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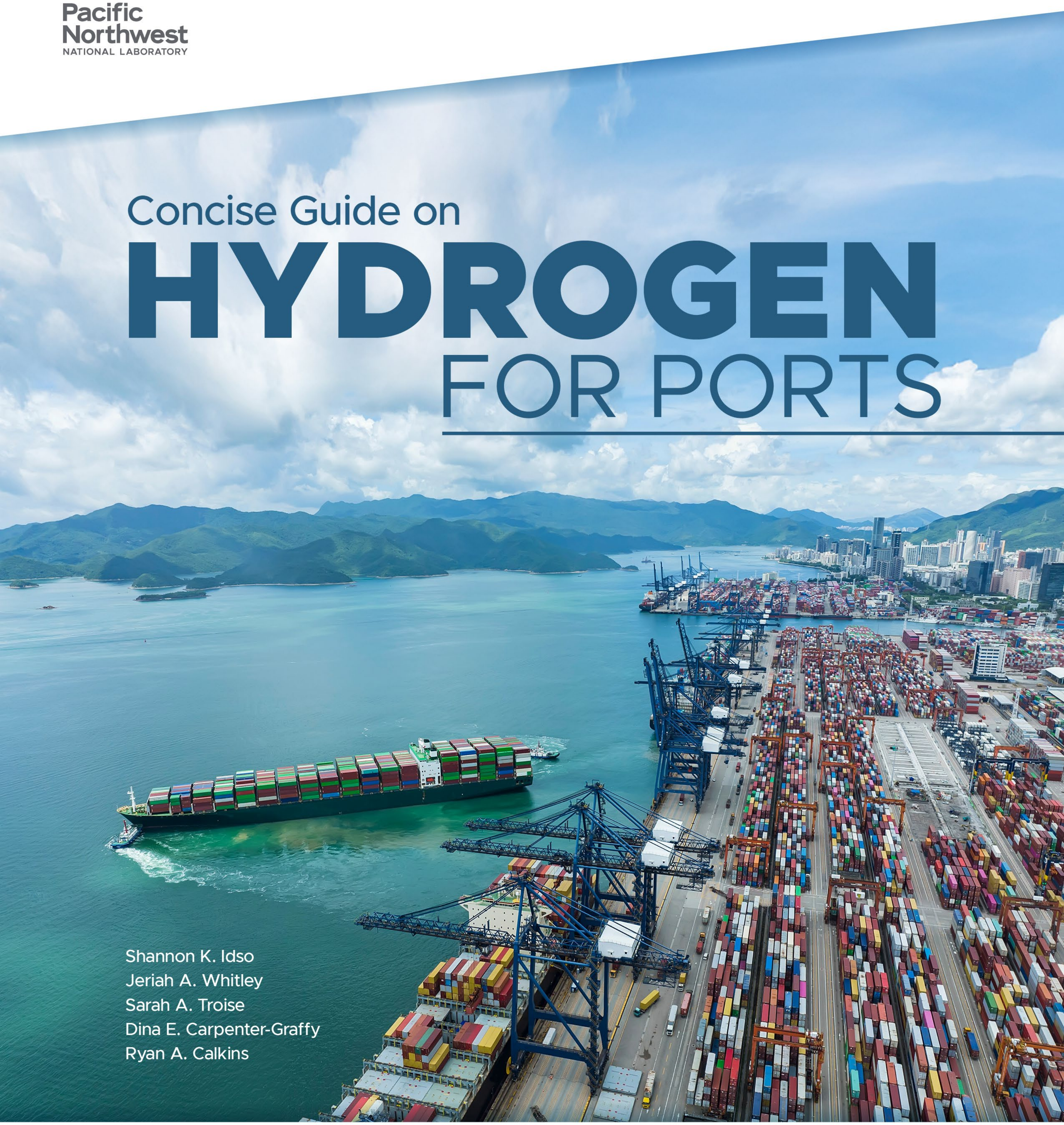
May 2026

Concise Guide on HYDROGEN FOR PORTS



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U.S. DEPARTMENT of ENERGY

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ACRONYMS AND ABBREVIATIONS

CCS	carbon capture and storage
CHE	cargo-handling equipment
CO_2	carbon dioxide
DOE	Department of Energy
EPA	Environmental Protection Agency
FCEV	fuel cell electric vehicle
GW	gigawatts
H	hydrogen
H2ICE	hydrogen internal combustion engine
HFC	hydrogen fuel cell
ICE	internal combustion engine
IFC	International Fire Code
kg	kilogram
kWh	kilowatt hours
LNG	liquefied natural gas
LOHC	liquid organic hydrogen carrier
MJ	megajoule
MW	megawatt
NFPA	National Fire Protection Association
NOx	nitrogen oxide
NTU	Nanyang Technological University
PEM	proton exchange membrane
PM	particulate matter
SMR	steam methane reforming
SOx	sulfur oxide
TCO	total cost of ownership
U.S.	United States

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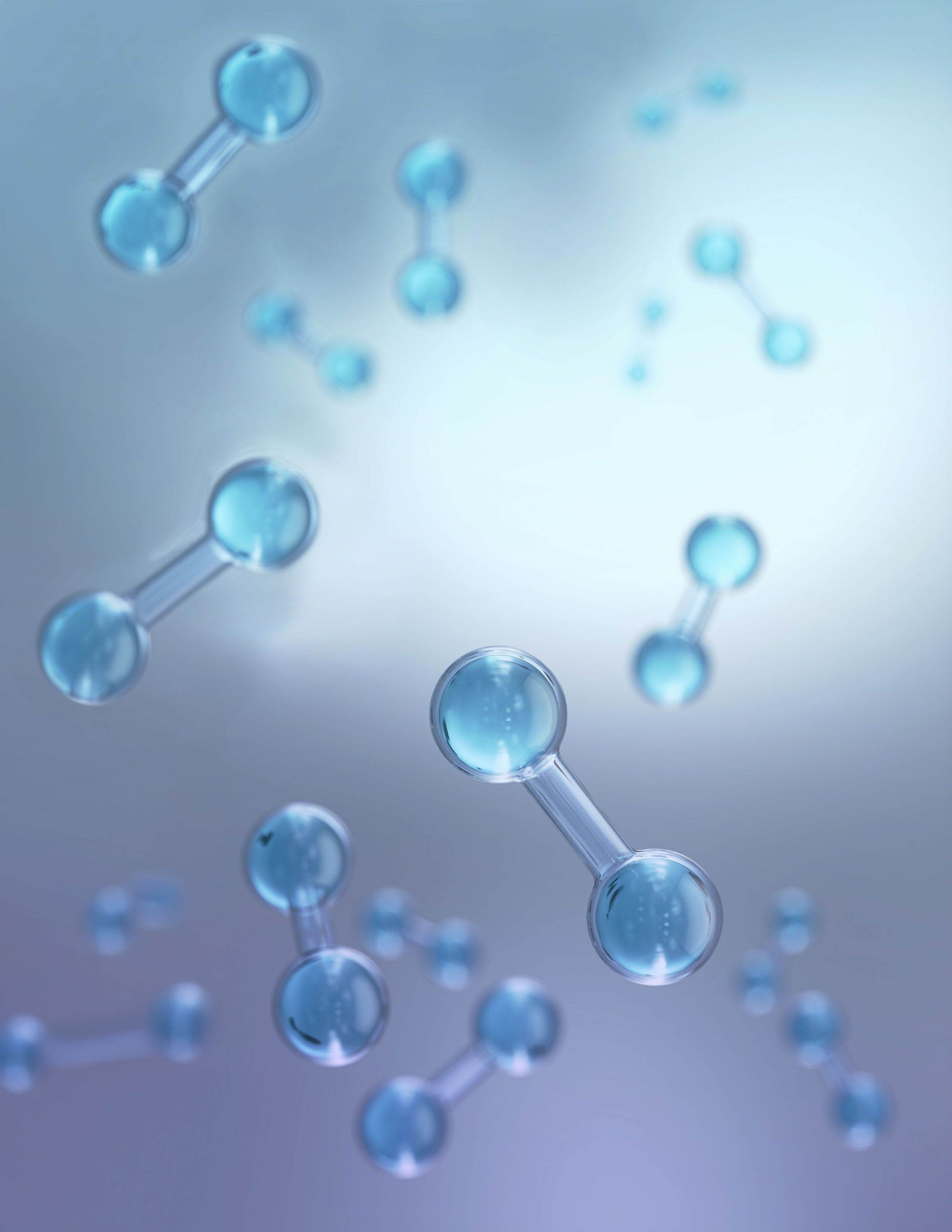

INTRODUCTION

Ports have benefited from relatively stable energy systems for the better part of a century, with fossil fuels powering most mobile port equipment, vessels, trains, and trucks, and grid electricity energizing facilities and stationary equipment. In the past decade, however—because of technological innovation and changing emissions regulations and customer needs—ports are considering significant changes to the way they power their operations.

Among the many technologies and alternative fuels that promise to deliver lower criteria pollutant emissions, greater resiliency, and cost savings, hydrogen—the most ubiquitous of all elements—and hydrogen fuel cell (HFC) technologies are viable solutions. This *Concise Guide on Hydrogen for Ports* (referred to in this document as "the Guide") aims to provide port executives, terminal and fleet operators, and port communities with a clear understanding of the state of hydrogen technologies, an overview of its benefits and challenges, and a pathway forward for ports that choose to consider implementation of hydrogen technology at their facility.

WHAT IS HYDROGEN?

Basic Chemistry

Hydrogen is the most common and basic element in the universe. Represented by the symbol H, hydrogen is made up of one proton and one electron, making it the lightest element. At room temperature, hydrogen is a colorless, odorless, and tasteless gas. Its basic structure and characteristics mean it can be a multipurpose building block in energy systems (Royal Society of Chemistry 2025).

Hydrogen is an energy carrier, not a primary energy source, since it serves as a medium through which energy can be transported, stored, and converted. It holds promise as an efficient energy carrier, primarily as a result of its high energy content per unit of mass, which is nearly three times the equivalent amount of gasoline (i.e., 120 megajoule [MJ]/kilogram [kg] for hydrogen compared to 44 MJ/kg for gasoline [DOE n.d.(a)]). The foundational chemical reaction that underscores hydrogen's role in energy systems is its reaction with oxygen to produce water, releasing energy in the process. When captured in fuel cells, this reaction generates electricity with no emissions other than water and heat as byproducts, presenting a compelling case for hydrogen's utilization in various sectors.

Current Uses

Hydrogen is largely utilized in chemical and industrial processes, including oil refining through hydrocracking, which breaks down hydrocarbons[1] and removes impurities like sulfur and metals to produce higher-grade fuels such as diesel, gasoline, and jet fuel (EIA 2013). It is important for ammonia production (a key fertilizer component) and methanol synthesis (SHEA 2025a), as well as for metallurgical processes, where it converts metal ores to pure metals (SHEA 2025b). In recent years, hydrogen has become a promising alternative to traditional fuels like gasoline and

[1] A hydrocarbon is an organic compound that consists only of hydrogen and carbon atoms. They are the primary makeup of fossil fuels, including natural gas, oil, and coal, and serve as the foundation for many chemical processes and materials, including plastics and synthetic products.

diesel, particularly within the transportation and industrial sectors, and at ports where both these sectors converge.

Hydrogen can power various types of port machinery (Steele and Myers 2019), such as lift trucks, cranes, and yard trucks, helping to lower emissions and improve operational efficiency. Furthermore, vessel owners—from major shipping conglomerates to small harbor craft companies—are undertaking a transformation of fleets to meet increasingly stringent emissions guidelines. Hydrogen-powered ships, whether utilizing HFCs or hydrogen combustion turbines or engines, represent viable technologies to reduce local air and water pollution. An increasing number of new ocean-going vessels can operate on hydrogen-based fuels, including methanol and ammonia. In the international context, hydrogen and hydrogen-based fuels offer a critical pathway aimed at limiting emissions across the global shipping sector.

Common Forms

Hydrogen can be stored in various forms to suit different applications, each with their own advantages and challenges outlined in Figure 1. **Liquid hydrogen**, cooled to −253°C (−423°F), offers dense storage ideal for space-limited uses like aerospace but requires energy for liquefaction and cryogenic storage. **Gaseous hydrogen**, stored at high pressures (H35–350 bar or H70–700 bar) in steel or composite tanks, is easier to handle than liquid hydrogen but requires more storage space. It is best suited for HFC vehicles and stationary power applications (EERE 2017; DOE n.d.[b]). **Liquid organic hydrogen carriers (LOHCs)**, an emerging technology, chemically bond hydrogen to liquid organic compounds for storage and transport at ambient conditions, providing a safe and dense option. There is ongoing research in this area exploring the benefits and challenges of different compounds to serve as hydrogen carriers (Ulucan et al. 2023). Ethanol and methanol, as hydrogen-based fuels, qualify as LOHCs because they act as organic carriers of hydrogen, offering a safe and effective method for hydrogen storage and energy transport. Conversely, some hydrogen-based fuels like ammonia are not considered LOHCs because they are inorganic and lack the specific organic structures intended for LOHC use. This distinction underscores the purpose of LOHCs as efficient and secure vehicles for harnessing hydrogen's potential in energy systems.

> *The Port of Singapore has become a significant site for hydrogen innovation with the demonstration of LOHC technology. PSA Singapore, in collaboration with Nanyang Technological University (NTU) Singapore and Chiyoda Corporation Japan, has established Singapore's first hydrogen refueling station at the port. The project utilizes LOHCs for safe and efficient hydrogen storage and transport, addressing the challenges of handling gaseous hydrogen. The dehydrogenation process enables hydrogen to be extracted from LOHCs and used to fuel heavy-duty vehicles, paving the way for cleaner and more sustainable transportation within port operations.*
>
> Source: Rahman 2024; NTU Singapore et al. 2024

DIFFERENT TYPES OF HYDROGEN

	Gaseous Hydrogen	Liquid Hydrogen	Liquid Organic Hydrogen Carriers
Energy Density	Low	High	Comparable to liquid fuels
Transport Efficiency	Inefficient for long distances	Efficient for regional trade	Uses existing infrastructure
Safety	High pressure poses risks	Cryogenic storage risks boil-off losses	Safer due to non-explosive properties
Infrastructure Needs	Specialized pressurized tanks/pipelines	Cryogenic tanks and cooling equipment	Chemical processing facilities
Energy Loss	Minimal for compression	High for liquefaction (~30%)	Energy required for binding/releasing

Figure 1. Comparison of hydrogen storage forms—gaseous hydrogen, liquid hydrogen, and LOHCs—highlighting key characteristics such as energy density, infrastructure requirements, and transportation logistics.


