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North Sea Hydrogen Valley Ports

Creating the hydrogen corridor between North Sea ports

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Development of Alternative Use Cases of H2

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Abbreviations

AFC	Alkaline Fuel Cell
AGV	Automated Guided Vehicle
BE	Battery Electric
BE-CHE	Battery-Electric Cargo Handling Equipment
CAPEX	Capital expenditures
CHE	Container Handling Equipment
CO_2	Carbon Dioxide
FC	Fuel Cell
FCE	Fuel Cell Electric
FID	Final Investment Decision
H2	Hydrogen
HE-CHE	Hydrogen-Electric Cargo Handling Equipment
HICE	Hydrogen Internal Combustion Engine
ICE	Internal Combustion Engines
LFP	lithium iron phosphate
LIB	Lithium-ion battery
NREL	National Renewable Energy Laboratory
OPEX	Operational expenditures
PEMFC	Proton Exchange Membrane Fuel Cell
PoDH	Port of Den Helder
RES	Renewable Energy Sources
RMG	Rail-Mounted Gantry Cranes
RTG	Rubber-Tyred Gantry Cranes
SoA	State of the Art
STS	Ship-To-Shore Cranes

Executive Summary

Ports play a crucial role in the energy transition and represent a highly promising domain for the expanded deployment of hydrogen-based solutions. In this regard, the Interreg project "North Sea Hydrogen Valley Ports" seeks to develop hydrogen roadmaps for four European ports: Brest, Esbjerg, Bremen, and Den Helder, as part of a future maritime Hydrogen Valley. This report outlines the project's initial phase, which focuses on identifying potential hydrogen use cases within port areas. These findings will later be applied and further elaborated in the four selected ports. The report demonstrates that hydrogen technologies have significant potential to reduce emissions in port operations, particularly in mobile and heavy-duty sectors. Moreover, the results emphasize the importance of coordinated infrastructure planning and strategic investment.

1. Introduction

As ports transition towards more sustainable and decarbonised operations, hydrogen emerges as a key energy carrier to support this transformation. While increasing electrification efforts support the reduction of CO_2 emissions severely, ports regularly face grid congestion and infrastructure limitations that limit large-scale electrification efforts. Therefore, hydrogen may serve as a complementary solution for achieving emission reduction and decarbonization goals by potentially enabling energy storage, grid balancing, and direct use in various port applications, from shore power to heavy-duty machinery.

The aim of Work Package 1 is to develop hydrogen strategies in four port regions, supporting the production and use of hydrogen and its derivatives. The work also seeks to identify and remove barriers to hydrogen production, use, and imports, thereby contributing to a reliable and safe hydrogen supply for port communities.

Within this framework, Activity 1.8 focuses on analysing non-implemented fuel cell use cases for energy-intensive applications in ports. This includes solutions for challenges such as grid congestion, which can hinder electrification and decarbonization. Potential use cases include shore power, grid balancing, port operations, and e-mobility charging infrastructure.

In this respect, this report provides an initial overview of possible hydrogen applications in port environments. It outlines technical and economic aspects and highlights opportunities and limitations. Additionally, the report examines hydrogen’s role in reducing emissions from port logistics, including hydrogen-powered tugboats and rail operations.

On this basis, relevant (non-implemented) use cases for the participating ports will be identified and developed.

2. Investigation of Hydrogen Applications for Port Environments

Before discussing specific hydrogen applications for port environments, it is important to first address the infrastructural requirements that are essential for a successful integration of different hydrogen applications in port environments. Therefore, it is essential to consider the following aspects:

- To ensure sufficient and reliable hydrogen production, storage, and distribution network
  - Local hydrogen production, e.g., through electrolysis.
  - Oftentimes, it is more feasible to produce hydrogen mainly in locations where renewable energy sources (RES) are abundant to ensure low prices for green hydrogen -> strong emphasis must be placed on hydrogen transport by pipeline and/or ship.
- Hydrogen imports may supplement local production, requiring integration into the existing port energy networks.
- Investments in grid balancing solutions will be necessary to avoid energy bottlenecks while enabling shore power and hydrogen infrastructure to coexist efficiently.

Efforts are already being made to pave the way for a growing demand for hydrogen. For example, it is planned to connect Bremen and Bremerhaven to the German hydrogen backbone by 2027 and 2030, respectively [1]. The country of Denmark has also published plans to establish a hydrogen backbone that connects Denmark and Germany [2]. This pipeline is expected to be operational by 2030 and will also pass through the port of Esbjerg. For Brest Port, being far from the envisaged H_2 backbone, studies are engaged with the Brittany Region and with the energy provider ENGIE and the gas operator GRDF to study local production and distribution networks covering port and industrial applications around. This will ensure a stable transport route for hydrogen between industrial zones, storage facilities, and distribution networks.

In parallel, the H2B project has outlined a strategic roadmap for integrating hydrogen into Bremen's urban and industrial infrastructure, further ensuring energy security and efficient resource allocation [3]. As a follow-up, the project hyBit (Hydrogen for Bremen's industrial transformation) is analyzing the development of a hydrogen economy in Northern Germany and takes a holistic view of Bremen's transformation. As part of its "Mobility and Logistics" cluster, the project also explores hydrogen opportunities in port logistics.

2.1. On-shore Power Supply, Congestion Management, and Grid Balancing

This section considers three general use cases in the context of port energy systems: on-shore power (direct power supply to ships), congestion management (local grid capacity), and grid balancing (energy equilibrium in the broader power grid).

2.1.1. On-shore Power Supply

The use of shore power is a very recent and largely discussed topic. Seagoing vessels also need energy in the harbor, whether to operate the on-board systems or to cool containers. Currently, ships are mostly using their so-called diesel-powered auxiliary engines to generate the required energy directly on board. According to the Fourth IMO GHG Study [4], an average of 16% of CO_2 emissions occur while ships are at berth or at anchorage.

An alternative for providing the ships at berth with energy is the use of shore power and, therefore, connecting the ships to the power grid on the land side of the port. Even though carbon footprints of grid power vary widely around the world, the global electricity mix has reached a 30% share of renewable energies in 2023 [5]. In the EU, the share of renewable energy in the electricity mix reached 47% in 2024, according to Eurostat [6]. If nuclear energy is included, 71% of the EU electricity supply was based on low-carbon sources [7].

The reduced carbon footprint of grid power in comparison to diesel can be used as an effective way to reduce CO_2, SO_2, and NO_x emissions at shore drastically – potentially even by 100% [8]. Moreover, under Article 9 of the Alternative Fuels Infrastructure Regulation (EU 2023/1804), the use of shore power to reduce local pollution will become a mandatory requirement (with very few exceptions) in the largest European ports by 2030 [9].

Although the use of shore power appears to be an effective and comparably fast-to-realize way of significantly reducing CO_2 emissions from shipping, there are a number of obstacles to its practical implementation [10].

- Low economic feasibility of shore power
- Volatile international fuel and electricity costs

- High installation/investment costs -> so far: major lack of sufficient shore power infrastructure
    - High investment costs for port operators
    - High retrofitting costs for ship owners
- The need for additional on-shore electrical facilities due to various types of ships and ship sizes
- Lack of standardization
- Insufficient international regulations

A pioneering example of hydrogen-powered shore power is Edinburgh's Port of Leith's Green Hydrogen Shore Power Demonstrator [11], which provides clean energy to docked vessels. The project utilizes water treatment technology to process wastewater from a nearby treatment facility, ensuring that electrolysis can be conducted without compromising local water supplies. Hydrogen is then produced through an electrolyzer, which splits purified water into hydrogen and oxygen. The hydrogen is subsequently used to fuel the Hydrogen Internal Combustion Engine (HICE) generator, which produces green electricity for Targe Towing's tugboats, allowing them to shut down their diesel generators while in port.

Another innovative example comes from the **Port of Esbjerg**, where a hydrogen-based on-shore power system is being developed in collaboration with Esbjerg-based technology company CS Electric A/S. The system utilizes green hydrogen, produced from surplus wind energy, which is converted into electricity using fuel cells supplied by Ballard. Once installed, ships docked at the port will be able to draw electricity from this 100% CO_2-neutral source. The mobile containerized setup allows for flexible deployment across the port and is seen as a pioneering solution for providing zero-emission electricity to ships using green hydrogen and fuel cell technology [12].

