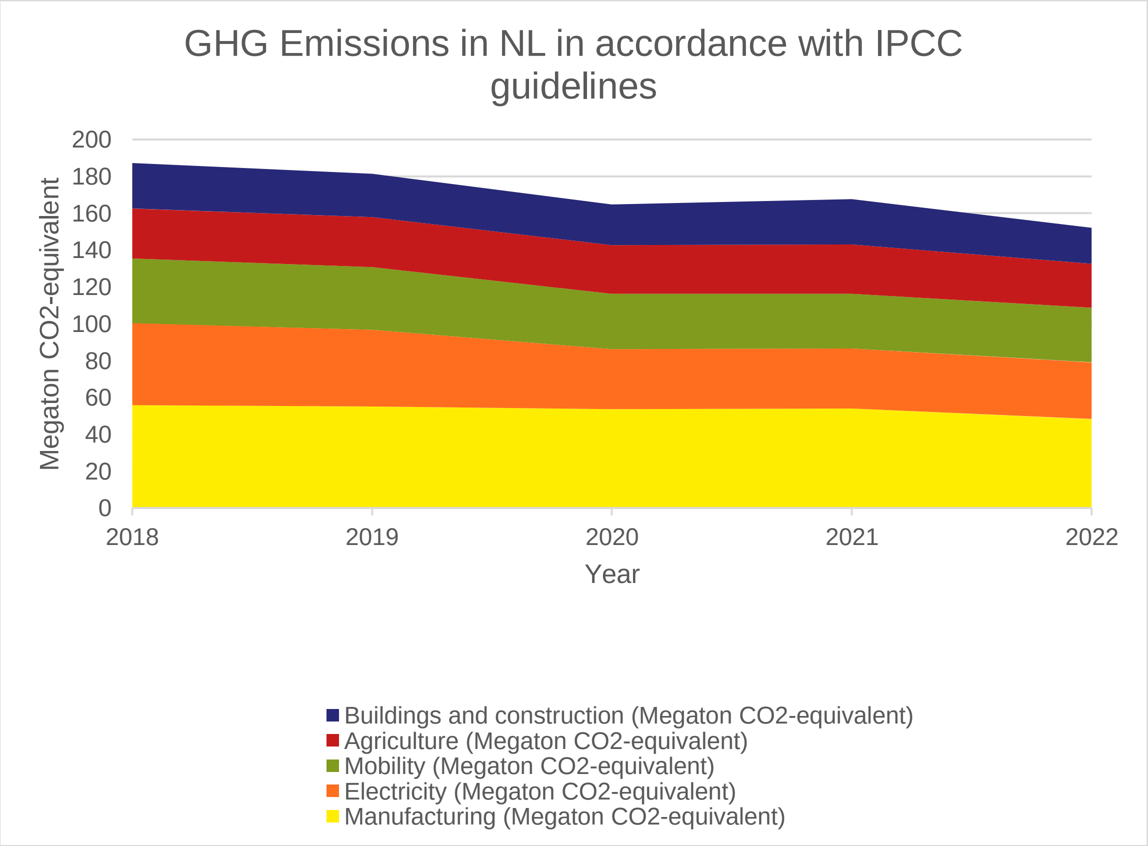

Figure 14. GHG emissions in accordance with the IPCC guidelines (CBS, 2023)

The total length of motorways in the EU (EU-28/EU-27) in 2020 was 74,502 km (Statista Research Department, 2023). Focusing on the Netherlands, the length of motorways for 2021 was 2790 km (eurostat, 2021) while the total passenger kilometers for bus/tram/metro modes of transport for 2022 was 5.0 billion passenger kilometers (CBS Statline, 2023). For the North of the Netherlands (i.e., Noord-Nederland) which consists of Groningen, Friesland and Drenthe, the total passenger kilometers for bus/tram/metro modes of transport in 2022 was 0.6 billion passenger kilometers (see **Figure 15**) (CBS Statline, 2023). Table 8 gives a comparison of how passenger kilometers in Northern Netherlands compares to the Netherlands as a whole.

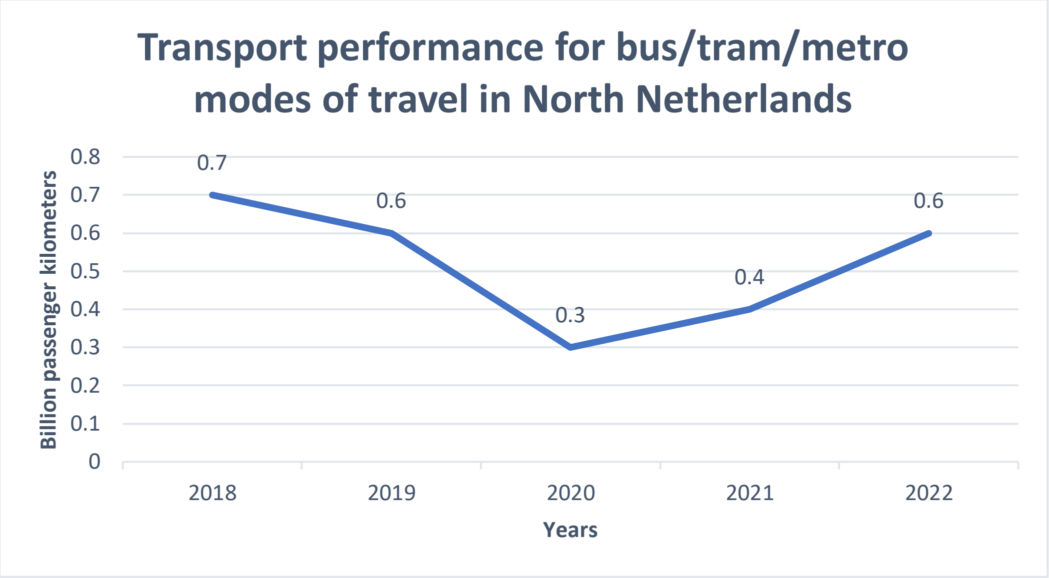

Figure 15. Bus/tram/metro modes of travel in North Netherlands from 2018 – 2022 (CBS Statline, 2023)

	2018	2019	2020	2021	2022
Northern Netherlands	0.7	0.6	0.3	0.4	0.6
Netherlands	6.5	6.5	2.9	3.5	5.0

Table 8. Comparison of total passenger kilometers for bus/tram/metro usage between Northern Netherlands and the Netherlands (CBS Statline, 2023). Units are in billion passenger kilometers for bus/tram/metro usage.

Table 9 and **Table 10** depict the energy consumption for traffic and transport in Noord-Nederland in TJ and the related CO_2 emissions respectively from 2018 to 2021.

	2018	2019	2020	2021
Groningen	14,758	14,651	13,582	13,989
Friesland	21,347	20,905	19,676	19,393
Drenthe	15,890	15,812	15,078	15,725

Table 9. Total known energy consumption for traffic and transport in Noord-Nederland provinces (incl. motorways and roads, excl. electric traffic) in TJ

	2018	2019	2020	2021
Groningen	982.8	962.2	926.1	956.6
Friesland	1410.4	1373.9	1333.4	1327
Drenthe	1044	1023.1	1013.5	1060

Table 10. CO2 emissions from traffic and transport activities in Noord-Nederland provinces (incl. motorways (highways) (fossil fuels)) in kton

In order to decarbonize the transportation sector, both Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs) are viable options. In the case of public transportation such as buses and trains, FCEVs or hydrogen-powered vehicles, are the most suitable option to reduce greenhouse gas emissions due to the longer-distances travelled. **Figure 16** below shows how FCEVs will play an essential role in decarbonizing transport based on the weight of the transport vehicles as well as the average mileage per day/trip.

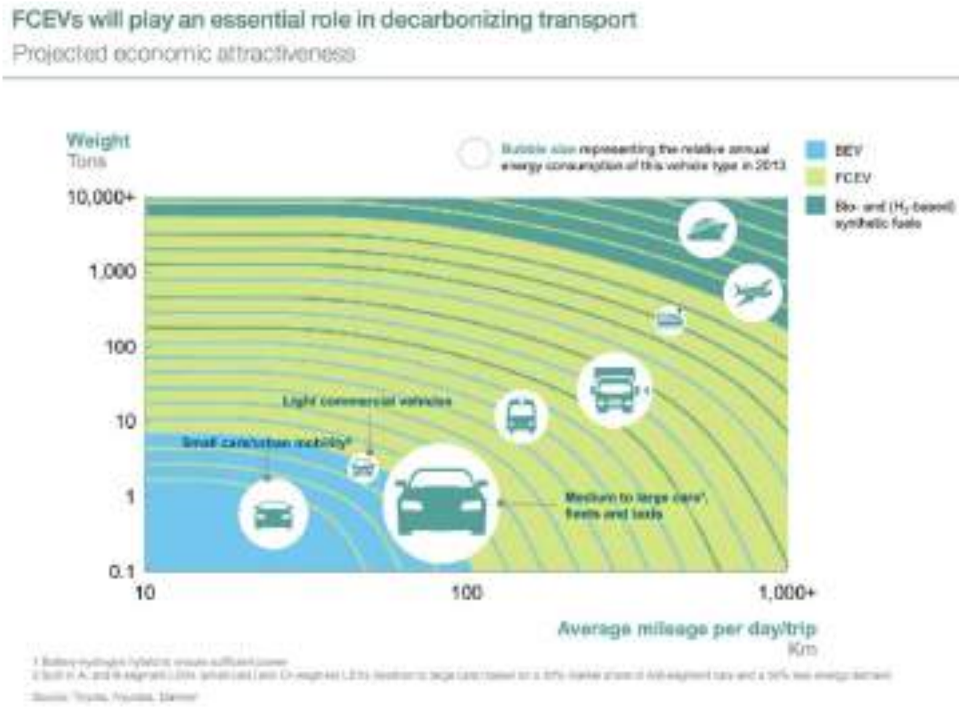

Figure 16. FCEVs will play an essential role in decarbonizing transport (Council H. , January 2017)

There are several significant benefits that FCEVs offer in addition to the decarbonization of the transport sector when compared to other sustainable transport alternatives. For instance, FCEVs can drive long distance without needing to refuel (already more than 500 km), FCEVs refuel quickly (3 to 5 minutes), and due to a much higher energy density of the hydrogen storage system (compared to batteries), the sensitivity of the FCEV powertrain cost and weight to the amount of energy stored (kWh) is low (Council H. , January 2017). Therefore, this increases its attractiveness and likelihood of adoption of vehicles that require significant energy storage, for example, heavy load capacity and/or long range/heavy use (Council H. , January 2017). Finally, the infrastructure for FCEVs can leverage the existing gasoline distribution and retail infrastructure, offering cost advantages while safeguarding local jobs and capital assets (Council H. , January 2017). FCEVs will emerge in all segments, and considering the aforementioned advantages, their significance will be particularly pronounced in the decarbonization of passenger vehicles, including medium to large cars, fleets, and taxis, as well as heavy-duty transportation, buses, and non-electrified trains (Council H. , January 2017).

It is crucial to mention that FCEVs, or hydrogen-powered public transportation can only help to decarbonize the transport sector when the sources and supply of hydrogen are decarbonized. In addition, the role of governments from a regional and national standpoint is critical in making the market for FCEVs and hydrogen-powered transportation take off.

In the case of the Northern Netherlands, the geographical location for producing green hydrogen from offshore wind in the North Sea can substantially reduce the greenhouse gas emissions for the transport sector when supplying the demand side of FCEVs in the region. In particular for railway transportation, the use of green hydrogen can also be promising. For instance, the Dutch railway network consists of over 3200 km of railway lines, of which more than 75% are electrified (HEAVENN R. G., 2021). The provinces of Groningen and Friesland, however, are two of four provinces having non-electrified railway lines, which makes the Northern Netherlands an interesting region to implement the use of hydrogen as a fuel for railway transportation (HEAVENN R. G., 2021). Furthermore, a feasibility study in Groningen showed that hydrogen trains can be a fully-fledged sustainable alternative to the current diesel trains; therefore, Groningen wants to start using passenger trains powered by hydrogen from 2024 onwards (HEAVENN R. G., 2021). This in turn will have a significant impact on emissions reduction in public transportation and the transportation sector.

Identification of limitations in hydrogen-powered public transportation. Overview of the specific regulatory framework for hydrogen vehicles at regional and national level

There are several limitations in hydrogen-powered public transportation, including economic, technical, regulatory and safety barriers. These limitations and barriers must be overcome in order to realize the full potential of hydrogen-powered public transportation.

To elaborate, one of the main limitations for hydrogen-powered public transportation is the **high investment costs associated with the construction and operation of hydrogen refuelling stations (HRS)** as well as the high supply costs for green and low-carbon hydrogen. Due to the high costs associated with the development of infrastructure as well as the high hydrogen-fuel prices, this can make it more difficult for public transportation to switch to hydrogen-powered vehicles if the refuelling stations are limited and expensive. In a project called ‘Hyspeed for H2 trucks’ initiated by Green Planet, a multi-fuel filling station in the Northern Netherlands which includes hydrogen refuelling, calculated a fixed investment cost for Compressor, Storage, and Dispensing (CSD) costs of an HRS facility to be 1.376 million euros with an additional 1 million euros of Capex, totalling to roughly 2M to 2.5M euros (HEAVENN R. G., 2021). This is a very high investment cost when comparing the costs of building a conventional gas station, between 100,000 and 300,000 euros, and therefore requires strong government financial support.

In addition, there is the **limited availability of hydrogen-powered public transportation fleets.** While hydrogen buses and trains have been implemented in some regions, they are not yet widely adopted throughout the Northern Netherlands. This lack of suitable vehicle fleets can slow down the transition to hydrogen-powered public transportation.

From a regulatory standpoint, there is progress being made towards sustainable mobility. According to the European Council, the reduction of fossil fuel use in the transport sector is key for the EU to reach climate neutrality by 2050. More specifically, the EU Green Deal strives for emissions reduction in transport by 90% until 2050. In addition, the alternative fuels infrastructure regulation (AFIR), part of the Fit for 55 Package, sets concrete targets for the deployment of such infrastructure in the EU in the upcoming years (Council E. , European Green Deal Fit for 55, 2023). This regulation also impacts the further developments within the Netherlands and Northern Netherlands region as the developments for alternative fuels such as hydrogen progresses.

Moreover, the **regulatory framework** for hydrogen vehicles in the Northern Netherlands includes national and local regulations, supportive policies, safety regulations, and environmental regulations. The national regulation in the Netherlands follows vehicle safety, emissions, and standards. Hydrogen-powered vehicles therefore must adhere to these regulations to ensure safety and environmental compliance. The regulations cover vehicle certification, safety standards, and emission requirements. Local municipalities in the Northern Netherlands also have specific regulations related to public transportation which include regulations on vehicle routers, emissions standards, and infrastructure development. The Dutch government has also been supportive of clean and sustainable transportation solutions, hence various policies and incentives have been introduced to promote the use of hydrogen as a clean fuel. These policies include tax benefits, subsidies for hydrogen infrastructure development, and support for hydrogen research and development. There are also safety regulations and standards for hydrogen fuelling stations and vehicle storage due to the flammability of hydrogen. These regulations aim to ensure the safe handling and use of hydrogen in public transportation. Lastly, the Northern Netherlands as well as the entire country, is committed to reducing greenhouse gas emissions, so environmental regulations play a role in encouraging the adoption of low-emission and zero-emission vehicles, including hydrogen-powered public transportation.

The Northern Netherlands also **faces several infrastructure-related barriers and challenges such as the insufficient availability of hydrogen refuelling stations along intercity and interregional routes**. This limitation can significantly impact the adoption of hydrogen-powered public transportation in the region. While there are limitations in the adoption of hydrogen-powered public transportation in the Northern Netherlands, the region benefits from a supportive regulatory framework at both national and local levels. These regulations and policies provide a foundation for the development and growth of hydrogen mobility in the region, emphasizing safety, environmental sustainability, and collaboration with EU standards.

The next section highlights the current hydrogen-infrastructure and hydrogen refuelling stations available in the Northern Netherlands region.

III. Hydrogen Supply Stations (HRS):

Overview of the importance of HRS in ensuring a reliable and accessible supply infrastructure

The growth of hydrogen refuelling stations worldwide has been slow and steady but has followed an upward trend. As an example, in 2015 there was approximately 300 public hydrogen refuelling stations (HRS) in the world (Ball & Weeda, 2015). By the end of 2022, 814 hydrogen refuelling stations were operational worldwide (**Figure 17**) (H2stations.org, n.d.). By the end of 2022 the number of hydrogen stations in Europe was 254. Compared to the 140,165 number of conventional fuelling stations in Europe in 2021 (Statista Research Department, 2023), the hydrogen refuelling infrastructure is still incipient but is gaining more traction and development. Within Europe Germany has been leading with the highest shares of HRS, followed by France, the UK, the Netherlands and Switzerland (H2stations.org, n.d.).

Figure 17. Hydrogen refuelling stations worldwide (H2stations.org, n.d.).

HRS are essential for ensuring the convenience and practicality of using hydrogen-powered vehicles since without adequate infrastructure, car makers would not be incentivized to produce FCEV’s. Refuelling stations however face challenges and predominating financial risks in their first years of operation which is mainly due to the long period of low utilization of stations during a transition towards a mass hydrogen market (Ball & Weeda, 2015). This state of affairs is a textbook definition of the “chicken-and-egg” problem where the introduction of hydrogen cars and the development of a refuelling infrastructure needs to occur concurrently but neither party is willing to become a first-mover since the financial risks are high and break-even periods can take several years. However, a specific emphasis needs to be placed on the development of fuelling stations since the installation of HRS needs to precede large-scale fuel-cell electric vehicles (FCEV’s) by a few years (Ball & Weeda, 2015). Adequate infrastructural coverage of HRS is crucial for customer satisfaction and acceptance of FCEVs, without it the market simply cannot take off. Under this circumstance the risk of missing out will be severe since the existence of a hydrogen based refuelling infrastructure can play a significant role in developing and maturing a hydrogen value chain all via encouraging the production and use of green hydrogen and ultimately reducing green-house gas emissions emanating from the transport sector within Europe.

Within the EU, the Netherlands has been an early adopter of HRS with the earliest station opening in 2003 in Amsterdam. **Table 11** provides an overview of these HRS locations in the Netherlands. As of October 2023, the number of HRS in the Netherlands amounts to 21 stations (WaterstofNet, n.d.). Moreover, there are significantly more HRS locations that are under construction, have received funding or are initiatives; for a broader overview refer to (WaterstofNet, n.d.). In **Table 11**, the “pressure” columns refer to the pressure at which hydrogen is stored and dispensed at stations. For the roll-out of a hydrogen infrastructure for passenger cars, industry has aligned on 700 bars refuelling globally[13] (Ball & Weeda, 2015). 700 bar storage allows for an increase in hydrogen storage capacity in order to store a sufficient amount of energy in a relatively small tank and for fast dispensing (3 min). There are also 350-bar dispensers which are mainly used for buses and material handling equipment such as forklifts etc. The development of these equipment standards and refuelling protocols is a good example of how standardization of technical components is key to reduce costs and develop a commercial market.

City	Pressure (bar)	Operator	Vehicle
Rhoon	350/700	Air Liquide	Car/Bus
Arnhem	350/700	TotalEnergies	Car/Bus
Den Haag	350/700	Kerkhof & Zn	Car/Bus
Hoofddorp	700	Shell	Car
Amsterdam	350/700	OrangeGas	Car/Bus
Nieuwegein	350/700	Hysolar	Car/Bus
Amsterdam	700	Shell	Car
Pesse	700	Green Planet	Car
Groningen	350/700	Holthausen	Car/Bus
Assen	700 (slow fill)	OrangeGas	Car
Doetinchem	350/700	Kuster Energy	Car/Bus
Breda	350/700	TotalEnergies	Car/Bus
Horst	350/700	Vissers Energy	Car
Veldhoven	350/700	TotalEnergies	Car/Bus
Emmen	350	Shell	Bus
Kolhorn	350/700 (slow fill)	AVIA Marees	Car
Hoofddorp	350/700	DCB Energy	Car/Bus
Amersfoort	350/700	Fountain Fuel	Car/Bus
Eindhoven	700	Twinning Energy	Car
Roosendaal	350/700	H2Point	Car/Bus
Dordrecht	350/700	Van Kessel	Car/Bus

Table 11. Operational public hydrogen refuelling stations (10/10/2023) (WaterstofNet, n.d.)

For the North of the Netherlands, comprised of the provinces of Groningen, Drenthe and Friesland, there are a handful of HRS that are publicly accessible as of now four of these are public while five are non-public stations that are meant for refuelling public bus fleets. As buses and fleet vehicles such as delivery vans operate locally to a large extent, run on short, regular routes and return to a central depot

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[13] An important step in further standardization was taken by the H2Mobility initiative Germany, by developing a functional description of 700 bar hydrogen refueling stations which serves as a basis for further rollout of HRS in Germany (see (ISO, 2023))

for refuelling and maintenance, they are ideal candidates for hydrogen during the early implementation phase as they do not need an extensive network of refuelling stations (Ball & Weeda, 2015). **Table 12** provides an overview of the locations and overall status of these HRS points while **Figure 18** shows a map of the HRS points in the Northern Netherlands.

Location - Province	**Status**
Groningen - Groningen	Public
Pesse - Drenthe	Public
Emmen - Drenthe	Public
Assen – Drenthe	Public
Groningen - Groningen	Non-public
Groningen - Groningen	Non-public
Delfzijl - Groningen	Non-public
Coevorden – Drenthe	Non-public
Emmen – Drenthe	Non-public
Around Delfzijl – Groningen	Initiative
Around Groningen - Groningen	Initiative
Hoogeveen - Drenthe	Initiative
Nieuw-Amsterdam – Drenthe	Initiative
Beilen – Drenthe	Initiative
Roden – Drenthe	Initiative
Assen – Drenthe	Initiative
Leeuwarden - Friesland	Initiative

Table 12. Public, non-public and initiatives for hydrogen refuelling stations in the North of the Netherlands (H2Benelux, n.d.).

Figure 18. A map of HRS points in the North of the Netherlands. Green points depict public hydrogen refuelling stations while light green points are non-public. Grey points illustrate HRS initiatives (H2Benelux, n.d.).

Hydrogen buses play an important role in raising awareness about hydrogen vehicles to the public. The most prominent local application of hydrogen for mobility in Groningen is the hydrogen refuelling station for the Qbuzz bus depot (**Figure 19**). It is one of the largest HRS in Europe and demonstrates the implementation of a new hydrogen ecosystem in northern Netherlands (Fuel Cell Electric Buses, 2021). Qbuzz has 30 hydrogen buses operational, of which 20 are in Groningen and 10 are in Drenthe/Emmen (hive mobility, n.d.). These fleets of buses were partly funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) under the JIVE 2 project (Fuel Cell Electric Buses, 2021). The HRS has two refuelling points. A bus is refuelled in less than a few minutes and can travel about 400 km. Thanks to this extended range, these buses can be used on regional routes, where a battery-electric bus is not always suitable (Fuel Cell Electric Buses, 2021). A part of the hydrogen supplied to these stations are sourced from Nouryon in Delfzijl (for example as a by-product of the chemical industry via chloroline-alkali electrolysis). For distances less than 200 km, compressed gaseous hydrogen trailers are currently the dominant delivery method to supply hydrogen to HRS points (Ball & Weeda, 2015) but other methods such as liquid hydrogen distribution by trucks and pipeline for longer distances also exists. The Rhoon HRS is directly connected to a branch of the hydrogen pipeline infrastructure of Air Liquide and part of the pipeline is inside the boundaries of the HRS (Honselaar, Pasaoglu, & Martnes, 2018).

Utilization of green hydrogen at HRS points is most ideal but not the precondition for introducing hydrogen as a transport fuel in the first place. For instance, hydrogen from natural gas already leads to a CO_2 reduction of some 30% on a well-to-wheel basis compared to conventional fuels, even without CCS (Ball & Weeda, 2015).

Figure 19. QBuzz filling station (Fuel Cell Electric Buses, 2021)

Electric and Hydrogen powered buses in NL- 2022		
	Electric buses, registered	**Hydrogen buses, registered**
Groningen	144	31
Fryslân	166	0
Drenthe	0	0
Overijssel	40	0
Flevoland	0	0
Gelderland	7	1
Utrecht	134	2
Noord-Holland	823	20
Zuid-Holland	117	0
Zeeland	1	0
Noord-Brabant	9	1
Limburg	3	0

Table 13. Electric and Hydrogen fuel cell buses for each province in the Netherlands in 2022 [18]

Table 13 provides a total overview of all electric and hydrogen fuel cell buses in the Netherlands. Groningen is clearly a leader in the country in terms of the number of fuel cell buses it has in its fleet. **Table 14** provides an overview of all the buses in the country regardless of motor type.

	2017	**2018**	**2019**	**2020**	**2021**

Netherlands	9,914	9,513	9,699	9,050	8,532
Noord-Nederland	1,743	1,709	1,827	1,799	1,754
Groningen	113	99	291	343	346
Friesland	1,480	1,466	1,395	1,362	1,308
Drenthe	150	144	141	94	100

Table 14. Total number of motor coaches, buses and trolley buses in the Netherlands and Noord-Nederland provinces [(eurostat, 2023)

Identification of HRS limitations

Despite the recognition of potential benefits of hydrogen-based mobility the pathways to achieve such a transition remain contented. **A particular challenge is that the implementation of a hydrogen supply infrastructure, comprising production, distribution and installation of hydrogen refuelling stations, will require considerable capital expenditures and involve a high investment risk regarding the future uptake of hydrogen demand** (Ball & Weeda, 2015). There is no single blueprint or universal strategy for rolling out a hydrogen delivery infrastructure (i.e., type of refuelling station, way of distribution and production of hydrogen) during the pre-commercial phase and approaches are likely to vary country to country (Ball & Weeda, 2015). All options are possible; the best practical and economic combination of centralized or decentralized hydrogen production and way of hydrogen distribution to retail stations depends on specific national, regional and local resources and conditions. The challenges for the development and growth of HRS infrastructure in Northern Netherlands is not so different from the challenges that the rest of the country and in fact many other countries face. Some of these challenges are:

1. **High Upfront Capital Costs:** Developing hydrogen refuelling networks require substantial investments in infrastructure, dispensing stations, transportation of hydrogen and the existence of hydrogen supply sources. The costs for these vital elements are high and is compounded by the challenges of a lack of sufficient demand for hydrogen vehicles.
2. **Limited Consumer Demand:** as mentioned in the previous point lack of demand is a serious challenge since a lack of consumer interest or demand for fuel cell vehicles slows down the development of refuelling infrastructure.
3. **Technical Challenges:** Infrastructure for HRS activities is sometimes reliant on elaborate technologies for the dispensing, storage and production of hydrogen. The technical difficulties that are related to safety, efficiency and reliability end up impeding the process.
4. **Regulatory Hurdles:** Any delay or uncertainties related to regulations of hydrogen production, transportation and dispensing ultimately creates delays. Lack of standardization with regard to certain components and hardware for HRS points also creates challenges that could be perceived negatively by the public.
5. **Supply Chain Challenges:** The hydrogen value chain is composed of production, transportation, and storage. Disruptions and inefficiencies within the supply chain will affect availability and the cost of hydrogen fuels.
6. **Coordination with Stakeholders:** Effective collaboration among various stakeholders, including government agencies, private companies, and local communities, is essential. Lack of coordination can lead to delays and uncertainties.
7. **Public Awareness and Education:** Opposition towards the development of HRS points in urban areas is also a rising issue and limits the adoption of hydrogen vehicles.
8. **Land and Zoning Issues:** Identification of suitable areas for establishing hydrogen refilling stations could potentially be challenging due to zoning regulations but also potential opposition from the public.

9. **Competing Technologies:** Competition that arises from other established infrastructure such as electric charging stations creates competition for investment and resources which ultimately slows down the development of hydrogen infrastructure.

Figure 20. Regional transport corridors in the North of the Netherlands. Thick blue lines depict the comprehensive/core road transport corridors. Also shown in black dots are the publicly available HRS points in the North of the Netherlands (European Commission, 2023).

Figure 20 shows the main road transport corridors in the North of the Netherlands with the handful of public hydrogen refuelling stations. These transport corridors are compliant to the TEN-T also known as the Trans-European Transport Network. The Trans-European Transport Network (TEN-T) is a comprehensive network of roads, railways, inland waterways, maritime ports, and airports in Europe. It is an initiative of the European Union (EU) aimed at improving transportation infrastructure and connectivity across the continent. The TEN-T network plays a crucial role in facilitating the movement of people and goods, promoting economic growth, and enhancing the overall competitiveness of the European Union. The Council of the EU has given the final approval for the EU's Alternative Fuels Infrastructure Regulation (AFIR) in order to ensure "seamless travel" of hydrogen-fuelled transport throughout Europe. Member states will have to ensure by the end of 2030 that publicly accessible gaseous H_2 filling stations capable of serving both heavy-duty and light vehicles are set up in every "urban node" and every 200km along the core routes of the planned Trans-European Transport Network (TEN-T) (Martin, 2023). **Figure 21** provides a national view of the transport corridors in the Netherlands with some HRS points located on the roads. With this new regulation in place, many more HRS will be dotted along the national road network.

Figure 21. TEN-T compliant national transport corridors of the Netherlands with hydrogen refuelling stations shown (European Commission, 2023).

The decades of experience that has been gained through numerous demonstration projects for hydrogen refuelling stations has resulted in the development of global standards and functional specifications such as the 350/700-bar fuelling protocols. Effectively, an HRS is a system of interconnected sub-systems that combined determine the configuration of the HRS (**Figure 22).** A sub-system consists of main components and auxiliaries *(Honselaar, Pasaoglu, & Martnes, 2018)*. The main components consist of the on-site hydrogen generator (electrolyzer, a reformer, or a hydrogen supply system such as a trailer or pipelines), a compressor and/or booster (for increasing pressure), a buffer storage (to store hydrogen), a pre-cooler (to cool hydrogen to enable fast-filling) a dispenser (to transfer hydrogen to the applications) *(Honselaar, Pasaoglu, & Martnes, 2018)* and safety monitoring systems.