H2
H2

HOW IS HYDROGEN PRODUCED?

Production Pathways

Hydrogen production can involve various methods and feedstocks or energy sources, referred to as “production pathways,” each differing in efficiency, cost, and environmental impact. Understanding these production pathways, including their energy and emissions intensities, is important to assessing potential benefits of hydrogen in port applications (DOE n.d.[c]) and to identify potential bottlenecks in feedstocks and electricity supply that could hinder scalability. Figure 2 below shows the current and projected distribution of U.S. hydrogen production by pathway.

Key Hydrogen Production Pathways:

1. **Steam Methane Reforming (SMR):** SMR is a cost-effective method of hydrogen production that uses established technology to extract hydrogen from natural gas. High-temperature steam reacts with methane under pressure and, in the presence of a catalyst, produces hydrogen, carbon monoxide, and limited carbon dioxide (CO_2). Subsequent steps are the water-gas shift reaction (to generate additional hydrogen) and pressure-swing adsorption (to purify hydrogen).
2. **Electrolysis**: Electrolysis splits water (H_2O) into hydrogen and oxygen using electricity. When powered by renewable energy sources (e.g., solar, wind, hydropower), it offers a near-emissions-free hydrogen production pathway. The primary methods are alkaline electrolysis, proton exchange membrane (PEM), and solid oxide electrolysis, each with unique advantages and challenges. Current research aims to enhance efficiency and reduce costs (DOE n.d.[d]).
3. **Methane Pyrolysis**: Pyrolysis thermally decomposes methane into hydrogen gas and solid carbon. Solid carbon byproducts can be used in industries like tire manufacturing or construction materials. While promising, methane pyrolysis still requires further optimization for commercial scalability (Patolla et al. 2023; Dagle et al. 2017).
4. **Biomass Gasification**: Biomass gasification converts organic feedstocks (e.g., agricultural residues, wood) into hydrogen and byproducts through high-temperature processes. While considered a renewable hydrogen production pathway, challenges include feedstock availability, collection, and pretreatment, which require refinement for broader adoption. Biomass gasification could face increasing competition for feedstock, as other sectors, such as ground transportation and aviation, seek to diversify their fuel options by leveraging sustainable biomass sources for biofuels and energy production (DOE n.d.[e]).
5. **Geologic Hydrogen:** Geologic hydrogen includes both hydrogen found within Earth’s subsurface (natural hydrogen) and hydrogen generated through engineered activities. Unlike manufactured hydrogen produced through industrial methods, natural geologic hydrogen is formed through natural mechanisms such as serpentinization (reaction of water with certain minerals like olivine), radiolysis (splitting of water molecules by natural radioactive decay), or degassing from deeper layers of Earth’s crust and mantle. Stimulated geologic hydrogen can be produced through two main methods: 1) injecting fluids into subsurface rocks to release trapped hydrogen and 2) processing mined rocks or legacy mine wastes in industrial facilities to extract hydrogen, similar to how ores are processed to extract metals (Hasiuk and Conley 2025). Because geological hydrogen is not made from

converting other energy sources to hydrogen, geological hydrogen is considered a direct energy source, not an energy carrier.

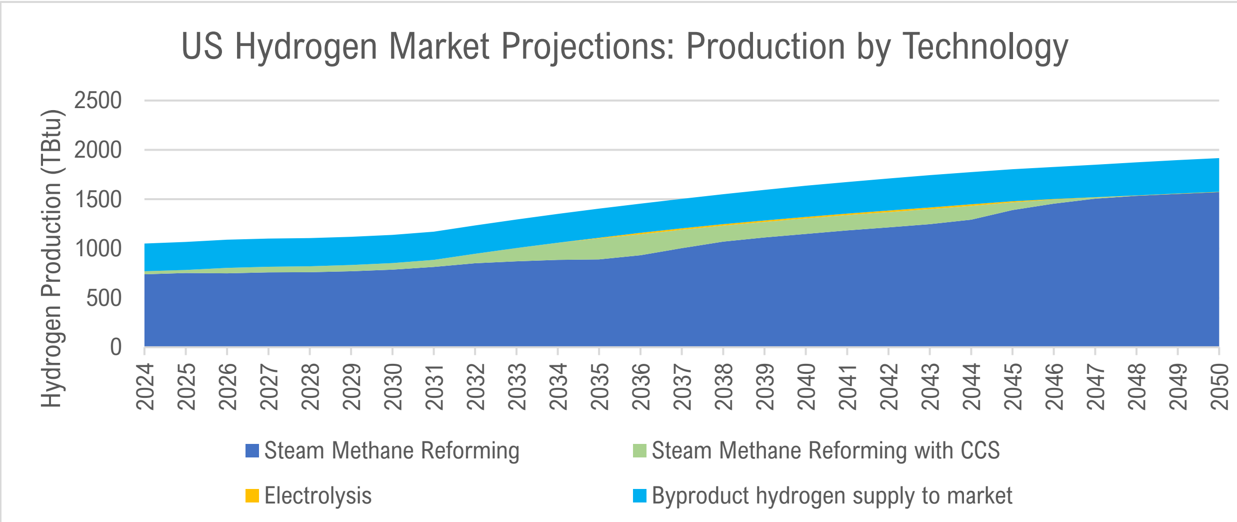

Figure 2. Projected U.S. hydrogen market growth by production technology from 2024 to 2050, illustrating contributions from SMR, SMR with carbon capture and storage (CCS), electrolysis, and byproduct hydrogen supply to the market (data sourced from EIA [2024a]). Forecasts for geologic hydrogen production are not included, as the technology is still in its early stages, making it too premature to estimate production volumes at this time.

Emissions Intensity

Since hydrogen serves as an energy carrier, with the exception of geological hydrogen, and is not a direct energy source, its emissions depend on variables like the production process, the type of fuel used, the technology adopted, and whether CCS is employed. In addition to direct emissions, hydrogen production results in indirect emissions stemming from the processes involved in producing, converting, and transporting input fuels like natural gas and electricity. These indirect emissions can add substantially to the overall emission footprint of hydrogen production. However, it is worth noting that indirect emissions are associated with energy movement regardless of its form, not just hydrogen. Analyzing criteria air pollutants and other emissions can help to better understand the trade-offs and co-benefits of hydrogen pathways in the broader context of energy innovation.

Criteria Air Pollutants

Hydrogen production processes vary in the emissions of regulated pollutants, such as nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM), particularly PM2.5. PM2.5 refers to fine particulate matter with a diameter of 2.5 micrometers or smaller. These particles can penetrate deep into the respiratory system, reaching the lungs and increasing risks for respiratory diseases, as well as other serious health impacts (EPA 2025). Fossil-fuel-based methods tend to emit higher levels of these pollutants because of combustion and fuel processing. Coal gasification is particularly detrimental, producing substantial quantities of SOx and PM2.5 criteria pollutants, which contribute to air pollution and adverse health effects. Natural gas SMR is comparatively cleaner but still emits NOx during the combustion phase. Electrolysis with grid electricity may indirectly lead to higher NOx, SOx, and PM2.5 emissions, depending on the fossil fuel content in the electricity supply; these emissions would also be associated with grid electricity used to charge battery-electric vehicles. Electrolysis with power from renewable energy is the least emission-intense pathway as it bypasses combustion processes entirely, resulting in lower life cycle emissions.

Production Bottlenecks

Production bottlenecks present significant challenges that must be addressed to scale hydrogen production effectively. These could include bottlenecks in the supply of electricity, feedstocks, and water. Additionally, for SMR, the dependence on natural gas ties hydrogen production to fossil fuel availability and price volatility.

- **Electricity:** The availability and cost of electricity are particularly critical for the broad adoption of electrolysis. In practice, typically, 50–55 kilowatt hours (kWh) of electricity are required to produce 1 kg of hydrogen, though the theoretical minimum is 39.4 kWh.[2]
- **Feedstocks:** The availability of biomass feedstocks for biomass gasification presents a potential bottleneck for hydrogen production, as feedstock supply is limited and subject to significant competition from other industries.
- **Water:** A significant amount of water is required to produce hydrogen, which can strain resources, particularly in arid regions of the United States. Approximately 20–30 liters of water are required to produce 1 kg of hydrogen via electrolysis, and approximately 20–40 liters of water are required to produce 1 kg of fossil-fuel-based hydrogen (Ramirez et al. 2023).

How Is Hydrogen Used?

Hydrogen is being increasingly seen as a flexible energy carrier that can have a transformative impact across sectors like transportation, power production, and industrial processes. Broadly, hydrogen's applications include fuel cells, engines that combust hydrogen, and hydrogen-powered gas turbines.

- **Hydrogen fuel cells** produce electricity via an electrochemical reaction involving hydrogen and oxygen, with water and low-grade heat as the sole byproducts. This process has higher energy efficiency (reaching 60 percent or higher [Andrade et al. 2024, Ogundimu and Richards 2025], compared to the 25 to 37 percent efficiency of diesel internal combustion

[2] For context, this is roughly equivalent to the energy required for an electric vehicle to drive 100 miles (DOE and EPA n.d.).

engine [ICE] vehicles [Albatayneh et al. 2020]) making HFCs particularly suitable for use in transportation, such as fuel cell electric vehicles (FCEVs). There are numerous potential applications for fuel cell technology at ports, including the integration of FCEV lift trucks, drayage trucks, and shuttle buses. Fuel cells can also be used to provide power to cranes, conveyors, other cargo moving machinery, or shoreside power.

A pilot project at the Port of Gothenburg is testing a hydrogen-powered generator to supply electricity to ships at berth, offering a promising alternative to conventional shore power systems in ports lacking infrastructure. The project, led by Stena Line, in partnership with Hitachi Energy, PowerCell Group, and Linde Gas, uses hydrogen to power vessels like the Stena Germanica *and* Stena Scandinavica *while at berth. This initiative aims to reduce emissions by replacing traditional engine usage with electricity generation. Hydrogen technology could play a pivotal role in helping ports comply with upcoming European Union regulations mandating on-shore power supply for container and passenger vessels by 2030. The successful trial highlights hydrogen's versatility, with applications extending to trucks, work vehicles, and heavy machinery.*

Source: FCW 2025

- **Hydrogen internal combustion engines (H2ICEs)** are not yet commercialized but present another application of hydrogen technology still under development. Unlike conventional internal combustion engines that burn gasoline or diesel, H2ICEs combust hydrogen to produce power. While they share similarities with traditional ICEs, H2ICEs produce only water vapor, heat, and minimal amounts of the criteria pollutant NOx, reducing their environmental impact (HFTO 2023). Daimler Truck has demonstrated a H2ICE engine with 44.5 percent efficiency (compared to 60 percent efficiency for FCEV and 25 to 37 percent for diesel ICE vehicles) (HTFO 2023). This technology can be adapted for use in various vehicles and machinery at ports, including harbor tugs, terminal tractors, and heavy-duty trucks. Though H2ICE technology is largely still in the development stage and not commercialized yet, there have been demonstrations of use cases in Europe and Asia.
- **Hydrogen gas turbines** offer a solution for large-scale power generation. These turbines operate by mixing hydrogen with air and igniting the mixture in a combustion chamber to drive a turbine, which then generates electricity. Hydrogen gas turbines can be integrated into existing power plants, allowing for a gradual transition from natural gas to hydrogen (Zhou et al. 2024). Ports, which often require substantial amounts of power for their operations, could utilize hydrogen gas turbines to meet their energy needs. One concern for turbines is that, depending on how they are operated, they can produce a minimum amount of NOx criteria pollutants. Significant efforts are underway to avoid these emissions.

BENEFITS AND CHALLENGES OF HYDROGEN AT PORTS

The diverse opportunities to integrate hydrogen energy into power port operations are linked to a variety of potential benefits and challenges, highlighted in Figure 3.

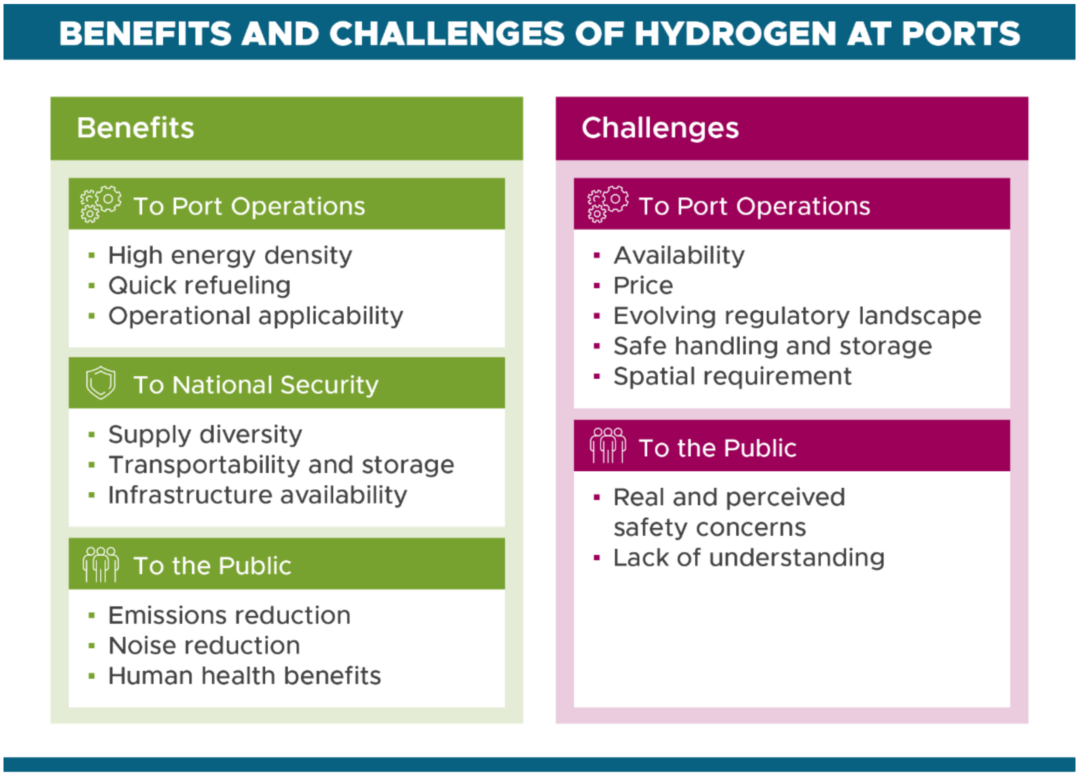

Figure 3. Potential benefits and challenges of hydrogen integration at ports.