2.1.2. Congestion management

H_{2-} can very well be used to alleviate congested grids. Additionally, hydrogen generators, either fuel cell-based or with an internal combustion engine (ICE), could be used to manage local grid congestion, i.e., situations where the local grid infrastructure is close to being overloaded due to demand exceeding the physical capacity of the grid. In the case of a port, generating power with a fuel cell at the time of peak demand, for instance, when a ship (or several) connects to the on-shore power supply, could be an effective way of keeping power on, without having to invest in significant grid reinforcements for the entire port area. It is worth noting that first options with lower OPEX-generation should be utilized, i.e., large batteries to buffer electricity for balancing, only using hydrogen-based electricity when the batteries or other energy storage facilities fail to meet the demand.

The Port of Esbjerg is piloting hydrogen-based solutions that directly address congestion challenges in local grids. In particular, modular containerized fuel-cell units (each ~100 kW, six installed so far) are being deployed to provide shore power without drawing additional load from the existing grid. These units operate flexibly and can be scaled according to vessel demand, thereby reducing peak loads and avoiding costly reinforcement of local transmission infrastructure.

In addition, Esbjerg is closely linked to Denmark's planned hydrogen backbone and the upcoming PtX developments in the region (e.g., the HØST Esbjerg PtX project and the Måde electrolyzer). Once connected, surplus hydrogen from large-scale production can be reconverted to electricity via fuel cells at the port. This creates an additional buffer for congestion management, ensuring that shipping activities and port operations can expand without waiting for major grid extensions.

The Esbjerg approach demonstrates that hydrogen can act both as a grid relief tool (providing power during peak demand) and as a flexible storage medium integrated into a wider hydrogen economy.

2.1.3. Grid Balancing

Hydrogen technologies could also be used for other purposes, such as grid balancing. Ideally, electricity is fed into the power grid at the moment it is generated. Any imbalance must be compensated in real-time through power reserves. Traditionally, this was addressed by requiring power plants to maintain reserves that could be rapidly deployed in cases of overproduction or excessive demand. However, this approach is becoming increasingly complex with the rising share of electricity generated from RES. The intrinsic variability in RES production, which is strongly dependent on factors such as time of day, seasonality, and weather conditions, further exacerbates these challenges. [13], [14]

Consequently, the ongoing electrification of all transport modes, coupled with the increasing integration of RES into global power grids, poses significant difficulties in maintaining grid stability. One potential solution to reconcile rising energy demand due to electrification with the growing share of RES while ensuring grid stability is the deployment of energy storage systems. These systems store surplus electricity during periods of overproduction and release it during times of heightened demand. While battery storage systems offer a direct method of storing and discharging electricity, long-term battery storage solutions designed to balance seasonal fluctuations in RES generation remain highly expensive. [13]

Hydrogen represents a viable alternative to battery storage. Hydrogen production via electrolysis can serve as a mobile storage medium. The stored hydrogen can later be reconverted into electricity when additional energy is required or used directly, either in its pure form or as hydrogen derivatives, across various applications, which are discussed in the following sections. [13]

Ports, which may host electrolyzers and hydrogen storage, are well-positioned to become energy hubs [13].

2.1.4. Hydrogen from surplus renewable energy

While hydrogen production from surplus energy is often considered a viable option for balancing energy grids, it is important to assess where and when energy surpluses occur. In areas near ports and industrial zones, energy surpluses tend to be minimal, as these areas consistently draw large amounts of power from the grid. In such cases, importing hydrogen from regions with high energy surpluses could be an effective solution. Possible transport methods include:

- Shipping hydrogen in liquid or gaseous form via specialized vessels
- Pipeline transport from production sites to industrial users
- Rail transportation of hydrogen in pressurized or liquid form
- Trucking hydrogen to port terminals for local distribution

2.2. Port Machinery and Equipment

Ports, essential to global trade, depend on various types of vehicles and machinery to maintain cargo flow. Central to these operations is cargo handling equipment (CHE), such as reach stackers, straddle carriers, gantry cranes, and forklifts for containers, and loaders, cranes, and forklifts for bulk goods [15]. According to the white paper "Reaching a tipping point in Battery-Electric Container Handling Equipment", Container Handling Equipment may be categorized as either tethered (~30% of units are tethered) or untethered [16].

Tethered equipment, such as ship-to-shore cranes (STS), rail-mounted gantry cranes (RMG), and certain rubber-tyred gantry cranes (RTG), are already largely electrified and connected to the local grid. This setup allows for emission-free operation when powered by renewably sourced electricity. In fact, a study published by Ramboll GmbH in 2022 confirms that RMGs and STS cranes are among the most electrified units in port operations, typically drawing power directly from the grid [17].

In contrast, untethered equipment, including straddle carriers, terminal tractors, reach stackers, forklifts, and mobile harbor cranes, remains largely dependent on diesel engines. These vehicles are mobile and operate over larger terminal areas, making electrification more challenging. As of 2021, the German port fleet included only around 7% of equipment powered by alternative systems (battery-electric or hybrid), with the vast majority still running on diesel [17].

Overall, several low-emission alternatives to diesel-powered machinery exist. However, these options vary strongly in terms of technological readiness. While battery-electric (BE) drives are already increasingly common in light-duty machinery, hydrogen-powered port equipment remains in an early development stage. Since BE drives quickly reach their theoretical limits in heavy-duty applications, and grid congestion in ports is becoming a growing challenge, the need for hydrogen-powered machinery is becoming increasingly evident.

Although fuel cell electric (FCE) drives are the most commonly discussed option for hydrogen utilization, several other approaches exist, which are explored in the following section.

In FCE vehicles, the fuel cell is powered by hydrogen, which can be supplied in either compressed gaseous or liquid form. Within the fuel cell, the chemical energy of hydrogen is converted into electrical energy and heat. The electrical energy then powers the electric motor. The most common types of fuel cells are proton exchange membrane fuel cells (PEMFC) for vehicles and stationary power applications, and solid oxide fuel cells (SOFC) for stationary power applications. Additionally, hydrogen derivatives such as ammonia or methanol can be utilized in specialized FCs. In certain applications, this can be advantageous due to the higher volumetric and gravimetric energy densities of these derivatives compared to hydrogen, as well as simplified refueling and handling procedures. However, the use of hydrogen derivatives typically results in lower overall energy efficiencies.

Beyond FCs, hydrogen and its derivatives can also be used in ICEs. Since SoA diesel-powered machines are equipped with ICEs, hydrogen-powered combustion engines could enable the continued use of existing fleets through retrofitting measures. This approach is particularly relevant for fleets with long operational lifetimes, as retrofitting can facilitate rapid emission reductions. However, ICEs generally achieve an overall efficiency of approximately 40%, which is significantly lower than the average efficiency of fuel cells at around 60%. Consequently, ICEs have lower overall efficiency and higher hydrogen or derivative consumption [18]. Also, while they do not emit any CO_2, ICEs do still emit NO_x, which can impact air quality in ports and coastal areas. Even though all those different options exist, BE and hydrogen FCE drives are the two primary zero-emission alternatives emerging. Therefore, those two options are the main focus within the following sections dealing with specific use cases in ports. To clarify the differences between the two options, a comparative overview is shown in Figure 1.