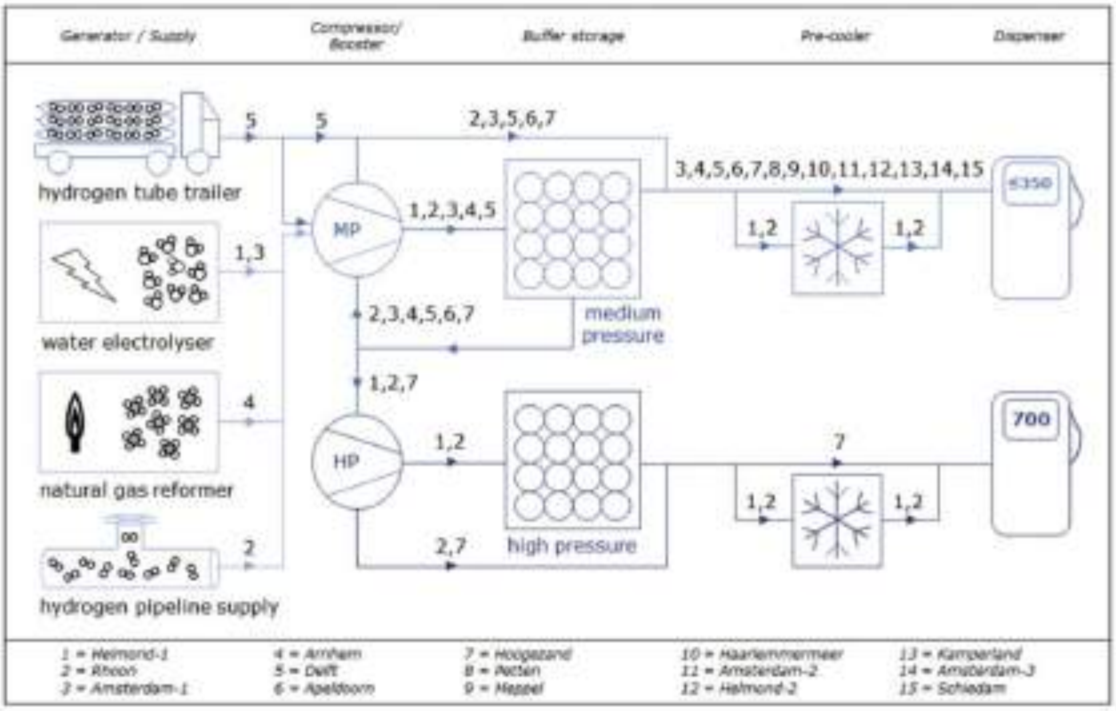

Figure 22. Overview of HRS configurations in the Netherlands (Honselaar, Pasaoglu, & Martnes, 2018)

Efforts to address standardization issues and promote the standardization of hydrogen refuelling station components are ongoing. International organizations, industry stakeholders, and government bodies are working together to develop common standards and regulations that can facilitate the growth of the hydrogen infrastructure and ensure the compatibility, safety, and reliability of components across regions and markets. ISO (International Standards Organization) and IEC (International Electro-Technical Commission) are the two major worldwide standard-publishing organizations. Within these organizations (ISO and IEC), as well as within the Society of Automotive Engineers (SAE), standards are established by technical committees with inputs from the European Committee for Standardization (CEN) members, referred to as National Standard Bodies (NSBs). The TC appoints a working group to fulfill a specific task by a certain time. The working group is ultimately responsible for standard development (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023). Some of the more significant standardizations are described below the list. Refer to the appendix of (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023) for a fully detailed overview codes and standards involved in HRS from ISO, IEC, SAE and CEN.

1. **ISO (International Organization for Standardization):**
    - ISO 14687: Hydrogen fuel — Product specification.
    - ISO 19880-1: Gaseous hydrogen — Fuelling stations — Part 1: General requirements.
    - ISO 19880-2: Gaseous hydrogen — Fueling stations — Part 2: Fuel quality control.
    - ISO 19880-3: Gaseous hydrogen – Fueling stations – Part 3: Valves
    - ISO 19880-5: Gaseous hydrogen – Fueling stations – Part 5: Dispenser hoses and hose assemblies.
2. **SAE International (Society of Automotive Engineers):**
    - SAE J2600: Compressed Hydrogen Surface Vehicle Fueling Connection Devices.
    - SAE J2601: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles.

  - SAE J2601-2: Fueling Protocols for Gaseous Hydrogen Powered Heavy Duty Vehicles.
  - SAE J2719: Hydrogen Fuel Quality for Fuel Cell Vehicles.
  - SAE J2799: Hydrogen Surface Vehicle to Station Communications Hardware and Software

3. **CEN/CENELEC (European Committee for Electro-Technical Standardization)**
   - Hydrogen – CEN/CLC/TC 6
   - CEN/TC 23 Transportable gas cylinders
   - CEN/TC 69 Industrial valves
   - CEN/TC 185 Fasteners
   - CEN/TC 197 Pumps
   - CEN/TC 234 Gas infrastructure
   - CEN/TC 235 Gas pressure regulators and associated safety devices for use in gas transmission and distribution
   - CEN/TC 236 Non-industrial manually operated shut-off valves for gas and particular combinations valves-other product
4. **IEC (International Electrotechnical Commission):**
   - IEC 62282-6-100: Fuel cell technologies — Part 6-100: Micro fuel cell power systems — Safety.
   - IEC 62282-6-200: Fuel cell technologies — Part 6-200: Micro fuel cell power systems — Test methods.
5. **EU Directives and Regulations:**
   - EU 2014/94/EU: Directive on the deployment of alternative fuels infrastructure.

The SAE J2601 standard is one of the more influential standards. It includes guidelines for the dispensing pressure, flow rate and other parameters (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023). The goal of the standard is to ensure the safe and efficient transfer of hydrogen fuel from the dispenser to the vehicle and to promote compatibility between different hydrogen fuelling stations and vehicles. The standard is continuously reviewed and updated to keep up with advances in hydrogen technology and to improve safety and performance (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023). An important outcome of this standardization is also the 3 min refuelling time which plays an important role in helping FCEVs compete with internal combustion engines, this allows for the refuelling of 5-7 kg's of hydrogen into FCEVs within 3-5 min (Reddi, Elgowainy, Rustagi, & Gupta, 2017). The SAE J2601-2 suggested ~20-30kg of hydrogen refuelling into heavy-duty vehicles within 5-10 min (Halder, et al., 2024), this protocol was developed with dispensing hydrogen into heavy-duty vehicles which rely on 350 bar dispensers. This protocol suggested a maximum hydrogen flow rate of 7.2 kg/min with an ambient temperature between -40 °C and 50 °C. The SAE J2799 standard developed requirements of communications for hardware and software (SAE International, 2019), SAE J2600 for design and test requirements of connected devices such as fuelling connectors, nozzles, and receptacles (SAE International, 2015) and SAE J2719 for hydrogen fuel quality standards (SAE International, 2020).

The ISO hydrogen standards are developed by the following technical committees (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023):

- ISO/TC 197 Hydrogen technologies
- ISO/TC 220 Cryogenic vessels

- ISO/TC 58 Gas Cylinders
- ISO/TC 22/SC 41 Gaseous fuels-specific issues

The ISO TC 197 is the most active in the HRS field since it focuses on hydrogen fuel stations and hydrogen-powered vehicles. The ISO TC 197 standards provide specifications and guidelines for the design, construction, operation, and maintenance of hydrogen fuelling stations, as well as the performance and safety requirements for hydrogen fuel cell vehicles (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023). The main standard associated with general and specific requirements for the design and operation of HRSs is the ISO 19880 standards which range from 1 to 9 provide guidance for safe and efficient hydrogen refuelling, ensuring compatibility between various refuelling stations and vehicles, and provide a framework for commercial operations (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023). Among these, the ISO 19880.5 standard suggests the requirements of dispensers for hydrogen dispensing at 70 MPa (or 700 bar) with a temperature between -40 °C and 65 °C (ISO, 2019).

There is another group of standards known as ‘European standards’ titled CEN or CENELEC (European Committee for Electro-Technical Standardization). They are responsible for the generation and publication of standards in Europe, as well as the ISO standard implementation (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023). They provide technical requirements and recommendations to assure product safety, quality, and interoperability throughout Europe (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023). European, national, and industry standards typically reference CEN and CENELEC standards, which are voluntary. After adoption, member states must consider these requirements while implementing EU law. CEN and CENELEC have developed and published several standards related to hydrogen, which provide specifications and guidelines for the safe and efficient use of hydrogen in various applications (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023). **Figure 23** provides an overview of CEN standards related to hydrogen derived from (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023)

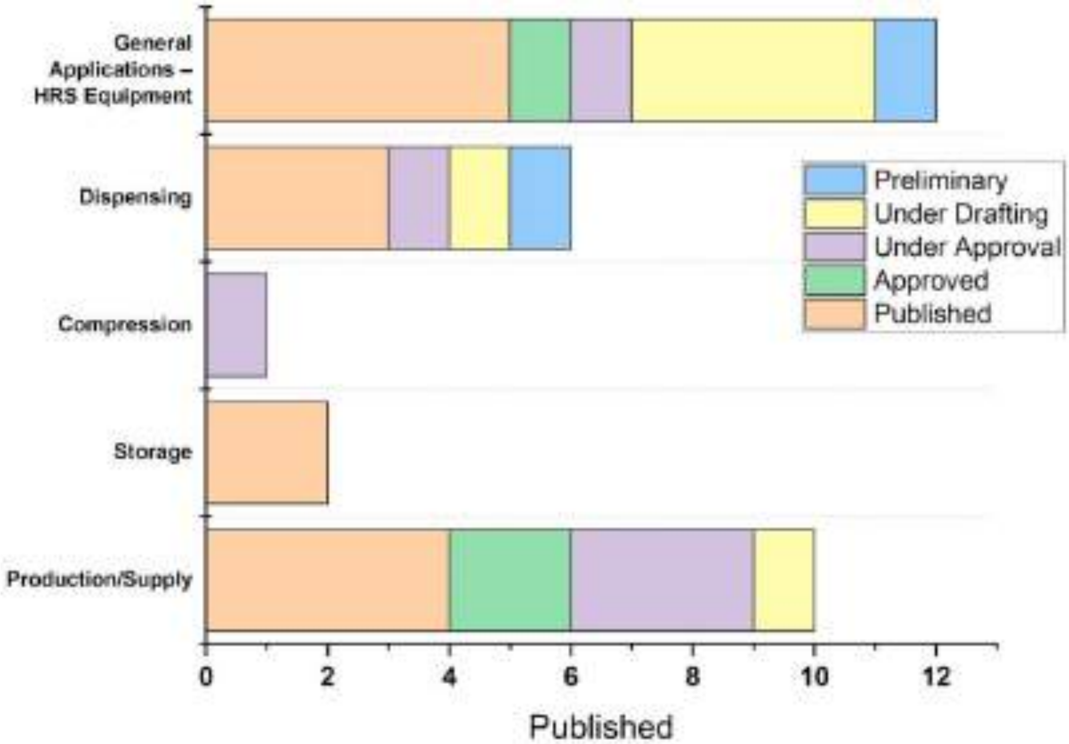

Figure 23. Relevant CEN/CENELEC standards regarding hydrogen (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023)

In terms of maturity of standards, (Genovese, Cigolotti, Jannelli, & Fragiacomo, 2023) states that LH_2 technology (liquid hydrogen) seems to have a greater degree of maturity in terms of published standards, but numerous GH2 technology (gaseous hydrogen) technology which cover the majority of hydrogen usage are in the process of being drafted or completed.

Challenges of hydrogen metering

Another challenge are issues related to hydrogen metering. Hydrogen metering is important since it involves the settlement of hydrogen refuelling costs, the measurement of inventory, as well as the calculation of the daily hydrogen loss rate of the HRSs (Zhao, et al., 2024). Especially, the hydrogen loss rate is used as the key basis for assessing the economic indicators of HRSs (Genovese, Blekhman, Dray, & Fragiacomo, 2020).

Hydrogen is known to be difficult to measure because of its low molecular weight and therefore low operating density (Micro Motion, 2003). Due to its low density, large volumes of gas need to be accurately measured. Additionally, it is highly volatile and leaks easily, this makes it crucial to have precise metering to prevent wastage and ensuring safety. There are also temperature effects since volumes of hydrogen can be affected by temperature variations. To ensure accurate metering, temperature compensation mechanisms must be incorporated into the metering system.

Standardizing and improving the metering accuracy of the HRSs will not only ensure the fairness of transaction settlement between hydrogen production plants, hydrogen refuelling stations, and customers. But also, the management personnel can master the production matching information and real-time dynamic loss and overflow data (Zhao, et al., 2024).

Currently there are two methods utilized for hydrogen metering (Zhao, et al., 2024):

1. Volumetric method also known as the pressure-volume-temperature (PVT) method.
2. Mass method with Coriolis mass flow meters (CMFs)

CMFs are widely employed in HRSs because of their convenient operation (Kolhe & Edlabadkar, 2021) (Cheong, et al., 2021) however they are known to be costly and difficult to install full coverage within the scope of HRSs (Zhao, et al., 2024) (Wu, Kenbar, & Pruysen, 2021). CMF metering has been shown to be more precise compared to the PVT method, a deviation of approximately 10% has been observed between the two measurement methods which can be caused by the diverse gas container design and the ambient hydrodynamic conditions (Cascetta, Rotondo, & Musto, 2008). Metering errors of CMFs have been known to be caused by changes in ambient air temperatures, it has been shown that with the increase between the flowing fluid and the ambient air temperature of the test instrument, the error of compensated fuel density will increase (Lindsay, Glen, Hay, Shariatipour, & Henry, 2020). Research by (Mills, 2020) has also discussed the influence of elevated pressure, temperature, and viscosity on CMF metering accuracy hence flowmeter calibration and zero adjustments according to service conditions are important. As hydrogen infrastructure continues to develop, advancements in technology and regulations will likely contribute to overcoming these challenges.

Safety-related barriers

Another aspect of utilizing hydrogen in the mobility sector is public perception and reception. Citizens' emotional response to energy technology projects influences the success of the technology's implementation (Huijts, 2018). Arguably, having a safe living environment, energy security (including access to useful vehicle fuels), and minimal environmental degradation (e.g., limited air pollution and climate change) is an important goal for many citizens in the context of energy technologies (Perlaviciute & Steg, 2015). It can therefore be presumed that the more one believes that an energy technology will positively or negatively affect these goals, the stronger one's positive or negative emotions respectively will be (Huijts, 2018). While hydrogen as a fuel for vehicles has been regarded as beneficial for the environment, it has also been laced with concerns for safety. HRSs have received resistance because of concerns in regard to safety risks, specifically when the fuelling stations are located close to private residences (O'Garra, Mourato, & Pearson, 2008). The release of high-pressure hydrogen and potential ensuing of fire and explosion is a large concern since the severity of such an incident is very high. A study by (Hienuki, et al., 2021) used a survey to determine some of the public opinions on operating self-hydrogen refuelling stations. One important finding showed that to obtain public trust in hydrogen self-refuelling technology, it is highly likely that improving anxiety related to equipment and handling would contribute to its successful introduction and dissemination. It is particularly important to reduce the psychological burden of station operation and maintenance, accident frequency, and difficulty using dispensers (Hienuki, et al., 2021).

Some of the key safety risks associated with hydrogen refuelling stations include:

1. **Hydrogen leakage and dispersion.** This is because hydrogen is a highly flammable gas, and leaks can result in the formation of explosive mixtures in the air. Management and mitigation of leaks is critical to prevent potential fires or explosions.
2. **Fire hazards.** Hydrogen fires burn with a nearly invisible flame, making them difficult to detect. Specialized fire detection and suppression systems are required to handle hydrogen-related fires.
3. **Pressure-related risks.** Hydrogen is stored and delivered at high pressures, which can pose risks if pressure relief systems fail or if there are equipment malfunctions.
4. **Material compatibility.** Hydrogen can cause embrittlement in some material, which can weaken storage and distribution equipment over time. Ensuring compatibility with materials is important to prevent equipment failure.
5. **Ventilation and gas detection.** Adequate ventilation and gas detection systems are necessary to monitor and control hydrogen concentrations in and around the refuelling station to prevent explosive atmospheres.
6. **Electrical hazards.** Hydrogen refuelling stations rely on electrical equipment, and the presence of hydrogen can create an added risk of electrical ignition. Proper electrical safety measures are crucial.
7. **Collision risks.** In the event of a collision involving a hydrogen-fuelled vehicle, there is a risk of hydrogen leakage and potential ignition. Proper safety measures for vehicle collisions are essential.
8. **Human error.** Human error in operating the station or refuelling vehicles can lead to safety incidents. Training and safety protocols for station personnel are vital.
9. **Natural disasters.** Earthquakes, floods, and other natural disasters can pose additional risks to hydrogen refuelling stations. Proper engineering and disaster response planning are essential.
10. **Regulatory compliance.** Compliance with safety standards and regulations is crucial to ensuring the safe operation of hydrogen refuelling stations. Regulations vary by location and can impact station design and operation.

To mitigate these safety risks, hydrogen refuelling stations are typically equipped with various safety features, such as gas detection systems, flame arrestors, pressure relief devices, emergency shutdown systems, and rigorous safety protocols. Proper maintenance and employee training are also essential to minimize the risks associated with operating hydrogen refuelling stations. Additionally, regular safety inspections and risk assessments are necessary to identify and address potential hazards. Studies have shown that prior awareness of HRS projects can cue stronger pride and joy and weaker levels of fear compared to prior unawareness. Therefore, informing citizens ahead of time about a technological project will increase acceptance (Huijts, 2018). However, this is not always guaranteed and the effects of such a tactic need to be pretested (Huijts, 2018). From an ethical point of view, it is crucial to inform people in a timely manner about new projects in their vicinity, especially when the risks can be considered considerable (Roeser, 2006) (Alfano & Huijts, Forthcoming).

IV. Volumes of Hydrogen production required

How many hydrogen tons must be produced and at what breakeven price to empower a real hydrogen mobility model to be implemented?

This section investigates the steps involved in order to derive an indication for the breakeven price of hydrogen in the Noord-Nederland for mobility applications such as in trucks, buses and light vehicles.

To start with the calculation, it would be beneficial to see what the energy consumption of mobile equipment in Noord-Nederland has been in the span of 2017 to 2021. Table 15 provides this yearly overview alongside values for each of the provinces and was sourced from the Regional Climate Monitor database of the Netherlands (Regionale Klimaatmonitor). Naturally, the total value for Noord-Nederland is a summation of all energy consumption values for each of the provinces of Groningen, Friesland, and Drenthe. It's important to note that these energy consumption values indicated a combined value for diesel, petrol, and liquefied petroleum gas (LPG) fuel types. Data from 2021 was decided to be used for the calculations since it was the latest data year that has definitive values.

Energy consumption of mobile equipment (Diesel, Petrol and LPG) in TJ					
Year	**2021**	**2020**	**2019**	**2018**	**2017**
Groningen	2266	1995	2124	2225	2111
Friesland	3304	3610	3411	3604	3411
Drenthe	2830	2356	1927	2015	1909
Noord-Nederland	8400	7961	7462	7844	7431

Table 15. Overview of energy consumption for mobility applications for diesel, petrol and LPG fuels combined in Terajoules (Source: Regionale Klimaat Monitor (Regionale klimaatmonitor, n.d.))

It was not possible to find data on what the energy contribution of each fuel type was for every province, hence the contribution of each fuel type needed to be estimated. **Table 16** provides numbers showing the final consumption of diesel, petrol, and LPG for final road transport applications in the Netherlands.

Total Consumption of Diesel, Petrol and LPG for road transport in million kg					
Year	**2017**	**2018**	**2019**	**2020**	**2021**
Diesel	5341.12	5480.01	5403.26	4630.16	4629.89
Petrol	4132.01	4234.54	4332.54	3708.28	3819.29
LPG	150.66	136.81	127.34	107.95	108.24
Total	**9623.79**	**9851.36**	**9863.14**	**8446.39**	**8557.42**

Table 16. Final consumption of Diesel, Petrol and LPG for final road transport applications in the Netherlands (Source: CBS Statline – from the Crude and petroleum products balance sheet; supply and consumption (CBS Statline, 2023))

A percentage can be derived for the share of each fuel type by dividing the consumption of that fuel by the total sum for diesel, petrol and LPG use combined. **Table 17** provides this information; it can be seen that diesel has a higher share of consumption averaging at around 55%, with petrol at 44% and LPG at 1%.

Percentage of each fuel type for road applications in %					
Year	**2017**	**2018**	**2019**	**2020**	**2021**	**Average**
Diesel	55%	56%	55%	55%	54%	55%
Petrol	43%	43%	44%	44%	45%	44%
LPG	2%	1%	1%	1%	1%	1%

Table 17. Share of each fuel type for road applications in % (Source: CBS Statline – from the Crude and petroleum products balance sheet; supply and consumption (CBS Statline, 2023))

With this information established, we can return to calculating the total weight of fuel used for mobility applications in Noord-Nederland. Going back to the TJ values established in **Error! Reference source not found.**, we should be able to convert TJ to kg with the help of energy density values for diesel, petrol and LPG shown in **Table 18**.

Fuel Type	**Energy Density (MJ/kg)**
Diesel	45
Petrol	46
LPG	50
Combined	45.5

Table 18. Energy density values based on fuel type

Table 15 established 8400 TJ of fuel consumption for mobility applications for 2021 for the Noord-Nederland region. Since this number reflects energy consumption for diesel, petrol and LPG combined, a specific energy density value needs to be derived in order to derive the total weight of fuel. This can be done with the equation below where energy densities of mixed fuels can be calculated:

$$ED_{mixed} = \sum_i (Fraction \times ED_i)$$

Fraction denotes the percentage of the fuel in the mix, ED_i represents the energy density of that specific fuel type in the fuel mix. The percentages for the fuel mix can be derived from the approximation from **Table 17**. Based on this, the energy density of this combined fuel is:

$$ED_{mixed} = \sum_3 (fraction\ of\ petrol \times ED_{petrol} + fraction\ of\ diesel \times ED_{diesel} + fraction\ of\ LPG \times ED_{LPG})$$

ED_{mixed} = (0.44×46 + 0.55×45 + 0.01×50) = 45.504645 ≈ 45.5 MJ/kg

Now we can derive the weight of the 2021 fuel mix for Noord-Nederland:

8400 TJ × (1/45.5 MJ/kg) × 1,000,000MJ[14] = 184,596,539.55 kg ≈ 184.6 kton

Table 19 executes this calculation for other years as well.

Fuel weight calculations for Noord-Nederland					
Year	**2017**	**2018**	**2019**	**2020**	**2021**
TJ	7431	7844	7462	7961	8400

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[14] Note that 1×10^6 MJ is 1TJ and is used to convert the TJ to MJ

kilograms	163302010.2	172378006.7	163983259.3	174949172.8	**184596539.55**
Kiloton (approx.)	163.3	172.38	163.98	174.95	**184.6**

Table 19. Kilogram of fuel consumed for Noord-Nederland from 2017 to 2021.

At this stage we have a total weight approximation of diesel, petrol and LPG fuels combined. Now we have to derive the weight for each of the fuel types. Based on the share of fuel approximation we should be able to get indicative values on how much of this total 184.6 kton of fuel in 2021 is distributed among diesel, petrol, and LPG. **Table 17** indicates that in 2021, 54% of fuel for mobility applications was used for diesel, 45% for petrol and 1% for LPG. As an example, we have:

184,596,539.55kg × 54% = 99,682.13 tons of diesel

Table 20 provides these weights for Diesel, Petrol and LPG.

	Weight (kg)	**Weight (ton)**
Diesel	99,682,131.38	99,682.13
Petrol	83,068,442.82	83,068.44
LPG	1,845,965.396	1,845.97

Table 20. Approximated weight by fuel type in Noord-Nederland for 2021

According to (Basma & Rodriguez, 2022), fuel consumption of a Fuel Cell Electric Truck will reach 6.7 kg/100 km at worst case and with 20% increase max cargo compared to the diesel-powered trucks. Diesel powered trucks have an average of 30 L/100 km (assuming between mid and heavy size trucks). Buses diesel consumption range between 19-24 L/100 km and Fuel Cell Electric Buses from 4-7 kg/100 km. With the weight of fuel determined by type, we should be able to calculate the CO_2 emissions from the usage of these fuels and also determine the hydrogen production required in order to replace these fuels. We will use the assumptions below to derive these results.

Assumptions:

- FCET: 6.7 kg/100 km
- FCEB: 5 kg/100 km
- FCEV: 0.79 kg/100 km (Toyota Mirai)
- Diesel Truck: 30 L/100 km
- Diesel Bus: 19 L/100 km
- Diesel Car: 6 L/100 km
- Diesel Density: 0.835 kg/L

- CO_2 emissions for Diesel:

One liter of diesel weighs 835 grams and contains 86.2% carbon, which is equivalent to 720 grams of carbon in each liter of diesel. It takes 1,920 grams of oxygen to burn 1 liter of diesel. The carbon dioxide produced is therefore equal to the sum of 720 grams of carbon and 1,920 grams of oxygen. That's 2,640 g/L CO_2 produced per 1 kg diesel burned.

Therefore for 1 kg of diesel: 2.640 kg_{co2} / 0.835 kg_{Diesel} = **3.162 kg CO_2 per kg diesel burnt.**

Emission of CO_2 for diesel sold at Noord-Nederland (2021):

99,682,131.38 kg_{Diesel} x 3.162 kg_{co2} = **315,194.90tons of CO_2** emitted.

Emission of CO_2 for the public transportation system of Noord-Nederland (2021) assuming all public transport was by bus[15]:

400,000,000 km travelled *19 L/100 km = 76,000,000 L Diesel used

76,000,000 L * 2.64 kg/L = 200,622,520 kg CO_2, **200,622.52 tons of CO_2** emitted.

- H_2 Production Required to replace Diesel:

H_2 in Noord-Nederland requirement to replace Diesel assuming it was used fully on diesel cars:

FCEV: 99,682,131.38 kgDiesel / 0.05 kg/km[16] = 199,364,262.77km

FCEV: 0.0079 kg/km * 199,364,262.77km = 15,749,776.8 kg, 15,749.78 tons H_2 needed.

H_2 in Noord-Nederland requirement to replace Diesel assuming it was used fully on diesel trucks:

FCET: 99,682,131.38 kgDiesel / 0.2505 kg/km[17] = 397,932,660.2 km

FCET: 0.067 kg/km * 397,932,660.2 km = 26,661,488.2 kg, 26,661.49 H_2 needed.

H_2 in Noord-Nederland requirement to replace Public Transportation system:

FCEB: 400,000,000 km travelled * 0.05 kg/km = 20,000,000 kg, 20,000 tons H_2 needed.

Assumptions:

- Average diesel price reference for 2021 (CBS Statline, 2023): 1.49 €/L[18]
- Diesel Used: 99,682,131.38 kg Diesel / 0.835 kg/L = 119,379,798.1L

(119,379,798.1L * 1.49 €/L = 177,875,899.1 €/year)

Target price for H_2 for FCEV: 177,875,899.1 € / 15,749,776.8 kg = **11.29 €/kg H_2**

Target price for H_2 for FCET: 177,875,899.1 €/ 26,661,488.2 kg = **6.67 €/kg H_2**

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[15] **Figure 15** provided data on passenger kilometers in Noord-Nederland. Since there are no metro or trams in Noord-Nederland, it's correct to assume that the passenger kilometers represent only bus transport which includes public transport in cities and in-between cities.

[16] 0.05 kg/km was calculated by taking the diesel car average consumption in liters and multiplying it by the diesel density: (6 L/100 km * 0.835 kg/L). In more detail: 6/100 we get the L/km -> (0.06 L/km * 0.835 kg/L) = 0.05 kg/km.

[17] 0.2505 kg/km was calculated by taking the diesel truck average consumption in liters and multiplying it by the diesel density: (30 L/100 km * 0.835 kg/L). In more detail: 30/100 we get the L/km -> (0.30 L/km * 0.835 kg/L) = 0.2505 kg/km.

[18] This value was derived from averaging diesel prices for highway manned petrol stations, local manned petrol stations and local unmanned petrol stations

Target price for H_2 for FCEB: 177,875,899.1 € / 20,000,000 kg = **8.89 €/kg H_2**

Breakeven:

The price of hydrogen per kilogram to be on par with the price of diesel for light vehicles, considering only the energy necessary to cover the same distance, would be **11.29 €/kg H_2**. Below this price, FC starts to get cheaper than using diesel powered engines.

The price of hydrogen per kilogram to be on par with the price of diesel for Heavy trucks, considering only the energy necessary to cover the same distance, would be **6.67 €/kg H_2**. Below this price, FC starts to get cheaper than using diesel powered engines.

The price of hydrogen per kilogram to be on par with the price of diesel for the public transportation system of Noord-Nederland, considering only the energy necessary to cover the same distance, would be **8.89 €/kg H_2**. Below this price, H_2 starts to get cheaper than using diesel powered engines.

Electrolyser capacity required to replaced Diesel usage:

To produce 1 kg of H_2 is needed 33.32 kWh/kg, but the efficiency is 65 % (average reference) the real necessity of electricity is 51,26 kWh/kg (33.32/0.65).

Power needed with μ = 65 % and 12 h a day working:

FCEB: 20,000,000 kg/year * 51.26 kWh/kg = 1,025,200,000 kWh/year / 12*365 h/year = 234,070.95 kW, **234 MW electrolyser capacity needed.**

FCEV: 15,749,776.8 kg/year * 51.26 kWh/kg = 807,333,556.65 kWh/year / 12*365 h/year = 184,322. 73 kW, **184 MW electrolyser capacity needed.**

FCET: 26,661,488.2 kg /year * 51.26 kWh/kg = 1,366,667,887 kWh/year / 12*365 h/year = 312,024.63 kW, **312 MW electrolyser capacity needed.**

Mapping of the most important long distance logistics companies regionally/nationally

Here is a list of the most important and well-known long distance logistics companies operating in the Netherlands:

- **DHL:** DHL is one of the world's leading logistics companies, offering a wide range of services, including express parcel delivery and freight transportation.
- **Vos Logistics:** Vos Logistics provided a wide range of logistics services, including road transport, warehousing, intermodal solutions, and logistics consultancy. They specialize in transporting goods throughout Europe, with a focus on sustainable and efficient transportation. Vos Logistics is at the forefront of innovative logistics solutions, including the use of alternative fuels and green logistics practices, aligning with the Netherlands' commitment to sustainability in the transportation sector.
- **PostNL Logistics Solutions:** The company offers a comprehensive suite of logistics services, including warehousing, fulfillment, e-commerce logistics, and international parcel delivery. They are in line with environmental and sustainability goals, PostNL Logistics Solutions has taken steps to reduce its carbon footprint and are actively exploring and implementing sustainable transportation solutions and green logistics practices to minimize their impact on the environment.

- **UPS: United Parcel Service (UPS)** is a well-known provider of package delivery and supply chain solutions with a significant presence in the Netherlands.
- **Kuehne + Nagel:** A global logistics provider, Kuehne + Nagel offers airfreight, sea freight, and road transportation services in the Netherlands.
- **DB Schenker:** DB Schenker is a division of Deutsche Bahn and provides logistics and transportation services in the Netherlands, including land transport, air and ocean freight, and contract logistics.
- **Maersk Line:** Maersk is a major player in the maritime and shipping industry, offering container shipping and logistics services worldwide, including the Netherlands.
- **Ceva Logistics:** Ceva Logistics provides supply chain management and logistics services, serving various industries in the Netherlands
- **Rhenus Logistics:** Rhenus Logistics is a European logistics provider offering a wide range of services, including road transportation, air and ocean freight, and warehousing in the Netherlands.

These long-distance logistics companies play integral roles in supporting the country’s logistics and supply chain needs. More importantly, they are also committing themselves to the Netherland’s Road transport sector towards a zero-emission future.

V. OMS and business model for decarbonization

Potential business models that would accelerate decarbonization considering the hydrogen price

Overview

The Netherlands as a whole is planning to incorporate renewable hydrogen production in order to achieve a wide array of applications. The uses and applications of green hydrogen will be vast, but some important applications are:

- Facilitating renewable electricity integration on a large-scale
- Distribution and transport of renewable electricity to molecules across various sectors and regions
- Grid-congestion management and the balancing of national and local energy systems
- Hydrogen storage and buffering capabilities in order to bolster the energy system
- Transport decarbonization
- Decarbonizing energy usage within industry
- Feedstock for industrial usage
- Decarbonizing building heating and districts

The Northern Netherlands is uniquely positioned to develop a green scale hydrogen economy because of its large-scale green electricity production (especially offshore wind), its knowledge infrastructure, its large-scale chemical cluster, its importation of green electricity and its existing gas infrastructure, which can be retrofitted easily and cheaply to transport green hydrogen (van Wijk, 2017).