Benefits

Integrating hydrogen at ports could offer significant environmental and operational benefits, helping ports remain competitive in an evolving policy landscape. Adopting hydrogen technologies may enhance national security by reducing dependence on imported fuels and promoting energy diversity. Additionally, the use of hydrogen can reduce emissions and improve air quality, creating a healthier environment for port workers and neighboring communities.

Operational Benefits

Energy Density – Hydrogen has a very high gravimetric energy density of approximately 120–142 MJ/kg and a volumetric density that varies based on its storage state. This high gravimetric density signals significant potential for using hydrogen in applications that require long-duration energy storage and transportation, where lightweight energy storage is beneficial. Compressed hydrogen (at 700 bar) and liquid hydrogen boast higher energy densities compared to lithium-ion batteries (< 0.8MJ/kg), making hydrogen a promising technology for heavy-duty applications, such as certain cargo-handling equipment (CHE), as an alternative to fossil fuels.

Fueling Operations – Filling a hydrogen storage tank is similar to refueling a gas tank, with different safety precautions. Hydrogen-powered equipment and vehicles have duty cycles comparable to those powered by diesel, allowing for replacement with minimal impact on daily operations. This is especially advantageous for ports where operational efficiency is crucial for goods movement and profitability. Unlike battery-electric vehicles, which take longer to energize (i.e., charge) and may have more limited range, hydrogen-powered solutions can offer a consistent and reliable alternative to diesel equipment without requiring significant changes to standard port operations.

Workforce Applicability – Because operating and fueling hydrogen-powered equipment and vessels closely resembles the processes for traditional equipment and vessels, the transition for workers can be relatively seamless. While some training and minor adjustments, such as fueling at different locations and safe hydrogen handling, may be necessary, the overall shift can be smoothly integrated into existing operations.

Energy Security Benefits

Supply Diversity – Hydrogen can be produced from various sources, including natural gas, biomass, and water via electrolysis. It can also be stored in various forms, including liquid, gas, and within a liquid organic hydrogen carrier. This diversity reduces the risk associated with dependency on a singular energy source or production method. Hydrogen can also be produced locally, regionally, or imported, providing flexibility in sourcing and mitigating the impact of potential disruptions, such as natural disasters or geopolitical conflicts. By leveraging multiple production pathways and diverse supply chains, hydrogen suppliers can provide a more stable and reliable energy resource, enhancing port energy resiliency and helping insulate the U.S. economy.

Transportability & Storage – Hydrogen can be generated on-site at the port or delivered via truck, pipeline, or vessel, offering multiple transportation options that provide redundancy and help ensure fuel availability, even during power outages or natural disasters. Compressed hydrogen offers a substantial weight advantage over lithium-ion batteries, as well as a size/footprint advantage, making it a superior option for energy storage and transportation, where reducing mass is crucial. Hydrogen can be stored in large quantities, acting as an energy reserve during periods of high demand or supply interruptions, thus ensuring a consistent energy supply. Additionally, hydrogen can be stored on-site at a port and easily transported from storage to its end use or generated on-site, as needed, enhancing operational reliability and flexibility.

Infrastructure Availability – Certain aspects of existing fossil fuel infrastructure can be repurposed or adapted for hydrogen use, though some modifications and considerations are necessary to ensure safety and efficiency. For example, many existing natural gas pipelines can be used to transport hydrogen, either by blending hydrogen with natural gas or by converting them to carry pure hydrogen. Using existing infrastructure for hydrogen, where feasible, enables more rapid deployment of this additional source of energy.

Public Benefits

Emissions Reduction – From a life cycle perspective, the emissions reduction benefits of using hydrogen are highly dependent on the feedstocks and production processes utilized. Life cycle analyses of 17 leading marine fuels have shown that hydrogen can generate comparatively lower impacts on climate change, ecotoxicity, and non-cancer-related human toxicity (Zincir and Arslanoglu 2024). The most acute environmental benefit for ports of replacing fossil fuels with hydrogen is realized during the combustion phase, which occurs on-port. The byproducts of generating energy through an HFC are only heat and water, and the emissions from hydrogen combustion are limited to NOx, which can be effectively managed with advanced technologies.

Noise Reduction – HFC equipment, vehicles, and vessels operate more quietly than their ICE counterparts, potentially reducing noise pollution in port operations. Noise reduction creates a safer and more comfortable working environment for port workers and enhances the living conditions for communities near the ports.

Human Health Impacts – Switching to hydrogen fuel from fossil fuels can significantly reduce point-source pollution at ports, as well as life cycle emissions, depending on the hydrogen production process, feedstocks, and location. If hydrogen is produced off-site and piped in, emissions at the point-of-use are eliminated or nearly eliminated.[3] Reducing these emissions can provide numerous human health benefits by improving local air quality and minimizing exposure to harmful pollutants, such as PM, NOx, and carbon monoxide at ports. These pollutants are linked to respiratory and cardiovascular disease, increased cancer risk, and other chronic health conditions (Bailey and Solomon 2004). Replacing fossil fuels with hydrogen fuel can significantly reduce exposure to harmful pollutants in the port environment, improve health outcomes for port workers and port-adjacent communities, and support a port's social license to operate by addressing community health concerns and fostering trust.

Challenges

Despite its potential to transform energy systems at ports, hydrogen faces significant challenges that must be addressed to ensure successful adoption and implementation. Obstacles range from limited availability and underdeveloped infrastructure to market uncertainty, high costs, regulatory complexities, and spatial constraints. Additionally, safe handling and public perception are critical factors that impact hydrogen projects at ports. Each of these challenges highlights the need for strategic planning, investment, and stakeholder engagement to unlock hydrogen's full potential to advance energy resilience and reduce emissions at ports.

Availability – Ports can either produce hydrogen on-site or have it produced elsewhere and delivered. Hydrogen production in the United States is currently geared toward industrial applications and is not available at scale for port operations. Furthermore, the supply chain infrastructure for delivering hydrogen to ports via trucks, barges, or pipelines is underdeveloped. Although some existing natural gas infrastructure may be repurposed, it would still require retrofitting and additional technology to accommodate new chemical properties. At present, hydrogen consumption for transportation purposes, including use at ports, is negligible, accounting for less than 0.1 percent of U.S. hydrogen consumption; however, this is projected to grow under nearly all scenarios forecasted in the EIA's 2025 Annual Energy Outlook (EIA 2024b). Many ports aim to utilize low emission hydrogen, but the low emission hydrogen supply is limited and expensive.

Market Uncertainty – The adoption of hydrogen technology at ports remains in its early stages, as fuel producers, equipment suppliers, and ports struggle to make substantial investments in an uncertain market environment. Hydrogen fuel providers often require long-term offtake

[3] Point-of-use emissions depend on if hydrogen is used in an HFC or hydrogen internal combustion engine.

agreements (10+ years) to hedge against market uncertainties, yet reaching such agreements can be difficult when equipment availability is inconsistent. For example, Nikola, a startup provider of HFC Class 8 trucks, declared bankruptcy in early 2025, leaving assets stranded and heightening investor apprehension. On the other hand, Hyundai, a well-established international vehicle supplier, has had better success deploying Class 8 trucks in multiple U.S. locations. The future availability of financial incentives can help address market uncertainty by reducing risk for early adopters.

Price – The price of hydrogen for transportation is higher than the price of gasoline on a per unit of energy basis and is predicted to remain higher over the coming decades. The EIA's Annual Energy Outlook reports a cost of $7.56/kg hydrogen for use in transportation in 2024 in the United States. This price is projected to increase slightly, reaching $7.81/kg hydrogen by 2050, and is over six times higher than the current and forecasted price of hydrogen for industrial and electric power applications, which is $1.19/kg hydrogen (EIA 2024c). The significant price disparity is attributed to several additional costs for hydrogen use in transportation, including "hydrogen purification to meet fuel cell requirements, hydrogen compression at dispensing stations, building and operating hydrogen dispensing stations, and state and federal taxes" (EIA 2024c). The price of hydrogen is also impacted by its production method, such as feedstocks and electricity sources, and hydrogen transportation costs.

Regulatory Landscape – The regulatory landscape for hydrogen in maritime applications is both evolving and fragmented, posing significant challenges to its widespread adoption and development. U.S. regulations exist across federal, state, and local levels, creating a patchwork of often inconsistent policies. The current landscape creates uncertainty for stakeholders, particularly investors, where unclear or absent regulations may deter financial commitments. In cases such as approving new hydrogen-powered vessels, stringent processes require individual reviews for each new build, further complicating project implementation. The regulatory landscape for land-based applications is established and defined by the National Fire Protection Association (NFPA) and International Fire Code (IFC).

Safe Handling and Storage – Hydrogen's unique chemical properties present specific challenges for safe handling and storage, requiring careful consideration and specialized systems. Because of hydrogen's high flammability, storage systems must adhere to strict safety standards, including setbacks to minimize risk. Furthermore, hydrogen's odorless and tasteless nature necessitates advanced leak detection technologies to ensure early identification of leaks. Storage materials must be engineered to withstand "hydrogen embrittlement," a process where reactive hydrogen atoms weaken metal containers, increasing the likelihood of material failure. Proper training is essential for personnel interacting with hydrogen, including education on its chemical properties, safe handling practices, and emergency response protocols. For additional support, the Department of Energy (DOE)'s Hydrogen Tools Portal[4] provides valuable resources for hydrogen safety evaluation and training, ensuring adherence to industry best practices.

Spatial Requirements – Hydrogen has a relatively high gravimetric density; however, its volumetric density varies significantly depending on its storage state. Whether hydrogen is stored at ambient pressure, compressed, or in liquid form, it remains less volumetrically dense than diesel or gasoline (see Figure 4 and Figure 5). This poses a challenge for storage, as larger physical volumes or highly pressurized storage is required to store the same energy compared to traditional fossil fuels. For ports with limited open space, allocating space for

[4] The Hydrogen Tools Portal can be accessed at https://h2tools.org/.

hydrogen storage can be particularly difficult, as it may displace valuable operational areas used for revenue-generating cargo-handling activities. Furthermore, hydrogen storage must adhere to setback requirements, as established by NFPA, because of hydrogen's higher flammability and explosiveness. Spatial requirement challenges also extend to vehicles, vessels, and equipment, where larger onboard storage tanks are necessary to achieve the same duty cycle performance as their fossil-fueled counterparts.

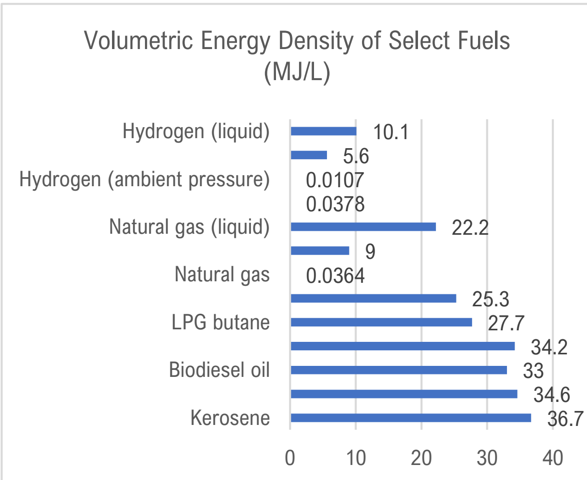

Figure 4. Volumetric energy of select fuels reported in MJ/L (source: Bhuiyan and Siddique 2025).

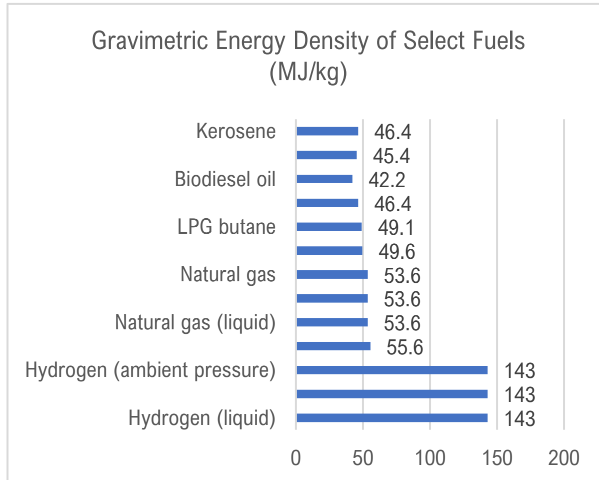

Figure 5. Gravimetric energy density of select fuels reported in MJ/kg (source: Bhuiyan and Siddique 2025).

Public Perception – Public awareness of hydrogen and HFC technologies remains limited, particularly in the context of their application in port operations. This lack of familiarity often leads to concerns, as many associate hydrogen with its high flammability and explosivity, which can understandably create resistance among near-port communities. Despite these perceptions, multiple studies (Oltra et al. 2017; Zimmer and Welke 2012; Lambert and Ashworth 2018) have identified a generally positive attitude toward the use of hydrogen technologies in transportation and residential sectors. These findings suggest that, while real and perceived risks exist, public opinion toward hydrogen remains broadly favorable, presenting opportunities to build support through education and outreach initiatives. Proactively addressing public perception is critical to the success of potential hydrogen projects. Public engagement is often a mandatory component of these initiatives, and negative sentiments or misunderstandings can significantly hinder progress or even halt a project altogether.


H2

THE HYDROGEN/ELECTRIFICATION NEXUS

While hydrogen and electricity are often viewed as competing technologies in port operations, they are deeply interconnected and have complementary roles. Hydrogen production relies heavily on electricity, such as in the case of electrolysis, where electricity is used to separate hydrogen from water. Conversely, HFCs convert stored hydrogen into electricity, which can then be used to power port equipment and infrastructure. This dynamic relationship and interplay between hydrogen and electricity is depicted in Figure 6. For ports considering on-site hydrogen production, reliable access to substantial amounts of electricity is essential to enable production at a meaningful scale. Alternatively, ports facing grid constraints could implement hydrogen delivery, on-site storage, and usage to bridge gaps between electricity demand and available grid supply. It is worth noting that charging battery-electric vehicles and equipment also requires electricity and would be subject to the same potential grid constraints.