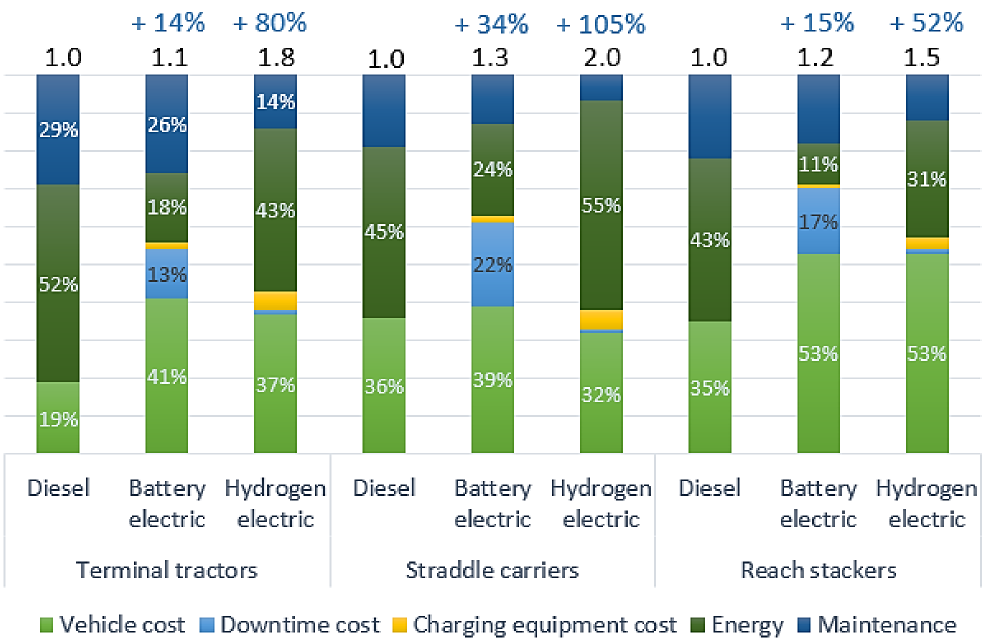

Figure 1: Cost Comparison of Diesel, Battery-Electric, and Hydrogen-Electric CHE by Equipment Type [16]

Figure 1 depicts the cost composition of diesel, battery-electric (BE-CHE), and hydrogen-electric cargo handling equipment (HE-CHE), the latter also encompassing fuel-cell-powered machines that produce electricity from hydrogen. The costs are divided into five main categories: vehicle cost, downtime cost, charging equipment cost, energy, and maintenance. For instance, in the case of terminal tractors, battery-electric models are roughly 14% more expensive than their diesel counterparts, driven by higher vehicle costs but offset by lower energy expenditures. Hydrogen-electric tractors, on the other hand, are approximately 80% more costly, primarily due to high energy and vehicle costs [16].

In other words, BE-CHE is the preferred solution due to its increasing availability, cost-efficiency, and compatibility with existing electric charging infrastructure. For instance, electric terminal tractors and reach stackers are being deployed at several European ports. AGVs (Automated Guided Vehicles), which are often fully electric, are already used extensively in container terminals.

HE-CHE (powered by fuel cells that generate electricity from hydrogen) is particularly relevant in environments with unreliable grid access or extreme operational conditions. While currently in pilot phases, such as in the Ports of Valencia and Hamburg, hydrogen-powered reach stackers and terminal tractors have shown promising performance.

Several ports have implemented hydrogen refueling infrastructure to support the deployment of zero-emission CHE [19]: Port of Los Angeles (piloted a mobile hydrogen fueling system with a 180 kg capacity at 450 bar), Port of Valencia (operating a dual hydrogen refueling setup as part of the H2Ports initiative [20]), and Port of Hamburg.

This section also examines examples of key cargo handling equipment types, highlighting innovative projects and demonstrations at various ports.

While ports are typically regarded as cargo hubs, a perspective reflected in this section, certain ports, such as Den Helder, serve primarily as an offshore maintenance and supply hub. This will be further discussed in the port-specific section.

2.2.1. Reach stacker

Reach stackers remain predominantly **diesel-powered** and are essential in container terminals and intermodal yards due to their high flexibility and heavy lifting capacity. According to the study conducted by Ramboll GmbH [17], these vehicles are a major contributor to emissions in inland ports, responsible for about 60% of total CO_2 emissions from cargo handling equipment in that context. While alternative propulsion technologies are technically viable, adoption is hindered by high investment costs and infrastructure demands.

Comparative technical data from the U.S. National Renewable Energy Laboratory (NREL) [19] provides additional insight into the operational performance of various reach stacker powertrains. According to NREL [19], **Diesel-powered models** remain the most mature (TRL 9 [21]) and can typically operate up to 39 hours per shift, with an average energy consumption of 2,269 kWh and a mid-range energy cost of around US$224 per shift. Furthermore, **Battery-electric** reach stackers, which are nearing full commercial readiness (TRL 8), offer operational ranges between 4 and 10 hours and consume approximately 1,014 kWh per shift [19]. Battery-electric reach stackers, such as the SANY SRSC45E5 model, offer up to 8–10 hours of operation per charge using a 422 kWh lithium iron phosphate (LFP) battery, and reduce operational costs by 40 to 60 % [22], [23]. Nevertheless, charging requires careful planning, as it is significantly slower than diesel refueling and depends on optimal positioning of charging stations within the terminal layout [24].

FCE reach stackers, still in earlier stages of market entry (TRL 6), provide a typical operational range of 8–10 hours and consume around 1,588 kWh per shift. Refueling times are fast, ranging from 10 to 15 minutes (0.16–0.25 hours), but current energy costs are higher, estimated at US$334 per shift, due to hydrogen production and infrastructure limitations [19]. Despite these challenges, fuel cell systems are actively being tested in real-world port settings and offer a viable path toward zero-emission heavy-duty equipment. In this respect, **FCE** reach stackers are being tested in the Port of Valencia (the Hyster H2 Reach stacker). These vehicles offer fast refuelling within 10 to 15 minutes [25], although limited hydrogen infrastructure remains a key deployment barrier.

In parallel, **hybrid alternatives** are available, such as SANY's model that combines an internal combustion engine with a hydropneumatic drive, resulting in approximately 20% emissions reduction compared to conventional diesel reach stackers [26].

2.2.2. Straddle Carrier

Straddle carriers in most ports are currently powered by **diesel-electric** systems. For example, straddle carriers represented a significant share of handling equipment in German seaports, with around 588 units in operation in 2021, projected to rise to over 800 by 2040 [17]. They are also the single largest source of CO_2 emissions in this category, accounting for up to 70 % of emissions in seaport cargo handling. Despite the technological readiness of **electric and hydrogen solutions**, the study conducted by Ramboll GmbH highlights high operational costs, limited working time, and infrastructure limitations as key barriers to broader application [17].

Technical data from the NREL further illustrates the comparative performance of straddle carrier powertrains. **Diesel-electric** straddle carriers, which currently dominate the market, exhibit the highest level of technological maturity (TRL 9), with an average operational range of 71 hours per shift and energy consumption of approximately 2,334 kWh. Their mid-range operational cost is estimated at US$230 per shift.

Battery-electric models, while increasingly deployed (TRL 8), offer significantly lower operational ranges of around 4 hours per charge, which may require multiple charging cycles to complete a full shift. They consume approximately 1,043 kWh per shift, with associated energy costs ranging from US$256 to US$365 per shift [19], depending on the local electricity tariff and operational intensity. Shorter battery range may require adjustments in routing, charging schedules, or even fleet size to maintain throughput [19]. Battery-electric models, such as those developed by Konecranes, can operate for approximately four hours on a single charge, with charging times between 90 and 120 minutes [27]. In some cases, ports may need to increase the number of units by up to 50% to maintain throughput capacity. Some ports, such as DP World, are investing £12 million (US$16.35 million) in electric models [28].

FCE straddle carriers remain in earlier stages of development (TRL 5), with no standardized data yet available for operational runtime. However, based on an energy consumption of 1,634 kWh per shift and refueling potential, they are expected to match or exceed the performance of battery-electric systems in certain scenarios. Despite potentially lower low-end energy costs (US$196/shift), their mid- and high-end costs remain elevated due to hydrogen production and storage infrastructure requirements.

Several **hybrid/dual-fuel alternatives** are being explored. It allows an internal combustion engine (ICE) to operate on a blend of hydrogen and diesel to reduce emissions while maintaining operational efficiency. It provides a transitional solution, as full hydrogen adoption is still limited by infrastructure availability. The CMB.TECH **hydrogen dual-fuel** straddle carrier, for example, operates using a blend of hydrogen and diesel, reducing fossil fuel consumption by up to 70%.

Additionally, synthetic diesel enables the continued use of existing fleets and logistics infrastructure without major modifications. However, significant energy losses occur during the synthesis of hydrogen-based diesel, requiring large-scale electrolysis capacity for widespread adoption.

2.2.3. Empty Container Handlers

Empty container handlers remain largely **diesel-based**, though electric models are emerging. Comparative technical data from the NREL [19] highlights the performance characteristics of various powertrains for empty container handlers. **Diesel-powered** units offer a high technological maturity (TRL 9), with an operational range of around 41 hours per refueling and energy consumption of 1,392 kWh per shift. Their average mid-range operational cost is estimated at approximately US$137 per shift [19].