Investments and economic activities will be both on large and small scales in local communities (van Wijk, 2017). Large-scale green hydrogen, oxygen, syngas, carbon dioxide, char, pure water and heat production, together with harbor transportation and storage facilities, will be located in Eemshaven, and green chemical production will be located in the Delfzijl industrial cluster.

Decentralized green hydrogen production projects via solar energy will take root and expand in various cities, villages and on the Wadden islands. Hydrogen distribution centers and fuelling stations will be located strategically to supply hydrogen to fuel cells for busses, trucks, trains, boats and cars across the region (van Wijk, 2017). Hydrogen pipelines in which a proportion of them will be retrofitted gas pipelines will transport and supply the Northern Netherlands industrial cluster of Delfzijl, and allow for connection to other key industrial clusters of Rotterdam/Maasvlakte, Noordzee Kanaal Zone/IJmuiden, Zeeland/Ternuezen and Limburg with green hydrogen produced and/or transported via the Northern Netherlands (van Wijk, 2017). It’s also expected that hydrogen innovation centers will be developed in cities such as Groningen, Leeuwarden and Emmen which will allow for the creation of a triple helix support system of government, knowledge institutions and industry to collaborate and allow for conducive regional growth for a well-educated work force and society.

Implementation Plan

One of the first attempts to develop a green hydrogen economy in the Netherlands was to develop a high-pressure transmission grid, the so-called “Hydrogen Backbone” as a first indispensable tool. To that end, Gasunie/GTS (Gas Transport Services) set up a study called HyWay27 to prepare a national hydrogen backbone throughout the country and connect to both Germany and Belgium and have that ready by 2027. The Hyway27 study led to the Dutch government approving a budget of 750M€ to start converting a part of the current natural gas transport assets to be ready to transport pure hydrogen. This work will be executed through a subsidiary of Gasunie called HNS (HyNetwork Services). A fortunate aspect of this project was that the overwhelmingly largest part could be based on existing transmission infrastructure/pipelines. This way, a first step is made in what is planned to be an eventually pan-European hydrogen backbone system. The backbone will connect four of the five main industrial clusters of the country: Eemshaven-Delfzijl, Noordzee Kanaal Zone/IJmuiden, Rotterdam/Maasvlakte, and Zeeland/Terneuzen. Moreover, there will be another hydrogen transport system called the Delta corridor, that will connect Rotterdam to the Ruhrgebiet in Germany, which is the largest industrial area in Europe and therefore expected to be one of the largest hydrogen consumers in the continent. Parallel to the backbone development another project was setup by Gasunie, called HyStock, developing hydrogen storage options in salt caverns near Zuidwending in the North of the country, where currently natural gas salt caverns are being operated. The government supported all this activity by approving the expenditures on this in the order of 1B€.

The development of the national hydrogen backbone is vital for any large-scale hydrogen production and consumption in any part of the country. Hence, the Northern Netherlands is set to become an important focal point. There are some inherent characteristics about the North of the Netherlands that stand out (van Wijk, 2017):

- The Slochteren gas field has contributed to a strong gas industry being located in the Northern Netherlands. This industry could switch to hydrogen with relative ease as the required knowledge, infrastructure and industrial activities for both gasses are fairly complete.
- There is a large future supply of electricity from Norwegian hydropower, Danish wind and Dutch and German offshore wind, whereas the electricity transport grid already has limited inland capacity today.
- Chemical and agricultural companies present in the Northern Netherlands could profit from a green hydrogen supply in combination with a green syngas and green carbon dioxide supply.
- Rapid development of electric transportation with batteries and hydrogen fuel cells in Europe is creating extra demand for green hydrogen, especially in neighboring Germany.

A noticeable successful result of the various pilots and innovative investments in the North of the country was the recognition by the European authorities of the Groningen-Drenthe area as the first ‘Hydrogen Valley’ of Europe, where a total investment of 100M€ is being done in demonstrating the connection of regional users of hydrogen with regional producers, which is the backbone of the concept of ‘Hydrogen Valley’.

At the end of 2022 and on top of the existing national hydrogen support schemes, 7 IPCEI projects (International Projects of Common European Interest, an EU based qualification), show in **Table 21,** on hydrogen production were selected for a total of subsidy amount of 783.5 M€, shown in **Table 22,** and representing a cumulative capacity of 1150MW electrolyzer capacity.

Project name	**Capacity (MW)**	**Location**
Holland Hydrogen I	200	Maasvlakte (Rotterdam/Maasvlakte)
H2ermes	100	IJmuiden (Noordzee Kanaal Zone/IJmuiden)
CurtHyl	200	Maasvlakte (Rotterdam/Maasvlakte)
H2-Fifty	250	Maasvlakte (Rotterdam/Maasvlakte)
ELYgator	200	Terneuzen (Zeeland/Terneuzen)

Haddock	100	Sluiskil (Zeeland/Terneuzen)
HyNetherlands	100	Eemshaven (Eemshaven-Delfzijl)
Total:	**1150 MW**	

Table 21. IPCEI (Important Projects of Common European interest) projects in the Netherlands that were granted subsidy in late 2022.

Region	**Total Capacity (MW)**
Rotterdam/Maasvlakte	650
Zeeland/Terneuzen	300
Eemshaven-Delfzijl	100
Noordzee Kanaal Zone/IJmuiden	100
All regions	1150
Total subsidy received	783.5 M€

Table 22. IPCEI project capacities (based on Table 1) based on region

Most hydrogen production capacities are being developed at the four clusters in the coastal areas (see Figure 24). These regions are attractive because landfall points are close to planned offshore wind capacities and the demand required by existing gas and electricity infrastructure in harbors allows for demand needs being met. It's foreseen that this capacity will be installed by 2026 at the latest. In the course of 2023 additional IPCEI projects are foreseen to be selected for comparable subsidies values, i.e., projects on hydrogen imports and on hydrogen storage.

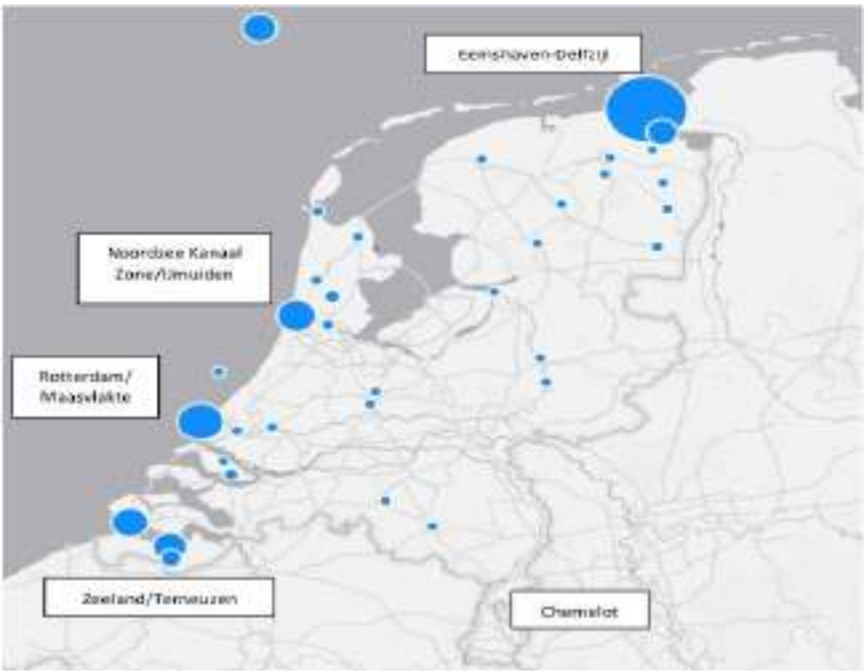

Figure 24. Locations in the Netherlands where most hydrogen-related activities are being done. Circles represent the magnitude of the projects, and the largest circles relate to the 7 IPCEI projects approved (Table 21 and Table 22)

Within the Netherlands, the projects with the highest level of concentration (30+) are in the production of hydrogen and end uses in mobility and transport (see **Figure 25**). Projects with medium levels of concentration (15 – 30) are in end uses for the built environment and knowledge and partnership studies. Projects with the lowest level of concentration are in storage, import of hydrogen, offshore hydrogen production and end uses in industry. **Figure 26** provides a count of the companies involved in hydrogen related activities.

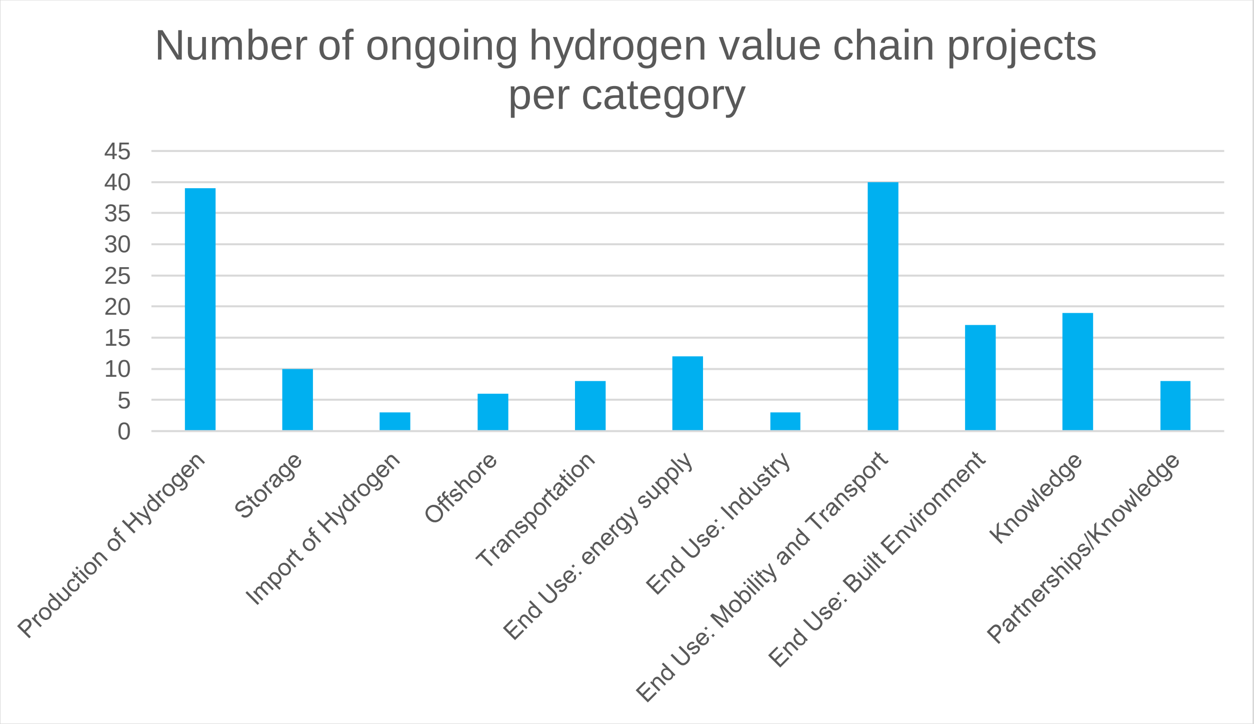

Figure 25. Number of ongoing hydrogen value chain projects per category as of 2022 based on information from (TKI Nieuw Gas, 2022)

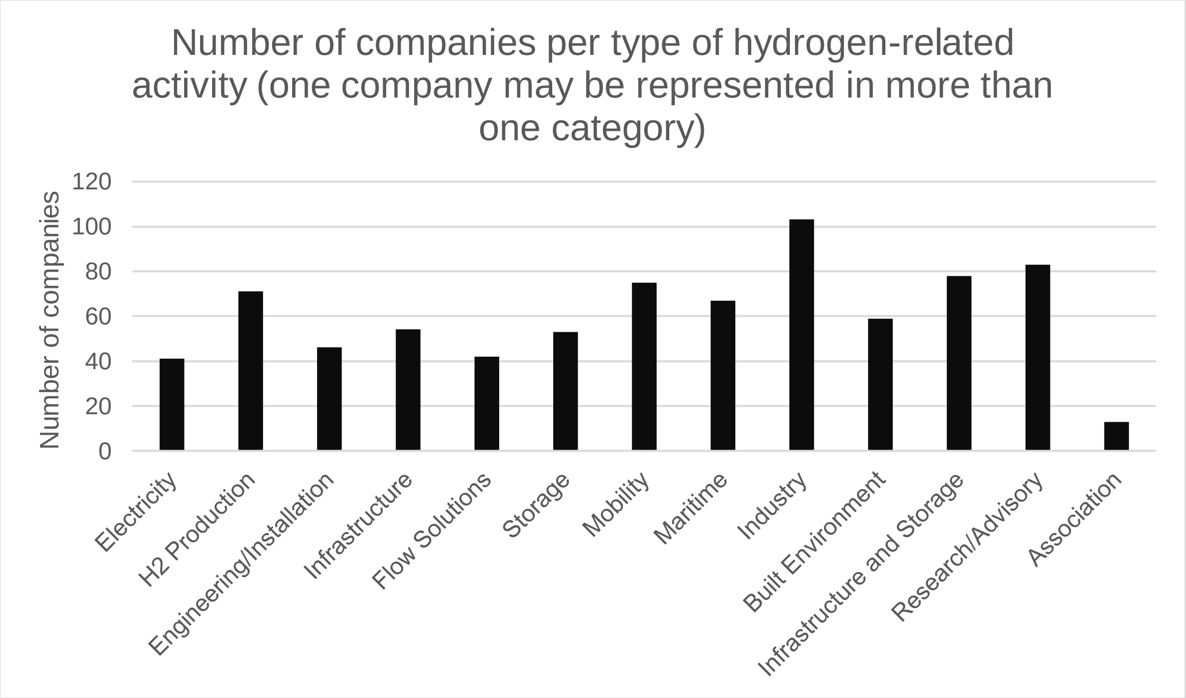

Figure 26. Number of companies per type of hydrogen-related activity in the Netherlands as of 2022 based on information from (National Waterstof Programma, 2020).

Market

A green hydrogen economy encompasses production, markets, infrastructure, and social aspects. This economy can only develop when these aspects are developed interdependently. During an initial phase, the following projects, activities, and system must be achieved in the Northern Netherlands by as early as 2025 or by 2030 at the latest. In the Northern Netherlands, the existing chemical industry can produce green ammonia and green methanol by using large quantities of green hydrogen. Projects that can most meaningfully accelerate the green hydrogen economy are large-scale green hydrogen production by electrolysis and biomass gasification in combination with retrofitted gas pipelines to transport the hydrogen to be used as a feedstock in the (petro)chemical industry in Delfzijl and in Rotterdam, Limburg and/or Germany (van Wijk, 2017). Using the existing gas infrastructure to transport hydrogen has the advantage that it can be provided to existing hydrogen feedstock markets at low costs. The transportation of hydrogen via retrofitted gas pipelines therefore offers a unique opportunity for a second life for the gas infrastructure.

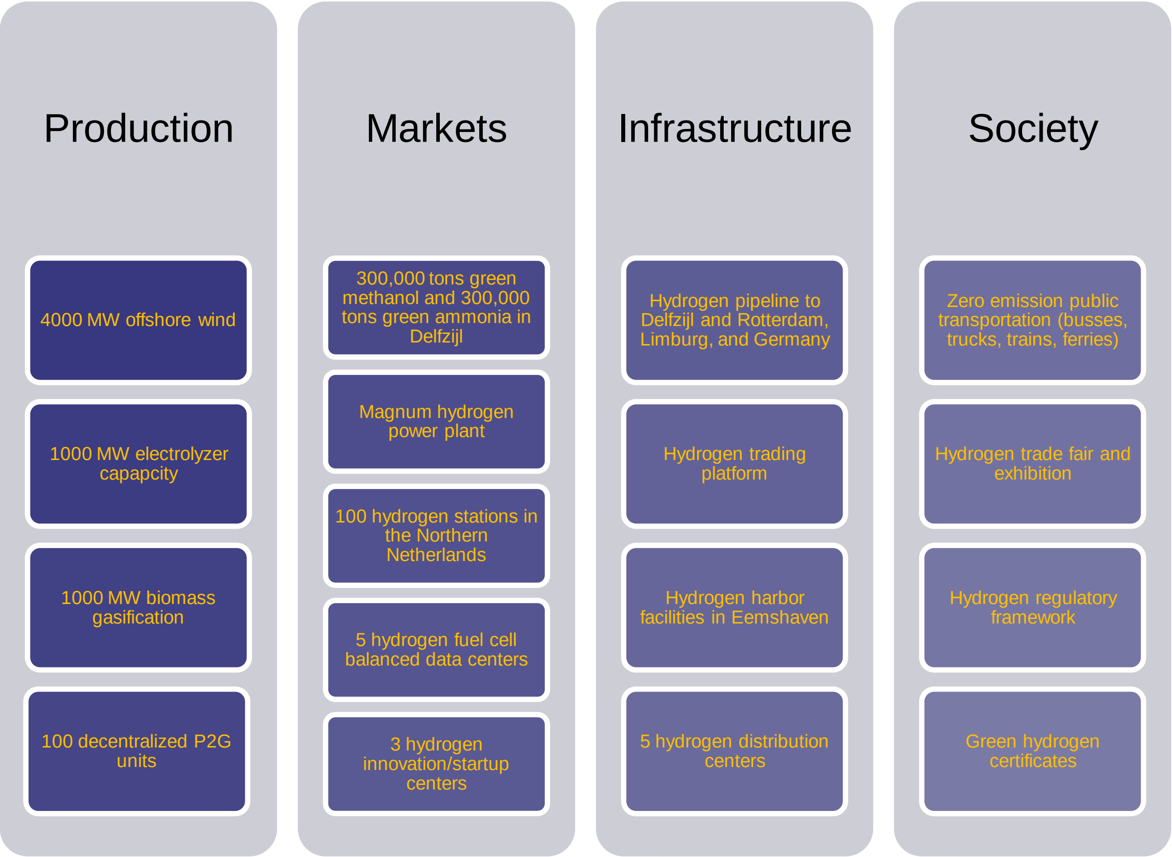

Figure 27. Main aspects of a green hydrogen economy in Northern Netherlands based on production, markets, infrastructure and societal aspects (Source: (van Wijk, 2017)).

It's expected that through these projects, activities and systems in the period between 2017 and 2030, about 270,000 tons of hydrogen (38 PJ) will be produced annually in Northern Netherlands (van Wijk, 2017). From these 270,000 tons of hydrogen, 160,000 tons of it can be produced by 1000 MW electrolysis, 100,000 tons by 1000 MW biomass gasification systems and 10,000 tons by 100 decentralized P2G units running in solar energy. **Table 23** provides an overview of these high-level calculations and is based on an estimation from 2017 (see (van Wijk, 2017)), seeing how there has been many challenges and delays for stimulating a hydrogen economy, it's expected that even by 2030 some of these capacities and activities will not fully take place.

	Expected Capacity (MW)	**Expected hydrogen production (tons)**
Electrolysis	1000	160,000
Biomass gasification	1000	100,000
Decentralized P2G units	Varied	10,000
Total	**2000+**	**270,000**

Table 23. High-level potential installed capacities and expected hydrogen production in Northern Netherlands by 2030 (Source: (van Wijk, 2017)). Note: It is expected that fulfilling these targets by 2030 is not feasible and that possibly by 2035 these targets could be achieved.

The main markets for hydrogen are the feedstock markets in the chemical and the petrochemical industries. The total amount of hydrogen that is currently generated in industry is estimated at 180 PJ per year (Weeda & Segers, 2020). In the Northern Netherlands, the existing chemical industry can produce green ammonia and green methanol by using large quantities of green hydrogen. The consumption of 270,000 tons of hydrogen can be broken down into 60,000 tons for methanol production and another 60,000 tons for ammonia production in Delfzijl. 12,000 tons can be utilized to fuel 100,000 cars, 10,000 tons for 1300 buses, 5000 tons for 50 trains and 3000 tons for other mobility purposes. It's also expected that 20,000 tons can be used for grid balancing purposes and 100,000 for pipeline transport to other locations such as Rotterdam, Limburg, and Germany. **Table 24** provides an overview of these high-level calculations and is based on an estimation from 2017 (van Wijk, 2017)).

Hydrogen consumption categories in Northern Netherlands	Expected consumption (tons)
Methanol production in Delfzijl	60,000 tons for the production of 300,000 tons of Methanol
Ammonia production in Delfzijl	60,000 tons for the production of 300,000 tons of Ammonia
Cars	12,000 tons for 100,000 cars
Buses	10,000 tons for 1,300 buses
Train	5,000 tons for 50 trains
Other Mobility	3,000 tons
Grid balancing[19]	20,000 tons
Pipeline transport to Delfzijl and Rotterdam, Limburg and Germany	100,000 tons

Table 24. Potential hydrogen consumption in tons in Northern Netherlands (Source: (van Wijk, 2017)). Note: It is expected that fulfilling these targets by 2030 is not feasible and that possibly by 2035 these targets could be achieved.

Figure 28 provides a potential of overview of how the Dutch hydrogen economy could look like in Northern Netherlands.

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[19] Possibly for data centers. The consensus before was that these data centers would utilize Fuel Cells for producing electricity but currently a lot of data centers already buy a lot of green electricity directly from the grid. What the role of fuel cells would be for producing electricity for data centers remains to be seen.

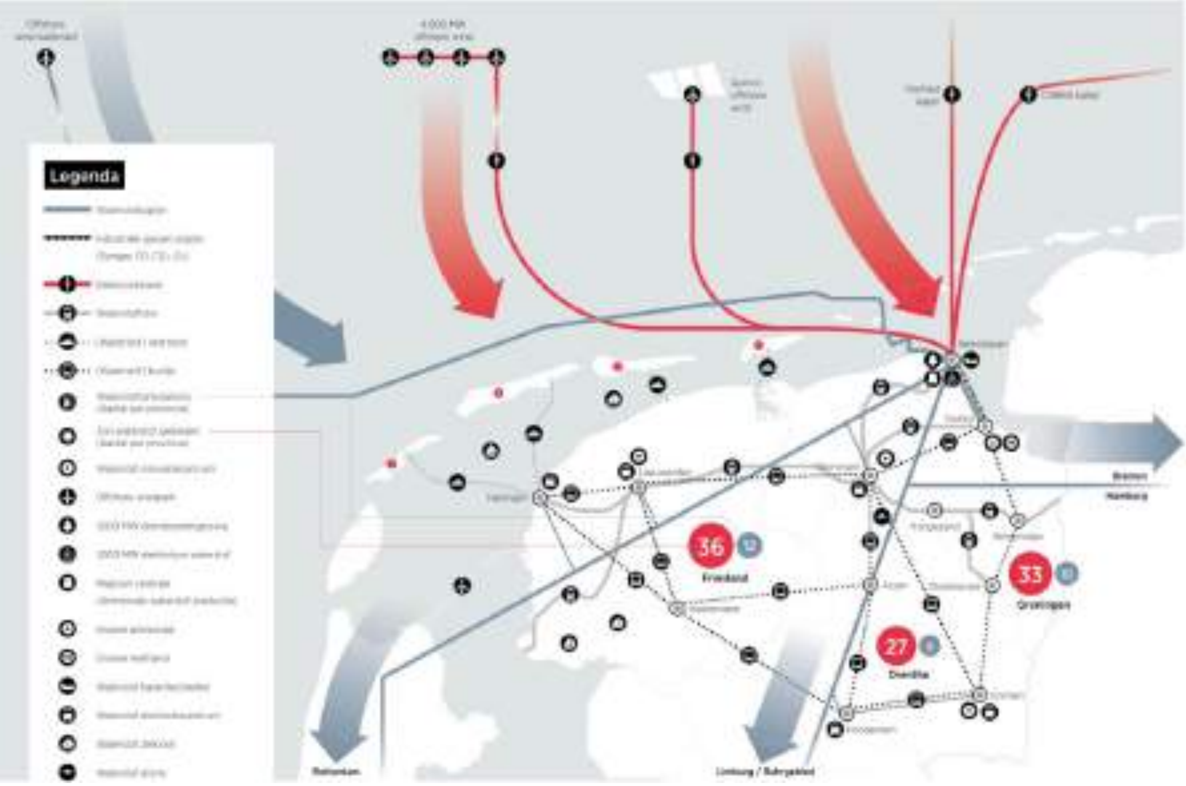

Figure 28. Potential map of how the hydrogen economy could like in Northern Netherlands in the future (Source: (van Wijk, 2017)).

Financial

Table 25 shows the total investments for the development of a green hydrogen economy in the Northern Netherlands up to the year 2030 and is estimated to be between 17.5 and 25 billion euros (van Wijk, 2017). These investments include 12 to 15 billion for offshore windfarms. The investments in hydrogen-related projects are estimated to be between 5.5 and 10 billion euros over the next 10 to 12 years. The priorities are large scale green hydrogen production by electrolysis and biomass gasification, together with investments in hydrogen pipeline infrastructure to Delfzijl and Rotterdam, Limburg and Germany. These large investments are expected to be made by a combination of electricity, oil and gas, industrial gasses, chemical, gas infrastructure and harbor companies.

Green Hydrogen Economy in the Northern Netherlands	Investment (million €) period: 2018 to 2030*
Production	**15,000 – 20,000**
4,000 MW offshore wind	12,000-15,000
1,000 MW electrolysis hydrogen production	500-1000
1,000 MW biomass-gasification hydrogen production	500 – 1000
100 solar-hydrogen smart areas	2000-3000
Markets	**1000-1800**

300,000 tons green methanol and 300,000 tons green ammonia Delfzijl	600 - 1000
Hydrogen Magnum power plant	Unknown
100 hydrogen fuelling stations in Northern Netherlands	100-200
5 hydrogen fuel cell balanced data centers	200-400
3 hydrogen innovation/SME/startup centers	100-200
Infrastructure	**700-2000**
Hydrogen pipelines to Delfzijl and Rotterdam, Limburg and Germany	200 - 1000
Hydrogen trading platform	50-100
Hydrogen harbor facilities in Eemshaven	400-800
5 hydrogen distribution centers	50-100
Society	**800-1200**
Zero emission public transportation (busses, trucks, trains and ferries)	800-1200
Hydrogen trade fair and exhibition	0-10
Hydrogen regulatory framework	0-10
Green hydrogen certificates	0-10
Total including offshore wind farms	**17,500-25,000**
Total hydrogen related investments	**5,500 – 10,000**

Table 25. Approximate estimation of investment required for fulfilling a green hydrogen economy in Northern Netherlands (Source: (van Wijk, 2017)). Note that the table below provides high-level estimates based on what the potential of the Northern Netherlands could be and that some of the activities have yet to be fulfilled or carried out even by 2030. It’s expected that some of these activities could be fulfilled by 2035.

VI. Subsidies/ aids/ support from local and regional governments that will support the implementation of the hydrogen model

Governments at the local and regional levels often play a crucial role in supporting the implementation of hydrogen models, especially for long-distance trucks, city/intercity mobility buses, city/intercity mobility vehicles, and last mile vans, through various subsidies, aids, and support programs. Some common types of support that local and regional governments can offer include purchase incentives for long distance hydrogen trucks, hydrogen bus purchase subsidies, vehicle purchase subsidies, hydrogen infrastructure grants, infrastructure planning assistance, operating cost support, funding for pilot programs, public-private partnerships, emission reduction grants, and regulatory support.

In the Northern Netherlands, the implementation of a hydrogen model in the mobility sector partially comes from the support of Pilot programs and grants within the region. For instance, the implementation of hydrogen refuelling stations and hydrogen buses and vehicles in the Northern Netherlands are supported from the HEAVENN project. More specifically, four hydrogen refuelling stations are being built in Groningen and Delfzijl, among other places, at 350 bar (suitable for heavy transport) and 700 bar (suitable for passenger transport) (HEAVENN, n.d.). In addition to the bus filling station in Emmen, this brings the number of hydrogen filling points to five (HEAVENN, n.d.). Furthermore, a vehicle fleet consisting of 105 passenger vehicles, 8 light duty trucks, 8 heavy duty trucks, 4 waste collection trucks, 2 long-distance buses (Qliners) and 2 eight-seater vans will be created (HEAVENN, n.d.). These vehicles and refuelling stations will provide an initial impetus for the development of hydrogen mobility in the Northern Netherlands region (HEAVENN, n.d.). In addition, another regional pilot project includes the Jive and Jive2 projects where the city/intercity mobility bus company, Qbuzz, helps to create the new hydrogen economy in the Northern Netherlands with public transport at the forefront (Qbuzz, n.d.). The Jive projects helped in developing a new hydrogen filling station which is one of the largest in Europe, along with the deployment of 20 hydrogen-buses (Qbuzz, n.d.). Not only do these pilots projects help in the development of hydrogen infrastructure and hydrogen-powered mobility by reducing the costs of investments through grants and financial funding, but these projects also help in fostering public awareness and support in hydrogen-powered public transport and vehicles.

In addition, organizations such as the Northern Netherlands Alliance (SNN), joins together the three northern provinces and the four largest cities (Assen, Emmen, Groningen, Leeuwarden) of the Northern Netherlands, in coordinating the economic strategy for the region. They are a Management Authority for the European Regional Development Fund (ERDF) and provide subsidies and grants in the Northern Netherlands (SNN, About SNN, n.d.). Subsidy programs which they coordinate include the regional innovation strategy (RIS3) for the Northern Netherlands, the European Regional Development Fund (ERDF), the Just Transition Fund (JTF), and the new European Rural Development Program, the Common Agricultural Policy (CAP) (SNN, The SNN and European grant programmes, n.d.). Furthermore, the Netherlands Enterprise Agency (RVO) helps entrepreneurs and organisations to invest, develop and expand their businesses and projects from a national level. They are a government agency which is part of the Dutch Ministry of Economic Affairs and Climate Policy which also provides subsidies and grants, including subsidies for sustainable transport (Agency, n.d.).

Moreover, regulatory backing from the European Commission for overseeing the Ten-T network of hydrogen refuelling stations along key road corridors will spur hydrogen infrastructure implementation, benefiting not just the Northern Netherlands but all of Europe. Prioritizing the demand for hydrogen in mobility vehicles is crucial for enhancing competitiveness against alternative sustainable transportation options.

The role of the government in initiating hydrogen activity next to providing subsidies also is taking shape in terms of regulation and other legal measures as well as planning both timewise and spatial-wise.

Local governments are typically responsible for most of the detailed spatial planning and permitting procedures while the national government facilitates and coordinates those processes. They can help with access to support money from government-owned banks and the bank of the Dutch municipalities. If they step in, national governments can contribute to making this a long-term solid position other than activating or modifying policies. Local governments and also port authorities will play an important role in organizing local networks and their endeavours are supported by the Ministry of Economic Affairs and Climate Policy.

VII. Scouting of innovating solutions on hydrogen mobilities

Mobility

Targets that have been set out in the National Climate Agreement regarding hydrogen in the mobility sector pointing to the implementation targets of 50 refuelling stations, 15,000 fuel cell vehicles and 3,000 heavy duty vehicles by 2025, ultimately leading to 300,000 fuel cell vehicles by 2030. Cooperation agreements have been signed with specific sectors such as urban logistics, waste collection vehicles and long-distance transport to hinterland connections and will be influential in providing roll-out of hydrogen (Ministry of Economic Affairs and Climate Policy, 2020).