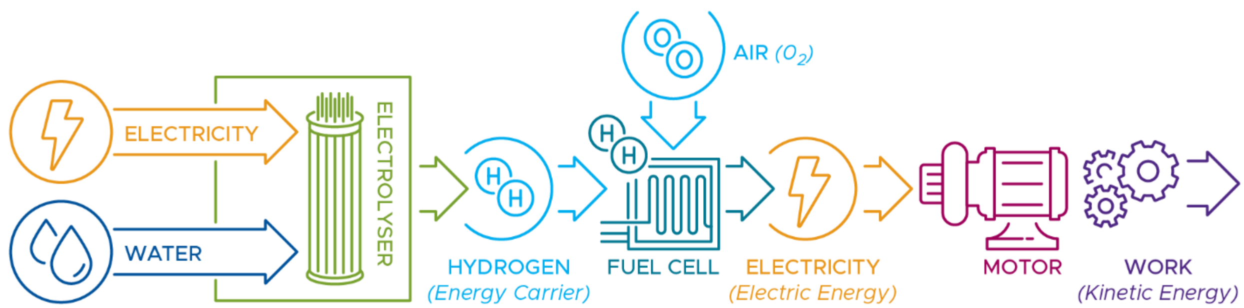

Figure 6. Depiction of how hydrogen, an energy carrier, is used to store energy, which is later converted into electricity and used to do work.

Electricity boasts higher energy efficiency in production compared to hydrogen and is less expensive. Therefore, hydrogen use is best suited for applications where electricity will not work. This could be because of, for example, a piece of equipment's duty cycle, refueling needs, or shift schedule. Hydrogen does offer distinct advantages over electricity in some applications, such as better energy storage capabilities, faster fueling times, and long-range use cases. A further comparison of electricity and hydrogen considerations at ports is provided in Table 1. Given the unique strengths of each, ports may benefit from adopting a hybrid approach that leverages both in their efforts to modernize port energy systems.

Table 1. Considerations for evaluating the implementation of electrification and hydrogen technologies in a port environment, adapted from the Port Electrification Handbook (Idso et al. 2024a).

Consideration	Electricity	Hydrogen
Cost	Electricity rates are generally predictable and vary by region. Consider potential demand charges and specialized rate structures (e.g., shore power rate).	Prices are dependent on feedstocks and production methods but are on-average higher than diesel prices in the United States. Hydrogen produced via grid-powered PEM electrolysis typically has the highest levelized cost, while hydrogen produced via SMR typically has the lowest levelized cost. Costs could come down over time with increasing supply and demand.

Consideration	Electricity	Hydrogen
Operational Requirements	Plan for charging time and charging frequency; this may require adjustments to standard operation.	Similar operations and fueling times compared to fossil-fueled equipment.
Weather Conditions	Extremely cold weather may impact battery chemistry and performance. Storms may impact grid reliability.	Design for operation in cold weather (10°C and lower); however, warmer weather conditions can present challenges for storage and safety.
Spatial Constraints	Plan for charging equipment footprint, conduit pathways, and battery storage (if desired). Additional vehicles, parking spaces, and charging equipment may also be required if battery-electric vehicles cannot provide a one-to-one replacement because of operational constraints.	Plan for fuel storage and associated setbacks, which depend on how hydrogen is stored (e.g., gas or liquid). Hydrogen refueling can occur rapidly, so additional spaces for refueling may not be needed.
Supply	Requires connection to the electrical grid, where electrical service upgrades are likely necessary and/or establishing an on-site microgrid with on-site generation. In all cases, utility coordination is key.	Requires establishing a hydrogen supplier, usually through an offtake agreement, or on-site production, likely through electrolysis. On-site production requires electricity and, likely, connection to the utility grid. Stored hydrogen could also be used to power a port microgrid in the event of an unplanned power outage.
Emissions Impacts	Overall emissions reduction depends on emissions factors for associated electricity generation. Electrification of fossil-fueled equipment and transportation at ports reduces Scope 1 emissions, non-point-source pollution, and improves near-port air quality.	Overall emissions reduction potential depends on feedstocks, production processes, and emissions factors for electricity used to produce hydrogen. Replacing fossil-fueled equipment and transportation at ports reduces Scope 1 emissions, non-point-source pollution, and improves near-port air quality.
Resiliency	On-site battery energy storage can provide backup power, potentially as part of a port microgrid. On-site generation can also provide a local supply of electricity to ports. Both could be used to provide backup power in the event of an unplanned outage.	On-site hydrogen storage can provide backup power (using single or multiple fuel cell generators) to a microgrid. Multiple delivery methods (e.g., truck, barge, pipeline) increase likelihood of access should one method be unavailable.
Safety	Available safety standards for electric equipment operation and charging. NFPA 855 covers stationary energy storage systems and continues to evolve along with industry standards such as CSA/ANSI C800:25. Local jurisdictions (e.g., fire department) may have additional reviews and restrictions.	Available safety standards for hydrogen generation, storage, and use that continue to be revised and expanded, including NFPA 2 and IFC. Local jurisdictions (e.g., fire department) may have additional reviews and restrictions.

Benefits of a Hybrid Strategy

While this guide focuses on hydrogen, and a separate guide covers electrification (Idso et al. 2024a), most ports will benefit from a hybrid approach. Combining battery-electric, hybrid, hydrogen-powered, and diesel (including renewable or biofuel blends) equipment allows ports to do the following:

- *Match best-suited powertrains to operational needs and cargo types.*
- *Reduce risk from energy supply disruptions.*
- *Optimize cost and emissions based on local conditions.*

A hybrid strategy also provides flexibility as technologies evolve. Battery-electric and hybrid options may be adopted first because of technology availability, with HFC and H2ICE solutions following. This approach can reduce demand on the utility grid compared to a fully electrified solution requiring more high-power charging infrastructure. It can also support long-term operational resilience.

Financial Incentives

The cost of hydrogen and hydrogen-related equipment remains higher than that of traditional fossil fuel counterparts, presenting a challenge for widespread adoption. Financial incentives play a crucial role in bridging this cost gap and accelerating the scaling of the hydrogen economy. Common financial incentives include grants and tax credits, which provide important mechanisms for offsetting upfront investment costs.

Grants are often available through a variety of organizations, including state and federal agencies. At the federal level, agencies such as DOE, the Department of Transportation, and the Environmental Protection Agency (EPA) administer funding programs relevant to ports and maritime industries, some outlined in Table 2. These programs may support hydrogen-related infrastructure, such as fueling stations, pipeline development, or vessel retrofits, though eligibility and funding amounts depend on the specific grant solicitation. Ports seeking to develop hydrogen infrastructure are encouraged to monitor open funding opportunities and align proposals with program goals to maximize financial support.

Table 2. Potential sources of financial assistance for hydrogen-related projects at ports.

Potential Financial Assistance Source	Administering Federal Agency
45V Tax Credit	Department of Treasury and the Internal Revenue Service
Clean Heavy-Duty Vehicles Program	EPA
Climate Pollution Reduction Grant	EPA
Port Infrastructure Development Program Grant	Department of Transportation – Maritime Administration
U.S. Marine Highways Program	Department of Transportation – Maritime Administration
Various	DOE – Alternative Fuels and Feedstocks Office, Office of Critical Minerals and Energy Innovation, Office Energy Dominance Financing

The 45V tax credit for clean hydrogen provides up to $3.00 per kilogram of hydrogen produced, with the exact amount determined by the production process and compliance with life cycle emissions thresholds. The tax credit is currently available for eligible projects that begin construction before the end of 2027. Even if a port is not interested in on-site production, they can work closely with hydrogen suppliers to discuss how the benefit of these tax credits would be accounted for in negotiated purchase prices.

PORT-RELATED INTEGRATIONS

Ports are increasingly evaluating hydrogen as an alternative energy option to power their equipment, provide energy storage, and enable flexible operations during grid disruptions.

Future Marine Fuel Corridors

International maritime shipping is expected to have an increasing demand for fuels like ammonia and methanol in the future. These fuels could use hydrogen as a feedstock, in which case their total delivered price is most influenced by the price of hydrogen feedstocks (RMI and Global Maritime Forum 2024), they are relevant to a port's overall energy landscape and hydrogen integration plans.

In response to anticipated international fuel markets, ports and relevant stakeholders are establishing future marine fuel corridors worldwide. These corridors represent a shipping route between two or more ports where the vessels plan to eventually use emerging innovative fuels. The formation of the corridor seeks to address some of the common challenges facing the adoption of the new fuels through aligning strategies and commitments across the variety of stakeholders involved in maritime transportation, including ports, shipping companies, bunkering providers, and government agencies. These corridors can help reduce the barriers of implementing emerging marine fuels by troubleshooting and identifying potential needs such as supporting infrastructure, policy, and tests/scaling methods.

Figure 7. Publicly announced future marine fuel corridor routes, as of July 2025 (source: Mission Innovation 2025).

Accessing Hydrogen

Ports can access hydrogen through various methods described in Figure 8. The optimal method depends on multiple factors, including infrastructure and storage space requirements, total port hydrogen demand, and the preferred transport and end-use states of hydrogen (e.g., gas, liquid, or LOHC).

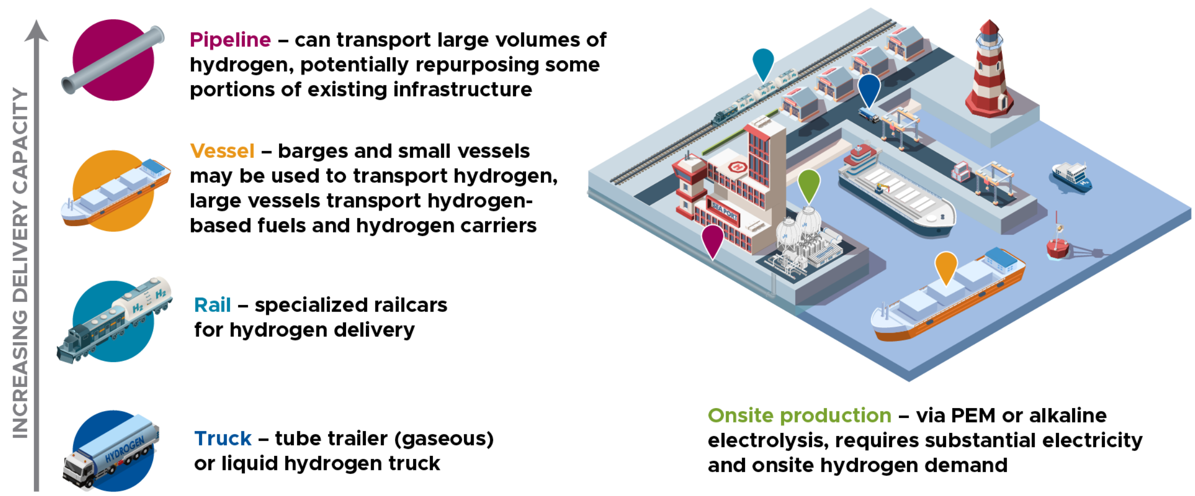

Figure 8. Potential methods for accessing hydrogen at ports.

Hydrogen Delivery Methods

Truck Transport

Hydrogen can be transported to ports via trucks, offering flexibility and accessibility without requiring extensive infrastructure investment. This method is commonly used because it allows hydrogen delivery directly into storage facilities or refueling stations, both stationary and mobile. There are two types of hydrogen delivery trucks: tube trailers that transport gaseous hydrogen and liquid hydrogen trucks. While each has varying capacities depending on their specific design, tube trailers can have a payload capacity of approximately 1,200 kg and liquid hydrogen trucks can have a payload capacity of approximately 4,000 kg (Frank et al. 2021).

Hydrogen Delivery Considerations: *Hydrogen delivery may occur in multiple segments, sometimes involving different methods for each segment.* **Transmission delivery** *refers to transporting hydrogen from the production site to centralized distribution facilities, while* **distribution delivery** *involves transportation from those facilities to a refueling station, on-site storage facility, or other end-use location. Hybrid delivery approaches could include, for example, transmitting hydrogen via pipelines and completing distribution to the port via truck.*

Maritime Transport

Hydrogen can be moved over long distances via specialized carrier vessels. Although the transport of liquid hydrogen by sea is still nascent, the first liquid hydrogen carrier began operation in 2019 (Kawasaki 2019). Additionally, ammonia and methanol carriers are being used to transport fuel compounds that can be converted to hydrogen for port use. For regional transportation, barge-based hydrogen transport is being explored because of its potential to offer unique advantages, particularly in congested urban areas. In one unique circumstance, this has occurred for years; NASA operates a specialized barge transporting liquid hydrogen inside its Space Launch System Core Stage rocket (NASA 2016). Maritime transportation is generally more cost-effective and emissions-efficient compared to trucking. Waterborne hydrogen transport requires specialized vessels that comply with rigorous safety standards, including the U.S. Coast Guard requirements.

Pipeline Transport

Pipeline delivery can be the most cost-effective hydrogen transport method in scenarios of large-scale demand. However, it requires significant upfront investment in infrastructure. Globally, the International Energy Agency tracks over 150 active hydrogen infrastructure projects, though only one is currently planned in the United States (IEA 2024). That project—which is currently in conceptual design—envisions hydrogen transport to multiple locations, including the Port of Corpus Christi, the nation's largest energy export gateway. Existing liquefied natural gas (LNG) pipelines can potentially be adapted for hydrogen transport, as proposed by projects such as the European Hydrogen Backbone initiative. However, hydrogen's unique chemical properties must be addressed, including its potential to embrittle metal pipelines, weakening them over time.