Battery-electric models, while less mature (TRL 7), are emerging as a viable zero-emission alternative. These units typically operate for 5 to 6 hours per charge and consume around 622 kWh per shift. Depending on local energy prices, their energy costs range from US$93 to US$218 per shift [19]. However, charging times of up to 8 hours may limit deployment in high-utilization environments unless operational schedules are adjusted. For instance, Hyster has developed an **electric handler** for Malta Freeport, powered by a 650-volt lithium-ion battery (LIB) [29]. The unit supports stacking up to eight containers high and is designed for handling single empty containers. Such equipment is suitable for terminals where range requirements are moderate and sufficient space for charging infrastructure is available.

Fuel cell electric variants are in early commercial testing (TRL 6), offering longer operational ranges of over 9 hours and faster refueling times (0.16 to 0.25 hours). Their energy consumption is approximately 975 kWh per shift, and energy costs vary between US$117 and US$292 per shift depending on hydrogen pricing and supply infrastructure. These systems are currently being piloted in selected port environments to evaluate their suitability for continuous container handling operations. For example, a **hybrid hydrogen-powered** empty container handler has started being implemented in the Port of Hamburg. The vehicle is powered by a 60 kW fuel cell combined with a 130 kWh LIB and includes onboard storage of 16 kg of hydrogen at 350 bar. The system is designed for an average energy consumption of approximately 2.2 kg of hydrogen per hour (equivalent to 34 kWh/h). A dedicated on-site refueling station has already been completed to support this deployment [30], [19].

2.2.4. Loaded Container Handler

According to the NREL, **FCE-loaded** container handlers are in early deployment, with a TRL of 7. In practice, as already mentioned, fuel cells are also combined with LIB to improve performance and flexibility. One example of such a configuration is a 52-ton top-pick unit was demonstrated by Hyster-Yale at the Port of Los Angeles between 2018 and 2022. The system featured two 45 kW fuel cells, a 130 kWh LIB, and 28 kg of hydrogen storage at 350 bar, enabling 8–10 hours of continuous operation. The configuration was successfully tested in lighter-duty applications [19].

2.2.5. Terminal Tractors

Terminal tractors are among the most commonly used mobile units in ports and are typically powered by **combustion engines**. According to Ramboll GmbH [17], electrification of terminal tractors is especially viable in operations with predictable duty cycles, enabling planned charging during off-peak hours.

Although **battery-electric** models are becoming more prevalent, the study ranks **hydrogen** terminal tractors as promising for heavy-duty applications. However, implementation is still challenged by medium-to-high infrastructure requirements and moderate technical maturity. Broader deployment depends on simultaneous upgrades to refueling and support systems.

Technical data from the NREL highlights the operational characteristics of different terminal tractor powertrains used in port environments. **Diesel-powered** units remain the most established option (TRL 9), offering an average operational range of 20 hours per shift and consuming approximately 936 kWh.

BE terminal tractors are equally mature (TRL 9) and are gaining traction in applications with predictable duty cycles and the ability to accommodate regular charging schedules. These vehicles typically operate for up to 12 hours on a single charge and consume approximately 418 kWh per shift. Charging time is estimated at one hour.

FCE terminal tractors (TRL 7) offer a promising balance between zero-emission operation and high availability, with a typical operational range of 17 hours and refueling time of just 15 minutes (0.25 hours). Their average energy consumption per shift is around 655 kWh. These systems are currently undergoing pilot testing in major ports, including demonstrations at the Port of Los Angeles and the Port of Hamburg.

One representative prototype tested in recent pilot projects *has **a fuel cell/battery hybrid** powertrain, which allows the vehicle to perform all the intensive tasks that are required during roll-on/roll-off operations* [31].

2.2.6. Rubber-Tyred Gantry Crane

RTGs are considered tethered systems when **connected to the grid** or untethered when powered by onboard **diesel or battery-electric systems**. Traditionally powered by diesel engines, grid-connected RTGs now represent one of the most electrified categories in terminal operations due to their compatibility with fixed infrastructure.

According to the NREL, **grid-connected RTGs** consume approximately 896 kWh per shift and have an average energy cost ranging from US$134 to US$314 per shift, depending on local electricity prices. In comparison, **fuel-cell-electric** RTGs, still in early demonstration phases (TRL 6), consume around 1,404 kWh per shift and are expected to operate up to 16 hours on a full hydrogen tank, with energy costs between US$169 and US$421 per shift. One such pilot project is being implemented by PACECO at the Port of Los Angeles (2024–2028), using a 60 kW fuel cell and 64 kg of hydrogen storage at 700 bar. This approach enables retrofitting of existing cranes while maintaining yard flexibility and supporting zero-emission goals [19].

2.2.7. Mobile Harbor Cranes

Mobile harbor cranes (MHCs) represent a flexible and widely used cargo handling solution, particularly in ports that lack fixed gantry crane infrastructure.

While traditionally powered by diesel engines, a significant proportion of MHCs in inland ports are already operated electrically, especially compared to seaports, where diesel variants remain dominant. Electrification of MHCs can be achieved either through direct grid connection or via onboard battery systems. Several manufacturers, including Konecranes, Liebherr, Mantsinen, and Sennebogen, offer electrically powered models, with most technologies reaching TRL 9, indicating full market maturity [17].

In addition to grid-powered solutions, emerging concepts for hydrogen-based or hybrid configurations are under consideration, though these remain at pilot or conceptual stages. Given their operational flexibility and emissions potential, MHCs are an important focus for the deployment of modular, zero-emission solutions in both sea and inland ports.

2.2.8. Heavy-Duty Forklifts

Heavy-duty fuel cell-electric forklifts, though less widely deployed, are also entering the market (for comparison, more than 20,000 **smalle**r units are already in operation today). The study notes that leading manufacturers such as Linde, Toyota, and Hyster already offer forklifts equipped with polymer electrolyte membrane (PEM) fuel cells, indicating early commercial maturity in this segment [17]. Fuel cell forklifts may provide advantages in operational flexibility and reduced refueling time, particularly for high-utilization scenarios or facilities with limited grid capacity.

The study assigns heavy-duty fuel cell-electric forklifts a TRL between 7 and 8, reflecting systems that are either in pilot deployment or early market adoption, while battery-electric models are considered to be at TRL 9, meaning they are fully commercially viable. [17]

Together, these developments demonstrate that both battery-electric and hydrogen-based technologies are advancing as viable alternatives for decarbonizing heavy-duty forklift operations, depending on terminal-specific energy infrastructure and operational needs.

2.3. Other Hydrogen-Powered Port Applications

In addition to the hydrogen use cases previously discussed within the port environment, further applications can be found in tugs, pilot vessels, barges, dredging equipment, and H_2 refueling stations. The following subsections provide a more detailed explanation of the hydrogen-powered tug and rail applications.

2.3.1. Hydrogen-powered tug

Tugboats play a critical role in port operations, assisting with vessel maneuvering, towing, and emergency support. Traditionally, tugboats rely on diesel engines, contributing to maritime emissions. Hydrogen-powered tugboats provide an opportunity to transition toward zero-emission port operations while maintaining performance and efficiency [32].

One key project in this area is the Hydrogen Zero-Emission Tugboat Project [33], which is developing a hydrogen FC-powered tugboat capable of performing regular towing operations with minimal environmental impact. Key features of hydrogen-powered tugboats include:

- Onboard Hydrogen Storage: High-pressure hydrogen tanks store sufficient fuel to support continuous operations.
- Operational Efficiency: Unlike traditional diesel tugs, hydrogen-powered tugs reduce noise pollution, minimize maintenance costs, and offer improved fuel efficiency.
- Infrastructure Needs: Hydrogen-powered tugboats require dedicated refueling stations in ports, integrating with existing bunkering facilities.

Another example is the Hydrotug 1, which consists of two innovative dual-fuel BeHydro engines that can run on either hydrogen or traditional fuel. This tug is part of an integrated greening program for the Port of Antwerp-Bruges fleet and is being deployed as a major step in the transition to a climate-neutral port by 2050. With the Hydrotug 1, CMB.TECH is affirming its international pioneering role in the transition to ships powered by environmentally friendly fuel [32].

