Zero-Carbon Fuels for Marine Shipping

CLEAN AIR TASK FORCE

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About this Report

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Clean Air Task Force (CATF) is a nonpartisan, technology agnostic, data-driven NGO that works with state, local, regional, and national organizations to educate the public, media, industry, and policymakers on the science and economics of a variety of climate and clean air policies. CATF collaborates with private sector technology, finance, and energy companies to develop and implement strategies for bringing clean energy to market.

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Executive Summary

This report examines the feasibility to decarbonize the global marine shipping sector by transitioning to zero-carbon fuels. This transition will deliver the direct benefits of reducing a significant source of greenhouse gas (GHG) emissions and air pollutants within the transportation sector, and potentially accelerate the economy-wide commercial adoption of clean fuels.

The International Maritime Organization (IMO) reports that GHG emissions from global shipping account for more than 3% of annual global emissions, and could grow to as much as 10% of emissions by 2050. Few policy regimes, commercial technologies, or investment pathways have been developed to address this significant source of GHG emissions. The goal of this project is to better understand the financial, economic, technological, geographic, and policy characteristics impacting hydrogen-based fuel source uptake and supply chains.

Decarbonizing the sector requires thoughtful planning, analysis, and coordination between policymakers, fuel producers, shipping companies, ports, and other key stakeholders across a broad range of complex topics regarding zero-carbon pathways in marine shipping. Thus, this study's analysis and recommendations for the marine shipping sector fall into five main areas:

- Strengthening coalitions
- Partnering for hydrogen-based fuel offtake
- Aggregating clean shipping demand
- Standardizing fuel production
- Financing the transition

Policy Background

The marine sector consumed 3.8 million barrels/day of fuel oil in 2017 and is responsible for half of global fuel oil demand. Most of the current ocean-going shipping fleet uses conventional internal combustion engines that rely on cheap but highly polluting bunker oil. These fuels emit carbon dioxide, sulphur dioxide, and nitrogen oxide. In 2018, the IMO released the IMO 2020 regulations with the goal of reducing air pollutants from highly polluting ships. At the same time, the IMO established a long-term target to achieve a 50% reduction in GHG emissions from maritime shipping below 2008 levels by 2050. While some strategies for meeting IMO 2020 standards will also yield some incidental decarbonization benefits, achieving the IMO 2050 goals require more significant efforts. For example, many global shipping fleets transitioned to liquefied natural gas (LNG) in response to the IMO 2020 regulations, but these efforts are insufficient for long-term decarbonization.

Hydrogen-based Fuels

Technologies exist today that have the potential to enable the shipping sector to implement zero-carbon fuels at scale. Carbon-free hydrogen-based fuels offer deep decarbonization opportunities without compromising performance and efficiency in shipping operations. Hydrogen is the most abundant chemical substance in the universe, and the lightest element in the periodic table. It is light, storable, energy-dense, and produces only water as a byproduct when consumed in a thermal process, making hydrogen a truly clean fuel. Ammonia is a colorless gas with a strong odor that combusts at low fuel-to-air mixture ratios, but can be toxic in moderate quantities. The ease of liquefaction is one of the main advantages that ammonia has over hydrogen, making it the more adaptable fuel of the two. Hydrogen and ammonia can be converted from one state to another quite easily to serve as an energy carrier. As energy products, hydrogen and ammonia are highly flexible. Hydrogen gas can power various types of fuel cells and turbines, and can compete with gasoline in terms of energy density.

Hydrogen-based fuels can be produced using different methods that impact the relative lifecycle carbon-intensity of the fuel:

- *Grey* hydrogen or ammonia is produced using the Steam Methane Reforming (SMR) process and a fossil fuel feedstock, without any measure to capture the high upstream GHG emissions. This process has the highest relative lifecycle emissions.
- *Blue* hydrogen or ammonia is produced using either grid electricity through electrolysis or a fossil fuel feedstock and the SMR process, combined with carbon capture utilization and storage (CCUS) technology to reduce GHG emissions in the process. This process has less emissions than Grey hydrogen or ammonia.
- *Green* hydrogen or ammonia is produced using electricity generated from renewable sources such as wind and solar, and therefore has zero lifecycle GHG emissions. It is the cleanest of the three fuel production processes.