On-Site Production

On-site hydrogen production becomes more cost-effective with increasing hydrogen demand, making it a potentially viable option for ports with high anticipated hydrogen usage. On-site production at ports can be achieved through technologies such as PEM or alkaline electrolysis. The economic feasibility of on-site production is also influenced by factors that include the port's electricity costs and space availability. Producing hydrogen on-site is energy-intensive and requires adequate electrical capacity and space—both of which are often limited in port environments. Studies suggest economic viability for on-site production at varying demand levels, some as low as 440 kg/day (Hajjaji and Cristofari 2024). These estimates are highly site-specific, and tools like the Hydrogen Delivery Scenario Analysis Model (HDSAM)[5] and the Hydrogen Analysis (H2A)[6] production model provide valuable support for U.S. ports seeking to evaluate the cost-effectiveness of delivery options versus on-site production scenarios.

Hydrogen Carriers

Hydrogen carrier technologies facilitate the storage and transportation of hydrogen and are being pursued as a more manageable way to handle this highly reactive chemical substance. Carriers can exist in both liquid and solid forms, with each type undergoing hydrogenation to encapsulate hydrogen for transit or storage, followed by dehydrogenation to release hydrogen when needed. Though their use is not yet widespread in transportation applications, recent research highlights their potential benefits and limitations (Otto et al. 2022). Solid-form carriers, such as metal hydrides, store hydrogen in a stable state, while LOHCs offer liquid-based solutions. Among LOHCs, aqueous solutions of formate ions are of interest because their solution is non-toxic and safe to handle, akin to baking soda (Gutiérrez et al. 2023). Notably, many ports are already familiar with storing potassium formate for deicing purposes and may find cross-applicability for hydrogen storage. However, LOHC technologies are still actively being researched to overcome potential challenges. One notable drawback of LOHCs is the energy loss from undergoing hydrogenation and dehydrogenation processes, which is approximately 35 to 40 percent of the energy content of the stored hydrogen (Revinova et al. 2024).

Rail Transport

Hydrogen transport via rail uses specialized railcars designed for hydrogen delivery. While not yet widely adopted, rail provides a more energy-efficient and lower-emission alternative to road transport and may gain importance as the hydrogen economy grows.

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[5] The HDSAM can be accessed at https://hdsam.es.anl.gov/index.php?content=hdsam.

[6] The H2A hydrogen production model can be accessed at https://www.nrel.gov/hydrogen/h2a-production-models.

Hydrogen as Commodity for U.S. Ports

Energy transport is one of the foundational activities for many ports across the United States. Among the top 150 U.S. ports ranked by tonnage (BTS 2024), publicly available data indicates that approximately 75 percent of these ports are engaged in the transportation of petroleum products. For large ports, this figure rises to 96 percent (Idso et al. 2024b). This underscores the critical importance of energy-related activities to the operational and economic success of U.S. ports. With the rapid development of new energy technologies, which complement or may eventually replace traditional fossil fuels, U.S. ports will need to adapt their energy transport businesses to accommodate an evolving market landscape, potentially one where hydrogen transport plays a much larger role.

Hydrogen transport presents U.S. ports with a significant opportunity for economic growth, potentially paralleling today's role in energy exports. For context, the United States has established itself as a global leader in the export of petroleum products and the leading exporter in LNG (EIA 2025). In the future, there is potential for hydrogen to occupy a similar role, setting the stage for U.S. ports to position themselves as crucial hubs in the global hydrogen economy. While this handbook primarily focuses on hydrogen's role in end-use applications at ports, it is worth highlighting its potential as an emerging business line for energy transport—a shift that would redefine port operations and energy export strategy. The Oceans of Opportunity report, led by Rocky Mountain Institute, is an insightful resource for ports considering a potential future role in the methanol or ammonia supply chains (RMI and Global Maritime Forum 2024).

Port of Rotterdam Example

The Port of Rotterdam (n.d.[a]) is positioning itself as a leader in the international hydrogen market as a hub for hydrogen production, use, and transport. As a key player in Europe's energy landscape, the port is developing large-scale infrastructure and fostering collaboration to meet growing hydrogen demand and establish efficient supply chains. These plans build on the port's existing energy infrastructure, for example, as depicted in Figure 9.

Figure 9. Storage tanks with heating pipes at the Port of Rotterdam (source: Port of Rotterdam n.d.[c]; photo by Eric Bakker ©).

The port is creating a robust hydrogen network that links producers, import terminals, mobility projects, infrastructure, and trade platforms (Port of Rotterdam n.d.[b]). Pipelines will connect hydrogen production sites and import terminals to industrial users across the region, while maritime terminals will handle the transport of hydrogen and related carriers. These terminals, dispersed throughout the port, will facilitate hydrogen imports from international suppliers.

The port will support a variety of local production facilities to supply hydrogen locally and for export. Hydrogen production will be fueled by renewable energy from solar and wind sources, with offshore North Sea wind farms projected to deliver 7.4 gigawatts (GW) of capacity by 2030. Additionally, some hydrogen will be produced utilizing natural gas and incorporating CCS technologies. The port also plans for on-site ammonia cracking—the process by which ammonia is converted into hydrogen for use or export.

Rotterdam's vision places it at the center of an evolving hydrogen economy, establishing itself as a global hub for hydrogen logistics, production, and application while strengthening industrial and energy supply chains across Europe.

Storing Hydrogen

Multiple hydrogen storage technologies are available or emerging, each suited to varying applications depending on their advantages, drawbacks, and regulatory considerations. Aspects of the most promising storage applications for ports are described below and summarized in Table 3.

Table 3. A summary of the characteristics of the different technologies used to store hydrogen modified to cover technologies most relevant to ports (additional information for this table sourced from Headley and Schoenung n.d.; AlZohbi et al. 2022).

Storage Technology	Volumetric Energy Density, MJL^{-1}	Advantages	Drawbacks	Storage Scale	Commercial Status
Compressed gas	25–30 kg/m^3	Mature technology; fast hydrogen charging and discharging; simple vessel structure	Limited hydrogen storage range; high pressure can cause safety issues; heat management required	1,000 kg	Available
Liquid hydrogen	50 kg/m^3	Higher gravimetric and volumetric density than gaseous hydrogen; high purity of hydrogen	Liquefaction process requires energy and reduces roundtrip storage efficiency; cryogenic storage required	15,000 kg	Available
LOHC*	60 kg/m^3	Possibility of storage in liquid form; use of existing infrastructure; storage viability > 1 year; reduced explosivity risk	Energy required for hydrogenation and dehydrogenation	10,000 kg	In development and trial
Ammonia	107 kg/m^3	High volumetric density of hydrogen; possibility of direct use and use of existing infrastructure; established knowledge from other industrial applications	Requires special treatment due to smell and toxicity; around 13% of hydrogen is needed for dehydrogenation and purification	10,000+ metric tons	In development and trial

* LOHCs include a diverse range of chemical compounds with distinct properties, and the applicability of these statements may vary across different LOHCs.

Converting between different types of hydrogen storage involves energy-intensive processes that introduce efficiency losses. Liquefaction, which cools hydrogen to a liquid state, is energy-intensive, with a specific energy consumption of 35 to 45 percent (Al Ghafri et al. 2022) of the lower heating value of hydrogen. For compounds like LOHCs or ammonia, dehydrogenation processes are required to release stored hydrogen, and these processes also require energy. Additionally, liquid hydrogen storage faces boil-off losses, where small quantities of hydrogen evaporate because of heat transfer from the surroundings. These cumulative energy losses must be considered when selecting storage solutions for specific applications, as they impact overall system efficiency and energy availability.

Compressed gaseous hydrogen is one of the most mature and common states for hydrogen storage. However, this storage method is limited by the relatively low volumetric energy density of gaseous hydrogen compared to liquid hydrogen and other fuels, making it less suitable for large-scale applications because of the space it requires. Additionally, high-pressure systems must be carefully designed to mitigate safety risks through implementation of, for example, proper setbacks, temperature management, signage, and maintenance requirements. These considerations are outlined in NFPA 2 and the IFC. Compressed gas storage is well suited for small-scale storage (e.g., 1,000 kg or less) and is commercially available, making it a practical choice for ports with immediate hydrogen storage needs.

Liquid hydrogen storage is a more energy-dense storage option that allows for the storage of larger quantities of hydrogen in smaller spaces. However, the liquefaction process is energy-intensive and results in energy losses during hydrogen conversion, reducing roundtrip efficiency. Furthermore, storing hydrogen in its liquid form requires substantial energy input to maintain cryogenic temperatures (−253°C). Liquid hydrogen storage is commercially available and, despite the challenges, may be the best suited storage approach for ports interested in large-scale hydrogen storage and/or storing hydrogen to be transported via liquid hydrogen trucks or carrier vessels.

LOHCs represent a set of chemical compounds capable of storing hydrogen in a stable state for extended periods. These carriers offer the advantage of being stored at ambient temperature and pressure. Additionally, some are non-toxic, which further simplifies their handling and storage processes. However, the hydrogen content within LOHCs is relatively low. Furthermore, the required dehydrogenation processes may result in losses of stored hydrogen, highlighting efficiency challenges that must be considered when implementing LOHC-based storage solutions (AlZohbi et al. 2023).

Ammonia is a promising hydrogen storage option, offering a relatively high hydrogen content and volumetric energy density, making it ideal for large-scale storage. Its appeal is particularly strong for ports planning to handle ammonia as a commodity, as investments in ammonia infrastructure and training can support the dual use of hydrogen storage. Additionally, ammonia cracking technology can allow ports to extract hydrogen from ammonia on-site. Despite its advantages, ammonia requires specialized handling due to its toxicity and odor. Ammonia dehydrogenation processes result in significant energy losses, as they consume about 13 percent of stored hydrogen (AlZohbi et al. 2023).

Overall Footprint Considerations for Hydrogen at Ports

Implementing hydrogen infrastructure at ports involves careful spatial planning that accounts for potential storage, generation, and refueling structures, as well as other support systems and associated setback requirements.

Hydrogen Storage

Storage is a critical component in the hydrogen infrastructure at ports, directly influencing footprint considerations. For instance, on-site storage systems require adequate space for high-pressure vessels and sometimes cryogenic equipment. An example of installation at the Port of Los Angeles highlights a setup where 1,500 kg of hydrogen is stored at 450 bar, occupying approximately 750 square feet using modular storage containers (Semchukova et al. 2024). The storage containers are installed on a concrete slab behind a protective fence. This project was designed to serve 10 HFC drayage trucks operating at the port. While the use of cascade storage systems offers efficiency in refueling operations, ports need to plan for setbacks and safety clearances, which can limit the available usable land. Additionally, scalability becomes an important concern as ports expand hydrogen storage capacity to meet increasing demand for drayage trucks and hydrogen-powered equipment.

Hydrogen Generation

On-site generation through electrolysis can significantly reduce logistical challenges related to hydrogen delivery but requires space for a pretreatment system for water, electrolyzers, and electrical infrastructure capable of supporting high power needs. For example, PEM-based electrolysis models, such as the H2B2 EL1000N electrolyzer, which can produce up to 89 kg of hydrogen per hour, consuming 5.1 megawatts (MW) at full load (H2B2 2025). This is nearly equivalent to the maximum power requirements of 15 battery-electric vehicle direct current (DC) fast charging stations operating simultaneously at full load.[7] This magnitude of demand necessitates sufficient energy supply and availability at the port and would also be present in the case of widespread port electrification. Ports with industrial-scale hydrogen production facilities can use adjacent land for production and export, moving beyond localized systems to regional hubs. These large-scale facilities, however, will need to balance energy requirements, permitting processes, and compliance with environmental regulations.

Refueling Infrastructure

Hydrogen fueling stations are designed for both fixed and mobile configurations, each with distinct footprint impacts. Fixed fueling systems, like those at the Port of Hamburg and Valencia, integrate reception, storage, compression, and dispensing components over consolidated locations to maximize utility while minimizing delays (Semchukova et al. 2024). These systems often require separate areas for input delivery pipelines or electrolysis units, high-pressure compression infrastructure, and dispensers that refuel medium- and heavy-duty vehicles. Mobile fueling units, like the cascade refueling system at the Port of Los Angeles, reduce permanent footprint demands but can introduce logistical inefficiencies, such as delays because of manual switching of supply banks (Semchukova et al. 2024). For effective implementation, ports must account for fueling frequency, throughput, and the ability to serve fleets with diverse hydrogen requirements.

Challenges and General Infrastructure

The footprint considerations for hydrogen infrastructure are further shaped by siting limitations, permitting complexity, and maintenance demands. Challenges such as setback requirements, availability of energy at the port for electrolysis, and unscheduled maintenance of compressors can impact both the spatial allocation and operational readiness of hydrogen systems.

[7] Assuming 350 kW DC fast chargers.

POTENTIAL HYDROGEN APPLICATIONS AT PORTS

Ports have the opportunity to use hydrogen in three primary ways: as a power source for mobile land-based equipment, as an energy solution for maritime transport, and as an on-site energy resource for hoteling, storage, and grid balancing. Each of these applications will be explored in detail in the following sections, including an analysis of the technology's current availability and future potential.

Land-Based Equipment

Hydrogen use is expected to be employed strategically in land-based mobile equipment at ports. It is a leading option for ports in situations where electrification technologies fall short of operational requirements and where reliance on fossil fuels is increasingly impractical, primarily because of environmental impacts. Hydrogen can also serve as an energy buffer, allowing port operations to continue in the event of planned or unplanned grid outages or voltage reductions. Hydrogen can be delivered even when the grid is down, which can extend this energy buffer.

Cargo-Handling Equipment

Future CHE fleets at ports are likely to feature a mix of battery-electric, hybrid, HFC, and H2ICE technologies, with specific options tailored to each terminal's cargo type and equipment duty cycles. Implementation at ports could include the following:

- Using HFC container handlers to support ship-to-shore transport of loaded containers and battery-electric container handlers in the empty container areas. The later use moves lighter cargo and does not operate 24/7.
- Deploying HFC equipment at ports with 24/7 operations and battery-electric equipment at ports that operate one eight-hour shift per day.
- Implementing a mixed fleet of equipment, such as both HFC and battery-electric yard tractors, to enhance operational resiliency in the event of an unplanned power outage or fuel shortage.

Commercial availability of alternatively powered CHE varies, as depicted in Table 4. Battery-electric and hybrid electric technologies are more widely available today. However, for high-demand applications, like mobile gantry cranes or reach stackers, hydrogen-powered equipment may be more suitable. This is because these types of equipment may have demanding shift schedules, such as 24/7 operation requirements, with little-to-no downtime for charging. Hydrogen fueling more closely approximates traditional fueling operations and can be done in less time compared to charging an equivalent electric piece of CHE with currently available charging technology. Stationary CHE, such as ship-to-shore cranes, is best suited for direct grid connections and could be supported by HFC backups for resilience.