2.3.2. Hydrogen-powered rail

While hydrogen-powered rail offers a promising low-emission alternative to diesel trains, several challenges remain. For example, onboard storage is technically demanding due to hydrogen’s low volumetric density, requiring it to be compressed to above 350 bar, or liquified at -253 °C for onboard fuel storage, both of which increase system costs and energy consumption [34]. Reducing these costs is essential for the wider adoption of hydrogen in rail transport.

Despite these challenges, development efforts are ongoing across Europe to bring hydrogen-powered rail into practical use. The first hydrogen fuel cell-powered shunter is currently being developed and tested in Poland and will be commercially available in the EU by 2026. The SM42-6Dn is a modernized hydrogen-powered shunting locomotive equipped with two 85 kW fuel cells for energy generation. It features an autonomous driving system and an anti-collision system [35].

The sH2unter project also examined the use of hydrogen-powered rail in ports. The sH2unter project [36], consisting of six project partners ranging from port operators and rail transport companies to research institutes, investigated the conversion of shunting operations in the ports of Hamburg and Bremerhaven to climate-neutral drives. Hydrogen drives were examined and compared with overhead line battery hybrid systems and HVO. Key results of the project show that a changeover to the drives assessed is already technically possible with an adaptation of the infrastructure. For this reason, the most appropriate technical solution significantly depends on the individual port settings and operational profiles.

2.4. Summary

Table 1 provides a summary of H_2 power equipment and use cases in ports with a synthetic cost/benefit analysis compared to classical equipment (using electricity or diesel).

Table 1: Summary of H2 power equipment and use cases in ports

Application	Equipment	Power	H_2 consumption	CAPEX	OPEX	Benefits
Electric power supply for vessels	H_2 fuel-cell gensets (shore power)	Up to ~600 kW (pilot: 6 × 100 kW units)	~65–75 kg H_2/MWh electricity	Containerized units; €1–4M for 0.3–1 MW scale	Fuel ~€140–210/MWh; lower maintenance vs diesel	Already piloted in Esbjerg, enables zero-emission docking; avoids grid upgrades.
Port logistics	Terminal tractors	~100 kW	~10 kg H_2/day	€200–300k each	<€50/day fuel	Zero-emission, no charging infrastructure required
Port logistics	Reach stackers	~1,600 kW peak; ~1,588 kWh/shift	Approx. 30–35 kg H_2/shift	Higher than BE/diesel units	OPEX ~€300–350/shift	Suitable for heavy-duty ops; fast refueling (~10–15 min)
Port logistics	Cranes (RTG / mobile harbor)	RTG: ~1.4 MWh/shift	~25–30 kg H_2/shift	Pilot projects; retrofitting costs high	Fuel cost ~€150–300/shift	Allows flexible, untethered crane ops; supports decarbonization
Port vessels	Hydrogen bunkering for RoRo & offshore vessels	Depends on vessel size (tens–hundreds kg H_2 per refuel)	Per voyage basis	Multi-million € for bunkering/storage infrastructure	Fuel cost varies with market price	Supports compliance with FuelEU Maritime; attracts green shipping routes

As shown in Table 1, hydrogen applications in ports cover a range of use cases from vessel power supply to port logistics and bunkering operations. The comparison highlights that while initial capital costs (CAPEX) remain relatively high, operational costs (OPEX) and emissions are significantly lower, offering clear advantages in zero-emission performance and energy flexibility.

3. Identifying Use Case Opportunities in Participating Ports

Building on the identified hydrogen applications in port environments, the next step is to examine how these could translate into specific use cases for the four participating ports: Bremen/Bremerhaven, Brest, Den Helder, and Esbjerg. While the concrete development of port-specific use cases is still at an early stage, this section outlines initial considerations and potential areas of application based on each port's context and infrastructure.

3.1. Bremen/Bremerhaven

The port of Bremerhaven plays a key role in handling containers, automobiles, and fruit, and also serves as a major hub for cruise shipping, while the Bremen port areas focus on conventional general and heavy cargo as well as bulk goods. Together, the ports of Bremen and Bremerhaven are part of three TEN-T corridors, underscoring their strategic importance as multimodal transport hubs within Europe. [37],[38], [39],

The city of Bremen is expected to be connected to the hydrogen core network by 2027, while Bremerhaven is scheduled to follow by 2030 [1].

Use Cases:

Hydrogen can potentially in the future fuel port handling equipment and working vessels such as dredging boats of harbor barges. At the moment, the technology transfer center (ttz) in Bremerhaven is already operating a small hydrogen-powered forklift [40]. Hydrogen infrastructure could also support zero-emission heavy-duty trucks and trains, linking the ports to inland freight corridors.

The ports also offer strong potential for maritime fuel transformation, serving as hubs for the handling and bunkering of alternative fuels like green methanol. The local maritime industry could benefit from related services, such as retrofitting or maintaining hydrogen-ready vessels.

When estimating future handling and bunkering capacities in the ports of Bremen and Bremerhaven, it must be taken into account that larger container ships are more likely to dock in Bremerhaven than in Bremen due to the depth and width of the Weser. In general, it can be concluded that the large container ships have to cope with larger loads and longer distances, which means that fuels with higher volumetric energy densities (such as methanol and ammonia) are more suitable there. Only smaller ships sail up the Weser to Bremen, for which the direct use of hydrogen may be more promising than for large container ships. It is therefore assumed that the demand for hydrogen derivatives will be greater in Bremerhaven. In general, the demand for both hydrogen and its derivatives will be higher in Bremerhaven due to significantly higher handling volumes. Proportionally, however, the demand for hydrogen as a marine fuel will be higher in Bremen than for hydrogen derivatives.

The production of hydrogen via electrolysis using renewable energy - especially wind - could be integrated into smart energy systems, as demonstrated, e.g., in the SHARC project in Bremerhaven. A local microgrid could stabilize renewable power use and ensure a clean energy supply for port operations.

In the future, hydrogen imports will be essential to meet long-term demand. Bremen's ports could play a strategic role in receiving, storing, and redistributing imported hydrogen and its derivatives (e.g., methanol, LOHC). This positions them as key entry points for hydrogen into national and European supply chains.

Finally, the ports could support the production of synthetic fuels, using captured CO_2 and green hydrogen to create e-fuels for aviation or shipping. They could also supply nearby industrial consumers, strengthening the regional hydrogen economy and driving sector coupling. There are already two green hydrogen production sites in operation in Bremerhaven, and additional electrolysis capacity is being realized in Bremen and the surrounding area [41], [42]. Furthermore, capturing CO_2 from wastewater streams is currently being tested [43]. A green methanol production site with a capacity of 500 kg per day is currently under construction in Bremerhaven [43]. The methanol produced will be used to fuel the Uthörn II research vessel, which is owned by the Alfred Wegener Institute.

3.2. Brest Port

3.2.1. Introduction

In the current state of H_2 development and port use cases analyzed in the document, BrestPort considers several possible port applications summarized in the table above. However, a more precise techno-economic analysis would be necessary to make decisions.

The present report provides the results of a preliminary study of the H_2 use case in the port of Brest carried out through the REDII Interreg NS project. The study concluded that the first application in Brest could be a refueling station for trucks. Brest Port is one node of the TEN-T network. The deployment of H_2 refueling stations along the TEN-T network is mandatory. However, the study did not cover the different use cases analyzed in the current NSH2VP study.

Following these results, other prospective actions have been engaged to complete the analysis:

- A study engaged with GRDF (the public gas network operator) and H2X (producer of H_2 gensets): to reduce the costs of H_2 production, using the gas (10% of bio-gas), CO_2 capture, and renewable energies. This study will also focus on use cases, in particular, the use of H_2 fuel cells/batteries to avoid grid congestion and the use of H_2 gensets
- A study engaged with Energy Observer developing an H_2-propelled containership, able to transport liquified H_2 in a container. This study provides preliminary data on the volumes of LH2 needed and the design of the port production/ distribution network required.

These different actions, once combined, give a preliminary perspective on H_2 refueling use cases and development in BrestPort.

3.2.2. REDII project: preliminary conclusions of H_2 use cases in BrestPort

Almost 140 stakeholders have been consulted in total, and 33 qualitative and quantitative interviews have been conducted.

The key stakeholders consulted were the City (Brest Métropole and the Regional Authority, owners of public transport means such as buses and vessels), the port operators, shipping companies, logistics actors, and local industries.