Subsidy schemes for zero emissions urban logistics and heavy-duty transport are being developed under the framework for the National Climate Agreement (‘Klimaatakkoord’). Further roll-out of refuelling stations will be encouraged, including the EU Alternative Fuels Infrastructure (AFIR) Directive. In addition to a refuelling infrastructure at the main Dutch and European transport axes, roll-out will also be required in adjacent regions (Ministry of Economic Affairs and Climate Policy, 2020).

The RED (Renewable Energy Directive) II is also a key factor for the development of the market for sustainable hydrogen for the mobility sector. Government will review how the implementation the RED II can contribute to encouraging the use of clean hydrogen within the existing framework conditions of the National Climate Agreement and with a view to ensuring a level playing field for battery-electric and fuel cell-electric applications (Ministry of Economic Affairs and Climate Policy, 2020).

At the point of writing this document, discussions about RED III are ongoing within the European Commission. An early indication of the European goals and the role of hydrogen have been made in the form of binding targets for industry and mobility:

- Producing 10 million tonnes of Renewable Fuels of Non-Biological Origin (RFNBOs) by 2030
- Raise the share of renewable energy in the EU’s overall energy consumption to 42.5% (the current consumption level is at 22.1%)
- 42% of all hydrogen used in industry (currently most of it as feedstock in the chemical industry) needs to come from RFNBOs (i.e., be low carbon) in 2030, and 60% in 2035
- Heavy-duty vehicles will be mandated to reduce their emissions by 45% in 2030 and 90% by 2040
- There has to be at least 1 HRS installed every 200 km on major roads along the Trans European Transport corridors (TEN-T)

In early 2023 the Dutch government announced plans to publish a tender for the development of hydrogen refuelling stations (HRSs) for heavy-duty vehicles. This tender aims at accelerating the development of HRSs along TEN-T corridors (that in the Netherlands are situated mostly to the south) as well as in urban nodes nearby cities with at least 100,000 inhabitants. The details of the tender are up to the point of writing relatively unclear; what is so far known is that the focus is on heavy duty transportation. This tender in the Netherlands is a response to similar tenders that have been published in Germany and France to boost hydrogen mobility and is part of the European plans to have a network of at least 665 HRSs by 2030.

Maritime

The Netherlands is a country that is dominated by inland waterways and 43.2% of inland freight transport in 2018 consisted of inland waterway transport. Existing inland shipping fleets are depreciating due to older engines running on diesel. In order to transition to more environmentally friendly and carbon-neutral options, the Dutch government is providing financial stimuli for ship-owners to opt for engines that are less environmentally polluting. Among the various propulsion methods for inland ships, hydrogen fuel cell propulsion is garnering attention and various projects are underway with many shipyards thinking of integrating hydrogen bunkers in their facilities. The first ever inland hydrogen vessel called the Antonie has been delivered and is set to transport salt between Delfzijl to Botlek in the Port of Rotterdam. Other inland ship developers have reported that they are (thinking of) developing hydrogen-ready vessels that can be easily converted to hydrogen propulsion once the market is more favourable to them.

The Dutch Green Deal Zeevart, Binnenvart and Havens (Green deal on maritime and inland shipping and ports) stipulates a target of 150 zero-emission inland vessels by 2030. Work is also being carried out in the RH2INE program in the transition to hydrogen-powered inland vessels in Northwestern Europe; their objective is to realize low-emission and climate-neutral inland shipping by 2050 (National Waterstof Programma).

The Netherlands governmental Department of Infrastructure and water management is proactive in providing subsidies for shipbuilders in order to stimulate the use of hydrogen as a fuel in order to make zero-emission shipping a reality; for example, Lenten Scheepvart which is a ship manufacturing company has received a €4 million subsidy for the construction of a vessel running on hydrogen (Bajic, 2023).

Studies are also being done by a group of leading European companies such as Vopak, Shell and Engie with the shipping company Anthony Veder to explore the option of producing, liquefying and transporting green hydrogen from Portugal to the Netherlands with aims of starting the production in 2025 (The Maritime Executive, 2022).

Aviation

In the short-term future, SAFs (Sustainable Aviation Fuels) are being considered for transcontinental and continental flights. Regulations set by the European Commission will set mandatory targets for the implementation of renewable fuels in the European transport sector, and as a result, SAFs will be blended with conventional kerosene for all flights departing from EU airports (Heuvel, 2022). Blending percentages will increase on 5-year intervals, starting from 2025, up to 2050. In 2025, the target is to have 2% of all fuel supplied to flights leaving the EU airports be in the form of SAF. In 2030 at least 5% of all supplied fuel shall be SAF, of which at least 0.7% renewable kerosene of non-biological origin (e-SAF) (Heuvel, 2022). The binding SAF target is increasing up to 63% by 2050, where the EU envisions that at least 28% of all SAF needs to come from synthetic fuels. Hydrogen will play an important role in SAF since the refining of SAF requires significant volumes of hydrogen (Heuvel, 2022), and the production of synthetic fuels will undoubtedly come from green hydrogen (and potentially biogenic or sequestered carbon dioxide). Companies like KLM are aiming to make its total fuel usage by SAF to be more than 10%.

Important breakthroughs are occurring in applications of hydrogen in the Dutch aviation sector. €383 million was granted to the Aviation in Transition program from the National Growth Fund in which the HAPSS project was the largest component. Hydrogen Aircraft Powertrain and Storage System (HAPSS) is a public-private partnership composed of Fokker, Royal Dutch Aerospace Center, TU Delft and other companies and institutions that is undertaking the development of the world’s first larger passenger aircraft (40-80 seats) that will run on liquid green hydrogen and is set to fly between the Netherlands and London in 2028 (Veenstra, 2022).

Groningen Airport in Eelde is also playing an important role in demonstrations for emission-free flying. Battery powered flights are expected to be feasible by the next decade and hydrogen plays an important role for these batteries via fuel cells. Eelde airport is planning on installing a multi-modal hydrogen refuelling facility that will get hydrogen produced from a solar park and will refuel both ground power units for providing electricity to parked aircrafts on the ground operations’ side, as well as cars and buses on the visitor’s side.

Conclusions

Summary of the limitations, constraints, and barriers identified in each key aspect of hydrogen mobility

In conclusion, there are several limitations, constraints, and barriers impacting the widespread adoption of hydrogen in mobility. Limited infrastructure, both in refuelling stations and distribution networks, inhibits accessibility. Service-related barriers, including investment requirements and refuelling times, impede consumer acceptance. In public transportation, the lack of suitable fleets and high implementation costs present hurdles. Infrastructure-related barriers along intercity routes limit the practicality of hydrogen vehicles. Furthermore, the scarcity and non-standardization of hydrogen refuelling stations pose challenges. Safety concerns, fueled by public perception and the absence of clear standards, compound the obstacles. Addressing these limitations necessitates collaborative efforts in infrastructure development, standardization, and public awareness to propel the hydrogen mobility ecosystem toward viability.

Importance of addressing these limitations to drive the development and adoption of hydrogen mobility

Addressing the limitations within hydrogen mobility is vital for advancing its development and widespread adoption towards a more sustainable and environmentally friendly future for transportation. A key aspect is the establishment of an expansive and robust infrastructure, including hydrogen refuelling stations, to enhance accessibility and usability. Overcoming challenges like high initial investment costs is essential to encourage private sector participation and instill confidence among investors. For example, targeted funding can expedite the integration of hydrogen refuelling stations along major transportation routes, easing infrastructure-related hurdles, and fostering a coordinated hydrogen transport ecosystem. By tackling service-related barriers, supporting transitions in public transportation, and ensuring standardization and safety, the industry can mature, aligning with broader carbon neutrality objectives.

Moreover, support is crucial for scaling up hydrogen production, particularly in the realm of green hydrogen. Financial incentives and research funding can accelerate technological advancements, reducing the cost of green hydrogen production and enhancing its competitiveness in the market. Establishing clear standards and safety protocols creates an environment conducive to public acceptance and industry engagement. Steering the hydrogen mobility agenda requires strategic resource allocation, cross-sector collaboration, and visionary leadership, positioning the sector as a leader in sustainable transportation technologies and contributing significantly to broader ecological and environmental sustainability goals.

Possible solutions and how to overcome the above-mentioned challenges

Addressing the challenges in hydrogen mobility requires a multifaceted approach involving the collaboration among key stakeholders, strategic infrastructure investment, and the implementation of supportive policies. Firstly, fostering collaboration among governments, industry players, and research institutions is crucial. Joint initiatives can streamline standardization efforts, ensuring a consistent regulatory framework and safety standards across regions. Additionally, establishing public-private partnerships can expedite infrastructure development, particularly the expansion of a hydrogen refuelling network. Governments can play a pivotal role in incentivizing private investments through subsidies, tax credits, and grants, reducing the financial burden on businesses venturing into the hydrogen sector.

Furthermore, supportive policies are essential for creating a conducive environment. Governments can implement regulations that encourage the adoption of hydrogen-powered vehicles, such as emissions standards and preferential treatment for hydrogen fleets. Financial incentives, including subsidies for vehicle purchases and infrastructure development, can significantly boost market adoption. In parallel, a clear roadmap for the phased implementation of hydrogen infrastructure, prioritizing key transportation routes and urban centers, can address logistical challenges. By combining collaborative efforts, targeted investments, and well-crafted policies, the hydrogen mobility sector can overcome its limitations and transition into a sustainable and widely embraced mode of transportation.

Task 5.1– The case of the Constanta Region

WP: Work Package 5: Mobility Use of Hydrogen

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the European Union

Task 5.1- Constanta

Introduction

The status of Hydrogen mobility

The National Context

The Romanian Government has embarked on a comprehensive strategy to promote hydrogen as a clean energy source. The National Hydrogen Strategy and the accompanying Action Plan for 2023-2030 outline a roadmap for developing the hydrogen sector in Romania, including regulatory reforms and investments in infrastructure.

Key steps have already been taken to establish a regulatory framework for hydrogen. In 2020, Government Ordinance 106/2020 amended the Electricity and Natural Gas Law 123/2012 to incorporate provisions specifically addressing hydrogen. This move signals the government's commitment to fostering a thriving hydrogen economy in Romania.

The National Hydrogen Strategy acknowledges that the existing regulatory framework for transporting hydrogen by road and rail aligns with the guidelines for handling hazardous materials. However, gaps exist in the regulatory framework governing the transmission and distribution of hydrogen through natural gas pipelines. Neither the Energy Law nor the secondary regulations of the National Energy Regulatory Authority (ANRE) provide specific guidelines for the injection of hydrogen or hydrogen-gas mixtures into the gas grid.

To fully implement the Hydrogen Law and enable the utilization of hydrogen for its intended purposes, the National Energy Regulatory Authority (ANRE) must establish secondary regulations outlining the conditions and standards for constructing hydrogen injection facilities within existing gas transmission and distribution networks.

While some aspects of hydrogen storage are governed by the guidelines for handling compressed or liquefied gases, the National Hydrogen Strategy emphasizes the need for comprehensive revisions and updates to existing technical specifications such as PT C 5-2003, edition 1, "Technical requirements for the use of cylinders for gases that are compressed, liquefied or dissolved under pressure" and PT C 4-2010, "Stable pressurized metallic containers", as well as the development of specific technical rules tailored to hydrogen storage.

The hydrogen value chain in Romania

In Romania, hydrogen primarily serves as a raw material, used mainly in refining, fertilizer manufacturing, and the chemical industry. Its application is primarily confined to the production site.

The anticipated hydrogen value chain, based on the outlined consumption and decarbonization objectives, will encompass a broader range of activities beyond its current role as a raw material. Hydrogen will not only serve as an energy carrier and fuel but also play a significant part in industrial processes and transportation, such as:

- Hydrogen production will prioritize green hydrogen, generated by electrolysis powered by renewable energy sources. However, other production methods, such as methane pyrolysis, may be considered in the future, after 2030.

- Hydrogen storage will involve both gaseous and liquid forms, including liquid organic hydrogen carriers (LOHC) and ammonia.

- Hydrogen transmission and distribution will utilize pipelines and pressurized vessels for transport by road, rail, river, and sea.

- Hydrogen applications will expand beyond its current usage, encompassing transportation as a fuel and industrial processes to reduce emissions in refining, petrochemicals, chemicals, metallurgy, cement, ceramics, and paper industries. It will also serve as an energy storage medium and a feedstock for synthetic fuels.

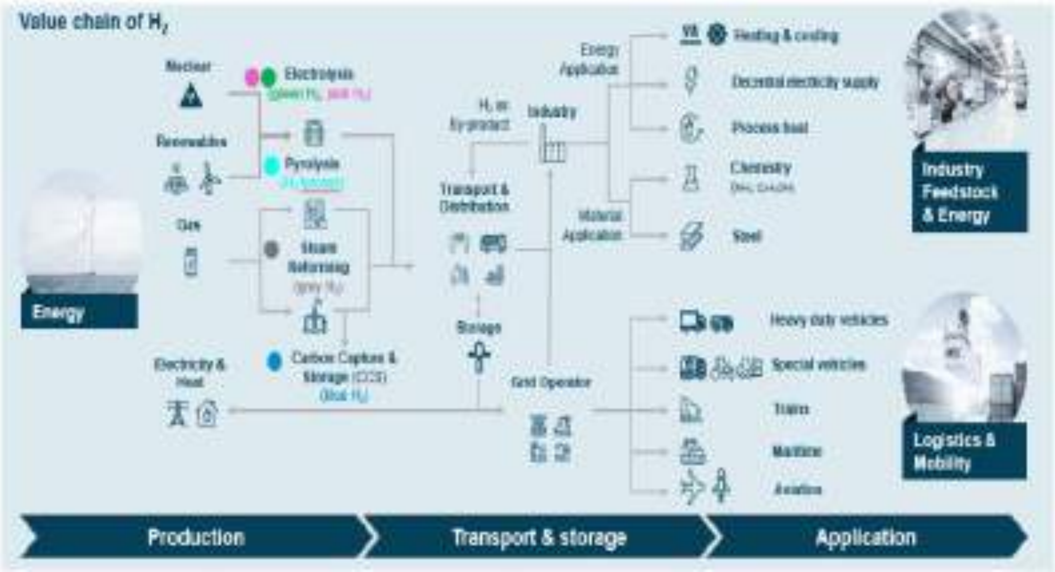


Figure 1. Potential hydrogen value chain in Romania (Romanian Hydrogen Strategy, 2023-2030)

Currently, there are no specific regulations governing hydrogen vehicles, as they are subject to the general rules applicable to all vehicles. However, there are minimum regulations in place for hydrogen refuelling stations, specifying the technical specifications they must meet for safe and efficient operation.

Presentation of the region

Nestled along the picturesque Black Sea coast, Constanta County emerges as a captivating region within the South-East Region of Romania, the second-largest administrative division. Its diverse landscape features a lagoon area, hilly terrain in the north, and vast, flat plains stretching across the central and western areas. The county's administrative environment consists of three municipalities, eight cities, 18 municipalities and towns, 59 communes, and 190 villages. Constanța Municipality, the county's heart, boasts the largest population, serving as its administrative hub.

The Constanta growth pole, a pioneering administrative structure unique to Romania, stands tall as a thriving hub with an estimated population of around 600,000 individuals. It plays a pivotal role in driving the region's economic growth, fostering innovation, and propelling sustainable development.

Figure 2. Constanta County map

Nestled on the Romanian Black Sea coast, the Port of Constanta stands as a maritime hub, its strategic location serving as a nexus for trade connections, linking landlocked European countries with markets in Transcaucasia, Central Asia, and the Far East. Its strategic positioning seamlessly integrates it into Central and Eastern Europe's transport network, utilizing Corridors IV (rail and road), VII (Danube inland waterway), and IX (road) passing through Bucharest. The nearby satellite ports of Midia and Mangalia form integral parts of the Romanian maritime port system under the management of the Maritime Ports Administration SA Constanta.

The Port of Constanta's versatility as both a maritime and river port enables it to accommodate a wide range of vessels, from tankers with a capacity of 165,000 dwt to bulk carriers of 220,000 dwt, and any type of river vessel. In an ongoing endeavor to enhance its cargo handling capabilities and optimize transport connections with its hinterland, the port is actively pursuing several infrastructure development projects.

A key strength of Constanta Port lies in its seamless connection to the Danube River via the Danube-Black Sea Canal. This vital waterway provides a cost-effective and efficient mode of transport, capable of carrying significant cargo volumes, offering an attractive alternative to the often-congested European rail and road networks.

General characterization of mobility issues, cities with implemented SUMPs

Constanța, a pioneer among Romanian cities, embarked on the development of a Sustainable Urban Mobility Plan (SUMP) in 2015-2016, supported by an assistance program from the European Bank for Reconstruction and Development (EBRD) specifically tailored to national Growth Poles, under the coordination of the Ministry of Regional Development and Public Administration (MRDPA). The SUMP aimed to create a sustainable, safe, integrated, and accessible transport system, fostering connections between people and places, while supporting the economy, environment, and quality of life within the Constanța Growth Pole.

Simultaneously, during this period, the Port Master Plan (PMP) was formulated, with the objective of driving the comprehensive development of the Port, encompassing all its sectors, while considering the diverse range of goods handled within the port area.

The City of Constanta and the Port of Constanta each developed their own strategies, focusing primarily on their respective developmental needs, without considering the integrated needs of the metropolitan area as a whole. To overcome such a situation, the governance authorities of both entities established a Mobility Forum, comprising key representatives from the various mobility stakeholders at different decision-making levels. The aim of this forum was to promote sustainable integrated urban mobility policies for the Constanța Metropolitan Area. The Mobility Forum envisioned itself as a think tank, tasked with identifying specific mobility and urban planning challenges in the area and developing a shared vision and approach for implementing integrated mobility solutions for the city and its Functional Urban Area, including the port.

Inspired by the SUMP's overarching goals, the Municipality of Constanța developed the Sustainable Energy Action Plan in October 2016, followed by the Air Quality Plan for NO2 and NOx in 2021. Both plans explicitly address air quality improvement and environmental impact reduction through the incorporation of renewable energy solutions. These measures include enhancing building energy efficiency, implementing small PV systems for public lighting, and replacing the existing public transport fleet with electric buses.

In terms of electrifying the public transport fleet, the plans outline three short-term measures, with one already accomplished and two nearing completions:

- Electric Buses acquisition for public transport: The purchase of 20 electric buses with a length of 12 meters, along with 20 slow recharging stations and 5 fast recharging stations, has been completed.
- Electric Buses acquisition for public transport: The acquisition of another 22 electric buses with a length of 12 meters, accompanied by 22 slow recharging stations and 7 fast recharging stations, is currently in progress.
- Electric Buses acquisition for public transport: The procurement of 21 electric buses measuring 10 meters, along with 21 slow recharging stations and 5 fast recharging stations, is also underway.

While plans for the Port of Constanta to harness renewable energy sources initially included wind turbines and a large solar farm, these projects remain at the conceptual stage with no immediate implementation timeline.

However, the Port of Constanta is actively involved in the PIONEERS project (Portable Innovation Open Network for Efficiency and Emissions Reduction Solutions), aimed at developing a Green Port Master Plan and Roadmap for the Port of Constanta. This project is in its early stages, but it is exploring various avenues for incorporating green technologies, including:

- Annual energy consumption reduction: Implementing measures to minimize energy usage throughout the port operations.
- Building renovation for energy efficiency: Enhancing the energy efficiency of port buildings through renovations and upgrades.
- Incorporating energy efficiency requirements in procurement: Integrating energy efficiency criteria into the port's purchasing processes.
- Enhancing building energy performance: Investing in energy-efficient technologies and practices to improve the energy performance of port buildings.
- Installing solar energy systems on buildings: Harnessing solar energy to generate electricity for port operations.
- Expanding electric vehicle charging infrastructure: Providing more charging points for electric vehicles to support the shift towards cleaner transportation.
- Utilizing renewable energy sources in buildings: exploring the feasibility of utilizing renewable energy sources like hydrogen for heating and cooling purposes.
- Promoting non-biological renewable fuels for transportation: Encouraging the use of alternative fuels like hydrogen and methanol for port vehicles.
- Increasing biofuel usage: Increasing the proportion of biofuels in port operations.

- Establishing infrastructure for electric vessel power supply and LNG (liquefied natural gas): Developing the necessary infrastructure to support electric vessels and LNG-powered vessels entering the port.

These efforts aim to transform the Port of Constanta into a more sustainable and environmentally responsible maritime hub, contributing to the port's long-term growth and environmental sustainability.

Current status of demonstration projects on Hydrogen mobility.

Hydrogen energy technologies have a long history in the Constanta Region, with deep roots in the oil processing sector. The modern approach to hydrogen technology development began in 2004 at the Ovidius University of Constanta, where research activities on fuel cell technologies were initiated in collaboration with Rompetrol Group, a leading Romanian oil and gas company. This collaboration led to the organization of international seminars with partners from across the European Union and the establishment of joint cooperation projects.

In 2006, the HyRES platform was established to explore the production of hydrogen from renewable sources. In 2011, capacity development initiatives were undertaken, including master's programs and clustering activities.

In 2012, the collaboration with Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) began, providing a significant boost to the cooperation of Constanta partners with other organizations on hydrogen energy projects. In 2013, the MEDGreen Innovation Cluster was established, further strengthening the region's position as a hub for hydrogen technology innovation.

Figure 3. EU Hydrogen regions (Rafael Ortiz Cebolla, 2019)

Since 2016, the Constanta Region has actively participated in the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) initiative of Regions, fostering stronger collaboration among local stakeholders involved in hydrogen technology development.

In 2014, Ovidius University joined the European Institute of Innovation and Technology (EIT) Raw Materials community, which provided additional momentum for the University's research efforts in developing innovative materials for fuel cell applications. This collaboration has resulted in the initiation of several projects focused on the utilization of advanced materials in fuel cell technology.

Challenges, Strategies & Roadmap on the introduction of Hydrogen mobility

Challenges for the introduction of Hydrogen mobility

Based on data from the Department of Public Services of the Municipality of Constanta, Constanta features a comprehensive road network spanning a remarkable 377 kilometers. This extensive network can be categorized into distinct segments:

- category I: 39km
- category II: 18km
- category III: 285km
- category IV: 35km

Despite its generally well-structured road network, Constanta faces challenges in managing traffic flow, particularly during peak seasons. Strategic roads connecting the city to other districts and neighbouring towns are relatively short, limiting access to tourist destinations like Mamaia. The primary and secondary road networks in the city center, and especially in the south and west, become congested during tourist seasons, with significant traffic congestion on DN39 and DN2A, leading to major traffic jams on Boulevards "1st May" - Tomis and "Alexandru Lăpuşneanu".

As a port city and major tourist destination, Constanta experiences a surge in population during the summer months, further exacerbating traffic congestion and negatively impacting the quality of life for residents. The city's road infrastructure needs to be further developed and modernized to accommodate the growing population and tourism influx, ensuring smoother traffic flows and enhancing the overall livability of Constanta.

Vision, strategies and roadmaps for introduction of Hydrogen mobility

Embedded within the Danube-Mediterranean-Black Sea ecosystem, the Constanta County is intricately linked to regional water dynamics, wildlife patterns, human-induced pressures, socioeconomic trends, and transportation and industrial networks.

The Intergovernmental Panel on Climate Change (IPCC) predicts that water scarcity in the Danube-Black Sea region is expected to reach an average of 40% in the coming decades. Simultaneously, rising sea levels are projected to significantly impact the Danube Delta's hydrology and have severe consequences for the upstream Lower Danube region. Climate change poses a threat of slow desertification coupled with the intrusion of saltwater into the Danube Delta and the Lower Danube, requiring urgent innovation initiatives to adapt to the region's changing climate.

The development of hydrogen energy technologies in Constanta County is envisioned as an integral component of the Danube Green Corridor, a proposed future axis of European Civilization tailored to address future challenges.

The proposed approach entails the establishment of a large-scale Living Lab named Dobrogea Blue Bay, encompassing a region spanning the Danube and Black Sea, anchored by the Danube-Black Sea Canal. This Living Lab will serve as a platform for developing a multi-level strategy to implement hydrogen energy innovation initiatives tailored to the specific conditions of the region.

Figure 4 Danube Green Corridor Vision

The successful implementation of innovation initiatives promoting hydrogen energy technologies in the Constanta County requires close collaboration with other Danube-adjacent communities. In this regard, the H2Market project presents a pivotal opportunity to foster meaningful partnerships and advance the region's transition towards a sustainable hydrogen economy.

Market analysis

The projected demand for hydrogen by 2030 is estimated to reach 288.8 thousand tonnes, with a significant majority (excluding 6.6 thousand tonnes required by the industrial sector) being met by green hydrogen. This demand is expected to come from various sectors, including:

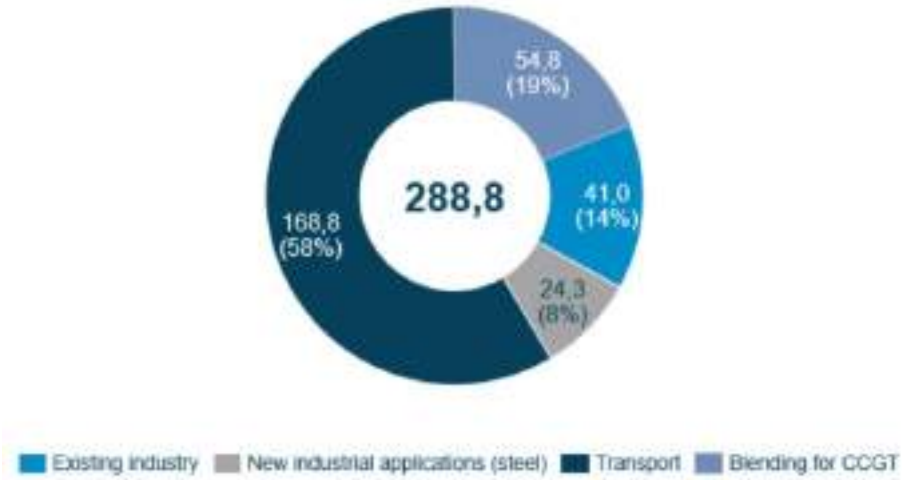


Figure 5. Estimated green hydrogen and clean hydrogen consumption broken down by sectors and expressed in percentages, for year 2030 (Romanian Hydrogen Strategy, 2023-2030)

The adoption of green and clean hydrogen is expected to result in a substantial reduction of CO2 emissions by 2,995 thousand tonnes in 2030. To meet the demand for green hydrogen, approximately 3,985 megawatts (MW) of electrolysis capacity will need to be installed. To power these electrolysis units, an estimated 7,969 MW of renewable electricity generation capacity will be required by 2030. This transition will require an estimated water consumption of 4.340 million cubic meters.

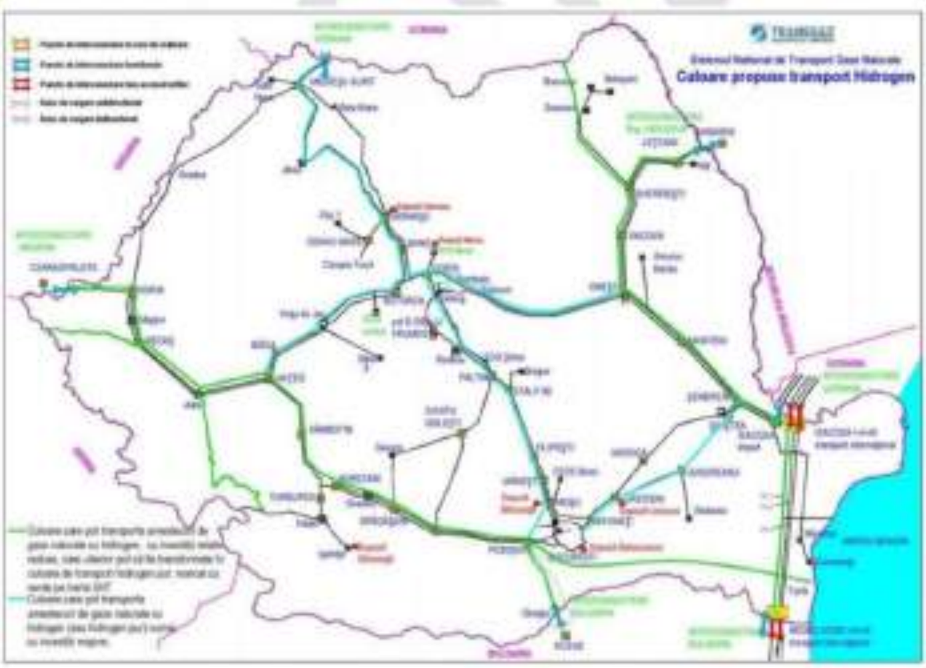
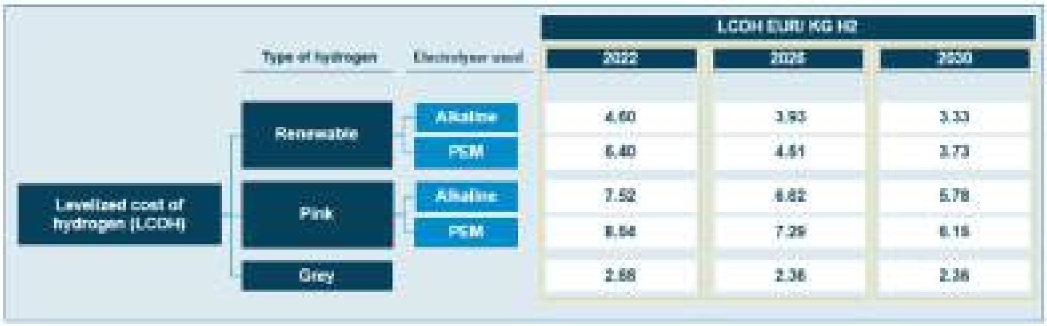


Figure 6. Proposal for the National Transmission System" backbone" for hydrogen transmission (Hydrogen transport corridors, 2021)



			LCOH EURO KG H2		
	Type of hydrogen	Electrolyser used	2022	2025	2030
Levelized cost of hydrogen (LCOH)	Renewable	Alkaline	4.60	3.93	3.33
		PEM	6.40	4.61	3.73
	Pink	Alkaline	7.52	6.62	5.78
		PEM	8.54	7.29	6.15
	Grey		2.68	2.36	2.36

Figure 7. LCOH per types of hydrogen produced (Romanian Hydrogen Strategy, 2023-2030)

SWOT analysis for the Constanta region

The Constanta region, a part of Romania's southeastern region, presents an ideal candidate for the development of ambitious hydrogen energy projects. Here are some of the potential opportunities:

Local Use of Renewable Hydrogen:

- Replacement of hydrogen from natural gas reforming (NG reforming) in the ROMPETROL Oil refinery: This would significantly reduce the refinery's carbon footprint and contribute to cleaner energy production.
- Deployment of renewable hydrogen in public transport and regional railways: Electrifying public transportation with hydrogen-powered vehicles would enhance sustainability and improve air quality in the region.
- Utilization of renewable hydrogen in transport and logistics sectors, including postal services and other operations linked to the Port of Constanta: This would reduce emissions from these sectors and promote a more sustainable transportation network.
- Integration of renewable hydrogen into stationary applications, such as power generation and heating systems: This would further enhance the region's energy efficiency and contribute to improved air quality in urban areas.

Transportation of Renewable Hydrogen to the European Union:

- Construction of a renewable hydrogen terminal at the Port of Constanta: This would serve as a hub for receiving, storing, and distributing hydrogen to various destinations in the region and beyond.
- Transportation of hydrogen by barges along the Danube River: This would provide a cost-effective and environmentally friendly mode of transport for hydrogen shipments.
- Blending hydrogen with natural gas for pipeline transportation: This would leverage existing infrastructure while reducing the carbon intensity of natural gas use.