Table 4. Available and anticipated types of CHE for ports, including battery-electric, hybrid electric, HFC, and H2ICE technologies, based on preliminary market research. Black circles indicate the equipment is commercially available, while blue circles indicate the equipment is not yet widely commercially available, though it may be deployed in a pilot context.

	Grid Connection	Battery Electric	Hybrid ICE/Battery Electric	HFC	H2ICE
Aerial Lift		•	•		
Backhoe		•		• (blue)	• (blue)
Container Handler		•		• (blue)	
Crane/Material Handler	•	•	•		
Dump Truck		•		• (blue)	• (blue)
Excavator		• (blue)	•	• (blue)	• (blue)
Forklift		•	•	•	
Rubber-Tire Gantry Crane	•	•	•	•	
Ship-to-Shore Crane	•				
Skid Steer Loader		•	• (blue)	• (blue)	
Sweeper		•	•	• (blue)	
Top Loader/Reach Stacker		•		• (blue)	
Tractor		•		• (blue)	• (blue)
Yard/Terminal Tractor		•	•	• (blue)	

Many U.S. ports are landlord ports who rent terminal space to tenants who purchase/lease and manage their own CHE. Though they may not own CHE, landlord ports still play an important role in enabling their tenants to transition to hydrogen-powered CHE, for example, through the following actions:

- Supporting tenants by providing funding or sponsoring grant applications.
- Coordinating negotiation with fuel suppliers.
- Providing information to tenants about relevant programs, incentives, and best practices.
- Establishing guiding policies for hydrogen integration at the port.
- Deploying infrastructure, such as fueling infrastructure, that can be used by others.

Early adoption of hydrogen-powered CHE has already begun at several ports, with momentum expected to grow in the coming years. Notable examples include hydrogen-powered gantry cranes, top-pick container handlers, and mobile hydrogen fueling at the Port of Los Angeles and hydrogen-powered reach stackers and yard tractors at the Port of Valencia. Additional projects are underway, such as deploying hydrogen-powered tractors at the Port of Honolulu and top handlers at the Northwest Seaport Alliance as part of the EPA Clean Ports Program.

Because hydrogen-powered CHE is still in the early phases of development and deployment, reliable cost estimates remain challenging. Market research indicates that hydrogen-powered CHE carries a cost premium. An analysis by the Rocky Mountain Institute (RMI 2024) compared the total cost of ownership (TCO) across four types of CHE and found the TCO was 13 percent to 200 percent higher for hydrogen equipment compared to diesel equipment. The TCO for hydrogen-powered yard tractors and rubber-tired gantry cranes was closer to their diesel counterparts, while the TCO for top handlers and forklifts were over twice as expensive.

Heavy-Duty Trucks

Class 8 trucks are among the highest polluting and energy-intensive mobile emission sources at most ports. They are used to transport goods between ports and nearby facilities, such as rail stations, warehouses, or final destinations. These trucks operate not only at ports, but also along routes through surrounding communities, contributing to widespread pollution and making them a key focus of emissions reduction efforts at many U.S. ports.

Currently, hybrid, battery-electric, and a limited number of HFC Class 8 trucks are available in the market. HFC trucks are particularly suited for operations that require medium-to-long distances and quick refueling times, where battery range and charging times may fall short of operational demands. However, HFC trucks are still in early stages of adoption and development, with several considerations needing evaluation before deployment, including the following:

- The reliability and long-term support from the original equipment manufacturer, including vehicle maintenance and warranty services.
- Availability of refueling infrastructure and consistent access to hydrogen fuel at stable prices.
- Operational impacts, such as potential route adjustments to incorporate refueling stops.
- Upfront and ongoing vehicle costs. Upfront costs are significantly higher than conventional truck options.

Research indicates that HFC trucks are projected to initially be approximately 60 to 90 percent more expensive than new ICE trucks in the 2025 to 2030 time frame (ICCT 2022). Grants and incentives can help mitigate this cost barrier. One example of a policy driving the adoption of HFC trucks is the Clean Truck Program at the Ports of Los Angeles and Long Beach, where HFC trucks, along with other qualifying truck types, are exempt from a $10/twenty-foot equivalent unit gate entry fee. This disparity is further compounded by the absence of HFC trucks in the used market, which is where many truck owners purchase their vehicles. Used options for these vehicles are expected to increase with time, market maturity, and an increased understanding of technology lifespan. One solution that may address these challenges is trucking-as-a-service contracts, allowing operators to access HFC trucks and fuel at a fixed cost over a defined contract period, eliminating the need for outright vehicle purchases.

Rail Freight

The locomotives employed in railyards within or adjacent to ports and in the short lines that connect terminals and nearby distribution and warehousing facilities could be candidates for conversion to hydrogen. With several companies field testing hydrogen locomotives, additional data on performance and operating costs should be available in the coming years. Tests include the deployment of a hydrogen-powered locomotive by CSX, in collaboration with CPKC, in 2024 (CPKC n.d.), and by Sierra Northern Railway in 2025 (Sierra Northern n.d.). Simulated activity modeling demonstrates limitations for battery-electric locomotives because of space requirements and battery mass. Researchers found simulated space and mass limitations for hydrogen-powered locomotives could be lower, potentially halved, which could allow for scaling and longer-distance applications (Cole et al. 2023).

Maritime Applications

Vessel Shore Power

Vessel shore power enables ships to connect to the local electrical grid while docked, allowing auxiliary engines to operate on electricity rather than fossil fuels. This technology is commonly available for smaller vessels and is increasingly adopted for larger ocean-going vessels. The primary driver for implementing shore power for ocean-going vessels is to reduce pollution impacts on port workers and nearby communities, as well as to comply with regulations, such as those enforced at California ports (California Air Resources Board 2025).

The electrical demand associated with vessel shore power for ocean-going vessels is substantial, as depicted in the notional shore power load profiles in Figure 10. For instance, a container ship may have peak loads below 2 MW, while a cruise ship's peak load exceeds 10 MW. Securing this level of power can be both challenging and costly for ports, often resulting in high demand charges. On-site hydrogen storage combined with HFCs offer an innovative alternative to providing shore power, either entirely off-grid or in combination with the grid, to manage peak loads and lower demand charges.

As with terrestrial cold-ironing, hydrogen could be used as the primary energy source for a mobile power barge, allowing ships to connect with an external power source not just at berth, but also while at anchor. Containerized fuel cell power systems could also be used in other situations, where traditional charging or shore power infrastructure is infeasible, for example, because of desired location, distance from grid infrastructure, or projected power demand. This type of system was demonstrated at the Port of Honolulu (Sandia 2014) but has not been widely adopted to date.

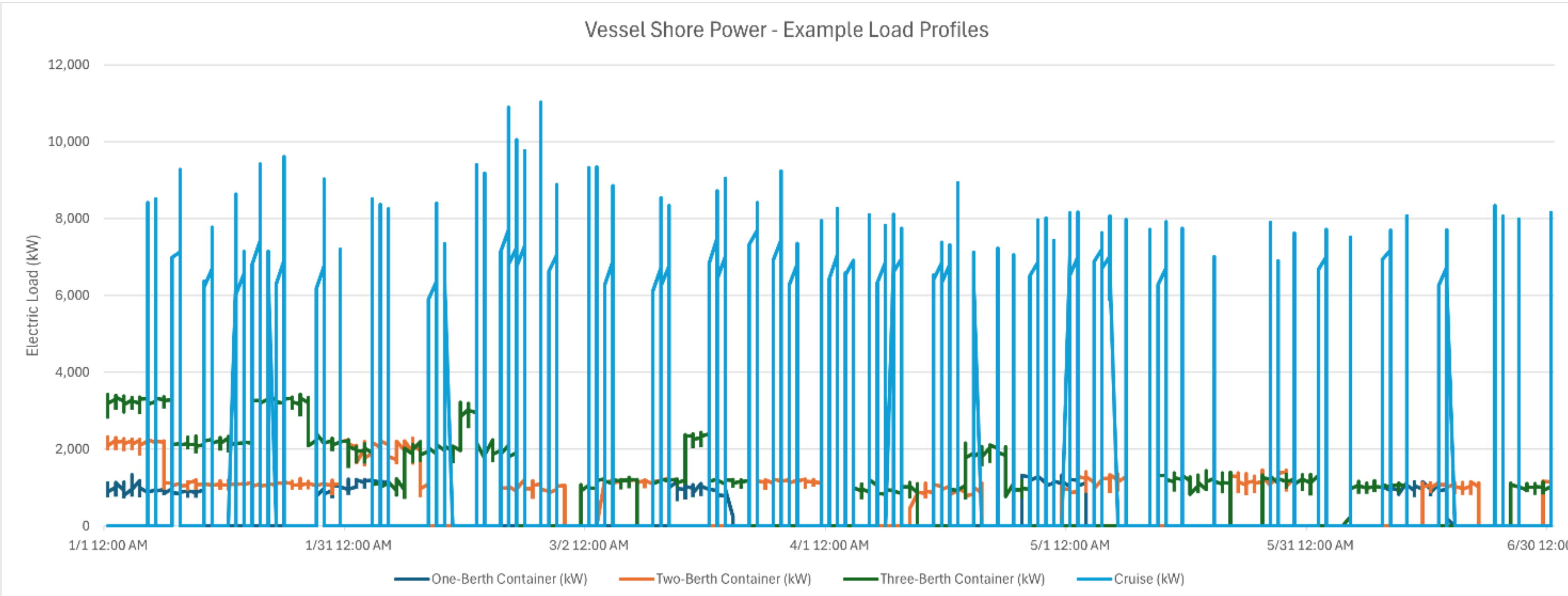


Figure 10. Vessel shore power—example load profile (Wang et al. 2024).

Maritime Transportation

Similar to its growing adoption in land transportation, hydrogen presents unique opportunities as a future fuel for specific ship segments. It may be particularly advantageous for vessels aiming to reduce emissions while operating on shorter routes and requiring fast refueling, such as commercial harbor craft. For instance, a San Francisco Bay Ferry company developed and piloted the world's first commercial hydrogen-powered ferry in 2024.

In the future, ports could access hydrogen delivered via maritime transport in the form of methanol, ammonia, or LOHC. Through processes such as methanol reforming, ammonia cracking, or LOHC dehydrogenation, ports could extract hydrogen to meet their own energy needs, fostering a cleaner and more versatile energy landscape.

On-Site Energy Applications

Hydrogen is emerging as a versatile on-site energy resource that addresses storage and grid balancing challenges, particularly in environments with fluctuating energy demands, such as maritime ports. Hydrogen's ability to act as both an energy storage medium and a flexible power source positions it as a key enabler of resilient, efficient, and low emissions energy systems. Potential on-site energy applications are depicted in Figure 11 and explained further below.

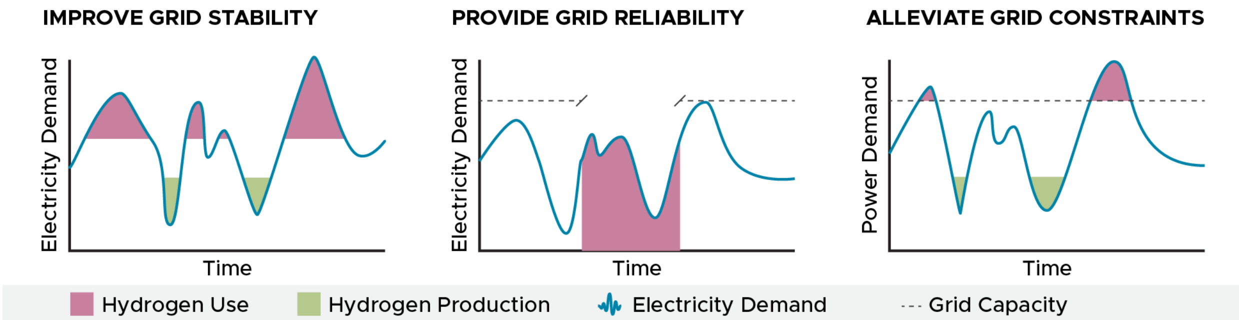


Figure 11. Examples of how hydrogen can be used in on-site energy applications for ports to improve grid stability, provide grid reliability, or alleviate grid constraints.

Hydrogen for Grid Stability

Integrating hydrogen technologies with the grid offers maritime ports an opportunity to optimize energy usage while addressing fluctuations in electricity supply and demand. Ports are characterized by significant electric load variability because of their industrial operations, shipping movements, and logistical activities. Stored hydrogen can be used for demand shaving to alleviate peak loads on the grid and may be able to provide other ancillary services.

Hydrogen Microgrid Solutions for Port Reliability

Microgrids are localized energy systems capable of operating independently or alongside the main electric grid, offering enhanced energy security, operational flexibility, and an opportunity to integrate on-site energy generation. Microgrids support the uninterrupted operation of critical port systems, including cranes, cargo refrigeration, lighting, and other essential infrastructure. Additionally, hydrogen microgrid systems could empower smaller ports to operate independently in "islanded mode," sustaining operations during external disruptions like severe weather events or outages in the main grid.

Hydrogen as a Solution to Grid Constraints

Hydrogen technologies may offer an effective solution to manage energy demand in ports faced with interconnection and transmission constraints. Stored hydrogen could be used to help alleviate these limitations and meet the port's peak power demands. As a flexible energy carrier, hydrogen can be stored efficiently and used to meet fluctuating demands, powering heavy-duty port operations, such as cranes, CHE, and auxiliary ship systems.


HySTRA
LH2
TUG
TUG
KAMIGUMI

ASSESSING POTENTIAL DEMAND FOR HYDROGEN AT A PORT

Hydrogen can be utilized in a variety of port applications, including land-based equipment and vehicles, and water-based equipment and vessels. In these use cases, hydrogen demand can be approximated by converting the energy needs served by diesel fuel. The approximate conversion rate from diesel fuel to hydrogen is 1 gallon of low sulfur diesel to 1.125 kg hydrogen gas (H2Tools 2020). Table 5 shows the approximate hydrogen demands for common port terminal equipment based on that conversion factor (Steele and Myers 2019).

Table 5. Approximate hydrogen demands for common port terminal equipment.