The main findings are summarized below:

Land-Based Uses of Hydrogen

On the short term (by 2030), H_2 demand is estimated at ~375 tons/year, requiring 2.5 MW of electrolysis capacity. This corresponds to the following use cases:

- Road freight (heavy-duty vehicles and refuse trucks)
- Public transportation (hydrogen buses for intercity lines)
- Light utility and private vehicles
- Handling equipment (cranes, forklifts)
- Backup generators for ships at berth

However, several barriers have been identified:

- The limited awareness and maturity among stakeholders, except for a few actors (e.g. Guyot, Brest Métropole) with early interest.
- The current cost of H_2 (€20/kg minimum), which restricts the capacity of users to engage in H2 solutions a lot

Main hypothesis concerning the terrestrial use cases

Usages	Parc	Hypothèses	2030	2040	2050
Trucks	1027 PL in the metropolis including 34 on the port*	Growth of the parc : + 50% à horizon 2050 Penetration ratio of H2 solutions H2 : 1/3 at horizon 2050	8 camions 0,8% du parc 36 t/an	301 camions 23% du parc 1,46 kt/an	539 camions 34% du parc 2,61 kt/an
BOM	31 BOM in the metropolis	Decrease of the parc : 5% à horizon 2050 Penertration ratio of H2 solutions: 90% at horizon 2050	1 BOM 3% du parc 4 t/an	9 BOM 30% du parc 32 t/an	19 BOM 90% du parc 67 t/an
Bus	371 Bus in the metropolis	Growth of the parc: 13% (report modal) à horizon 2050 Penetration ratio of H2 solutions: 55% at horizon 2050	14 bus-cars 4% du parc 41 t/an	129 bus-cars 33% du parc 362 t/an	234 bus-cars 55% du parc 671 t/an
Light vehicles	14 000 in the metropolis (14 in the port)	Stability du parc à horizon 2050 Penetration ratio of H2 solutions: 25% à horizon 2050	247 VUL 1,7% du parc 99 t/an	2109 VUL 15% du parc 843 t/an	3587 VUL 25% du parc 1435 t/an
Cars	115 500	Decrease of the parc: 35% at horizon 2050 Penetration ratio of H2 : 8% at horizon 2050	1133 VP 0,9% du parc 204 t/an	3682 VP 3,8% du parc 663 t/an	5562 VP 7,4% du parc 1001 t/an
Port equipment	83	Parc stable Progressive conversion of the equipment (the most powerful) with an acceleration post 2030	4 engins 5% du parc 8 t/an	15 engins 18% 23 t/an	22 engins 26% 34 t/an
Gensets	7 GE in the port + GE rented (shipyard in particular)	N/A as no visibility on the needs not covered by a direct OPS (electricity from the grid)	/	/	/
Heit systems	2 sites industriels dans la métropole dont 1 dans le port	N/A in the port	/	/	/
Fire	2 entreprises de réparation navale à minima	N/A as no vibility on the quantities of gas used	/	/	/

* a minima, selon les entretiens réalisés

Figure 2: Main hypothesis concerning terrestrial use cases (source: Port of Brest)

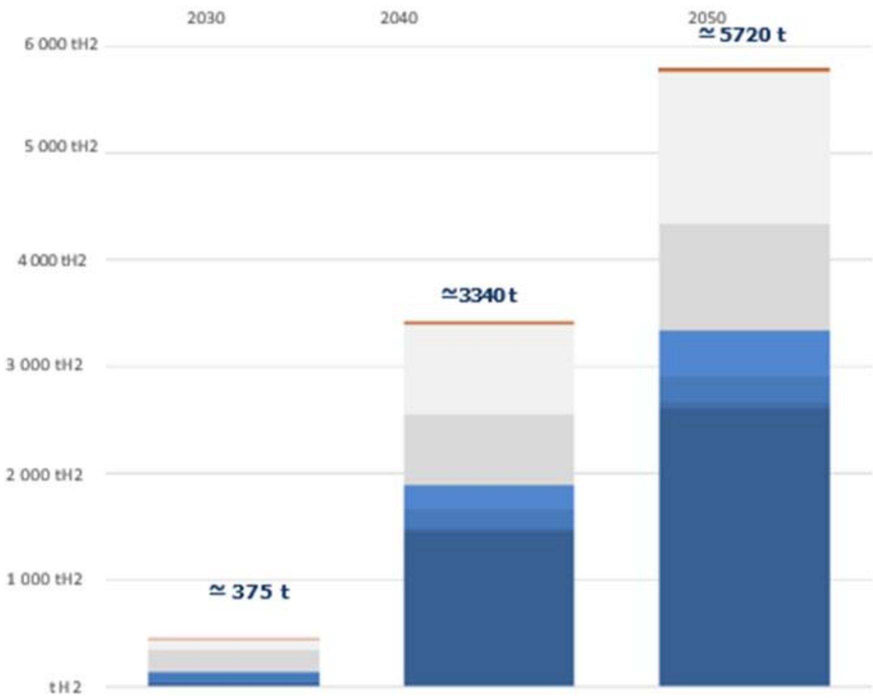

Figure 3: Terrestrial use cases constitute the core potential of H2 use cases in the port in the short term (375 t – 2.5 MW electrolysis), mainly for road mobility (source: Port of Brest)

Maritime Uses of Hydrogen

These use cases are highly dependent on whether BrestPort can develop competitive H_2 bunkering services (dependent on the cost of H_2)

Three ship categories have been analyzed:

- Captive vessels (fishing, service, pilot boats): limited potential (<400 t/year in 2050)
- Repair ships: low volumes except for large vessels, which could refuel during drydock
- Transit and offshore-passing ships: up to 6,400 t/year if 1% of port calls and 0.01% of offshore traffic are bunkered

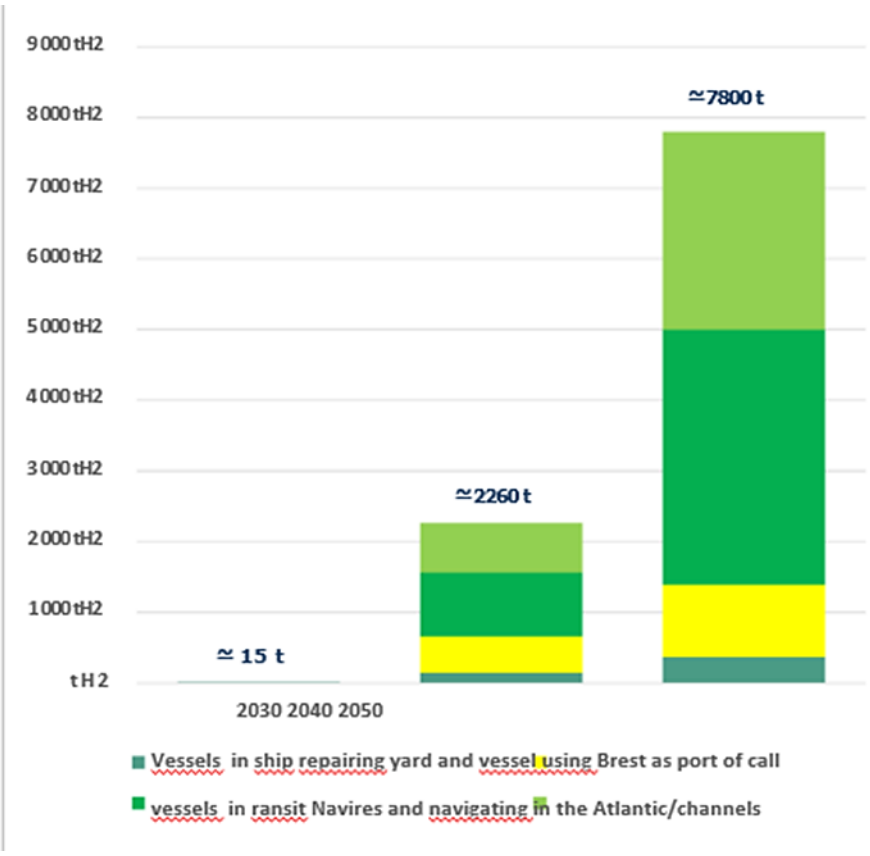

Figure 4: Projected hydrogen demand in the Port of Brest by ship category (source: Port of Brest)

Conclusion

Key Hypothesis (Proactive Scenario 2050): Up to 13,600 t/year of H_2 demand, requiring ~94 MW of electrolysis (or 131 MW with 40% oversizing)

The maritime usage will dominate in the long term, but in the short term, the terrestrial usage (for road mobility) will dominate. This leads to considering as first use case the installation of a refueling station for trucks.