Evaluation of the main players from the region:

The County of Constanta could actively engage in a range of projects by collaborating with various partners:

Academia/research centers:

- Institute for Nanotechnologies & Advanced Energy Sources, “Ovidius” University of Constanta,
- 3Nano – SAE Center at the University of Bucharest,
- National Research Platform on Hydrogen & Fuel Cells at Ramnicu Valcea

Industry sector:

- ROMPETROL Group,
- MONSSON Group,
- UT Midia,
- GSP Group,
- NUCLEARELECTRICA
- TRANSGAZ,
- TRANSELECTRICA
- MEDGreen Innovation Cluster
- HIDROELECTRICA
- LINDE GAS Romania

Governments/public institutions:

- Constanta County Council,
- Municipality of Constanta,
- National Company Administration of Maritime Ports
- National Company Administration of Navigable Canals

End-users for Hydrogen from Romania:

- Public Transport Company CT Bus,
- District Heating Company Termoficare,
- Romanian Railways Company
- National Company “Romanian Post”

Innovation Clusters

- Innovation Cluster MEDGreen on ecotechnologies and alternative energy sources

Potential for innovation and strengthening of competitiveness.

The Constanta County, as part of southeastern Romania, is recognized as a Smart Specialization Region within the European Union, with a focus on several key priorities. These priorities were carefully defined through a comprehensive consultation process and multiple iterations. Hydrogen energy technologies align with the priorities of ecotechnologies, information and communication technologies (ICT), high-tech, nanotechnology, and advanced materials.

The focus on ecotechnologies emerged from concerns about environmental degradation, the environmental impact of existing industries in the region, and the trend of locating highly polluting industries in southeastern Europe and less developed regions of the European Union.

The development of regional strategies on hydrogen energy technologies could have a transformative impact on the Constanta County. On one hand, utilizing renewable energy sources to produce hydrogen for use in the refinery could significantly reduce pollution in the region. Additionally, employing renewable hydrogen in public transportation and stationary applications could improve air quality in the city. Simultaneously, hydrogen technologies could foster the growth of innovative companies and generate new employment opportunities in this sector.

Conclusions

The Romanian Government has embarked on a comprehensive strategy to promote hydrogen as a clean energy source. The National Hydrogen Strategy and the accompanying Action Plan for 2023-2030 outline a roadmap for developing the hydrogen sector in Romania, including regulatory reforms and investments in infrastructure.

According to the vision of the Government, the anticipated hydrogen value chain, based on the outlined consumption and decarbonization objectives, will encompass a broader range of activities beyond its current role as a raw material. Hydrogen will not only serve as an energy carrier and fuel but also play a significant part in industrial processes and transportation.

The Constanta Region has a long tradition on hydrogen production and use, with deep roots in the oil processing sector. The modern approach to hydrogen technology development began in 2004 at the Ovidius University of Constanta, where research activities on fuel cell technologies were initiated in collaboration with Rompetrol Group, a leading Romanian oil and gas company. This collaboration led to the organization of education and training activities with partners from across the European Union and the establishment of joint cooperation projects.

The development of hydrogen energy technologies in Constanta County is envisioned as an integral component of the Danube Green Corridor, a proposed future axis of European Civilization tailored to address future challenges.

At local level, the proposed approach entails the establishment of a large-scale Living Lab named Dobrogea Blue Bay, encompassing a region spanning the Danube and Black Sea, anchored by the Danube-Black Sea Canal. This Living Lab will serve as a platform for developing a multi-level strategy to implement hydrogen energy innovation initiatives tailored to the specific conditions of the region.

The initiatives related to the implementation of hydrogen energy technologies are coordinated with the local and regional policies on sustainable mobility, green energy transition and circular economy.

Hy2Market

Task 5.1 – Raven: H2 Mobility Barriers in Europe & Mapping Key Trucking Routes and Hydrogen Hubs to support the identification of potential locations for reinforcing H2 infrastructures

WP: Work Package 5: Mobility Use of Hydrogen

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RAVEN

Font Corporation

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Task 5.1 – Raven

Introduction:

In the global landscape of sustainable mobility, hydrogen emerges as a crucial player for the future. Its potential to transform the automotive industry and reduce carbon emissions places it at the core of the transition to cleaner energies. However, this path is not without challenges.

At the European level, the widespread adoption of hydrogen mobility faces barriers and limitations that pose challenges for its short, medium, and long-term implementation. Understanding these complexities is essential for devising effective strategies that drive the successful deployment of hydrogen technologies.

In this context, the transition to heavy-duty hydrogen transport marks a crucial milestone in Europe's pursuit of a more sustainable and decarbonized industry. In this process, the identification of strategic centers and the optimization of hydrogen transport emerge as fundamental elements. Industrial centers, historically notable CO2 emitters, become focal points for decarbonizing the energy system and sustaining the foundations of the European economy.

These strategic measures go beyond merely facilitating transport; they have a substantial impact on the broad decarbonization of key industrial sectors. As crucial sources of CO2 emissions, these sectors play a central role in shaping a sustainable future. The deliberate placement of hydrogen stations and centers along Europe's major transport routes is a fundamental step toward cultivating a sustainable and decarbonized ecosystem.

Highlighting the importance of strategically identifying hydrogen hubs, hydrogen valleys, and productive plants, with the latter being the primary emitters of hydrogen and fundamental drivers of technological and scientific advancements related to its production. Additionally, it is crucial to emphasize the significance of industrial focal points, which stand as key locations, not only due to their impact on global carbon emissions but also as primary points of hydrogen demand. Finally, underscoring meticulous route planning as facilitating channels for the flow of hydrogen from emitters to recipients.

This strategic approach not only propels technological innovation associated with hydrogen transport in trucks but also paves the way for more sustainable industrial practices across Europe. These strategic elements are not merely logistical components; they are pillars underpinning a broader transition toward a sustainable industry and economy, marking a paradigm shift in Europe's trajectory toward a greener and more efficient future. Essentially, they represent the foundation of a new chapter in Europe's industrial evolution, where sustainability is not just a goal but the very fabric of future prosperity. This comprehensive approach addresses not only the optimization of hydrogen transport but also the fundamental transformation of the industry towards environmentally friendly and economically viable practices.

Analysis of Hydrogen Mobility Barriers in Europe: A Comprehensive Overview

In examining the current state of hydrogen mobility across Europe, various barriers and constraints are evident, hindering the widespread adoption of hydrogen as a viable transportation fuel.

Technological Diversification and Infrastructure challenges:

The value chain of hydrogen mobility involves various technologies. To begin with, it will depend on the type of hydrogen used in terms of production. The main challenge will be choosing between gray, blue, or green hydrogen (Gray hydrogen: produced through steam methane reforming without carbon capture and storage (CCS), using natural gas; high levels of greenhouse gas emissions. Blue hydrogen: produced through steam methane reforming with carbon capture and storage (CCS); low levels of greenhouse gas emissions. Green hydrogen: produced through water electrolysis, using electricity from renewable sources; greenhouse gas emissions close to zero.) Currently, green and blue hydrogen are the main contenders, especially in Europe. The major difference lies in the fact that while blue hydrogen supports the extraction of natural gas and the CCS industry, green hydrogen encourages the production of renewable energies.

Furthermore, green hydrogen, produced through water electrolysis, involves significant water pressure, making its production challenging in arid regions. Since, due to global warming, the availability of clean water will further decrease, these countries should invest in desalination capacity. Desalination appears to be the best solution to enhance green hydrogen production on an increasingly arid planet, albeit requiring additional energy consumption in a process that is already penalized by low conversion efficiency.

Regarding transportation and storage challenges, the key issues involve the establishment of extensive infrastructure and the necessity for cross-border cooperation within the European Union. At present, hydrogen is primarily produced and consumed on-site at relatively low costs. Therefore, creating a global hydrogen market would demand significant investments in infrastructure development, encompassing pipeline networks and distribution (a topic thoroughly covered in the subsequent sections of this report). Moreover, ensuring an efficient value chain necessitates a variety of technologies capable of storing and transporting hydrogen in the most effective and economical ways.

Primarily, the storage of hydrogen poses challenges, requiring a careful consideration of different methods, each with its unique advantages and disadvantages. Currently, hydrogen is commonly stored in tanks as gas or liquid for small-scale applications. However, for large-scale commercialization, a broader range of options needs to be explored, with efficiency contingent on factors like volume, storage duration, required discharge speed, and geographic availability of different options. In general, geological storage (such as in salt caverns) emerges as the optimal choice for large-scale and long-term storage, while tanks prove more suitable for short-term and small-scale storage (IEA (2019)).

Secondly, the transmission and distribution of hydrogen present difficulties due to its low density, leading to various options being considered for different scenarios. The choice of transportation method depends on the distance to be covered and the volume of hydrogen to be transported. For shorter distances and smaller volumes, trucking may be the preferred option, whereas for longer distances and larger volumes, liquid tankers or pipelines tend to be more cost-effective. Notably, initiatives within the European Union aim to repurpose the natural gas infrastructure connecting Europe to North African countries. Importantly, these operations require cross-border cooperation, as diplomatic relations between importing and exporting countries will shape the future hydrogen economy. International collaboration is essential to establish extensive infrastructures, facilitated through public-private partnerships (Rossana Scita, Pier Paolo Raimondi & Michel Noussan).

In any case, the implementation should take into account efficiency and adaptability to each specific geographical context.

HRS limitations:

Scarcity of Stations:

Despite the growth experienced by the hydrogen refuelling station (HRS) network in Europe, the quantity of these stations is still limited compared to electric vehicle charging stations. This scarcity presents significant challenges, as hydrogen vehicle owners may face difficulties in finding convenient refuelling stations, limiting accessibility and convenience compared to electric vehicle drivers.

Geographic Concentration:

The location of hydrogen refuelling stations in specific areas such as metropolitan cities or economically developed regions, and their concentration in certain countries, poses logistical challenges. Those residing in less populated areas or desiring long-distance travel may encounter limited infrastructure, reducing the practical utility of hydrogen vehicles outside certain geographical zones.

Figure 1. development of HRS in selected European countries. Source: https://www.h2stations.org/statistics/

Limited Interconnection:

The absence of an interconnected network of hydrogen stations implies additional difficulties for users planning to travel across borders and regions. Coherence and uniformity in infrastructure are far from being completed, complicating the planning and execution of more extensive and diversified journeys. Currently, cross-country travel using hydrogen-powered vehicles is unfeasible. As it can be seen in the Figure 2, below, most of the HRS are concentrated in the Northern and Central Europe.

Figure 2. H2 Stations Map. Source: https://www.h2stations.org/stations-map/?lat=49.139384&lng=11.190114&zoom=2

High Initial Costs:

Establishing an HRS network involves significant initial costs, from the construction of stations to the implementation of specific technologies for hydrogen storage and distribution. These elevated costs act as a barrier to the rapid expansion of infrastructure, especially compared to more established alternatives such as electric vehicle charging stations or conventional gas stations.

Dependency on Public and Private Investments:

The expansion of the HRS network depends heavily on both public and private investments. Fluctuations in fund availability can impact the speed at which new stations are planned, built, and maintained. Dependency on investments may create uncertainty in terms of continuous development and sustainability of the infrastructure.

Challenges in Regulatory Standardization:

Significance of a Unified Regulatory Framework: The establishment of a shared regulatory structure is pivotal to ensuring global safety and effectiveness, encompassing safety standards, environmental evaluations, and consistent operational requirements.

European legal framework and objectives regarding the hydrogen recharging infrastructure in vehicles overview:

The new Regulation for the Deployment of Alternative Fuels Infrastructure (AFIR) introduces mandatory objectives for deploying electric charging and hydrogen refuelling infrastructure across the road sector, onshore electricity supply in maritime and inland ports, and stationary aircraft electricity supply. By ensuring a minimum level of charging and refuelling infrastructure across the EU, this regulation will alleviate consumer concerns regarding the challenges of recharging or refuelling vehicles. AFIR also paves the way for a user-friendly refuelling and recharging experience, featuring transparent pricing, standardized payment options, and consistent customer information throughout the EU.

Regarding infrastructure for road, maritime, and aviation transport, the new AFIR regulations will ensure the availability of sufficient and user-friendly alternative fuel infrastructure. This will enable the use of zero-emission road vehicles, particularly light and heavy electric and hydrogen-powered vehicles, alongside supplying electricity to moored vessels and stationary aircraft. In specific terms, the following main deployment objectives must be met by 2025-2030:

1. **Targets for recharging infrastructure dedicated to heavy-duty electric vehicles**

Member States must ensure that recharging stations dedicated to heavy-duty vehicles offer a power output of at least 1400 kW, including a recharging point with a minimum output of 350 kW. These stations should be deployed to cover at least 15% of the length of the TEN-T road network by the end of 2025. This coverage target is set to increase to at least 50% of its length by December 31, 2027. Also, by the end of December 2027, along the TEN-T core network, these stations must provide a power output of at least 2800 kW and include at least two recharging points with an individual power output of at least 350 kW. Similarly, along the TEN-T comprehensive road network, the requirement is a power output of at least 1400 kW, including at least one recharging point with an individual power output of at least 350 kW.

Recharging stations specifically designed for heavy-duty vehicles must be strategically placed at intervals of 60 km along the TEN-T core network and every 100 km throughout the more extensive TEN-T comprehensive network starting in 2025. The ultimate objective is to achieve full network coverage by 2030.In addition, recharging stations must be installed at safe and secure parking areas for overnight recharging as well as in urban nodes for delivery vehicles.

2. **Targets for recharging infrastructure dedicated to light-duty electric vehicles**

Member States shall ensure that, in their territory, publicly accessible recharging stations dedicated to light-duty electric vehicles and that they provide sufficient power output for those vehicles.

To that end, for each registered battery-electric car in a given Member State, a power output of 1.3 kW must be provided by publicly accessible recharging infrastructure and a total power output of at least 0,80 kW for each light-duty plug-in hybrid vehicle registered in their territory.

In addition along the TEN-T core road network, publicly accessible recharging pools dedicated to light-duty electric vehicles are deployed in each direction of travel with a maximum distance of 60 km between them, offering a power output of at least 400 kW and including at least one recharging point with an individual power output of at least 150 kW by the end of December 2025 and a power output of at least 600 kW including at least two recharging points with an individual power output of at least 150 kW by 31 December 2027.

3. **Hydrogen refuelling infrastructure:**

Recharging infrastructure that can serve both cars and lorries must be deployed from 2030 onwards in all urban nodes and every 200 km along the TEN-T core network, ensuring a sufficiently dense network to allow hydrogen vehicles to travel across the EU

Member States must guarantee the deployment of a minimum number of publicly accessible hydrogen refuelling stations in their territories by December 31, 2030.

To achieve this, Member States must ensure, by the same date, the installation of publicly accessible hydrogen refuelling stations with a cumulative capacity of at least 1 tonne per day and equipped with a 700-bar dispenser along the TEN-T core network, maintaining a maximum distance of 200 km between each station.

Furthermore, each urban node is required to have at least one publicly accessible hydrogen refuelling station by December 31, 2030.Member States are obligated to conduct an analysis to determine optimal locations for these refuelling stations, with a specific focus on deploying them in multimodal hubs to cater to various transportation modes.

National policy frameworks must outline a clear, progressive trajectory toward achieving the 2030 targets, including a well-defined indicative target for 2027 to adequately cover the TEN-T core network and address the evolving demands of the market.

4. **Operators of electric recharging and hydrogen refuelling stations**

Operators must guarantee complete transparency in pricing, provide a universally accepted on-the-spot payment method like debit or credit cards, and deliver essential information, including location details, through electronic channels to ensure customers are well-informed.

Constraints, barriers and challenges:

The implementation of the new European regulatory framework for hydrogen refuelling infrastructure in vehicles introduces several specific challenges. One notable challenge involves the substantial investment required to meet mandatory objectives for expanding hydrogen refuelling stations and electric charging stations. For instance, constructing a comprehensive network of hydrogen refuelling stations along the Trans-European Transport Network (TEN-T) road network demands significant financial commitments from member states.

Moreover, the development of large-scale infrastructure is hindered by logistical challenges, such as coordinating the construction efforts across multiple regions and ensuring timely project completion. For example, achieving the target of deploying recharging stations dedicated to heavy-duty electric vehicles covering at least 15% of the TEN-T road network by the end of 2025 necessitates meticulous planning and coordination to overcome regional variations in terrain and population density.

The establishment of an efficient and accessible network also requires addressing financial challenges. While the regulatory framework aims for transparent pricing standards and standardized payment options, the actual implementation faces hurdles related to the costs associated with deploying and maintaining advanced refuelling infrastructure. Clear examples include the need for ongoing investments in cutting-edge technologies to ensure a seamless and user-friendly refuelling experience for both hydrogen and electric vehicle users.

Collaboration among member states becomes paramount in addressing these challenges. Joint efforts are crucial for sharing best practices, coordinating infrastructure development plans, and pooling resources. For instance, countries within the European Union may collaborate on the deployment of hydrogen refuelling stations in urban nodes, sharing expertise, and optimizing locations based on regional traffic patterns and user needs.

Substantial investments, both public and private, are essential for the successful implementation of the regulatory framework. Member states must allocate financial resources strategically to support the expansion of infrastructure, taking into account the diverse geographical and demographic characteristics of different regions. For instance, countries may need to prioritize funding for the construction of hydrogen refuelling stations in densely populated urban areas while considering alternative solutions, such as innovative financing models, for sparsely populated regions.

Proactive resolution of emerging challenges involves adapting to changing market demands and evolving hydrogen technology. For example, as the demand for hydrogen-powered heavy-duty vehicles increases, member states may need to reassess and adjust their infrastructure plans to accommodate the growing needs of this sector. Additionally, staying abreast of technological advancements and incorporating them into the regulatory framework is crucial for ensuring the long-term viability and sustainability of the hydrogen refuelling infrastructure.

Analysis of Hydrogen production and consumption in Europe:

Production:

According to the European Hydrogen Observatory (Observatory, The European hydrogen market landscape), by the conclusion of 2022, Europe had 476 operational hydrogen production facilities capable of generating an annual output of 11.33 million tonnes of hydrogen. In the same year, the actual hydrogen production reached 8.23 million tonnes. Considering the estimated hydrogen consumption, these production facilities, on average, operated at a utilization capacity of 73%. Germany, the Netherlands, Poland, Italy, France, and Spain together contribute to 63% of Europe's total hydrogen capacity. The variation in hydrogen production capacity among countries is primarily influenced by their industrial foundations, particularly linked to the reforming capacity required in the refining and ammonia sectors. The top eight countries in production capacity collectively represent 74% of Europe's total hydrogen production capacity. In contrast, the remaining 18 countries with hydrogen production capabilities contribute just 26% to the overall installed capacity in Europe.

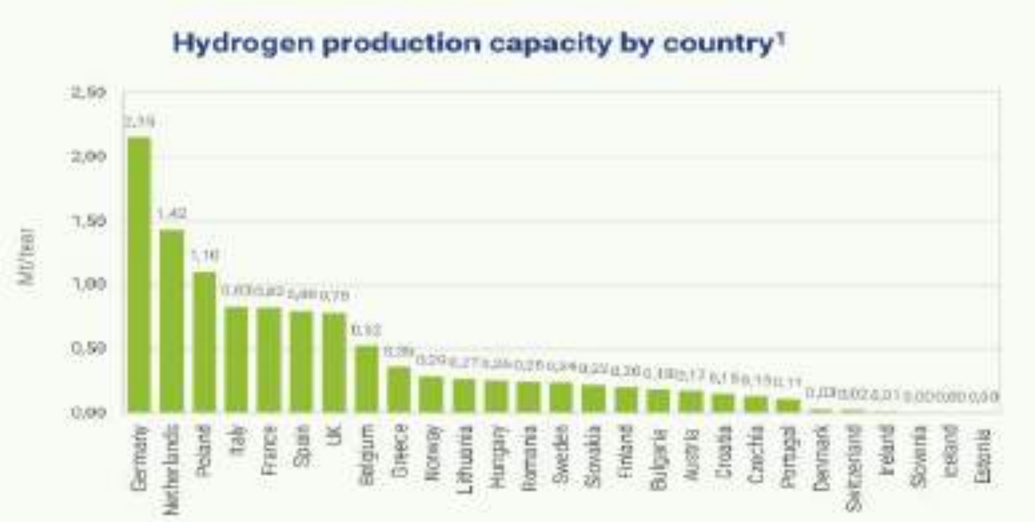

Figure 3. Hydrogen production capacity by country

When looking at the annual hydrogen production output measured in million tons, Germany, the Netherlands, Poland, Spain, and Italy together constitute 57% of Europe's total hydrogen output.

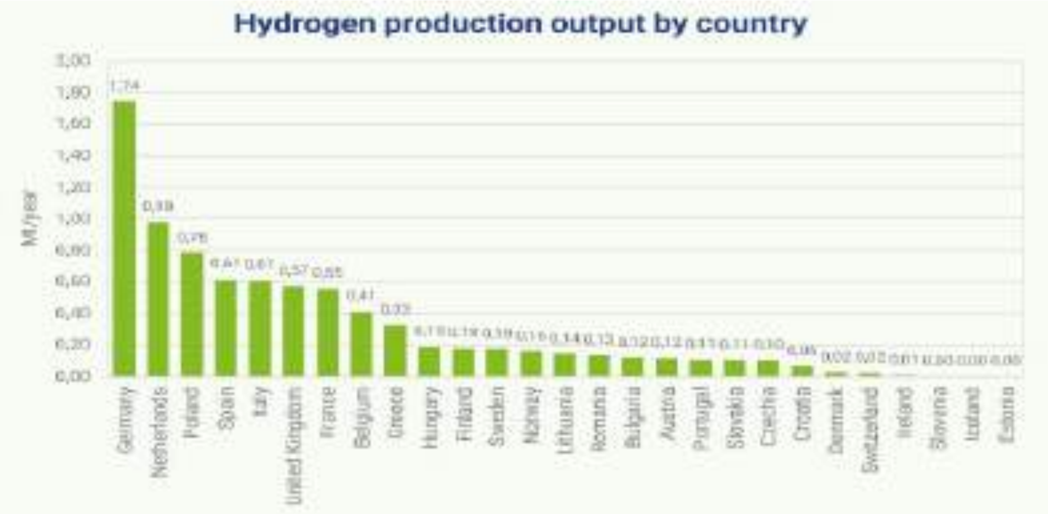

Figure 4. Hydrogen output by country

Consumption:

According to data provided by the European Hydrogen Observatory, the estimated demand for hydrogen in 2022 reaches 8.2 million tons (MT) in Europe. Note that this total demand is slightly deviating from the total production (8.23 Mt)[20] (Observatory, s.f.). This significant growth reflects the increasing adoption of hydrogen-based strategies to address climate challenges and move toward a decarbonized economy.

The **refining industry emerges as the primary driver of hydrogen demand, accounting for 57% of the total hydrogen consumption in the European region. Following closely, the ammonia industry positions itself as another fundamental player, contributing 24%** (Observatory, s.f.) to the overall demand. These data underscore the critical importance of hydrogen in key industrial processes, where its versatility and capacity to facilitate clean processes make it an essential component. In addition to its predominant role in refining and ammonia production, hydrogen also plays a significant role in other industrial sectors, with 12% allocated to ethanol production and other uses in the chemical industry.

It is relevant to highlight that, despite its substantial contribution to CO2 emissions, the mobility industry utilizes only 0.04% of the consumed hydrogen (Observatory, s.f.). This low percentage emphasizes the extensive room for future adoption of hydrogen in mobility, presenting a key opportunity to progress toward more sustainable transportation solutions.

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[20] The demand for hydrogen in Europe may vary from the produced quantity, as it considers factors such as hydrogen imports, exports, or release into the atmosphere.

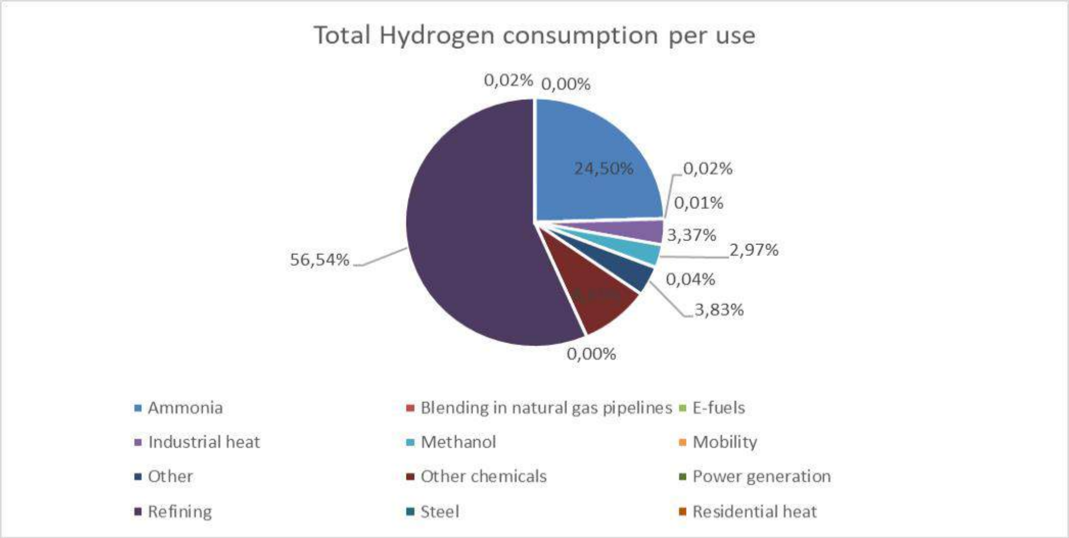

Figure 5. Total Hydrogen consumption per use

On another note, regarding hydrogen consumption by country, **Germany** takes the lead with a substantial 21.2%, followed by the **Netherlands** at 12.0%, **Poland** at 9.6%, and **Spain** at 7.5% (Observatory, s.f.). These figures underscore the significance of considering consumption trends when strategically planning the expansion of hydrogen infrastructures in the European Union.

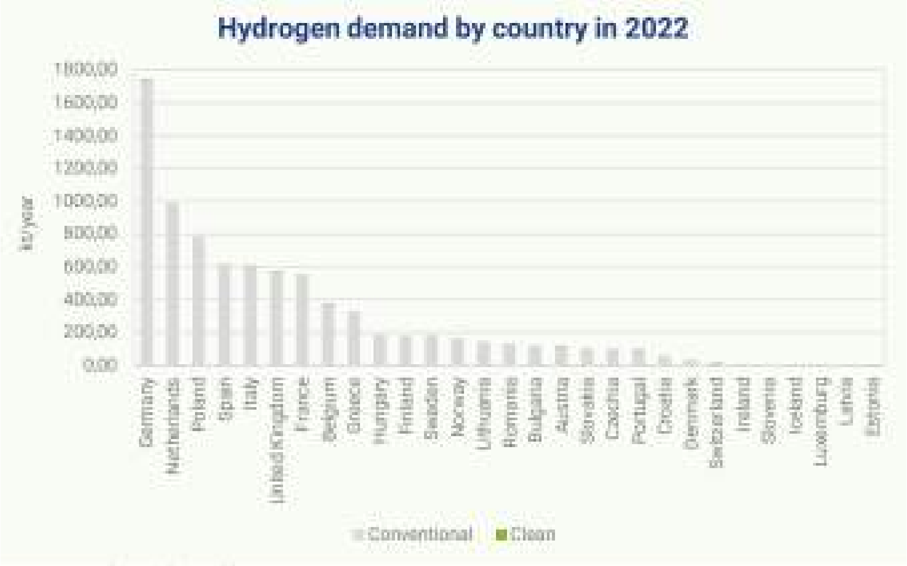

Figure 6. Hydrogen demand by country (2022)

Hydrogen demand forecast

This segment explores and contrasts the key scenarios envisioning the prospective hydrogen demand in Europe for the years 2030, 2040, and 2050, encompassing diverse sectors such as industry, transport, buildings, and electricity. The prognoses indicate an anticipated upward trend in the overall hydrogen demand in Europe for the upcoming decades. Projections suggest a substantial surge of 127% from 2030 to 2040, followed by a 63% increase from 2040 to 2050. Taking into account the present hydrogen demand, a projected 51% rise is expected by 2030 (Observatory, The European hydrogen market landscape).

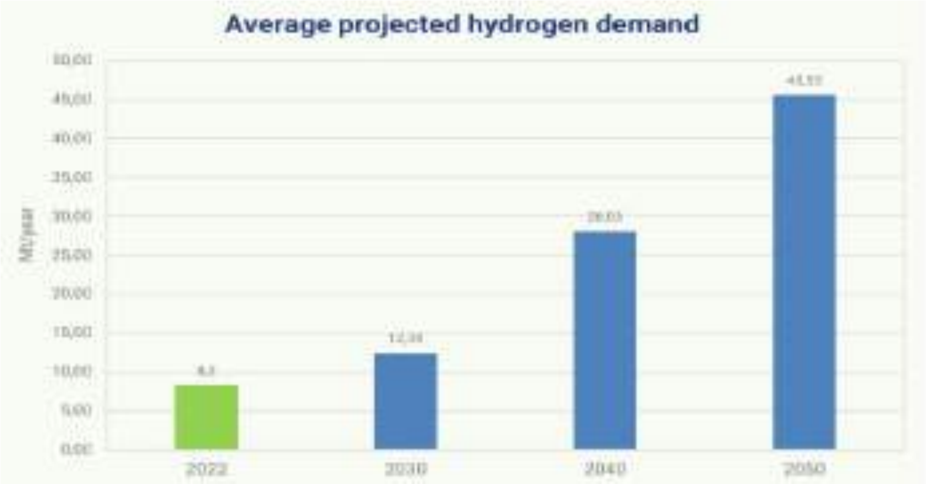

Figure 7. Average projected hydrogen demand

Hydrogen demand forecast broken down by sector (Observatory, The European hydrogen market landscape)**:**
In the projected scenario, the **industrial sector** is anticipated to experience a steady demand increase, from 9.86 million tonnes in 2030 to 14.62 million tonnes in 2040 (a 48% rise) and further to 16.88 million tonnes in 2050 (a 15% increase). Despite this growth, the industrial sector's relative share of the total hydrogen demand is expected to decline gradually, from 78% in 2030 to 15% in 2050. The current hydrogen demand in the industrial sector is forecasted to witness a 23% increase by 2030. The transport sector is expected to closely follow, consistently increasing its share of the total average hydrogen demand. Starting with a 15% share in 2030, the transport sector's contribution is projected to significantly grow, reaching 37% by 2050, aligning with the industrial demand. Anticipated growth is also foreseen in the remaining sectors, namely building and power, with their shares of total hydrogen demand projected to reach 15% and 11%, respectively, by 2050. This growth is expected to initiate slowly before 2030, after which it accelerates.