A significant challenge facing hydrogen and ammonia fuel adoption is their present costs. Hydrogen and ammonia are far from global commodities, meaning the price of fuel may vary from one port or fueling station to another, conditional on regional and national political and economic realities. Without policy-driven initiatives to mitigate the financial risks to long-term investment in ships, engines, infrastructure, and technologies related to hydrogen-based fuel adoption, a situation emerges where LNG is a less risky and more affordable choice than zero-carbon fuels. To complicate the situation, shipping companies are not transparent by nature, have very low public visibility, and are slow to adopt new technologies without sizable economic incentives given the long lives of their assets and the difficulty in significantly modifying ship engines once ships have been deployed.

First-Mover Port Evaluation

This report assessed a representative set of major international shipping ports based on their ability to catalyze a transition to hydrogen-based fuels in the shipping sector. While ports cannot unilaterally force a shipping fleet to fuel-switch, they are a critical connection point between the supply and demand of hydrogen-based fuels. Because of the inherent global nature of the shipping industry, multiple ports around the world will need to be able to deliver hydrogen-based fuel to complete the shipping value chain. The ability for a port to produce or bunker hydrogen-based fuel sources from both conventional and renewable feedstocks may be the deciding factor for a shipping company to invest in hydrogen-based fuel ships with certainty that their fleets will have end-to-end access to fuel.

Likely first-mover ports that were analyzed in this report include: New York and New Jersey, Houston, Los Angeles, Rotterdam, Hong Kong, Shanghai, Tokyo, Singapore, and multiple ports across Australia.

Trade routes and bunkering resources create advantages to hydrogen-based fuel adoption, and those ports in zones such as the Asia-Pacific will likely see faster adoption due to agreements among key strategic fuel bunkering hubs. However, fuel adoption will likely move in a piecemeal fashion in certain regions before being adopted on a global scale. Primary movers in the hydrogen-based fuel switch will most likely be those that make a conscious decision to deploy hydrogen technology against the economic grain.

A number of supply and demand conditions must be met to create a hydrogen-based fuels market in the shipping sector, including financial engagements, infrastructure capacity, trade agreements, technology capacity, industry coalitions, and policy incentives.

Recommendations

Shifting to a hydrogen-based fuel shipping industry in the near future could yield numerous long-term economic and environmental benefits. Like any transitional technology, the adoption of hydrogen-based fuel is posed as a chicken-and-egg situation. Demand is reliant on the reliability and existence of the supply, and any development or investment for the supply chain is dependent on consumer demand. To break the cycle, this report recommends the following actionable steps that major market movers – shipping companies, oil and gas, policy-makers, etc. – could take to ensure that the shipping industry will adopt either blue or green ammonia.

The key criteria used in analyzing the shift toward hydrogen-based fuel include: existing market demand and supply, technological feasibility, political will, transit routes of ports, port logistics, and trading capacity. While the adoption of ammonia for deep sea shipping will require many components of the energy and commodity market to move simultaneously, it would still be possible through the following recommendations.

Recommendation 1: Shipping regions, such as Europe, Southeast Asia, Asia-Pacific, or Northeast Americas, should establish trans-oceanic coalitions between government, energy-industry companies, shipping companies, and financial institutions.

Recommendation 2: Shipping companies must partner with fuel suppliers aligned with the most relevant trade lanes through first-mover ports.

Recommendation 3: First-mover ports must work within their country or region to aggregate economy-wide demand for hydrogen fuels.

Recommendation 4: Fuel producers must coalesce around standard production methods for green hydrogen / ammonia while continuing to innovate.