3.2.3. Reduction of H_2 costs – Study with GRDF (Gaz Réseau Distribution France) and additional use cases

Considering the conclusions of the REDII project [44], it has been decided to study alternative production means for small quantities of H_2. The goal is to reduce the cost of H_2 to 8€/kg in order to kick off the local market.

The principles of the system are represented below.

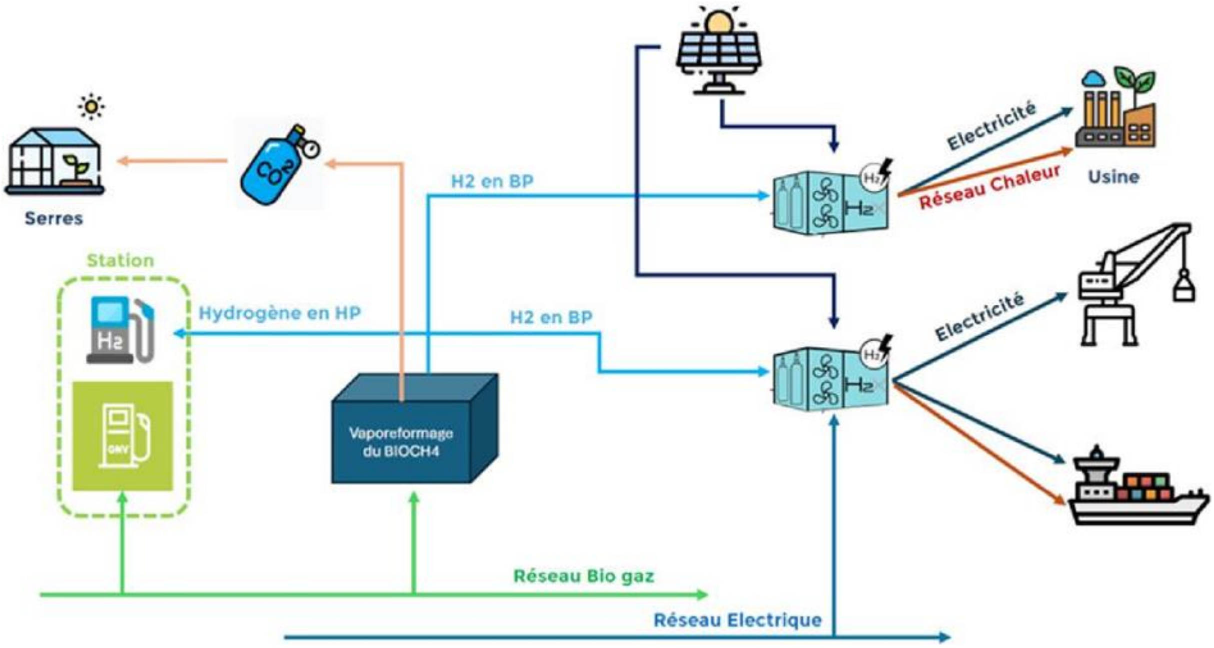

Figure 5: Small-scale hydrogen production system (source:Port of Brest)

Production of H_2 at lower costs. The core process is known as “The French term **"steam reforming"**. It refers to a process commonly used to produce hydrogen by reacting hydrocarbons (like natural gas, green lines on the picture) with steam at high temperatures.

To reduce the cost of H_2 production, the system uses green renewable energies such as solar, wind, or wood (producing steam. Moreover, a module is dedicated to the capture of CO_2 in order to fit the EU regulations and to respond to a local demand from greenhouse operators (and increase the economic value of the system).

The study is not yet ended, but the goal is to start local use cases:

- Feeding the H_2 refueling station for trucks
- Producing electricity (H_2 gensets) to replace the current ones using oil
- Use H_2 fuel cells (batteries) to store energy in H_2 and release electricity on demand (manage the pics of consumption)

3.2.4. Study of an H_2 propelled containership (Short Sea Shipping)

Following the first vessel "Energy Observer" which made several trips around the world with H_2 fuel cells, wind wings, solar panels as only energy sources on board, the conceptor Didier Bouix (company "EO concept") is currently specifying a short sea shipping container ship propelled by H_2 solutions and able to transport LH_2 in containers.

BrestPort has decided to work with EO concept on the refueling needs and the SSS line, not necessarily to refuel the vessel in Brest, but also to introduce the project to the NS H2V port partners, which could be interested in acting as import/export or refueling ports.

Figure 6: The "Energy Observer" - a hydrogen-powered vessel showcasing renewable energy technologies and sustainable maritime innovation. (source: Port of Brest)

The studies related to the refueling needs and H_2 transport capacities are still ongoing. The first results are summarized below.

Main dimensions	
Type:	Zero emission Feeder
Length:	155 m
Width:	24.5 m
Air/ Water draft (design):	32 m / 8 m
Deadweight tonnage (design):	~12 000 GT
Crew:	18 pax
Capacity:	1100 TEU
Flag:	TBD - Europe
Energy systems	
Fuel cell:	4.8 MW / 12 modules 400 kW LH_2
LH_2 stored:	42 t (Net) - 50t (Gross)
Batteries:	1 MWh
Safety diesel generators:	2 x 1.8 MW
H_2 regulations	IMO MSC.1 Circ 1455, BV NR 547,BV NR 678, IGF
Operational data	
Commissioning:	2030
Navigation:	Inter-regional / Intra-european
Number of stopovers:	~10
Distance:	~1600 nautical miles
Cycle duration:	14 days
Service speed:	12.5 knots
Boost capacity:	16 knots

3D Rendering of the Fuel Cell Room conceived by EO Concept, Integrating EoDev fuel cell modules based on Toyota new gen fuel cells (Gen 3), commercialised in 2026/2027.

Figure 7: Technical overview of the vessel, including main dimensions, energy systems, and operational data (source: Port of Brest)

One example of commercial routes is shown in Figure 8.

Navigation cycle	
Total duration:	14 days (336h)
Northbound:	8.4 days
Southbound:	5.6 days
Time buffer:	33h (to be include dockside)

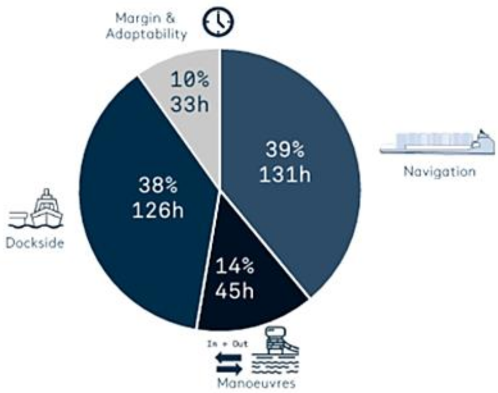

Figure 8: Example of commercial routes for hydrogen-powered vessels (source: Port of Brest)

This means that the NS H2VP partner ports can position themselves and include the vessel refueling needs in their own H_2 development plans. The goal is to fix the routes in under one year from now, finding a shipping operator willing to operate the lines.

The study of the port infrastructure (shown below) led to an estimation of 100 million € for port investments in the electrolyzer, the storage, and the refueling equipment. Thus, BrestPort is interested in taking part in the adventure, for

- importing LH_2,
- providing ship repairing/maintenance services (with DAME, the shipyard operator)
- provide small refueling capacities for vessels in the ship yard to reach the next refueling station

This is a concrete case for NS H2VP ports and partners.

3.2.5. Summary

To summarize the status of our perspectives in BrestPort, we could announce that:

Until 2030: BrestPort

- focuses on the refueling station for trucks
- Contributes to all studies that may induce new markets, thanks to
  - A reduction of H_2 costs (8 €/kg according to market studies)
  - The development of SSS lines using H_2 as the main propulsion source (e.g., EO)

3.3. Port of Den Helder

The Port of Den Helder (**PoDH)** is suffering from severe grid congestion issues. With zero electricity availability in both the interregional transmission grids (TSO) and distribution grids (DSO) until 2039 (expected date of expansion completion), PoDH witnesses significant barriers to deliver the needed electrification of port operations as demanded by EU under the Alternative Fuels Infrastructure Regulation (EU2023/1804 and 1805), demanding that passenger vessels over 5,000 GT use shore-side electricity. There simply is no grid capacity available, so an alternative solution to maximize the existing grid capacity has been designed.