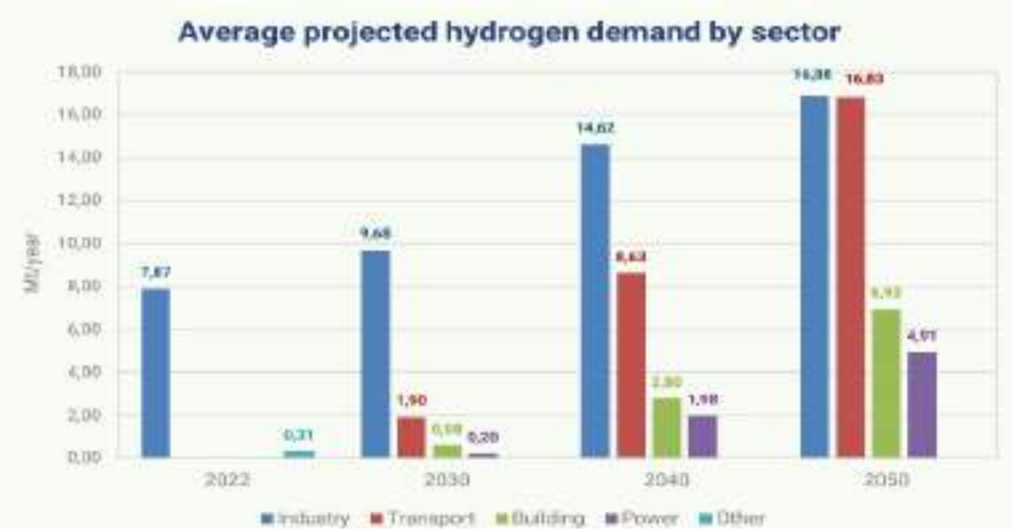

Figure 8. Average projected hydrogen demand by sector

European Industrial Hub Locations

Across the globe, manufacturing activities that produce, transport, and/or consume large amounts of energy are typically concentrated in major industrial hubs. These industrial hubs represent the main source of CO2 emissions and play a key role in decarbonizing our energy system. For example, in

Germany, the six largest industrial hubs emit nearly 40% (Several: Niels van Buuren, Lucas Prat, Peter Daemen, Rowan Huisman. (Power2X), 2022) of the country's total industrial emissions. The energy and feedstock transition to achieve climate and energy security goals presents a major transformation challenge for industrial hubs in the decades to come.

It is crucial to emphasize the significance of these industrial hubs in the decarbonization process using hydrogen. Heavy industry emerges as a key player in the decarbonization journey via hydrogen. By adopting hydrogen-based technologies, industrial hubs can not only mitigate their own emissions but also spearhead the transition toward a more sustainable and environmentally friendly industrial system. Implementing hydrogen technologies in these industrial hubs will not only contribute to emission reduction but can also foster innovation, create jobs, and strengthen the economic resilience of these regions. By becoming pioneers in hydrogen utilization, these industrial hubs can serve as role models for other areas, accelerating the global transition toward a cleaner and more sustainable production mode.

According to experts from PowertoX (Several: Niels van Buuren, Lucas Prat, Peter Daemen, Rowan Huisman. (Power2X), 2022), and as depicted in the image below, there are major concentrations of industrial hubs, especially in Germany and the Netherlands, but also along the coast of Spain, Poland (several locations), the Normandy and Provence Regions (France), the North of Italy, the North of Belgium, the South-West region in Sweden, etc.

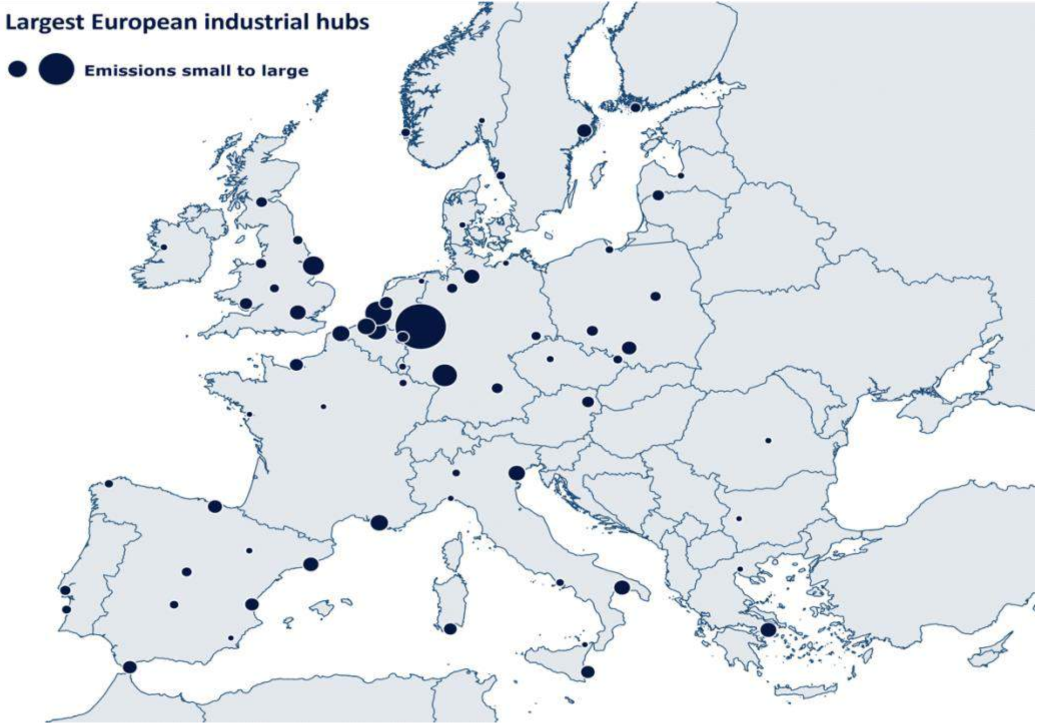

Figure 9. Largest industrial European Hubs

This aligns with the latest data provided by the European Hydrogen Observatory on hydrogen demand by country in 2022.

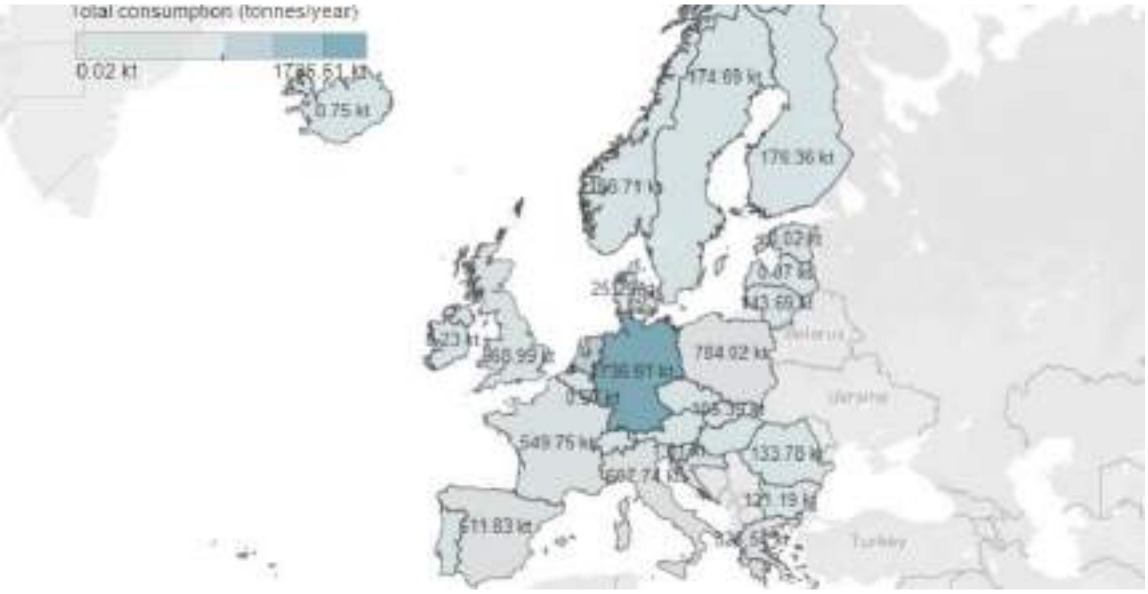

Figure 10. European countries by hydrogen demand

Figure 11. Mainstream and specialised refineries processing crude oil map in Europe

Since refinery currently represents almost a **60% of the total hydrogen consumption** (Observatory, The European hydrogen market landscape) in the European region is important to analyze where the main refineries are in Europe. Concawe, the European Fuel Manufacturers Association, has recently compiled an extensive map delineating the geographical distribution of both mainstream and specialized refineries engaged in the processing of crude oil across Europe (Concawe , s.f.). The map provides a comprehensive overview of the refining landscape in 2023. Once again, **Germany** takes the lead, followed by **Italy**, the **UK**, and **Spain**.

Key Heavy Transport Routes in Europe:

Heavy transport routes in Europe vary based on economic demand and geography. However, the most important transport network is the Trans-European Transport Network (European Commission, s.f.).

The Trans-European Transport Network (TEN-T) is an initiative of the European Union (EU) aimed at improving and developing transportation infrastructure in Europe to promote mobility and connectivity across the continent. TEN-T encompasses various modes of transportation, including roads, railways, inland waterways, ports, and airports, with the goal of creating an integrated and efficient transportation network throughout Europe.

TEN-T is divided into several corridors and priority areas that connect key European regions and countries, facilitating the flow of people and goods. This network seeks to promote sustainability, safety, and efficiency in European transportation, as well as foster interoperability between different modes of transportation and the removal of technical and administrative obstacles.

The TEN-T initiative is also aligned with the EU's objectives on climate change and the promotion of cleaner and more sustainable transportation modes, such as railways and maritime transport, rather than relying excessively on road transportation, which can be more polluting.

For these reasons, the TEN-T network emerges as a crucial component for hydrogen (H2) transport in Europe due to its extensive coverage of major routes. This network strategically connects regions, facilitating the efficient transport of H2 over significant distances. By placing refuelling stations and hubs along the TEN-T, it ensures not only the logistical viability of heavy-duty H2 transport but also effective hydrogen distribution in key areas. Consequently, the TEN-T **becomes the backbone driving the transition towards a more sustainable heavy transport system and contributes to the decarbonization of industries across the entire European network**. Therefore, its significance lies in its ability to optimize the reach of H2 transport, enabling a seamless transition towards a greener and more efficient future in Europe. Moreover, the strategic integration of Hydrogen Hubs and plants with the Trans-European Transport Network (TEN-T) yields several advantages:

1. **Decarbonization and Emission Reduction:**

The interconnection through the TEN-T Network enables these Hydrogen Hubs to efficiently reach the most significant industrial regions when pipeline transportation is unavailable or insufficient. This is particularly relevant for decarbonizing emissions-intensive sectors, such as heavy industry and manufacturing. By being well-connected, these projects can supply green hydrogen to industrial facilities, gradually replacing more polluting energy sources and reducing greenhouse gas emissions. To illustrate this, consider the following examples based on the information above:

2. **Development of an Integrated Hydrogen Ecosystem:**

Connectivity through TEN-T corridors creates an integrated hydrogen ecosystem, where the production, storage, and transport of hydrogen are efficiently coordinated. This not only improves logistics but also fosters collaboration among different projects and industry players, promoting standardization and widespread adoption of clean hydrogen technologies.

3. **Boosting Sustainable Mobility:**

Effective connection to the TEN-T Network facilitates the distribution of hydrogen for transportation, especially for heavy vehicles and industrial fleets. This directly contributes to decarbonizing the transportation sector, reducing exhaust emissions, and advancing towards more sustainable mobility.

4. Resilience and Energy Security:

Interconnection through the TEN-T network enhances resilience and energy security by diversifying the supply sources and ensuring that Hydrogen Hubs are not dependent on limited routes and connections. This is crucial for maintaining supply stability and reducing vulnerability to disruptions.

4.1 Diversification of Supply Sources:

Connecting Hydrogen Hubs through the TEN-T network ensures that these hubs are not overly reliant on a single source or transportation route. By diversifying the supply sources, the hydrogen supply chain becomes more robust and adaptable to potential disruptions. The backbone infrastructure and pipelines, working in conjunction with road transport, contribute to a multi-faceted network that can seamlessly adapt to changes in the energy landscape.

4.2 Strategic Deployment of the Backbone and Pipelines:

The backbone infrastructure and pipelines, forming the backbone of the hydrogen transport system, serve as high-capacity conduits for bulk hydrogen transportation. These modes of transportation are particularly efficient for long-distance, large-volume transfers, providing a stable and continuous supply. Their strategic deployment ensures that Hydrogen Hubs can tap into diverse production facilities and navigate through different geographical terrains, contributing to a resilient and versatile supply chain.

4.3 Advantages of Road Transport:

While the backbone infrastructure and pipelines excel in long-distance transportation, road transport adds a crucial layer of flexibility and accessibility. Road networks, facilitated by the TEN-T, offer the advantage of reaching areas that may not be directly served by pipelines or backbone infrastructure. This flexibility proves invaluable during unforeseen disruptions or changes in demand patterns, enabling the seamless delivery of hydrogen to a wide array of industrial centers.

4.4 Stability Amid Disruptions:

In times of disruptions, whether due to geopolitical events, natural disasters, or technical issues, the combination of backbone infrastructure, pipelines, and road transport ensures that the hydrogen supply chain remains resilient. The redundancy provided by multiple transportation modes minimizes the risk of supply chain interruptions, contributing to the stability of hydrogen availability for industrial processes.

It's important to note that the TEN-T is constantly evolving, with regular reviews and updates of its priorities and projects to adapt to Europe's changing transportation and mobility needs.

Figure 12. TENT-T network (road transport). Source: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html

However, some key routes include (European Commission, s.f.):

1. **Baltic–Adriatic Corridor** (Poland–Czechia–Slovakia–Austria–Italy);
2. **North Sea–Baltic Corridor** (Finland–Estonia–Latvia–Lithuania–Poland–Germany–Netherlands/Belgium);
3. **Mediterranean Corridor** (Spain–France–Northern Italy–Slovenia–Croatia–Hungary);
4. **Orient/East–Med Corridor** (Germany–Czech Republic–Austria/Slovakia–Hungary–Romania–Bulgaria–Greece–Cyprus);
5. **Scandinavian–Mediterranean Corridor** (Finland–Sweden–Denmark–Germany–Austria–Italy);
6. **Rhine–Alpine Corridor** (Netherlands/Belgium–Germany–Switzerland–Italy);
7. **Atlantic Corridor** (formerly known as Lisboa–Strasbourg Corridor) (Portugal–Spain–France);
8. **North Sea–Mediterranean Corridor** (Ireland–UK–Netherlands–Belgium–Luxembourg–Marseille(France),
9. **Rhine–Danube Corridor** (Germany–Austria–Slovakia–Hungary–Romania with branch Germany–Czechia–Slovakia.

The following details the different corridors of the network, including examples of heavy industries and specific companies located in or near them that are susceptible to decarbonization.

1. Baltic–Adriatic Corridor

The Baltic-Adriatic Corridor represents one of the most significant trans-European transportation routes within Central Europe. It extends from the **northern Baltic seaports of Gdansk, Gdynia, Szczecin, and Świnoujście** to the southern Adriatic ports of **Koper, Trieste, Venice, and Ravenna**. Along its route, it encompasses the industrial areas of **Central and Southern Poland**, subsequently traversing the borders of the **Czech Republic, Slovakia, Austria, and Slovenia** on its journey towards **Italy and Slovenia in the south**. This corridor encompasses critical railway projects, including Austria's Semmering Base Tunnel and Koralm Railway Line, as well as essential cross-border connections that link the six countries within the corridor.

Figure 13. Baltic–Adriatic Corridor. Road Network. Source https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html

Industrial Landscape:

Steel Industry:

The steel industry involves the transformation of iron ore into steel through processes that require high temperatures and release significant amounts of carbon dioxide (CO2) due to the combustion of coke and other fossil fuels in blast furnaces.

- **Location within the Corridor:** The Silesia region in Poland is a major hub for steel production within the Baltic-Adriatic Corridor.
- **Examples of Companies within the Corridor:** ArcelorMittal Poland: One of the largest steel producers in the region, ArcelorMittal operates several production facilities in Poland.

Chemical and Petrochemical Industry:

The chemical and petrochemical industry involves the conversion of raw materials such as crude oil and natural gas into a wide range of chemicals and plastics. These processes consume a significant amount of energy and generate CO2 emissions due to the combustion of fossil fuels.

- **Location within the Corridor:** This industry has a prominent presence in Gdansk and Plock, Poland, within the Baltic-Adriatic Corridor.
- **Examples of Companies within the Corridor:** PKN Orlen (Poland): A leading company specializing in oil refining and chemical production, with operations located within the Corridor.

Cement Industry:

Cement production involves the heating of limestone to high temperatures, resulting in CO2 emissions due to the calcination of limestone and the use of fossil fuels such as petroleum coke.

- **Location within the Corridor:** Cement production facilities are located in Trieste, Italy, in the region of Friuli-Venice Giulia, within the Baltic-Adriatic Corridor.
- **Examples of Companies within the Corridor:** Buzzi Unicem: A leading producer of cement and construction materials with a presence in Italy and other countries, including locations within the Corridor.

Energy:

Energy generation from fossil fuels, such as coal and natural gas, is carbon-intensive due to the CO2 emissions associated with the combustion of these fuels in power plants.

- **Location within the Corridor:** Several fossil fuel-based power plants are situated in Poland and Austria, within the Baltic-Adriatic Corridor.
- **Examples of Companies within the Corridor:** Verbund (Austria): A prominent company in hydroelectric and renewable energy in Austria, with operations located in Vienna and Graz.

  PGE Group (Poland): Operating various power plants in Poland, including coal and gas-fired facilities, contributing to carbon emissions within the Corridor.

Automotive Industry:

The automotive industry encompasses the production of vehicles and their components, involving various stages of manufacturing and transportation within the supply chain.

- **Location within the Corridor:** The automotive industry has a strong presence within the Baltic-Adriatic Corridor, with manufacturing facilities and supply chain activities located in various regions, including Poland, the Czech Republic, and Slovakia.
- **Examples of Companies within the Corridor:** Skoda Auto (Czech Republic): A leading automobile manufacturer in Central Europe, with production plants in the Czech Republic, situated within the Baltic-Adriatic Corridor.

  Hyundai Motor Manufacturing, Nižní Lhoty, Chequia (Czech Republic): This Hyundai plant in the Czech Republic is part of the Baltic-Adriatic Corridor.

2. North Sea–Baltic Corridor

The North Sea-Baltic corridor is a multimodal transportation route that links the Baltic Sea region with the North Sea region, enhancing accessibility for the northern Member States and fostering connectivity between the northwest and northeast of the European Union. This corridor traverses through Belgium, the Netherlands, northern Germany, Poland, and onwards through the Baltic States. In 2021, its expansion included the entirety of Finland, the northern part of Sweden, and a portion in Poland extending up to the Ukrainian border. Following this extension, the North Sea-Baltic Corridor now spans 8828 kilometers of railways, 6934 kilometers of roads, and 2839 kilometers of inland waterways.

The primary goal is to develop and complete a competitive and interoperable trans-European transport network that adheres to the highest standards. This network aims to connect the regions along the corridor, accelerate the transition towards environmentally friendly transportation, and harness the economic potential of the area. The key means to achieve the objectives of the NSB Corridor are transportation infrastructure projects, encompassing the construction and improvement of roads, railways, and inland waterways. Among these projects, the most notable is Rail Baltica, a European-standard railway system that links Estonia, Latvia, and Lithuania to Poland[21].

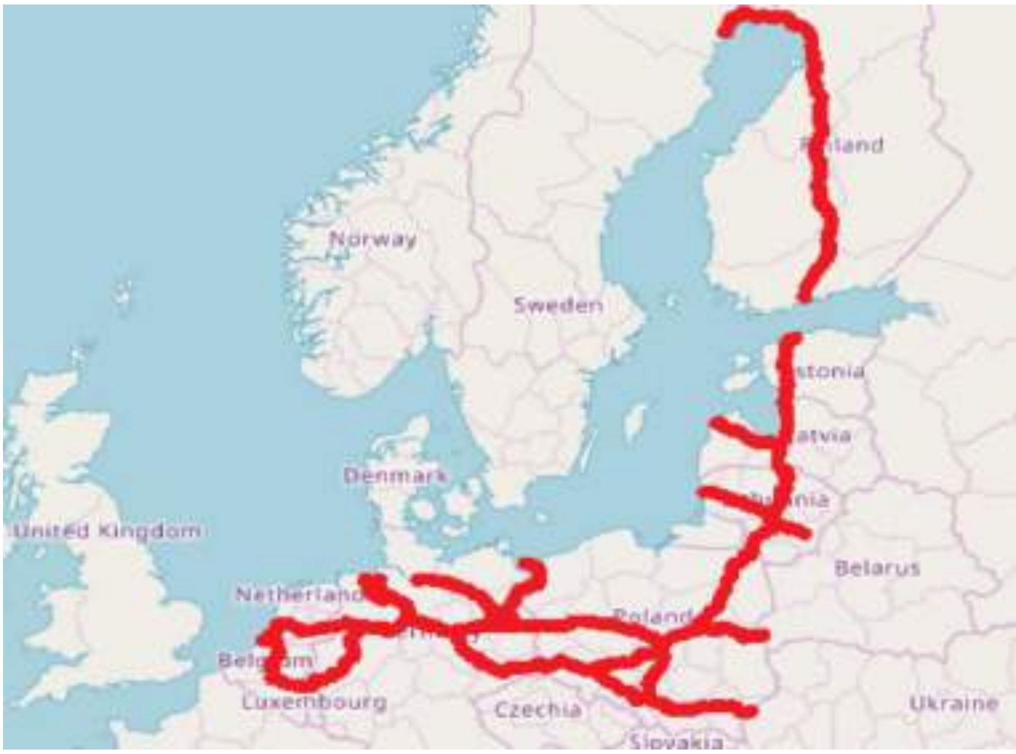

Figure 14. North Sea–Baltic Corridor. Road Network. Source: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html

Industrial landscape:

Manufacturing and Heavy Industry:

- **Location within the Corridor:** Manufacturing and heavy industry facilities are distributed throughout the North Sea–Baltic Corridor.
- **Examples of Companies within the Corridor:** Nokia (Finland): A multinational corporation known for its telecommunications equipment and consumer electronics, located in Helsinki, Finland.

  Estonian Cell (Estonia): A notable producer of kraft pulp and paper located in Kunda, near Tallinn, Estonia.

  Valmiera Glass Group (Latvia): A leading manufacturer of fiberglass products, headquartered in Valmiera, Latvia.

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[21] In July 2022 the European Commission proposed to extend the corridor further, also to Ukraine. The co-legislators, i.e. the European Parliament and the Council, are still working on the proposal.

Hella (Lithuania): Part of the Hella Group, specializing in lighting and electronics for the automotive industry, located in Kaunas, Lithuania.

Logistics and Distribution:

- **Location within the Corridor:** logistics and distribution centers are strategically located along the North Sea–Baltic Corridor.
- **Examples of Companies within the Corridor:** DHL Estonia (Estonia): Part of the global logistics company, providing services in Tallinn and across Estonia.

  Cargobus (Latvia): A logistics company offering transport services within Latvia and neighboring countries, based in Riga.

  Kuehne+Nagel (Netherlands): A global logistics provider with operations in Amsterdam and other Dutch cities.

Port Operations:

- **Location within the Corridor:** Ports and related operations are key points within the North Sea–Baltic Corridor.
- **Examples of Companies within the Corridor:** Port of Hamburg (Germany): One of Europe's largest and busiest ports, handling a wide range of goods, including containers, bulk products, and energy products.

  Port of Gdansk (Poland): One of the largest and busiest ports in the Baltic Sea, handling a wide range of cargo, including containers, bulk goods, and energy products.

  Port of Rotterdam (Netherlands): Europe's largest and one of the world's busiest ports, serving as a major gateway for goods entering and leaving Europe.

  Port of Klaipėda (Lithuania): The largest port in Lithuania, specializing in general cargo, bulk cargo, and container handling.

3. Mediterranean Corridor

The Mediterranean Corridor stands as the principal east-west axis within the TEN-T Network, situated below the Alps. It stretches from the southwestern Mediterranean region of Spain to the Ukrainian border alongside Hungary, tracing the coastlines of Spain and France before crossing the Alps towards the east, passing through Italy, Slovenia, and Croatia, and finally extending through Hungary to reach its eastern border with Ukraine. This corridor primarily comprises road and rail infrastructure, with the inclusion of the Po River, various canals in Northern Italy, and the Rhone River route from Lyon to Marseille. Spanning approximately 3000 kilometers, it serves as a multimodal link connecting the Western Mediterranean ports to the heart of the European Union. Additionally, it establishes an east-west connection through the southern EU region, encourages a shift from road to rail transport in environmentally sensitive zones like the Pyrenees and the Alps, and facilitates high-speed train connectivity for several major urban areas within the EU.

Figure 15. Mediterranean Corridor. Road Network. Source:
https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html

Industrial landscape:

Steel Industry:

The steel industry involves processes that emit significant carbon dioxide (CO_2) due to high-temperature operations and fossil fuel usage.

- **Location within the Mediterranean Corridor:** The steel industry is present in various regions, including Catalonia in Spain (Tarragona), Lombardy in Italy (Milan), and Budapest in Hungary.
- **Examples of Companies within the Corridor:** Acerinox (Spain): A global stainless steel manufacturing company with facilities in Cadiz, Madrid and Barcelona.

  ArcelorMittal (Italy): Operating steel plants in Milan, Italy, ArcelorMittal is one of the world's largest steel producers.

  Dunaferr (Hungary): A Hungarian steel company with operations in Dunaújváros, near Budapest.

Chemical and Petrochemical Industry:

The chemical and petrochemical industry is known for its energy consumption and CO_2 emissions.

- **Location within the Mediterranean Corridor:** This industry has a presence in Tarragona, Spain (Catalonia), and Milan, Italy (Lombardy).
- **Examples of Companies within the Corridor:** Repsol (Spain): A major energy company with petrochemical operations in Tarragona, contributing to the chemical and petrochemical sector.

  Versalis (Italy): An Italian chemical company, a subsidiary of Eni, with petrochemical operations near Milan.

Cement Industry:

Cement production is energy-intensive and emits CO2 due to the high-temperature processes involved.

- **Location within the Mediterranean Corridor:** cement production facilities are found in Catalonia, Spain (Tarragona), and Lombardy, Italy (Milan).
- **Examples of Companies within the Corridor:** cementos Molins (Spain): A Spanish cement manufacturer with a cement plant in Tarragona, Spain.

  Italcementi (Italy): An Italian cement producer with cement plants in Lombardy, Italy.

Energy:

Fossil fuel-based power generation is a carbon-intensive sector.

- **Location within the Mediterranean Corridor:** several fossil fuel-based power plants are located in regions like Catalonia, Spain (Tarragona), and Lombardy, Italy (Milan).
- **Examples of Companies within the Corridor:** Endesa (Spain): An energy company operating power plants in Catalonia, Spain, including some fossil fuel-based facilities.

  Enel (Italy): A major energy company with power generation facilities, including fossil fuel-based plants in Lombardy, Italy.

4. Orient/East–Med Corridor

The Orient/East-Med Corridor establishes vital connections between significant portions of Central Europe and the ports situated along the North, Baltic, Black, and Mediterranean Seas. Its primary aim is to promote the growth of these ports as major multimodal logistics hubs and to furnish economic hubs in central Europe with updated, versatile connections to the Motorways of the Sea. This corridor prominently features the Elbe River as a crucial inland waterway and seeks to enhance the multimodal links connecting Northern Germany, the Czech Republic, the Pannonian region, and Southeastern Europe. Furthermore, it will enhance the connectivity to Cyprus.

Figure 16. Orient/East–Med Corridor. Road Network. Source:
https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html

Industrial Landscape:

Automotive and Transportation Equipment

- **Location within the Corridor:** The automotive industry is a prominent sector in cities like Budapest (Hungary), Sofia (Bulgaria), Vienna (Austria), Brandenburg (Germany), Bratislava (Slovakia), Bucharest (Romania), Thessaloniki (Greece), Timișoara (Romania), and Craiova (Romania). These cities, along with their associated industrial zones, host automotive manufacturing plants and related facilities.
- **Examples of Companies within the Corridor:** Győr Automotive Industrial Park (Győr, Hungary): This industrial park in Győr, Hungary, houses Audi Hungaria's manufacturing plant, one of the largest engine production facilities globally.

  Mercedes-Benz Manufacturing Plant (Kecskemét, Hungary): Mercedes-Benz opera una planta de fabricación en Kecskemét, Hungría, que produce vehículos Mercedes-Benz compactos.

  Ford Craiova (Craiova, Romania): Ford's manufacturing facility in Craiova, Romania, focuses on automobile production, including the Ford EcoSport.

Aerospace and Aviation:

- Location within the Corridor: Aerospace and aviation industries are present in cities like Vienna (Austria), Sofia (Bulgaria), Bucharest (Romania), and Thessaloniki (Greece). These industries often operate in specialized aerospace industrial zones.
- Examples of Companies within the Corridor: Vienna International Airport Area (Vienna, Austria): The Vienna International Airport area includes aerospace and aviation companies that support airport operations and maintenance.

  Bozhurishte Industrial Zone (Sofia, Bulgaria): Bozhurishte hosts aerospace manufacturers and suppliers, including Avioteh and Aerometals Bulgaria.

Steel Production and Manufacturing

- **Location:** Thessaloniki and Vienna have a notable presence of heavy industries, particularly in steel production and manufacturing.
- **Examples of Companies within the Corridor:** Hellenic Halyvourgia is a major steel producer with operations in Thessaloniki.

  Voestalpine Group is a global steel and technology company with significant operations in Vienna.

  Stomana Industry, located in Pernik near Sofia, is a leading steel producer in Bulgaria.

5. Scandinavian–Mediterranean Corridor

The Scandinavian-Mediterranean Corridor traverses seven countries: Finland, Sweden, Norway, Denmark, Germany, Austria, and Italy.

The corridor plays a pivotal role as a north-south axis within the European economy.

Starting from Finland and crossing the Baltic Sea to Sweden, it then passes through Germany, the Alps, and Italy, connecting major urban hubs and ports in Scandinavia and northern Germany to the highly industrialized production centers in southern Germany, Austria, and northern Italy. It eventually extends to Italian ports and Valletta.

This extensive Core Network Corridor initiates at the Finnish-Russian border, traversing through Helsinki, Stockholm, and Malmö before reaching the European mainland. From there, it continues through the German seaports of Hamburg and Rostock, following the primary traffic flows in western Germany, including Hannover, and eastern Germany, passing through Berlin and Leipzig. The eastern and western sections converge in Nuremberg and proceed southward to Munich, following the Brenner Corridor to Verona. Within Italy, the corridor extends through Bologna, Rome, and Naples, with branches leading to the ports of Genova, Livorno, Bari, and Taranto, before ultimately reaching Palermo.

Scandinavian–Mediterranean Corridor

Figure 17. Scandinavian–Mediterranean Corridor. Road Network. Source: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html

Steel Production:

- **Location within the Corridor**: Steel production facilities are distributed across the Scandinavian-Mediterranean Corridor.
- **Examples of Companies within the Corridor:** Acciaierie d'Italia (Taranto, Italy): Acciaierie d'Italia operates one of Europe's largest steel plants in Taranto, contributing significantly to the steel industry.

  SSAB (Luleå, Sweden): SSAB specializes in high-strength steel and operates a major steel mill in Luleå, Sweden.

Outokumpu (Tornio, Finland): Outokumpu is a leading stainless-steel manufacturer with a major plant in Tornio, Finland.

Chemical Manufacturing:

- **Location within the Corridor:** Chemical manufacturing facilities are prevalent along the corridor.
- **Examples of Companies within the Corridor:** Yara International (Uusikaupunki, Norway): Yara is a global leader in fertilizers and has several production facilities in Finland, Helsinki, including major facilities in Uusikaupunki, near Turku.