Recommendation 5: Private and public capital must work with fuel producers to de-risk investments and lower the cost of capital for new fuel production and infrastructure.

Key Takeaways

The IMO and nations around the world that are motivated by an urgent need to reduce carbon emissions and improve air quality are the main drivers of decarbonization trends in global shipping. Additionally, the promise of hydrogen economies offers new opportunities for innovation as demand for clean fuels grows across the energy system.

While hydrogen-based fuels and related technologies are certainly promising, few models around the world exist for ports and shipping companies that have successfully implemented these solutions. As shipping fleets and ports gain more experience with hydrogen-based fuels and understand barriers and opportunities to implementation, continuous information sharing and the development of best practices is critical to the global growth of this market.

Additional Research Needs

While this report has addressed many opportunities and challenges to the transition to zero-carbon fuels in shipping, more research is needed as the global shipping sector moves toward hydrogen-based fuels. The following areas were out of the scope of this report and represent outstanding needs that require further investigation:

- Research needed to understand hydrogen and ammonia cost curves and how price hubs will emerge
- Deeper analysis needed to understand resources available for production of hydrogen-based fuels including renewable energy and carbon storage capabilities
- Long-term monitoring capabilities to track developments and watch signpost movement
- Stakeholder engagement through CATF and other advocates to implement recommendations

Introduction and Summary of Current State

Introduction to hydrogen-based fuels and their potential as zero-emission solutions, the current state of ship technology, regulations, and challenges to adoption.

Introduction

The International Maritime Organization (IMO) reports that greenhouse gas (GHG) emissions from global shipping represent more than 3% of annual global emissions, and could grow to as much as 10% of emissions by 2050. While some global shipping fleets transitioned to liquefied natural gas (LNG) in response to the IMO 2020 regulations targeting air pollutants from dirty ships, these efforts are insufficient for long-term decarbonization. The IMO established the target of achieving a 50% reduction in GHG emissions below 2008 levels by 2050.[1]

The transoceanic shipping sector has the potential to implement zero-carbon fuel sources at scale. Carbon-free fuels such as hydrogen (H2) and ammonia (NH3), collectively referred to hereafter as "hydrogen-based fuels," can help solve pressing carbon-emissions problems while working with the grain of modern energy systems. The goal of this project is to better understand the financial, economic, technological, and policy characteristics impacting hydrogen-based fuel source uptake and supply chains.

This report examines a representative set of major international shipping ports and assesses their capacities to produce or bunker hydrogen-based fuel sources from both conventional and renewable feedstocks. Each port's key physical and economic characteristics, the main shipping routes and markets it supports, relevant domestic and international regulations, and the proximity to and/or capacity to access relevant energy resources are analyzed. The report also analyzes macro-level trends and potentials for fuel adoption, including financial engagements, infrastructure capacity, trade agreements, technology capacity, industry coalitions, and policy incentives.

Given the great uncertainties facing a range of stakeholders including global shipping companies, fuel suppliers, port authorities and operators, private and public investors, multilateral organizations, and government decision-makers at many levels, this work is a timely input to encourage the adoption of zero-carbon fuels in the marine shipping industry. This report can be a practical tool for informing industry leaders, policymakers, and investors on near- and long-term decisions regarding zero-carbon pathways in marine shipping.

[1] International Maritime Organization. "Low carbon shipping and air pollution control." Accessed 7 May, 2020. http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx

Summary of Current State

Hydrogen and Ammonia

Hydrogen and ammonia are two of the most promising zero-carbon fuel options in the world for the marine shipping industry, with massively scalable production processes that emit no greenhouse gases. Collective byproducts of burning hydrogen and ammonia as fuels are water, heat, and nitrogen.