In PoDH, the existing grid connection of 500 kW will be optimized, leveraging a 3 MWh BESS (Battery-Electric Storage System) charging when no ships are docked. Adding to this, there will be a 1 MW_e fuel cell system providing electricity to power the shore power system when the battery and grid capacity are insufficient. A deal with the DSO has allowed 1 MW of extra capacity at night when there is excess grid capacity available to charge the BESS, provided that the FC-system can deliver power to the grid when demand exceeds supply in the DSO-grid, factually selling the electricity to the DSO-operator Alliander. PoDH and the stakeholders involved in developing this use case (PoDH, HVC, Peterson, RWE, NEC) expect to take a Final Investment decision (FID) for the FC-based grid-balancing and shore power unit by the end of 2025 once funding has been procured (outside of NS H2V Ports).

Rijkswaterstaat (RWS, Dutch infrastructure ministry) will deploy an LH_2-powered dredge operating in Den Helder and the Port of Amsterdam (working closely together with Den Helder), and currently, the port is operating one H_2-powered (gaseous) vessel deployed under the Zephyros program.

Besides the shore power unit, Den Helder expects to develop 1 H_2 bunkering unit for gaseous hydrogen, a barge for LH_2 bunkering, Methanol bunkering infrastructure, which will be dealt with in WP4 (bunkering and infrastructure), as well as charging infrastructure for trucks and an H_2 refueling station of mobility (also as part of Zephyros).

3.4. Port of Esbjerg

- Use Case: Supplying hydrogen as fuel for ships. (Hydrogen Bunkering)
  - Purpose: To enable zero-emission shipping.
  - Target Users: RoRo vessels, offshore support vessels, and cargo ships.
  - Benefits: Helps ship operators meet EU FuelEU Maritime regulations and IMO decarbonization targets.

- Use Case: Powering port machinery (e.g., reach stackers, cranes, terminal trucks) with hydrogen fuel cells. (Heavy-Duty Port Equipment)
  - Purpose: Decarbonize internal logistics.
  - Target Users: Port operators and logistics companies.
  - Benefits: Reduced emissions, noise, and local air pollution.

- Use Case: Exporting green hydrogen produced in Denmark to other European markets via shipping or pipelines. (Hydrogen Export Hub)
  - Purpose: Position Port Esbjerg as a strategic hydrogen export terminal.
  - Target Users: Hydrogen producers, EU energy importers.
  - Benefits: Economic development and EU energy security

- Use Case: Development of bunkering stations for hydrogen or hydrogen-derived fuels.
  - Purpose: Serve incoming vessels needing refueling.
  - Target Users: Shipowners investing in hydrogen-powered vessels.
  - Benefits: Enable low-carbon marine transport and attract green shipping routes.

- Use Case: Supplying hydrogen for nearby industrial processes or integrating into the local energy system.
  - Purpose: Decarbonize industry and balance local renewable electricity supply.
  - Target Users: Local industries and municipalities.
  - Benefits: Lower emissions and enhanced local energy resilience.

Hydrogen use cases and projects for Port Esbjerg are shown in Table 2.

Table 2: Overview of hydrogen use cases and projects for Port Esbjerg

Application area	**Use Case / Equipment**	**Indicative Power / H_2 Consumption**	**CAPEX / OPEX (indicative)**	**Benefits / Notes**
Shore power	Modular H_2 fuel-cell containers (6 × 100 kW Ballard units)	~600 kW total; ~65–75 kg H_2 per MWh electricity	CAPEX = modular container systems; OPEX = H_2 fuel + service	Already piloted in Esbjerg, enables “zero-emission docking” without grid upgrades
Hydrogen production	Måde electrolyzer (3 MW, expanding toward 12 MW)	~1,500 t H_2/year (phase-1 output)	Multi-million € investment in electrolysis, storage, and compression	Provides local green hydrogen supply for port & transport
Export corridor	H_2 export pipeline from Esbjerg to Germany (planned by 2030–31)	Large-scale (national pipeline volumes)	> €2 billion national investment	Positions Esbjerg as strategic export hub in EU hydrogen backbone
Port logistics	Terminal tractors, reach stackers, cranes (future pilots)	100 kW–1,600 kW depending on equipment; ~10 kg H_2/day for tractors	CAPEX premium vs diesel/electric; OPEX = H_2 fuel	Enables decarbonization of heavy-duty port machinery

Bunkering	Hydrogen refueling for RoRo & offshore vessels	Varies (tens–hundreds kg H_2 per refuel)	CAPEX for storage, pumps, safety systems	Supports compliance with FuelEU Maritime rules; attracts green shipping routes
Industrial integration	H_2 for local industry & grid balancing	Depends on demand; integrated with PtX	Shared infrastructure reduces incremental cost	Improves energy resilience; supports sector coupling

4. Conclusion

Activity 1.8 focuses on the analysis of fuel cell use cases that have not yet been implemented, with the focus on the ports of Bremen/Bremerhaven, Brest, Den Helder, and Esbjerg. These use cases include on-shore power supply, congestion management, grid balancing, hydrogen-fueled port machinery and equipment, as well as other hydrogen-powered port applications illustrated in Figure 9.

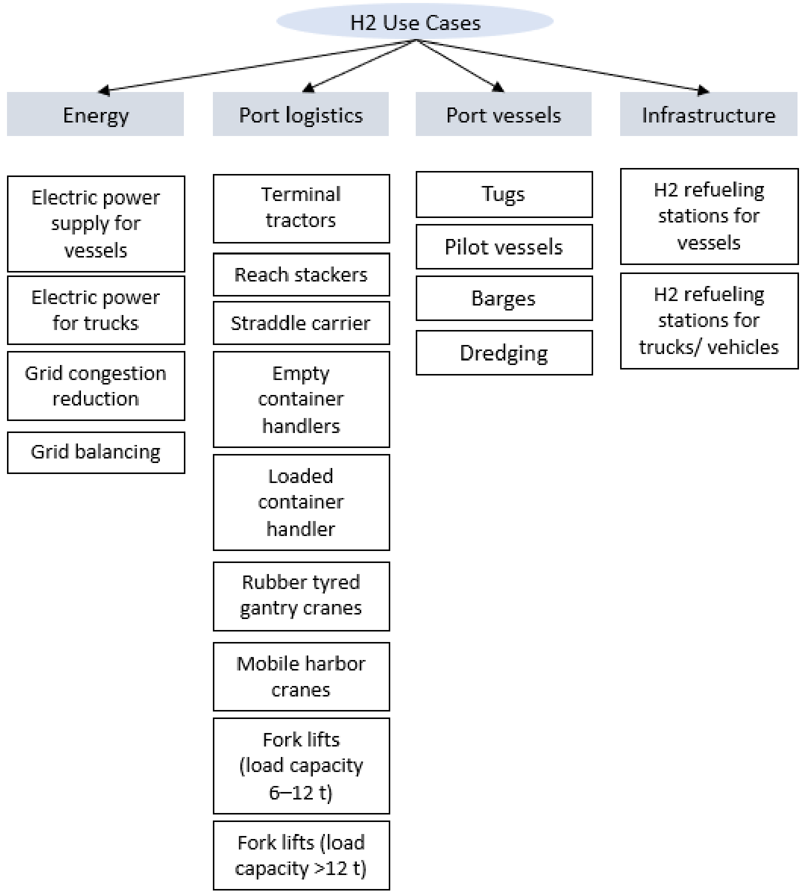

Figure 9: Potential Uses of Hydrogen in Port Operations

Although ports are typically perceived as cargo handling hubs, their functions can differ significantly. Den Helder, for example, is among others, as an offshore maintenance and supply hub. This underlines the importance of first analyzing the strategic role of a port before identifying and investing in the most suitable decarbonization technologies. In this respect, further research is needed to examine how the strategic role of ports influences the feasibility of different hydrogen applications.

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