Equipment	Approximate Hydrogen Demand (kg/day)
Rubber-tired Gantry Crane	45
Lift Trucks	5
Straddle Carrier	46
Container Handler	56 (Loaded)/25 (Empty)
Reach Stacker	33
Yard Tractor	21

A critical factor when assessing demand is accounting for the timelines in which technologies will be available. Certain heavy-duty vehicles and lift trucks, for example, are either currently or imminently available in fuel cell configurations. In contrast, larger or more specialized equipment, like excavators, may not be commercially available for years. When considering potential demand, projects must then consider market availability of different vehicles relative to project time frames.

Another aspect of demand assessment is considering potential needs of tenants and other on-site stakeholders. It may be most cost-effective and efficient to coordinate hydrogen supply and fueling infrastructure across multiple operational needs and tenants. On the other hand, some vehicles, such as drayage trucks, require conveniently located fueling infrastructure outside the port, ideally situated along key transportation corridors. Research across nineteen major U.S. ports estimates that drayage trucks present the most significant average potential on-shore hydrogen demand at nearly 89 percent of potential demand (Steele and Myers 2019), as seen in Figure 12. For overall port energy infrastructure planning, it is helpful for ports to understand the approximate hydrogen demand of drayage trucks to support the development of a reliable fuel supply chain, even though they are unlikely to directly provide hydrogen fuel to drayage trucks. This aspect of demand assessment is helpful for project strategy, such as planning potential collaborations or anticipating tenant land-use changes to accommodate hydrogen infrastructure.

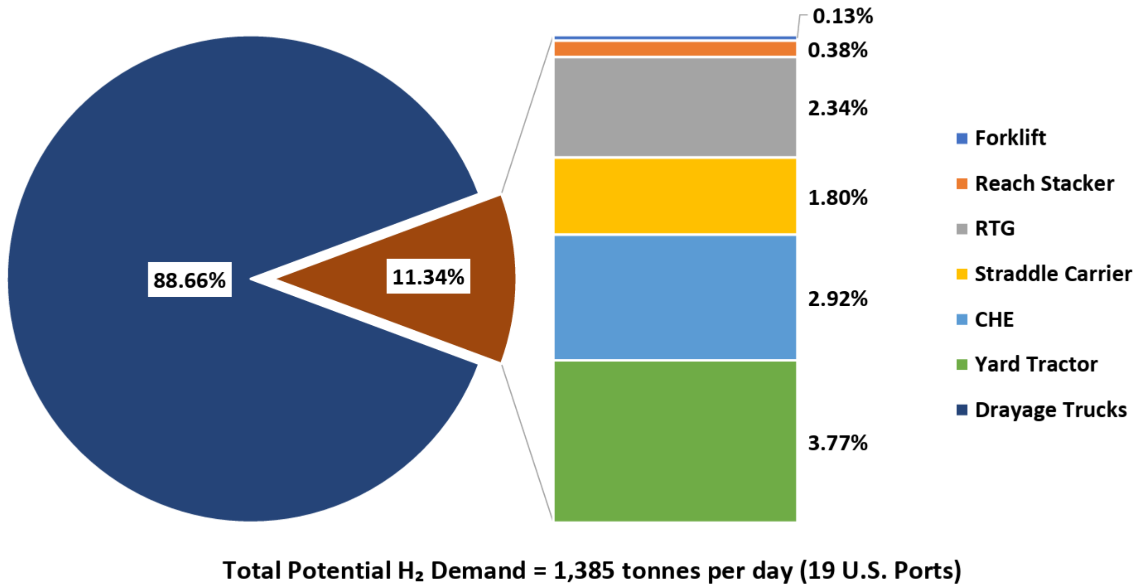


Figure 12. Potential daily hydrogen demand percentage by equipment type for U.S. ports (Steele and Myers 2019).


H2
Hydrogen

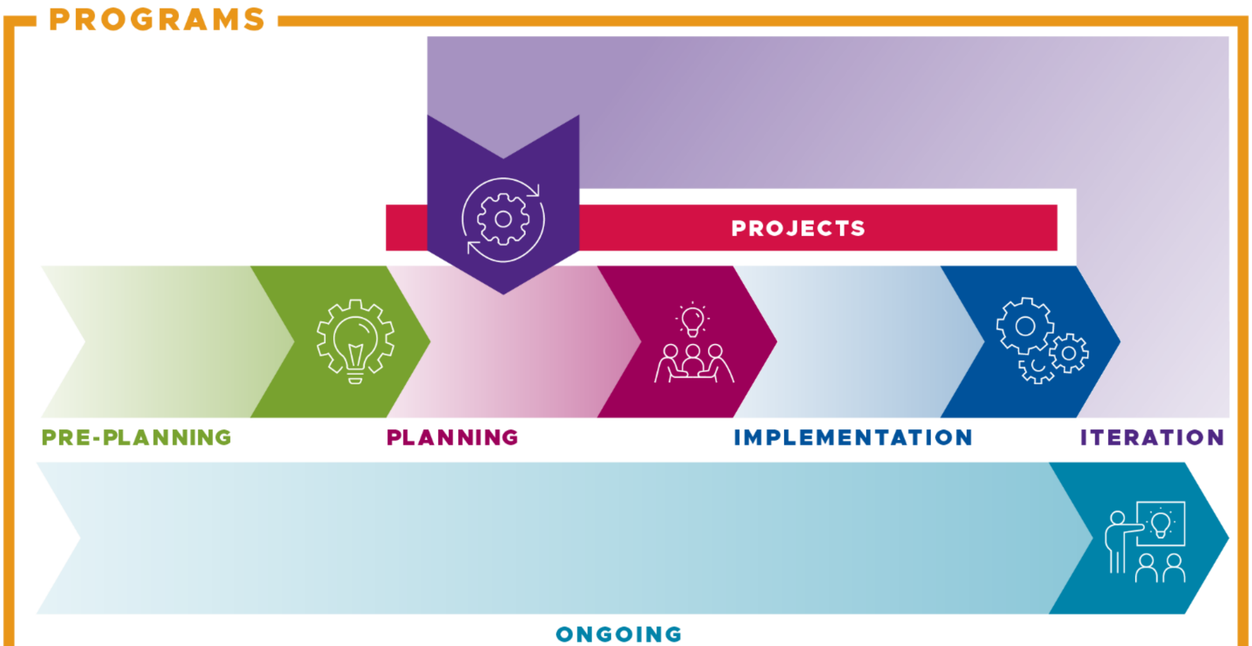
IMPLEMENTATION CONSIDERATIONS

Successfully planning and implementing hydrogen projects may require buy-in from port tenants and users, permitting and regulatory bodies, and the nearby public, among many other stakeholders. While hydrogen has many similarities with current fuels, its differences can drive significant concerns about safety, handling practices, and regulation. This section provides a high-level overview of potential steps to take and key considerations involved in implementing hydrogen projects. It is intended to serve as a non-location-specific framework to support a port, tenant, or other port stakeholders through evaluating and implementing hydrogen projects at a port.

Appointing a Project Leader

It is helpful to assign a project leader at the port for hydrogen-related activities, to provide oversight and coordination. This is particularly useful at ports, such as landlord ports, that may have multiple ongoing projects across various tenants. The project leader helps ensure uniform implementation of policies and the ongoing integration of lessons learned and best practices across the port, as well as supports streamlined internal and external (e.g., community-focused) communication.

In this section, the project development process is divided into phases like those used in the Port Electrification Program Framework: Pre-planning, Planning, Implementation, Iteration, and Ongoing considerations throughout (Idso et al. 2024a). The phased approach helps ensure that necessary information is gathered and steps are taken in logical order; this can help smooth licensing and permitting processes, alleviate negative stakeholder responses, and result in a project that is neatly tailored for its specific setting. Bear in mind that the boundaries between phases are not strict and phase activities may occur concurrently. For example, additional Planning or even Pre-planning iteration may be required during the Implementation phase, as stakeholders and port users gain experience with hydrogen technologies. Many of the phase activities described in the *Port Electrification Handbook* are also recommended for hydrogen projects, so this section is adapted from the *Port Electrification Handbook* to better apply to hydrogen development. The recommended phases and potential tasks within each phase are depicted in Figure 13, and a detailed discussion of activities taken as part of these tasks can be found in Appendix A.



Pre-planning:

- Establish preliminary goals and vision
- Assess technology options
- Baseline use cases
- Plan and initiate engagement with stakeholders and partners
- Evaluate the market and policy environment
- Assess preliminary risk

Planning:

- Establish scope, goals, and budget
- Develop emergency management plans and protocols for H2 handling
- Plan for fueling logistics
- Manage risk and impacts
- Infrastructure needs assessment and development schedule
- Initiate permitting and regulatory actions

Implementation:

- Define project management and timeline
- Secure project resources
- Implement stakeholder communication channels
- Coordinate with other related projects
- Pilot testing

Iteration:

- Evaluate outcomes and success metrics
- Document progress toward overall goals
- Discuss next steps
- Catalogue lessons learned

Ongoing:

- Engagement plans for internal and external stakeholders
- Track developing regulatory and funding spaces
- Coordinate with hydrogen supporting industry
- Satisfy ongoing requirements

Figure 13. Potential steps to implement a hydrogen program at a notional port. These steps are adapted from the *Port Electrification Handbook* (Idso et al. 2024a) to more specifically apply to hydrogen development.

STAKEHOLDER MAPPING AND ENGAGEMENT

One of the most significant components of planning hydrogen integration is stakeholder mapping and engagement. These groups may be internal or external to the port and span a range of physical or operational proximity, and it is critical to engage a wide variety across that range, from regulatory bodies to tenants to local community organizations. Table 6 shows a range of potential stakeholders and project partners, along with some of the engagement topics that may be relevant to those stakeholders. The Port of Seattle *Large Scale Hydrogen Storage Risk Assessment* case study, illustrated in the callout box example below, provides an example of specific and categorical stakeholder mapping (Veeramany et al. 2024).

Table 6. Potential port hydrogen stakeholders and partners.

STAKEHOLDER TABLE

	Examples	Engagement Topics
Internal Stakeholders	▪ Port departments	▪ Organization sustainability goals ▪ Maintenance capacity ▪ Business targets ▪ Legal processes
External Stakeholders	▪ Tenants ▪ Vessel owners/operators ▪ Equipment suppliers ▪ Labor unions	▪ Training needs ▪ Technology development plans ▪ Business targets ▪ Infrastructure goals
Remote Stakeholders	▪ Utilities ▪ Regulators ▪ Policymakers ▪ H2 supporting industry ▪ Community ▪ Hydrogen Safety Panel	▪ Regulatory requirements ▪ Local and environmental impacts ▪ Technology access ▪ Available incentives ▪ Training availability ▪ Energy needs and restrictions ▪ Job Creation ▪ Water Needs

Regular engagement with an expert stakeholder group results in key input for project scoping, analytical refinement, and regulatory considerations. Engagement with non-expert stakeholders provides insight into local incentives and resistances, labor priorities, environmental interests, and potential areas of support or buy-in. Incorporating this feedback throughout the planning process creates a smoother ongoing revision cycle and can help avoid last-minute changes or scope shifts. Additionally, coupling stakeholder insights with risk assessment analysis and findings helps project developers prevent negative local impacts, address stakeholder concerns, and avoid potential points of resistance like protests or lawsuits.

Each group, and each individual stakeholder, will have unique priorities and concerns that influence their engagement with a hydrogen project at the port. Examples include the following:

- Potential users will need to train fuel handlers.
- Regulatory bodies may be evaluating new rulemaking.
- Equipment operators may experience elevated exhaust exposure.
- Vessel owners may be looking to update fleet technology.
- Environmental management agencies may focus on protecting sensitive maritime resources.
- Nearby communities may fear safety risks.

These priorities and concerns can also be location-specific, based on an area's prior exposure to other technologies. Consider the following:

- A port accustomed to handling petrochemical throughput
- Previous spillage or fire incidents
- Notable natural disasters
- Other resiliency factors, like power instability

These stakeholder insights can then guide development targets and establish feasibility metrics. For example, preliminary engagement may find that most port tenants or nearby communities are uncomfortable with proximity to gaseous hydrogen storage tanks. In this situation, the project could prioritize liquefied hydrogen or the use of hydrogen carriers rather than compressed gaseous storage. In contrast, several tenants may identify individual technology targets that involve hydrogen for shore power or equipment and are, therefore, willing to be near or even host hydrogen storage infrastructure. Early engagement with regulatory or other oversight entities can also provide advance guidance about potentially novel permitting pathways, feedback about upcoming rulemaking, or even opportunities to collaborate on new permit requirements.

In addition to project guidance, stakeholder engagement strategies can utilize risk assessment findings to address specific stakeholder concerns. For example, hydrogen is commonly perceived as having significant safety risks, including flammability and volatility. Early-phase stakeholder engagement can unearth those concerns, which can then be integrated into risk assessment topics. The findings from the risk assessment can then be incorporated back into later-stage stakeholder engagement materials to address the original concerns. By following this cycle of communication and analysis, projects can be attentive to stakeholder input and develop more effective engagement materials, which helps effectively achieve buy-in.

Example – Large-scale Hydrogen Storage Risk Assessment at the Port of Seattle

The Large-Scale Hydrogen Storage Risk Assessment at the Port of Seattle (Veeramany et al. 2024) serves as an insightful case study for stakeholder mapping, engagement, and incorporation of findings. The project assembled two stakeholder groups and utilized different methods for each—one "expert stakeholder" group consisted of industry, academia, subject matter specialists, and local partners, while the other "community" group was the Port of Seattle's own Community Advisory Panel. Expert stakeholders were engaged through quarterly meetings that involved progress update and project development presentations, followed by discussion. The community group was engaged through a presentation introducing maritime fuels tailored to a non-technical audience, followed by questions and discussion. Significant findings were reported from each group that helped guide the continued development of both the risk assessment project and the Port of Seattle's ongoing work on fuels. The expert stakeholder group suggested additional risk dynamics and circumstances, called attention to local industrial activities that may influence project optics, and discussed the value of different risk assessment methodologies. The community engagement group, in contrast, raised concerns about lifespan emissions for future fuel technologies, technology viability in port-specific settings, and the local impacts of additional industrial activity involved in a hydrogen site.