Hydrogen: Hydrogen is the most abundant chemical substance in the universe, and the lightest element in the periodic table. It is light, storable, energy-dense, and produces only water as a byproduct when consumed in a thermal process, making it a truly clean fuel. It produces no direct emissions, pollutants, or greenhouse gases when burned, and can be extracted from fossil fuels, biomass, water, or a mixture of the three.[2] Natural gas is currently the primary source of hydrogen production, accounting for roughly three quarters of the 70 million tonnes of annual global hydrogen production.[3]

Hydrogen is primarily produced in two ways: the first is through steam-methane reforming (SMR), a process that splits natural gas (CH4) to derive hydrogen. Steam-methane reforming represents the conventional pathway of hydrogen production, but this process can be paired with carbon capture, utilization, and sequestration (CCUS) to reduce its carbon emissions. The second method is through a technologically simple process of electrolysis, in which a positive (cathode) and negative (anode) separated by an electrolyte membrane split a water molecule into hydrogen and oxygen using an electric current.[4] The electrolysis pathway is attractive because it could result in a "green" hydrogen adoption with zero greenhouse gas emissions in its lifecycle, depending on the source of electricity used. However, electrolysis is the more energy-intensive production method of the two.[5]

Ammonia: Ammonia ranks as one of the most abundantly produced inorganic compounds in the world, with a total of 175 million tonnes created in 2016. Ammonia is a colorless gas with a strong odor that combusts at low fuel-to-air mixture ratios, but can be toxic in moderate quantities. Ammonia consists of nitrogen and hydrogen, and is produced on an industrial level principally through the Haber-Bosch process, in which nitrogen and hydrogen gas react at high pressure. While most of global ammonia production is used to fertilize crops, it is also used in products such as plastics, explosives, and the intermediates for pharmaceuticals. The ease of liquefaction is one of the main advantages that ammonia has over hydrogen.

The Potential for Hydrogen-Based Fuels

Hydrogen and ammonia are highly flexible as energy products. Hydrogen gas can power various types of fuel cells and turbines, and can compete with gasoline in terms of energy density. Hydrogen has nearly three times the energy density of gasoline by mass—120 MJ/kg for hydrogen versus 44 MJ/kg for gasoline. However, on a volume basis, gasoline trumps liquid

[2] US Department of Energy. Office of Energy Efficiency and Renewable Energy. *Hydrogen Fuel Basics*. https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics Accessed May 13, 2020.
[3] IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen. Accessed May 13, 2020.
[4] US Department of Energy. Office of Energy Efficiency and Renewable Energy. *Hydrogen Production: Electrolysis.* https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis. Accessed May 13, 2020.
[5] US Department of Energy. Office of Energy Efficiency and Renewable Energy.*Hydrogen Basics.* https://afdc.energy.gov/fuels/hydrogen_basics.html. Accessed May 13, 2020.

hydrogen, as gasoline has a density of 32 MJ/L, whereas liquid hydrogen only has a density of 8 MJ/L, as shown in Figure 2-1 comparing energy densities of fuels.[6]

The challenge is storing hydrogen. Maintaining pure hydrogen in a liquid form normally requires extreme cooling. There is experimental technology that binds hydrogen with liquid organic hydrogen carriers (LOHCs), which allows hydrogen to be transported under normal temperature and pressure conditions and without the same level of care.[7] Although LOHCs are still hazardous themselves, they are liquid at ambient temperatures and show similar properties to crude oil-based liquids like diesel and gasoline. This means that the handling and storage can be adapted from well-known processes. Nevertheless, LOHC technology and processes are still in their infancy. Thus, converting hydrogen into the more stable state of ammonia is currently the most feasible method of storage and transportation, especially since the ammonia industry has already established mature supply chains and transportation methodologies.