  Perstorp Group (Nol, Sweden): Perstorp is a major specialty chemicals company with a plant in Nol, near Gothenburg Sweden.

Heavy Machinery and Equipment:

- **Location within the Corridor:** Heavy machinery and equipment manufacturing facilities are dispersed across the corridor.
- **Examples of Companies within the Corridor:** Siemens (Munich, Germany): Siemens is a global technology company with a presence in Munich, specializing in various heavy machinery and equipment.

  Volvo Group (Gothenburg, Sweden): Volvo Group manufactures trucks, buses, and construction equipment in Gothenburg, Sweden.

  CNH Industrial (Bologna, Italy): CNH Industrial is involved in the production of agricultural and construction machinery, with operations in Bologna, Italy.

Shipbuilding:

- **Location within the Corridor:** Shipbuilding activities are notable within the corridor.
- **Examples of Companies within the Corridor:** Fincantieri (Palermo, Italy): Fincantieri is a leading shipbuilding company with a shipyard in Palermo, Italy.

  Meyer Turku (Turku, Finland): Meyer Turku specializes in shipbuilding and is based in Turku, Finland.

Aerospace and Defense:

- **Location within the Corridor:** Aerospace and defense industries are present in Germany.
- **Examples of Companies within the Corridor:** Airbus (Bremen, Germany): Airbus operates a major aerospace manufacturing facility in Bremen, Germany.

6. Rhine–Alpine Corridor

The Rhine-Alpine Corridor is one of Europe's most heavily utilized freight routes, linking the North Sea ports of Rotterdam and Antwerp to the Mediterranean region in Genoa. It passes through Switzerland and connects with significant economic hubs such as the Rhein-Ruhr, Rhein-Main-Neckar regions, and the metropolitan area of Milan in Northern Italy. This multi-modal corridor incorporates the Rhine River as an inland waterway. Major initiatives include the base tunnels, some of which have already been finished, in Switzerland, along with their connecting routes in Germany and Italy.

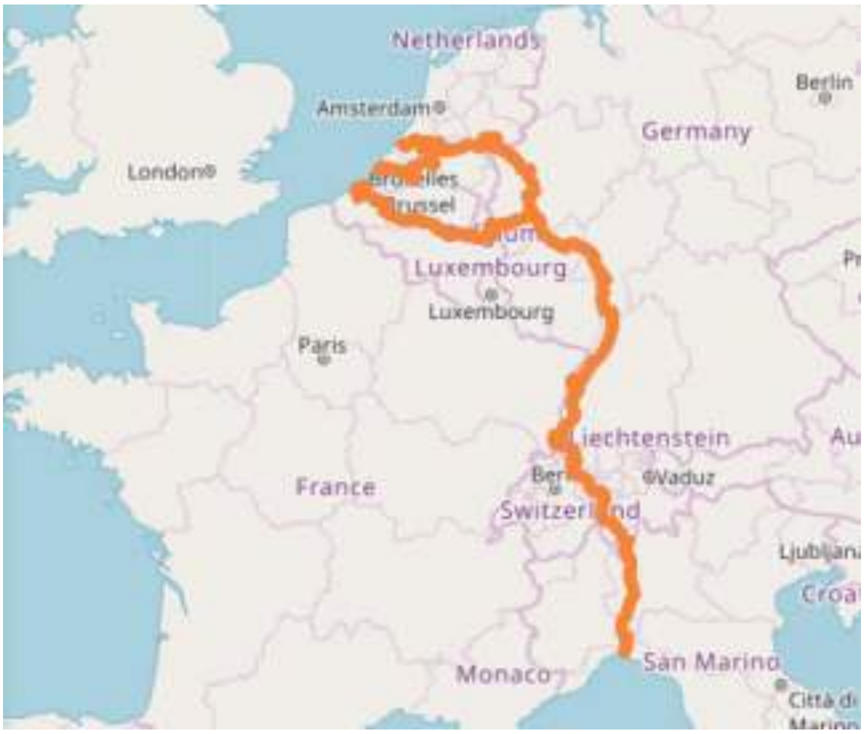

Figure 18. Rhine–Alpine Corridor. Road Network. Source: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html

Industrial Landscape:

Manufacturing and Heavy Industry:

The Rhine-Alpine Corridor hosts a significant concentration of manufacturing and heavy industrial activities. The Rhein-Ruhr region in Germany, for instance, is renowned for its heavy industry, including steel production, chemical manufacturing, and machinery production.

- **Location within the Corridor:** The Rhein-Ruhr region in Germany is a major hub for manufacturing and heavy industry within the Rhine-Alpine Corridor.
- **Examples of Companies within the Corridor:** ThyssenKrupp (Germany): A prominent steel and industrial conglomerate with operations in the Rhein-Ruhr region.

  BASF (Germany): A leading chemical company with facilities in the corridor, specializing in chemicals, plastics, and more.

Logistics and Distribution:

Given its role as a major transportation corridor, logistics and distribution businesses play a pivotal role in the region's economy. There are numerous warehouses, distribution centers, and logistics companies that ensure the seamless flow of goods along the corridor.

- **Location within the Corridor:** The logistics and distribution sector is widespread along the entire Rhine-Alpine Corridor.
- **Examples of Companies within the Corridor:** DHL (Various Locations: Bonn, Antwerpen, etc): A global logistics company with a strong presence along the Rhine-Alpine Corridor.

DB Schenker (Various Locations): A major logistics provider with operations spanning the corridor.

Port Operations:

The North Sea ports of Rotterdam and Antwerp, both accessible via the corridor, are among the largest and busiest ports in Europe. These ports handle a wide range of cargo, including containers, bulk goods, and petroleum products. The industries related to port operations, such as shipping, warehousing, and transportation, are essential components of the corridor's industrial landscape.

- **Location within the Corridor:** Rotterdam and Antwerp are key port cities located within the Rhine-Alpine Corridor.
- **Examples of Companies within the Corridor:** Port of Rotterdam (Netherlands): One of the largest ports globally, serving as a major gateway for goods entering the corridor.

  Port of Antwerp (Belgium): Another major European port, facilitating the flow of goods within the corridor.

Automotive and Transportation Equipment:

The Rhine-Alpine Corridor is a hub for the automotive industry. Germany, in particular, is known for its automobile manufacturing, with major carmakers and their suppliers located in the corridor. Road transport is integral to the supply chain of these industries, ensuring the delivery of auto parts and finished vehicles.

- **Location within the Corridor:** The automotive industry is prominent in regions like Baden-Württemberg and Bavaria in Germany, both part of the Rhine-Alpine Corridor.
- **Examples of Companies within the Corridor:** Volkswagen (Germany): A global automotive giant with manufacturing facilities along the corridor.

Chemical and Petrochemical:

Chemical and petrochemical industries are prevalent along the corridor, with notable clusters in Germany, Switzerland, and the Netherlands. These industries produce a wide range of chemicals, plastics, and pharmaceuticals. Road transport is crucial for the safe and efficient movement of hazardous materials.

- **Location within the Corridor:** Chemical and petrochemical facilities are distributed throughout the corridor, with significant clusters in the Rhine-Main-Neckar region in Germany and Basel in Switzerland.
- **Examples of Companies within the Corridor:** Bayer (Germany): A major pharmaceutical and chemical company with operations within the corridor.

  Novartis (Switzerland): A multinational pharmaceutical company headquartered in Basel.

Agriculture and Agribusiness:

Agriculture is a significant sector in the corridor's rural areas. The transportation of agricultural products, including grains, produce, and livestock, relies on road networks to reach markets and processing facilities.

- **Location within the Corridor:** Rural areas within the corridor, including parts of Switzerland, Germany, and the Netherlands, support agricultural activities.
- **Examples of Companies within the Corridor:** Fendt (Germany): A manufacturer of agricultural machinery with operations in the corridor.

Syngenta (Switzerland): A global agribusiness company headquartered in Basel.

High-Tech and Innovation:

In addition to traditional industries, the corridor is also a hub for high-tech and innovation-driven sectors. Cities like Zurich and Munich are known for their research and development centers, startups, and tech companies. Road transport connects these knowledge hubs with the broader European market.

- **Location within the Corridor:** High-tech and innovation hubs are found in cities like Zurich, Munich, and Stuttgart within the Rhine-Alpine Corridor.
- **Examples of Companies within the Corridor:** Siemens (Germany): A global technology powerhouse with innovation centers within the corridor.

  ABB (Switzerland): A multinational corporation known for robotics, power, and automation technology, has several operation centers within the corridor.

7. Atlantic Corridor

The Atlantic Corridor stretches from the ports of the Iberian Peninsula to the port of Le Havre in Northern France, and cities of Strasbourg and Mannheim on the French/German border. The corridor's railway component will feature new high-speed rail links and parallel conventional lines, providing for cross-border continuity between Lisbon, Madrid, Paris, Strasbourg, Mannheim and Le Havre. The corridor has strong multimodal dimensions, utilising rail, road, inland waterway and maritime routes. Key projects for the corridor include the Basque Y rail connection and a new high-speed rail link between Bordeaux and Tours.

Figure 19. Atlantic Corridor. Road Network. Source: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html?corridor=5&layer=8,9

Industries within the Corridor:

Port and Maritime Services:

- **Location within the Corridor:** The Atlantic Corridor is home to major port cities like Algeciras (Spain), Lisbon (Portugal), and Le Havre (France).
- **Examples of Companies within the Corridor:** APM Terminals Algeciras (Algeciras, Spain): APM Terminals operates a significant container terminal in Algeciras, one of the busiest ports in Europe.

  Port of Lisbon (Lisbon, Portugal): The Port of Lisbon is a key maritime hub, facilitating cargo and passenger transport.

Aerospace and Defense:

- **Location within the Corridor:** Aerospace and defense industries have a notable presence in cities like Madrid (Spain) and Toulouse (France).
- **Examples of Companies within the Corridor:** Airbus Defense and Space (various locations, Spain): Airbus Defense and Space has manufacturing facilities in Getafe (Madrid region), Toledo and Cadiz.

  Airbus (Toulouse, France): Airbus has a major aerospace manufacturing facility in Toulouse, France, producing commercial aircraft.

Logistics and Distribution:

- **Location within the Corridor:** Logistics and distribution play a pivotal role in the corridor, with significant hubs in cities like Paris (France) and Madrid (Spain).
- **Examples of Companies within the Corridor:** Geodis (Paris, France): Geodis is a global logistics provider with a strong presence in Paris, offering transportation and supply chain solutions.

  Grupo Sesé (Zaragoza, Spain): Grupo Sesé, based in Zaragoza, Spain, specializes in logistics, transportation, and supply chain management.

Automotive and Transportation Equipment:

- **Location within the Corridor:** The automotive industry is prominent in cities like Porto (Portugal), Bilbao (Spain), and Bordeaux (France).
- **Examples of Companies within the Corridor:** Stellantis (Mangualde, Portugal): Stellantis operates a manufacturing plant in Mangualde, producing automobiles and components.

  Michelin (Clermont-Ferrand, France): Michelin, headquartered in Clermont-Ferrand, France, is a major tire manufacturer with a presence in the corridor.

8. North Sea – Mediterranean Corridor

The North Sea-Mediterranean Corridor extends from the northern city of Edinburgh in Scotland to the southern French ports of Marseille and Fos-sur-Mer. Along its route, it passes through Ireland, England, the Low Countries, and the capital of France, before running alongside the French-German border on its way south. Once it's fully developed, this corridor will provide enhanced multimodal connections between North Sea ports, major European river basins such as the Maas, Rhine, Scheldt, Seine, Saone, and Rhone, as well as the southern French ports of Fos-sur-Mer and Marseille. Additionally, it will enhance the links between the British Isles and Continental Europe.

Figure 20. North Sea- Mediterranean Corridor. Road Network. Source: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html?corridor=5&layer=8,9

Maritime and Shipping Services:

- **Location within the Corridor:** The North Sea-Mediterranean Corridor connects major ports such as Dublin (Ireland), Marseille (France), and Antwerp (Belgium) with cities like Paris (France) or Louxembourg.
- **Examples of Companies within the Corridor:** Dublin Port Company (Dublin, Ireland): Dublin Port plays a crucial role in Irish trade and offers various maritime services.

  Port of Marseille-Fos (Marseille, France): Marseille-Fos is one of the largest ports in France, handling diverse cargo types.

Aerospace and Technology:

- **Location within the Corridor:** The corridor includes cities like Brussels (Belgium) and Lyon (France), which have aerospace and technology sectors.
- **Examples of Companies within the Corridor:** Brussels Airport (Brussels, Belgium): Brussels Airport supports air freight and houses aerospace companies contributing to the industry.

  Lyon-Saint Exupéry Airport (Lyon, France): Lyon-Saint Exupéry Airport is a logistics hub with aerospace activities. Is the second largest. With 170 tonnes of freight per day, CargoPort, the freight platform of Lyon Airpoort, is the leading French freight airport platform after Paris.

Automotive and Manufacturing:

- **Location within the Corridor:** The automotive and manufacturing industry has a presence in regions such as Luxembourg and Dijon (France).

- **Examples of Companies within the Corridor:** Goodyear (Dudelange, Luxembourg): Goodyear operates a tire manufacturing facility in Dudelange, Luxembourg.

  Dassault Aviation (Mérignac, France): Dassault Aviation's Mérignac facility in Bordeaux manufactures military and civil aircraft.

9. Rhine – Danube Corridor

The Rhine-Danube Corridor serves as the primary east-west transportation route across Continental Europe. Tracing its path alongside the Danube River, it links Strasbourg and Southern Germany with central European cities such as Vienna, Bratislava, and Budapest, before continuing through the Romanian capital Bucharest and culminating at the Black Sea port of Constanta. A second branch of the corridor follows a route from Frankfurt to the Slovakian/Ukrainian border, connecting Munich, Prague, Zilina, and Kosice. Key projects along the corridor encompass enhancements to the navigational status of the Danube River in all the riparian countries.

Figure 21. Rhine- Danube Corridor. Road Network. Source: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html?corridor=5&layer=8,9

- **Location within the Corridor:** Cities like Bucharest (Romania), Sibiu (Romania), Deggendorf (Germany), Augsburg (Germany), and Salzburg (Austria) are prominent hubs for manufacturing and heavy industries within the Rhine-Danube Corridor.
- **Examples of Companies within the Corridor:** Automobile Dacia (Pitesti, Romania): A subsidiary of Renault and a major automobile manufacturer in Romania, producing a range of vehicles.

  BMW Werk Deggendorf (Dingolfing, Germany): The BMW Group Dingolfing plant is a network of BMW plants in Dingolfing, , Lower Bavaria, Germany, covering a total area of around 280 hectares. The plant is the largest production site of BMW Group in Europe.

MAN Energy Solutions (Augsburg, Germany): the headquarters of MAN Energy Solutions, the plant is the multinational company engaged in the manufacturing of large diesel engines and turbomachinery.

Logistics and Transportation:

- **Location within the Corridor:** Presov (Slovakia), Zilina (Slovakia), etc serve as vital logistics and transportation hubs within the Rhine-Danube Corridor.
- **Examples of Companies within the Corridor:** DHL Supply Chain (Presov, Slovakia): A significant logistics and supply chain company with a presence in Presov, facilitating the seamless movement of goods.

ZSSK Cargo (Zilina, Slovakia): A leading rail freight transportation company in Slovakia, contributing to the efficient movement of goods within the region.

Energy and Renewable Resources:

- **Location within the Corridor**: Salzburg (Austria) has companies related to energy production and renewable resources.
- **Examples of Companies within the Corridor:** Verbund AG (Salzburg, Austria): One of Austria's leading electricity companies, actively involved in hydroelectric power generation and renewable energy initiatives.

Západoslovenská distribučná, a.s. (Bratislava, Slovakia): This company is involved in electricity distribution in the Bratislava region.

Advanced Technology and Engineering:

- **Location within the Corridor**: Augsburg (Germany) is recognized for its advanced technology and engineering industries within the Rhine-Danube Corridor.
- **Examples of Companies within the Corridor:** KUKA Robotics (Augsburg, Germany): A global automation corporation that designs and manufactures industrial robots and automation solutions, contributing to advanced manufacturing processes.

The Strategic Significance of Hydrogen Hubs, hydrogen infrastructure and hydrogen projects in Europe.

Hydrogen Hubs

In the quest for sustainable and efficient solutions to address environmental and energy challenges, Hydrogen Hubs have emerged as fundamental pillars in the transition towards a cleaner energy future in Europe. These strategic centers represent key nodes in the distribution and production network of hydrogen, playing a crucial role in the consolidation, storage, and transportation of this innovative energy source.

According to the Clean Hydrogen Partnership, an extensive list of all Hydrogen Valleys is currently presented on the map below (Clean Hydrogen Partnership)**.** Although the status of most of them is either under ongoing feasibility studies, project concept development, pre-FID (Final Investment Decision), or under construction, this information is crucial for understanding the future hydrogen flows from the hubs to the main industrial centers in Europe for their decarbonization. With the available information, **the leading countries in the development of hydrogen valleys are Germany, the Netherlands, and Spain**

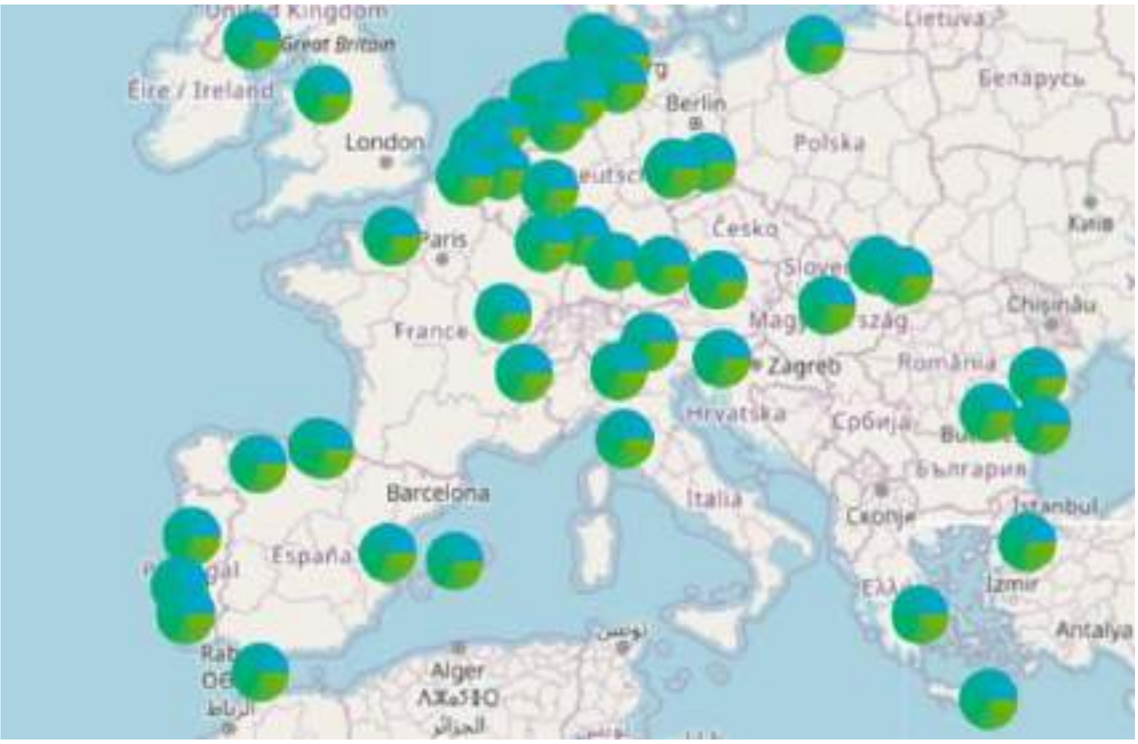

Figure 22. Hydrogen Valleys (Europe)

Hydrogen production plants

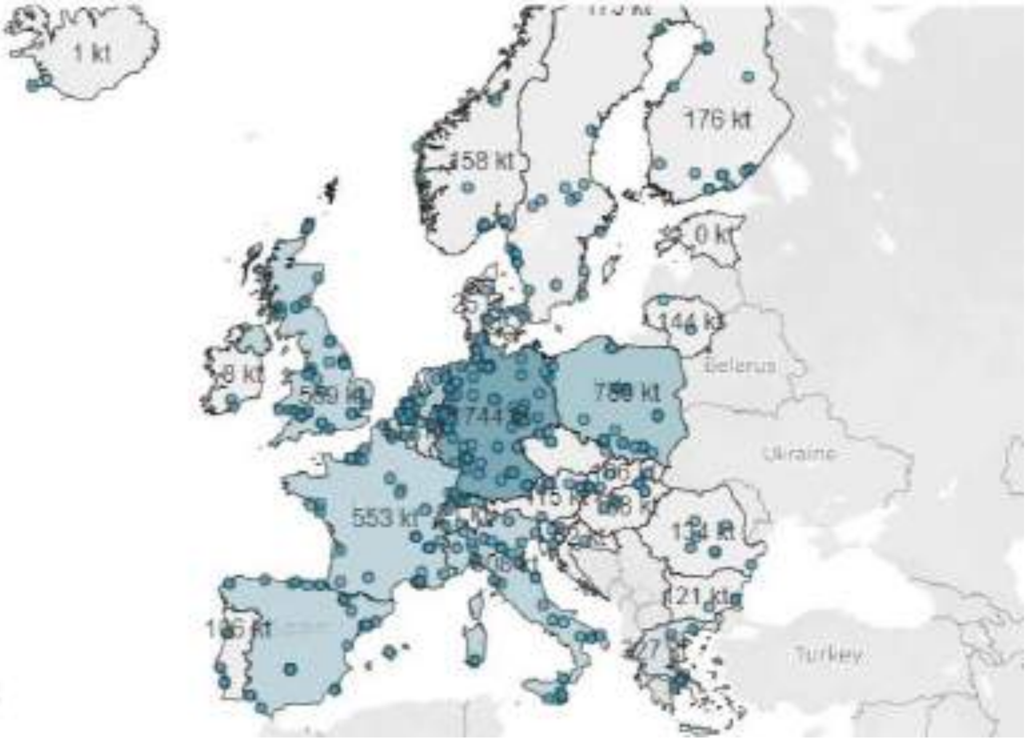

Figure 23. Hydrogen production plants (Europe)

The following map (European Hydrogen Observatory) illustrates hydrogen production by country in Europe using a color scale (darker shades indicate higher production levels). According to the data, the leading countries are **Germany (Rhine area)**, the **Netherlands (southwest region), Poland (south), Spain (north), Italy (north), the UK (Wales)**, and **France (north and southeast)**. Additionally, the map (European Hydrogen Observatory, s.f.) displays various hydrogen production plants represented by blue dots. This information proves valuable for identifying the primary hydrogen-emitting areas. **The leading countries by the number of plants are Germany, the Netherlands, Italy, and Spain.**

Hydrogen infrastructure

During the 36th European Gas Regulatory Forum (Madrid Forum), the European Commission mandated (H2inframap. ENTSOG, EUROGAS, GIE, GEODE, GD4S, and CEDEC , s.f.) to visually **represent all hydrogen infrastructure projects gathered through various existing processes.** This representation, known as the "Joint Initiative," depicts hydrogen infrastructure projects and illustrates their progression in 2030, 2040, and 2050. **The projects are categorized into five groups, encompassing transmission pipelines, distribution pipelines, terminals and ports, storages, as well as demand and production projects (see legend below).**

Figure 24. Legend (Infrastructure projects)

The following are the infrastructure projects for the periods 2030, 2040, and 2050

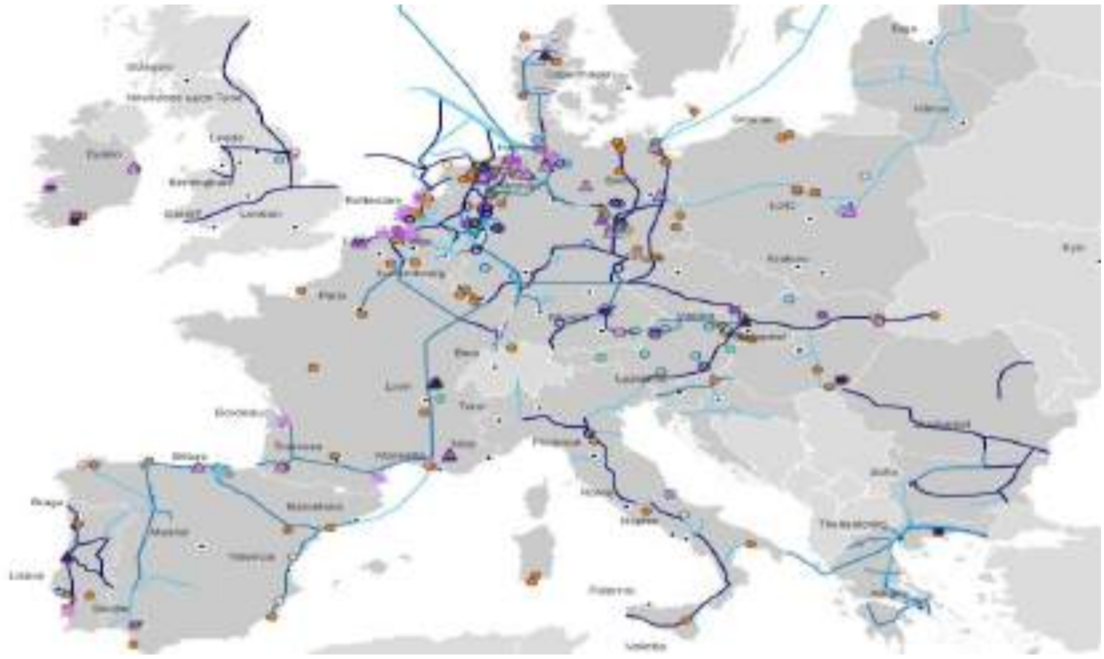

Figure 25. H2 infrastructure map 2030

As can be seen on the map, most of the infrastructure in 2030 is distributed among Germany and the Netherlands, with notable presence in Spain, Italy, the UK, and Central Europe. Examining the distribution channels and their conditions, we observe that Germany, Central Europe, the UK, and the Netherlands have existing gas infrastructure that they plan to convert for hydrogen transportation. Highlighting new and/or partially new transmission projects are Spain, France, Greece, Croatia, Finland and Germany (expanding its existing network).

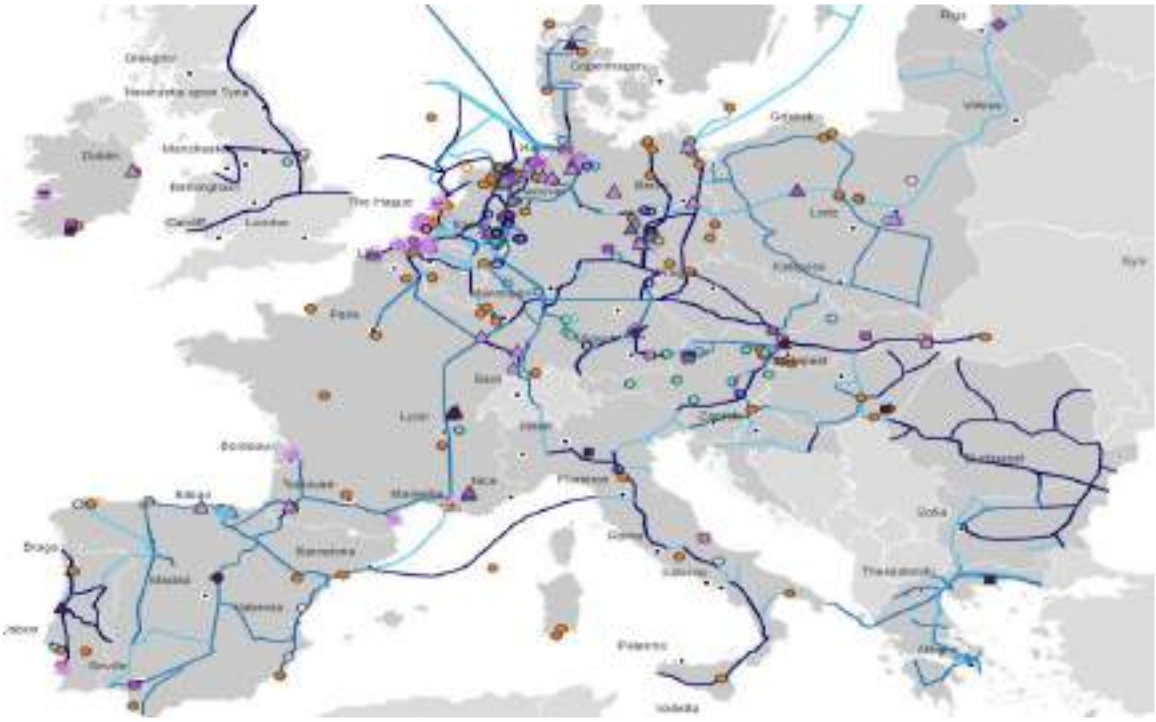

Figure 26. H2 infrastructure map 2040

In this case, additional projects are deployed in Germany, Poland, and Italy. Examining the distribution channels and their conditions, regarding the refurbishment of existing infrastructure, Romania, Hungary, Belgium, the Czech Republic and Italy-Spain are taking the lead. Concerning new and/or partially new transmission projects, Poland and Spain are notable contributors.

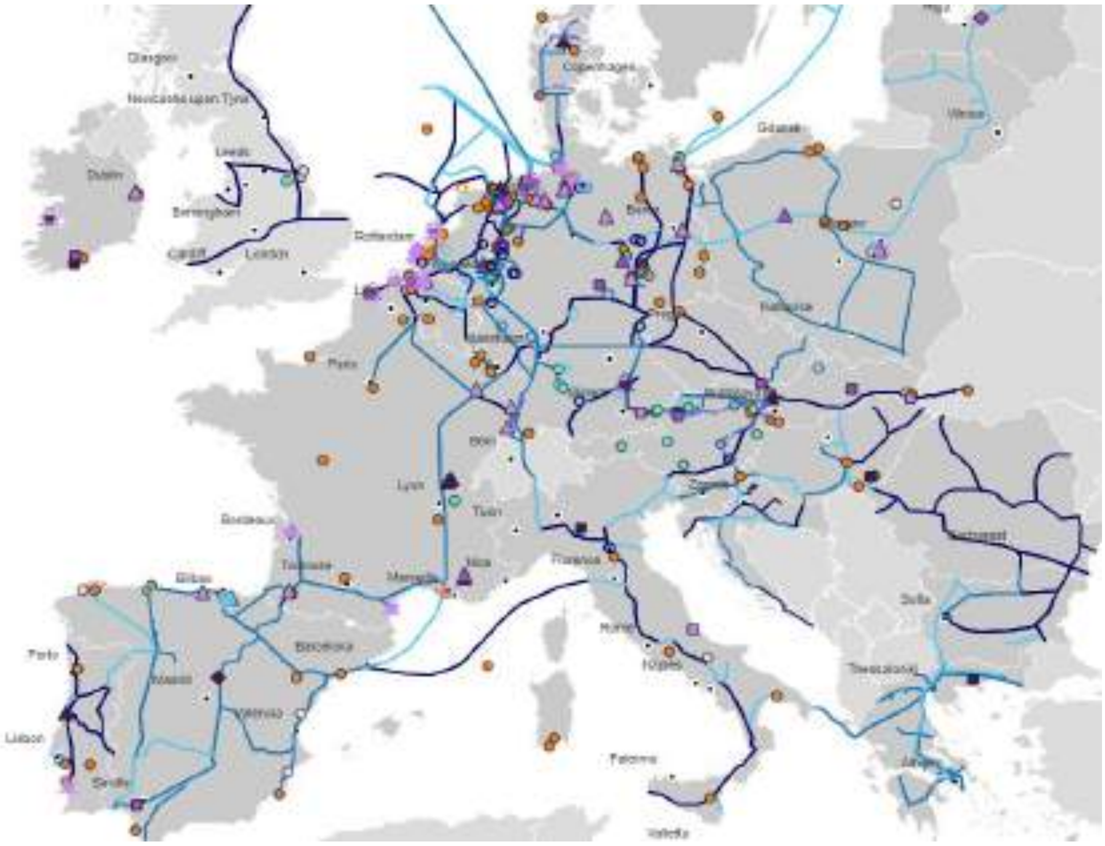

Figure 27. H2 infrastructure map 2050

As for the year 2050, the situation only varies slightly, with Croatia being the country undergoing the most significant changes. Croatia is deploying and refurbishing hydrogen transmission infrastructures extensively across the country.