The Large-Scale Hydrogen Storage Risk Assessment findings also highlighted the necessity of performing location-specific stakeholder engagement rather than relying only on generalized knowledge or best practices. Both the expert and community groups raised concerns and priorities that are unique to the Port of Seattle setting—the presence of culturally significant salmon populations, a history of air quality concerns related to Port of Seattle activities, and noise pollution caused by truck traffic.

Figure 14 shows an example of preliminary stakeholder mapping for the Port of Seattle including both specific stakeholders and generalized stakeholder groups. The primary categories were maritime organizations (blue), industrial organizations (green), utilities (yellow), state agencies (red), and port- and hydrogen-specific stakeholders; specific examples within each category were identified by Port of Seattle project partners.

Figure 14. Example preliminary stakeholder map for the Port of Seattle *Large-Scale Hydrogen Storage Risk Assessment* (Veeramany et al. 2024).


ZERO EMISSION
H2
Hydrogen
FUEL CELL SHIP

RISK ASSESSMENT

Risk assessment can evaluate specific local risks (e.g., seismic activity or flooding) alongside generalized statistical risks like equipment lifespan and standard failure modes and help identify which factors are of greatest concern. The findings can contribute to practical design considerations, like avoiding pipelines for hydrogen transport in seismically active areas. Matching the risk factors with stakeholder priorities also helps with developing effective communication materials and methods to increase stakeholder buy-in. Evaluating risk and effectively communicating it to stakeholders is important for hydrogen projects because many stakeholders lack familiarity with it or, crucially, only know of hydrogen's reputation for fire or explosion. These perceptions can cause resistance to some hydrogen applications by stakeholders and potentially influence project outcomes.

Different risk assessment methodologies can be applied at various phases in the project. During Pre-planning and Planning phases, when technology options or facility design may not be known, utilizing a probabilistic approach can probe risks associated with environmental factors (e.g., earthquakes, hurricanes) in addition to generalized technological factors (e.g., failure rate of cryogenic fittings for liquid hydrogen). Once the project has progressed to Implementation and Iteration, more accurate quantitative methodologies can be applied to facility designs, equipment, and fuel choices.

A key resource in hydrogen risk assessment is the Hydrogen Safety Panel (HSP) (H2Tools 2025a).[8] The HSP is a team of experts from national laboratories and private industry that can provide guidance through design reviews, risk and safety analysis, inspections, and training, as well as contribute to stakeholder engagement and outreach activities.

[8] See H2tools.org for more information, including a valuable lessons learned section.

CONCLUSION

Recent innovations in hydrogen technology offer a promising energy solution that could enable ports to enhance resilience, reduce emissions, and comply with environmental regulations. However, evaluating this option is both complex and highly specific to individual ports. This guide aims to illuminate the key considerations ports should weigh when assessing the potential benefits of integrating hydrogen into their operations. Hydrogen's versatility in port environments spans land-based equipment, maritime applications, and on-site energy solutions. Nevertheless, unlocking its full potential requires addressing significant challenges, including limited supply chain infrastructure, safety concerns (both real and perceived), a fragmented regulatory landscape for maritime applications, and the high costs associated with hydrogen fuels and technologies, which are, in part, related to the nascent market. Ports should evaluate on a case-by-case basis how hydrogen implementation costs compare with other project alternatives, such as electrification, because the most cost-effective strategy will be determined by port-specific factors. Strategic planning, informed risk assessments, and robust stakeholder engagement will be essential to overcoming these hurdles and developing tailored pathways for adoption.

Through coordinated efforts between public and private stakeholders, technological advancements, and supportive financial incentives, hydrogen has the potential to become a cornerstone of modernized port operations. By drawing on lessons learned from case studies, pilot projects, and international initiatives, ports can incorporate hydrogen as part of a comprehensive port energy strategy. As the hydrogen economy continues to expand, ports are well-positioned to emerge as leaders in energy innovation, maintaining competitiveness in the global economy while fostering healthier and more sustainable environments for workers and neighboring communities.

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APPENDIX A – DETAILED DISCUSSION OF PROJECT DEVELOPMENT PHASES

Step 1: Pre-planning

The Pre-planning phase is research-based and focuses on evaluating hydrogen technologies and how they may fit into the port's broader energy portfolio. Activities during this phase probe hydrogen's feasibility for the port, its tenants, and other stakeholders, and establish the direction and goals for hydrogen integration.

- **Establish preliminary goals and vision** – Initial goals are the programmatic or organizational vision that specific project goals may eventually stem from. Goals may be informed by the benefits detailed earlier—fueling operations, supply diversity, emissions reductions, or human health impacts, for example—or by considerations like technology development targets, market pressures, economic opportunities, or tenant needs. These goals should serve as the guide for future project planning and relate to broader organizational goals.
- **Assess technology options** – Since hydrogen is at a lower technology readiness level than other energy types for some specific port applications, it is important to carefully consider market availability and cost of hydrogen fuels, equipment, and fueling technologies against the port's timeline to implement changes. As hydrogen technologies develop over time, this information can be updated at regular intervals to inform future projects.
- **Baseline use cases** – Depending on project goals, hydrogen may be employed as a replacement for current energy types, serve alongside other fuels, or fill entirely new technology spaces. Characterizing these use cases for hydrogen applications involves analyses like examining current energy use, related emissions impacts, load forecasting, and evaluating fuel or energy handling practices. Based on these baselines, hydrogen needs and impact estimates can be determined.
- **Plan and initiate engagement with stakeholders and partners** – Early collaboration with stakeholders and partners is crucial; the sooner they are involved, the better a project can integrate their needs and perspectives. Engagement at this stage should consist primarily of two-way communication through mechanisms like workshops, meetings, and focus groups. Stakeholders should be informed of preliminary project goals and considerations, and their insights and input should be welcomed in return. Analyses and conclusions should remain flexible as stakeholder feedback is taken into account, so the project concept can adapt. At the conclusion of this initial round of stakeholder engagement, project goals and priorities should be shaped by a combination of port considerations and stakeholder input. Having a clear, publicly communicated schedule for stakeholder engagement can help set expectations and maintain forward progress. See the Stakeholder Mapping and Engagement section for further discussion. Engagement of hydrogen industry stakeholders could include equipment manufacturers and hydrogen infrastructure developers.
- **Evaluate the market and policy environment** – Organizational, local, national, and international policies may all influence hydrogen feasibility and applications. These are continuously evolving. For example, available incentives may specifically support production or clean fuels applications, while existing or future regulations may drive demand for hydrogen fuels within the port. Market levers may also be present—a market assessment should be attentive to current or future offtake customers, estimated demand, and projected growth.

- **Assess preliminary risk** – Once initial conclusions are reached about potential applications, technology options, and feasibility, a useful tool to employ is a probabilistic risk assessment, which will help contextualize key concerns and provide additional project design guidance. Risk assessment outcomes, paired with feasibility studies and technoeconomic analyses that investigate aspects like capacity, infrastructure, and energy needs, can lead directly to an initial project framework that will be expanded on in future steps. See the Risk Assessment section for further discussion.

Step 2: Planning

The Planning phase takes concepts developed during Pre-planning and turns them into action that incorporates capacity, technology needs, technoeconomic considerations, and stakeholder inputs. As discussed, the outcomes from pre-planning research and engagement should include an initial programmatic framework that provides clear direction for next steps, including individual projects. Moving forward into practical planning involves expanding toward draft strategies, facility designs, and regulatory actions.

Many of the outcomes from the Planning phase should be concrete deliverables that move the project from concept to implementation. Some key draft products from this phase may include the following:

- **Establish scope, goals, and budget** – Pre-planning analyses should guide the proposed scope and budget. These guidelines may change as the project develops. For new hydrogen projects, it can be helpful to develop conservative budgets that account for a high level of uncertainty and potential timeline delays related to lower technology readiness or first-time implementation. Establishing a set of final goals or success metrics at the Planning phase will also help measure success during the Iteration phase.
- **Plan for fueling logistics** – Fueling considerations for different hydrogen technologies can vary dramatically and involve different regulatory requirements than other fuels. For example, different use cases will require mobile or stationary fueling, which require different supporting infrastructure and are covered under different regulations. Additionally, some hydrogen fuel types may have significantly different handling considerations than current fuels, like liquid hydrogen at cryogenic temperatures or compressed gas. The project plan should consider these handling and regulatory differences in advance, as they may influence the viability of certain hydrogen technologies.
- **Manage risk and impacts** – Revisit the Pre-planning risk assessment at this phase, replacing the generalized risk categories with design specifics. The updated risk assessment will feed directly into final facility design, ongoing communication, and safety protocols during site development. Draft facility designs can also be used to perform more site-specific risk assessments, such as plume or jet fire modeling, based on known geometry and operational metrics. Based on risk metrics, potential negative impacts should be quantified and tracking and mitigation plans can be developed. Impacts of hydrogen projects may include workforce (e.g., additional training), safety (e.g., volatility), environmental (e.g., emissions reduction), or operational (e.g., new fuel handling practices).
- **Infrastructure needs assessment and development schedule** – Many hydrogen technologies will require additional infrastructure, including storage systems, fueling facilities, and transportation mechanisms. In cases where hydrogen is intended to replace fossil fuel technologies, this new equipment may be able to be sited in the same locations, since other volatile fuels may require similar standoff distances or zoning requirements. It is

most efficient to replace equipment at the end of its lifespan, so the project development schedule must take current infrastructure timelines into account.

- **Initiate permitting and regulatory actions** – Hydrogen technologies may not have as robust regulatory support as legacy fuels because they are relatively new. Stakeholders may also perceive that a project is not adhering to all regulatory requirements, like suitable public comment periods or environmental assessments. Sensitivities may vary greatly by location—in areas where vulnerable environmental resources are present, stakeholders or lawmakers may prioritize environmental impact assessments, whereas areas with wildfire incidence may be attentive to fire risk and water usage.
- **Develop emergency management plans and protocols for hydrogen handling** – Hydrogen can be volatile and require different emergency response and handling guidance than other fuels (H2Tools 2025b). Since hydrogen may take familiar forms (e.g., liquid, pipelined) but behave differently than other fuels (e.g., rapid leaks, cryogenic temperatures), clearly identifying management practices is crucial for safety and success.

Step 3: Implementation

The Implementation phase executes the strategies and designs developed during the Planning phase. This phase generally spans from funding and resource acquisition to project close.

- **Define project management and timeline** – Identify stakeholders that could serve on the project team (e.g., tenants, port departments) and define a project management plan that delineates responsibilities. The management team should be responsible for continued oversight of the scope, budget, timeline, and any other administrative requirements.
- **Secure project resources** – For projects to succeed, they will need a blend of human and financial capital. It is vital to establish a project team by clearly defining management, leadership roles, and responsibilities among all contributors. Regarding financial capital, some projects may be financed internally, while others will require grants, loans, or additional financial support for implementation. Funding opportunities may be available from DOE, EPA, and the Department of Transportation. Additionally, various states and local jurisdictions might offer their own funding for such initiatives. Joint implementation projects may be funded by multiple stakeholders through cost-sharing or cooperative research agreements.
- **Implement stakeholder communication channels** – The Implementation phase is when direct impacts to stakeholders become reality. To ensure accurate accounting of impacts and maintain buy-in, this phase should lead with implementing communication and ongoing engagement plans, so stakeholders can be kept informed about project progress and have avenues to reach out.
- **Coordinate with other related projects** – If there are other large-scale energy projects within the organization, coordinating across projects can benefit stakeholder engagement, use of resources, and overall organizational strategy.
- **Pilot testing** – Once infrastructure and facilities are in place, it is recommended to stage out the use of hydrogen through a series of pilot tests, particularly if there are several planned applications. By using a phased approach that tests each use case before broad roll-out, unforeseen issues can be resolved and the process can incorporate user feedback. Since hydrogen may be unfamiliar to port stakeholders, or even the cause of some safety concerns, slowly introducing hydrogen into functional environments also helps build trust and familiarity with the systems. If pilot tests are not possible—for example, because of

cost—another approach is to visit a port already using hydrogen-powered equipment to gain better understanding of operations and meet with the equipment operator(s) and maintenance team.

Step 4: Iteration

Hydrogen technologies, especially in port settings, have few long-term case studies to reference, and system-scale energy project timelines can be quite long. Some projects may also be implementing early-stage technology, meaning that project managers will be identifying best practices and refining processes for the first time. The Iteration phase reflects on project outcomes, with a focus on ongoing refinement or new, future projects.

- **Evaluate outcomes and success metrics** – Review success metrics established during the Planning phase and determine whether project outcomes are in line. Clearly identify unexpected outcomes and areas where the project under- or over-delivered.
- **Document progress toward overall goals** – Reflect on overall project goals laid out in Pre-planning and evaluate whether the project supported those goals. Identify what future activities could further these goals or build toward newly identified priorities.
- **Discuss next steps** – Document outcomes and engage internal and external stakeholders about future work. Two-way, deliberative communication strategies are crucial, so stakeholders can provide meaningful input.
- **Catalog lessons learned** – Many hydrogen projects may be early adopters of a particular hydrogen use case. Documenting lessons learned is a necessary step for future projects or project iterations within the organization, but in the case of hydrogen adoption, may also provide similar external projects with crucial guidance and information if able to be shared publicly.

Step 5: Ongoing

Some tasks are necessary to maintain throughout all phases of the project. The tasks considered in this section should be integrated whenever practical.

- **Engagement plans for internal and external stakeholders** – See the Stakeholder Mapping and Engagement section.
- **Track developing regulatory and funding spaces** – Since hydrogen is a developing technology area, the regulatory and funding landscape changes frequently. By keeping abreast of these topics, projects can maintain efficiency by accessing the largest amount of external funding and avoiding regulatory missteps. Recommended activities for this task include engaging with state and federal agencies, national laboratories, and organizations like the Hydrogen Council or the HSP, as well as attending conferences.
- **Coordinate with hydrogen-supporting industry** – Whether a project scope involves manufacturing hydrogen on-site or transporting it in, developing market connections with the hydrogen industry is critical. Since the hydrogen technology space is still developing, this is considered an ongoing task. Recommended activities for this task include participating in equipment demonstrations, developing relationships with hydrogen-related professional organizations, engaging with potential industry partners, and attending conferences.
- **Satisfy ongoing requirements** – External funding opportunities and partnerships may have regular status or reporting requirements.

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