Hydrogen projects

In line with this strategic importance**, the International Energy Agency (IEA) reports that there are currently 162 operational hydrogen projects in Europe** (International Energy Agency (IEA), s.f.). The projects encompass goals to either minimize emissions linked to hydrogen production for current purposes or utilize hydrogen as an energy carrier or industrial feedstock in innovative applications, aiming to become environmentally friendly technology alternatives. Highlighting the significance of these projects, it is crucial to note that they play a fundamental role in the decarbonization process by contributing significantly to emissions reduction and advancing towards a more sustainable, low-carbon economy. This is achieved through the transfer of technology and technological advancements, addressing not only hydrogen production itself but also implementing cleaner and more efficient technologies throughout the entire hydrogen lifecycle, from production to its use as an energy carrier or industrial feedstock. Below, there is a list of different projects organized by country and type of production technology:

Nº	**Project name**	**Countr**	**Date online**	**Status**	**Technology**
1	Underground Sun Storage	AUT	2018	Operational	ALK
2	MPREIS Hydrogen (within “Demo4Grid”)	AUT	2022	Operational	ALK
3	HySnowGroomer (within HyWest)	AUT	2017	Operational	ALK
4	Fronius Solhub – SAN Group Herzogenburg	AUT	2022	Operational	Other
5	Energie Steiermark plant in Styria	AUT	2023	Operational	Other
6	H2FUTURE	AUT	2019	Operational	PEM
7	Renewable Gasfield	AUT	2023	Operational	PEM
8	Hotflex	AUT	2020	Operational	SOEC
9	Don Quichote	BEL	2015	Operational	ALK
10	HRS CMB Port of Antwerp	BEL	2021	Operational	PEM
11	Gaznat methanation project	CHE	2023	Operational	ALK
12	Wasserstoffproduktion Ostschweiz AG	CHE	2022	Operational	Other
13	Hydrospider – St Gallen	CHE	2020	Operational	PEM
14	Solothurn, STORE&GO	CHE	2019	Operational	PEM
15	PtG Switzerland	CHE	2022	Operational	PEM
16	Apex Energy, Rostock-Laage	DEU	2021	Operational	ALK
17	Wyhlen hydroelectric power plant	DEU	2020	Operational	ALK
18	Carbon2Chem	DEU	2018	Operational	ALK
19	Rostock, Exytron Demonstrationsanlage	DEU	2018	Operational	ALK
20	Alzey, Exytron Null-E	DEU	2017	Operational	ALK
21	RH2 Grapzow, Mecklenburg Vorpommern	DEU	2015	Operational	ALK
22	H2BER (Berlin airport)	DEU	2014	Operational	ALK
23	ETOGAS, Solar Fuel Beta-plant AUDI, Werlte	DEU	2013	Operational	ALK
24	WindGas Falkenhagen	DEU	2013	Operational	ALK
25	H2Herten	DEU	2012	Operational	ALK
26	H2 research center BTU Cottbus	DEU	2012	Operational	ALK
27	Cotbus	DEU	2012	Operational	ALK
28	Hamburg Hafen City, CEP	DEU	2011	Operational	ALK
29	Hybrid Power Plant Enertrag, Prenzlau	DEU	2011	Operational	ALK
30	EnBW H2 station, Stuttgart	DEU	2011	Operational	ALK
31	Regenerativer Energipark Ostfalia/hybrid	DEU	2009	Operational	ALK
32	Green Hydrogen Esslingen (P2G2P)	DEU	2021	Operational	ALK
33	PFI – Pirmasens-Winzeln	DEU	2019	Operational	Other
34	Localhy	DEU	2019	Operational	Other
35	MicroPyros, Altenstant	DEU	2018	Operational	Other
36	MicroPyros, Staubing	DEU	2014	Operational	Other
37	Eucolino Schwandorf	DEU	2012	Operational	Other
38	HYPOS (several projects)	DEU	2019	Operational	Other
39	Leuchtturmprojekt Power-to-Gas Baden-	DEU	2020	Operational	PEM
40	eFarm (5 production sites in North Frisia)	DEU	2020	Operational	PEM
41	MEFCO2	DEU	2019	Operational	PEM
42	Windgas Haurup, 2nd phase	DEU	2020	Operational	PEM
43	Stromlückenfüller 2nd phase	DEU	2019	Operational	PEM
44	Falkenhagen STORE&GO	DEU	2018	Operational	PEM
45	Wind to Gas Südermarsch	DEU	2019	Operational	PEM
46	H2ORIZON	DEU	2020	Operational	PEM
47	Windgas Haurup, 1st phase	DEU	2018	Operational	PEM
48	Methanation at Eichhof	DEU	2018	Operational	PEM
49	Hassfurt	DEU	2016	Operational	PEM
50	HPEM2GAS (R&D)	DEU	2016	Operational	PEM
51	Hamburg – Schnackenburgallee	DEU	2016	Operational	PEM
52	WindGas Hamburg-Reitbrook	DEU	2015	Operational	PEM
53	RWE PtG plant Ibbenbüren	DEU	2015	Operational	PEM
54	Stromlückenfüller 1st phase	DEU	2015	Operational	PEM
55	Hanau, Wolfgang Industrial Park	DEU	2014	Operational	PEM
56	P2G plant Erdgas Schwaben	DEU	2013	Operational	PEM
57	CO2RRECT-Niederaussem	DEU	2013	Operational	PEM
58	MicrobEnergy GmbH, Schwandorf	DEU	2013	Operational	PEM
59	H2Move, Fraunhofer ISE	DEU	2013	Operational	PEM
60	Refhyne	DEU	2021	Operational	PEM
61	H&R Ölwerke Hamburg-Neuhof	DEU	2017	Operational	PEM
62	Energiepark Mainz	DEU	2017	Operational	PEM

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[22] The various equivalences for the abbreviations are as follows: ALK = Alkaline electrolysis, NG w CCUS = Hydrogen production from natural gas reforming (steam reforming, autothermal reforming or other advanced reforming technologies) coupled with CO_2 capture, utilisation and storage, Oil w CCUS = Hydrogen production from oil-based processes (reforming, cracking or gasification of oil products) coupled with CO2 capture, utilisation and storage, PEM = Proton exchange membrane electrolysis, SOEC = Solid oxide electrolysis cells.

63	Wunsiedel Energy Park (Phase 1)	DEU	2022	Operational	PEM
64	Wuppertal refuelling station	DEU	2020	Operational	PEM
65	SALCOS – WindH2 Windwasserstoff Salzgitter	DEU	2021	Operational	PEM
66	HRS Bremervörde – trains	DEU	2022	Operational	PEM
67	Fairfuel Atmosfair	DEU	2021	Operational	PEM
68	GrInHy2.0	DEU	2020	Operational	SOEC
69	Hydrogen Lab Leuna (136oll 1)	DEU	2021	Operational	SOEC
70	P2G-Biocat – Continued (Ref 508)	DNK	2015	Operational	ALK
71	H2 Logic HRS with onsite electrolysis Aalborg	DNK	2013	Operational	ALK
72	H2KT – Hydrogen Energy Storage in Nuuk	DNK	2010	Operational	ALK
73	Nukissiorfiit Nuuk Hydrogen Plant	DNK	2010	Operational	ALK
74	H2 Logic HRS with onsite electrolysis in Vejle	DNK	2013	Operational	ALK
75	H2 Logic HRS with onsite electrolysis Holstebro	DNK	2013	Operational	ALK
76	H2 Logic 3 HRS with onsite electrolysis in	DNK	2013	Operational	ALK
77	H2RES – Orsted offshore wind	DNK	2022	Operational	ALK
78	HRS Aalborg	DNK	2020	Operational	ALK
79	Power2Met	DNK	2020	Operational	Other
80	HyBALANCE	DNK	2020	Operational	PEM
81	REMOTE – Spain, Canary Islands	ESP	2023	Operational	ALK
82	HRS CNH2 Puertollano	ESP	2015	Operational	ALK
83	Abanto Technology Park	ESP	2023	Operational	Alk
84	Seafuel project	ESP	2022	Operational	Other
85	Pamesa – eCombustible	ESP	2023	Operational	Other
86	Iberdrola – Puertollano I	ESP	2022	Operational	PEM
87	Green Hysland Mallorca – Phase 1	ESP	2022	Operational	PEM
88	HRS TMB Zona Franca de Barcelona	ESP	2022	Operational	PEM
89	H2-Login	ESP	2022	Operational	PEM
90	CoSin: Synthetic Natural Gas from Sewage,	ESP	2018	Operational	SOEC
91	Parnu refuelling station	EST	2019	Operational	ALK
92	Narva power plant ELY	EST	2010	Operational	Other
93	H2Nodes, Riga	EST	2019	Operational	PEM
94	Woikoski Kokkola H2 plant	FIN	2014	Operational	ALK
95	Tecoil	FIN	2020	Operational	Other
96	Tecoil	FIN	2020	Operational	Other
97	Houdain bus station HRS (TADAO/Bulle 6	FRA	2019	Operational	ALK
98	FaHyence	FRA	2017	Operational	ALK
99	Minatec's semiconductor labs in Grenoble	FRA	2018	Operational	ALK
100	Vallée Hydrogène Grand Ouest (VhyGO) – H2	FRA	2021	Operational	ALK
101	Hyport – Toulouse-Blagnac Airport	FRA	2023	Operational	ALK
102	AuxHYGen (Phase 1)	FRA	2021	Operational	ALK
103	Veolia wastewater sludge plant	FRA	2021	Operational	Biomass
104	Port Jerome	FRA	2015	Operational	NG w CCUS
105	Vallée Hydrogène Grand Ouest (VhyGO) – EffiH2	FRA	2022	Operational	Other
106	Vallée Hydrogène Grand Ouest (VhyGO) – Saint-	FRA	2023	Operational	Other
107	Sirea – Castres site	FRA	2021	Operational	Other
108	H2PiyR Pamiers	FRA	2021	Operational	Other
109	Fébus Pau bus station HRS	FRA	2019	Operational	PEM
110	GNVert H2	FRA	2018	Operational	PEM
111	Energy observer	FRA	2017	Operational	PEM
112	Sealhyfe	FRA	2023	Operational	PEM
113	Porte de St Cloud HRS station	FRA	2023	Operational	PEM
114	Aberdeen Conference Center	GBR	2018	Operational	ALK
115	Hydrogen mini grid system Yorkshire	GBR	2012	Operational	ALK
116	Baglan Energy Park Wales	GBR	2008	Operational	ALK
117	HARI project, West Beacon Farm	GBR	2004	Operational	ALK
118	PURE Project, Unst	GBR	2005	Operational	ALK
119	Fife, Levenmouth Community Energy Project	GBR	2016	Operational	Other
120	Energy Hub at MIRA Technology Park.	GBR	2023	Operational	Other
121	Hydrogen plant – Orkney Islands – BIG HIT 2n	GBR	2019	Operational	PEM
122	HyDeploy	GBR	2020	Operational	PEM
123	Hydrogen plant – Orkney Islands – BIG HIT 1st	GBR	2017	Operational	PEM
124	Tyseley Energy Park refuelling hub Birmingham	GBR	2021	Operational	PEM
125	HRS Swindon	GBR	2018	Operational	PEM
126	REMOTE – Agkistro (Greece	GRC	2021	Operational	ALK
127	Agios Efstratios	GRC	2012	Operational	Other
128	Linde Hellas – Mandra	GRC	2022	Operational	Other
129	Aquamarine	HUN	2023	Operational	PEM
130	Taleghan solar hydrogen energy system	IRN	2009	Operational	Other
131	Commercial Plant Svartsengi/George Olah plant	ISL	2012	Operational	Other
132	Hellisheidi ON Power ely	ISL	2018	Operational	Other
133	Hydrogen Valley South Tyrol – Bolzano, CHIC	ITA	2014	Operational	ALK
134	INGRID	ITA	2016	Operational	ALK
135	Sapio – Mantova	ITA	2016	Operational	NG w CCUS
136	Troia, STORE&GO	ITA	2018	Operational	PEM
137	REFLEX	ITA	2018	Operational	SOEC
138	Alliander Oosterwolde – solar park of	NLD	2022	Operational	ALK

139	Shell heavy residue gasification CCU – Pernis	NLD	2005	Operational	Oil w CCUS
140	Hysolar Green on Road – Nieuwegein	NLD	2022	Operational	Other
141	Hydrogenpilot Oosterwolde	NLD	2022	Operational	Other
142	GROHW	NLD	2023	Operational	Other
143	DNV Kema/DNV GL	NLD	2011	Operational	PEM
144	Hystock (EnergyStock)	NLD	2021	Operational	PEM
145	Multiphly	NLD	2023	Operational	SOEC
146	ASKO Midt-Norge	NOR	2017	Operational	ALK
147	Oslo, CHIC	NOR	2013	Operational	ALK
148	Grimstad Renewable Energy Park	NOR	2000	Operational	ALK
149	Energy-Norweigian Catapult Centre	NOR	2023	Operational	ALK
150	Heroya Industrial Park	NOR	2022	Operational	ALK
151	HyNor Lillestrøm, Akershus Energy Park	NOR	2013	Operational	Biomass
152	Laboratory System at IFE Kjeller 137olli 2	NOR	2016	Operational	PEM
153	HAEOLUS	NOR	2021	Operational	PEM
154	Tauron CO2-SNG	POL	2019	Operational	Other
155	Trzebinia refinery	POL	2021	Operational	Other
156	Steklarna Hrastnik glass 137olling137uring plant	SVN	2021	Operational	Other
157	Thermal Power Plant Sostanj	SVN	2000	Operational	Other
158	TPJ Jesenice	SVN	2000	Operational	Other
159	HYBRIT pilot	SWE	2021	Operational	ALK
160	Vårgårda Bostäder housing complex	SWE	2019	Operational	ALK
161	Hofors 137olling project	SWE	2023	Operational	ALK
162	Oskarshamn nuclear plant	SWE	1992	Operational	ALK
163	Oxelösund Forklifts	SWE	2018	Operational	PEM

Table 1. Operational Hydrogen projects (Europe)

As we can see on the list, most of these projects are being developed in Germany followed by Denmark, Spain, France and UK.

The map below (IEA) represents the hydrogen projects from the aforementioned list, including those in conceptual stages, demonstration, feasibility studies, and FID/under construction. Examining the map, we observe that **the projects with the highest capacity are in Germany, the UK, Spain, and the Netherlands. Additionally, we note that if we include any project regardless of its status, the top countries are Germany, Spain, the UK, and France.**

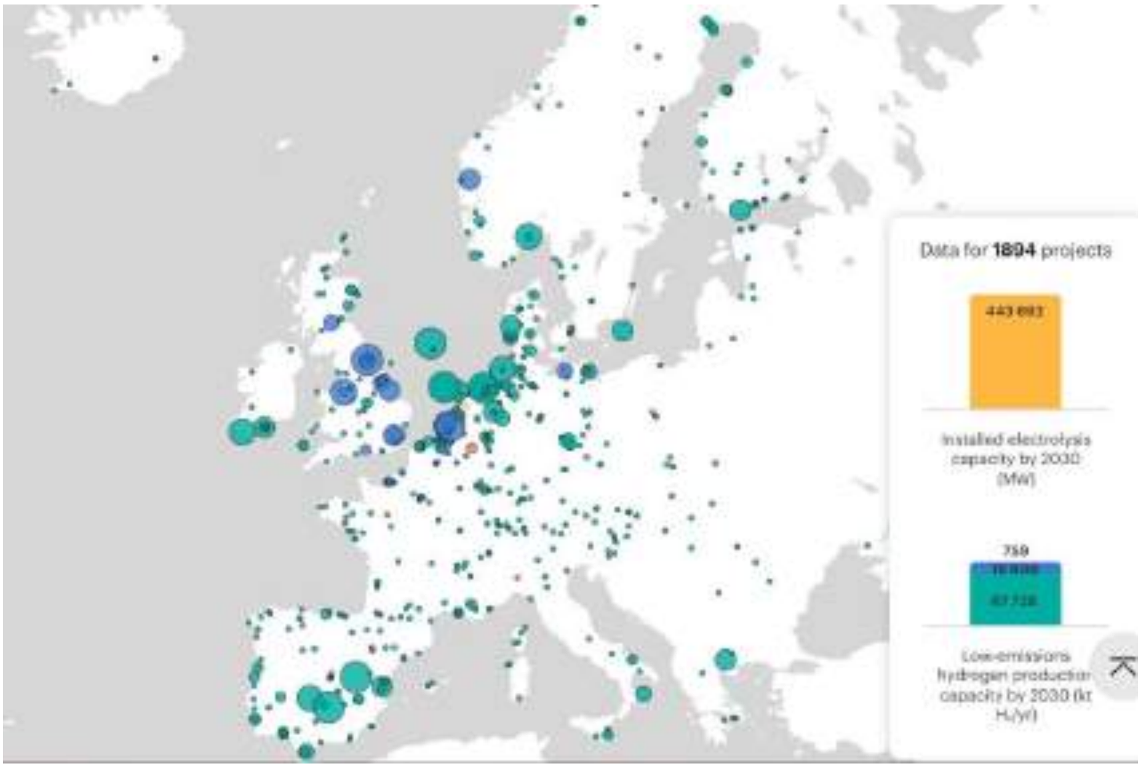

Figure 28: Hydrogen Projects (Europe) map

Strategic integration of Hydrogen Hubs and plants with the TEN-T Network and potential locations for the reinforcement of H2 infrastructures

After analyzing both the hydrogen supply and demand (current and future), the locations of production plants and hubs, and the key industrial focal points suitable for decarbonization, and understanding that the development of the gas pipeline transmission network is insufficient and will take several years to be established, the proposal is to use the TEN-T network as the primary or secondary transportation route (depending on the case) to transmit the flow of hydrogen from producers to industrial consumers.

On the other hand, the predominance of Germany is evident in all fields (demand, global production both in terms of overall and installed capacity, industrial centers, refineries, hydrogen valleys, transmission infrastructure and hydrogen-related projects across various applications). Also leading, with some variations in the analyzed variables, we find the Netherlands, Spain, Italy, Poland, and the UK.

Starting from the closest completion date of hydrogen transmission projects (pipelines) and considering that the development is expected to be ready by 2030 (6 years after the preparation of this report), the following recommendations are proposed (see the map below where

1 and 2 represent hydrogen production and hubs, 3 and 4 represent the transmission network via road and pipeline, respectively, and 5 and 6 represent consumption (largest European industrial hubs and refineries):

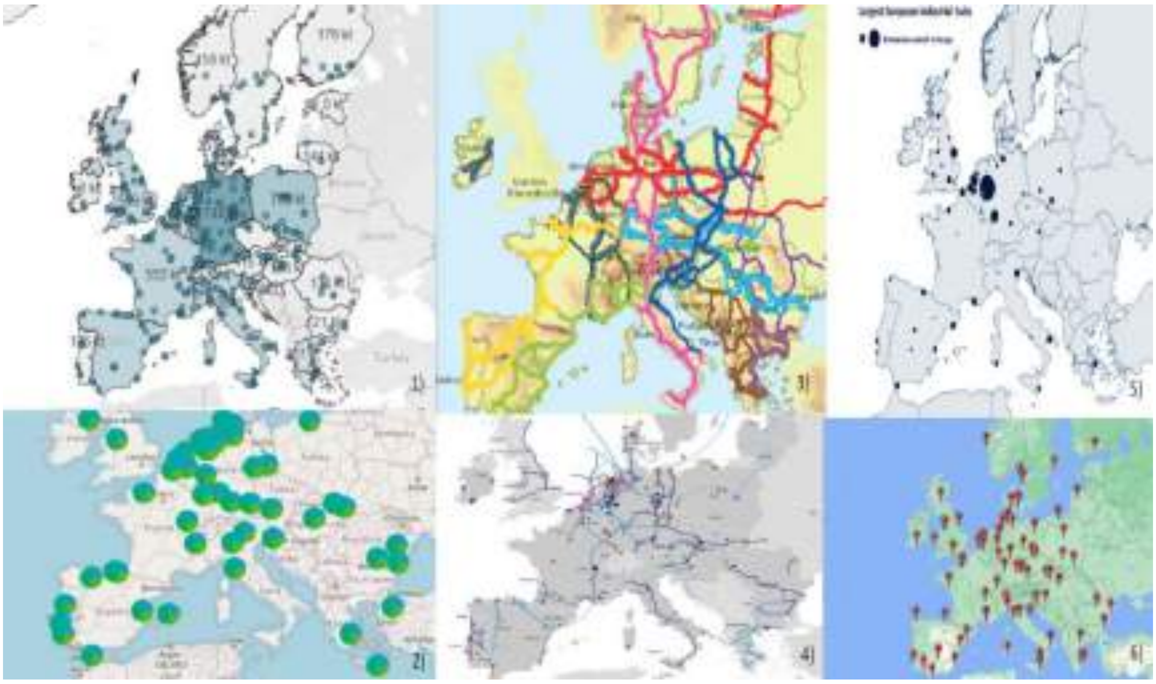

Figure 29. Compilation of hydrogen supply, transmission networks and demand maps. Several sources

Germany possesses an extensive pipeline distribution, supporting major production and demand centers. Additionally, five corridors pass through the country (North Sea-Baltic, Orient/East-Med, Scandinavian-Mediterranean, Rhine-Alpine, and Rhine-Danube). The recommendation in this case is to pay attention to the supply-demand dynamics and the evolution of hubs between the East and West in the area from Dusseldorf to Dresden (paralleling below the North Sea-Baltic corridor and above the Rhine-Danube).

In **Poland**, the central zone near Warsaw will be covered by the hydrogen pipeline by 2030. However, the Gdansk area and the industrial area near the border with Slovakia would be outside the reach of the network. This could be addressed by utilizing the North Sea Baltic and Baltic-Adriatic corridors. It is advisable to conduct an ad-hoc analysis to assess the situation in cities such as Koszalin, Zamosc, Tarnobrzeg, and Radom, as well as their surrounding areas.

For **Romania**, the gas pipeline network is very limited by 2030 (although this situation changes drastically towards 2040). Additionally, the Ten-T network only includes the Rhine-Danube corridor in this country, and its layout covers only the central and southern parts, leaving the central and northern provinces without sufficient infrastructure. This should be considered during the implementation of infrastructure from 2030 to 2040.

Regarding **Spain**, while the deployment of transmission infrastructure would efficiently cover major production and demand centers until 2040, the southernmost part of the Andalusian region would remain uncovered. Therefore, the Atlantic and Mediterranean corridors would be crucial for hydrogen distribution in the country while the rest of the transmission infrastructure is being constructed. However, the more northwest regions of the country, Galicia, Asturias, and Cantabria, outside the Ten-T network (Asturias would also be outside the planned pipeline network until 2050), are recommended to implement a transmission-distribution plan in the coming years. Considering the estimated data, connecting the Asturian region with the pipeline deployment in the northern part of the country would be the most efficient option.

Italy is expected to be well-connected via pipelines once the construction is completed, effectively linking production hubs and hubs with industrial centers and refineries. While construction and transformation of its pipeline are underway, it is recommended to use the Scandinavian and Baltic-Adriatic corridors for effective distribution. Additionally, using the Mediterranean corridor for the northwest zone, as it will initially be the only area not covered by the pipeline deployment, is advisable both now and in the future.

In the case of **France**, the transmission network will cover both demand and supply in the eastern part of the country, as well as the northern part. While the work is underway, the North Sea-Mediterranean corridor could be used to support the eastern part of the country. On the other hand, the North Sea-Mediterranean and Atlantic corridors would cover the Normandy and Brittany regions. However, there is no corridor or pipeline connecting these two regions, so reinforcing infrastructure between them should be considered.

Conclusions:

The shift toward **heavy-duty hydrogen transport represents a pivotal moment in Europe's pursuit of a more sustainable and decarbonized industry**. Throughout this transformation, the **recognition of strategic centers and the enhancement of hydrogen transport stand out as foundational components.**

In 2022, Europe's actual **hydrogen production** amounted to 8.23 million tonnes**. Germany, the Netherlands, Poland, Italy, France, and Spain collectively account for 63% of the continent's total hydrogen capacity.** Furthermore, when considering the annual hydrogen production output measured in million tonnes, **Germany, the Netherlands, Poland, Spain, and Italy together represent 57% of Europe's overall hydrogen output**.

In 2022, the anticipated **hydrogen demand** in Europe is projected to be 8.2 million tons (MT). The **refining sector stands out** as the predominant factor behind this demand, **constituting 57%** of the total hydrogen consumption in the European area. Additionally, the ammonia industry plays a significant role, contributing 24% to the overall demand. Analyzing **hydrogen consumption by country, Germany leads with a notable 21.2%, trailed by the Netherlands at 12.0%, Poland at 9.6%, and Spain at 7.5**%

Forecasts for hydrogen demand indicate a substantial increase, **with a projected surge of 127% from 2030 to 2040, followed by a 63% rise from 2040 to 2050**. The industrial sector is poised for a consistent rise in demand, starting from 9.86 million tonnes in 2030 and escalating to 14.62 million tonnes in 2040 (a 48% increase). Further, it is estimated to reach 16.88 million tonnes in 2050, representing a 15% increase. The transport sector is expected to play a significantly growing role, projecting a contribution of 37% by 2050, aligning with the expanding industrial demand.

Globally, **significant energy-intensive manufacturing activities, responsible for substantial energy consumption, are typically clustered in major industrial hubs**. These hubs serve as primary sources of CO2 emissions, playing a pivotal role in the decarbonization of the energy system. **Concentrations of these industrial hubs are prominent, particularly in Germany and the Netherlands**, as well as along the coast of **Spain**, various locations in **Poland**, the **Normandy** and Provence Regions in **France**, the North of **Italy**, the North of **Belgium**, and the South-West region in **Sweden**. Additionally, given that refineries currently account for almost 60% of total hydrogen consumption in Europe, analyzing the main refinery locations becomes significant. Once again, Germany takes the lead, followed by Italy, the UK, and Spain.

With hydrogen transmission infrastructure (pipelines) deployment progressing unevenly and expected to take several years for completion, **heavy-duty hydrogen transport emerges as a vital solution for efficient decarbonization**. **The Trans-European Transport Network (TEN-T) is a well-connected system designed to promote sustainability, safety, and efficiency in European transportation**. **Utilizing its extensive coverage of major routes, the TEN-T network becomes a key player in facilitating hydrogen (H2) transport**. By strategically placing refuelling stations and hubs along its corridors, the network not only ensures the feasibility of heavy-duty H2 transport but also facilitates efficient hydrogen distribution in key areas.

Regarding **hydrogen production** and the main areas within the leading countries, they are as follows: **Germany (Rhine area), the Netherlands (southwest region), Poland (south), Spain (north), Italy (north), the UK (Wales), and France (north and southeast).**

Based on the hydrogen infrastructure mapping, in **2030**, most of the infrastructure is concentrated in **Germany** and the **Netherlands**, with a notable presence in **Spain**, **Italy**, and **Central Europe**. Analyzing the distribution channels and their conditions, it is evident that Germany, Central Europe, and the Netherlands have existing gas infrastructure that they plan to convert for hydrogen transportation. Noteworthy new and/or partially new transmission projects include Spain, France, Greece, Croatia, Finland, and Germany (expanding its existing network). In **2040**, additional projects are implemented in **Germany, Poland, and Italy**. When examining the distribution channels and their conditions, **Romania, Hungary, Belgium, the Czech Republic**, and **Italy-Spain** are leading in the refurbishment of existing infrastructure. Regarding new and/or partially new transmission projects, Poland and Spain are notable contributors. Lastly, in **2050**, the situation only varies slightly, with **Croatia** undergoing the most significant changes by **deploying and refurbishing hydrogen transmission infrastructures** extensively across the country.

The **International Energy Agency** (IEA) states that **Europe currently hosts 162 operational hydrogen projects**. These initiatives have diverse objectives, ranging from reducing emissions associated with current hydrogen production to exploring innovative applications, where hydrogen serves as an environmentally friendly technology alternative, either as an energy carrier or industrial feedstock. **Germany** takes the lead in the number of projects, followed by **Denmark**, **Spain**, **France**, and the **UK.**

The following countries have a planned infrastructure network for 2030 and/or one or more Ten-T corridors sufficient to cover, a priori, supply and demand: **Belgium** (except the Hainaut region), Ireland (except the western region), The **Netherlands**, the **Nordic countries** (excluding the southwestern part facing the Gulf of Bothnia), the **Baltic countries**, **Czech Republic**, **Slovakia**, **Austria**, **Greece**, **Bulgaria**, **Hungary** (though a greater deployment of pipeline infrastructure covering the central-northern region is recommended), **Luxembourg**, and **Slovenia**. **In these cases, periodic reviews are recommended based on emerging needs and opportunities, new production plants, hydrogen valleys, and developments in industrial and hydrogen-related technology.**

The analysis of the hydrogen infrastructure in the next European countries reveals specific recommendations:

Germany, with its extensive pipeline distribution and five major corridors, has its demand and supply flow well covered. The country should closely monitor supply-demand dynamics and hub evolution in the area from Dusseldorf to Dresden.

In **Poland**, while the central zone near Warsaw will have hydrogen pipelines by 2030, attention is needed for areas like Gdansk and the border region with Slovakia, which could benefit from the North Sea Baltic and Baltic-Adriatic corridors.It is also advisable to conduct an ad-hoc analysis to assess the situation in cities such as Koszalin, Zamosc, Tarnobrzeg, and Radom, as well as their surrounding areas.

Romania faces limited gas pipeline networks by 2030, with the Rhine-Danube corridor covering only the central and southern parts. Additionally, the Ten-T network only includes the Rhine-Danube corridor in this country, leaving the central and northern provinces without sufficient infrastructure. This should be considered during the implementation of infrastructure from 2030 to 2040.

Spain's transmission infrastructure covers major centers until 2040, but the Andalusian region requires attention, relying on the Atlantic and Mediterranean corridors until then. Northwest regions like Galicia, Asturias, and Cantabria are advised to plan transmission-distribution, connecting the Asturian region efficiently.

Italy's well-connected future via pipelines suggests using Scandinavian and Baltic-Adriatic corridors during ongoing construction, while the Mediterranean corridor becomes essential for the uncovered northwest zone.

In **France**, ongoing work ensures coverage in the eastern and northern parts, with additional support from the North Sea-Mediterranean corridor. The Normandy and Brittany regions, covered by the North Sea-Mediterranean and Atlantic corridors, may benefit from reinforced infrastructure between them.

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