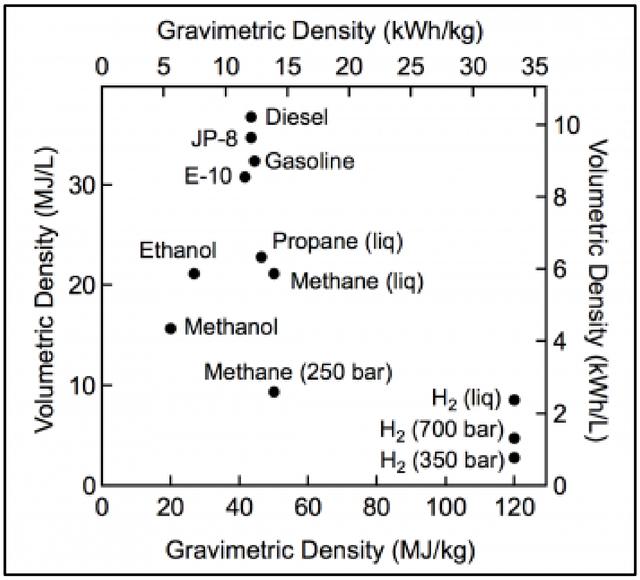
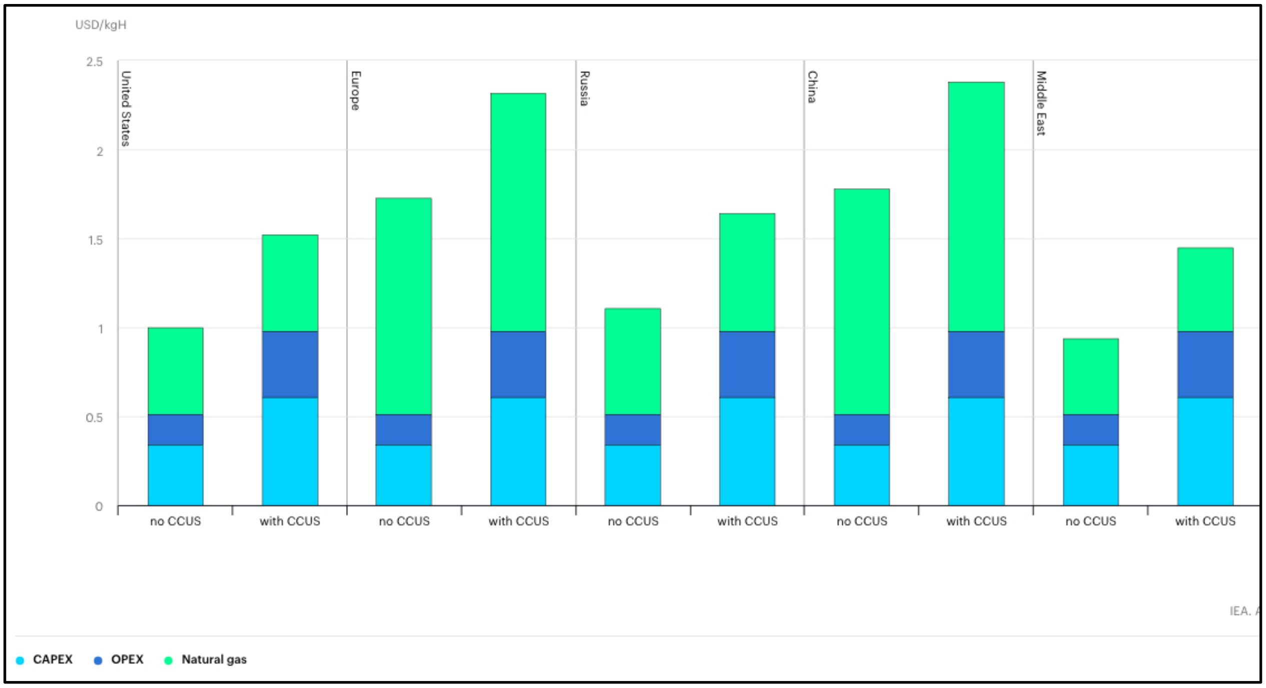


Figure 2-1: Chemical Properties

Ammonia is the more adaptable fuel source compared to hydrogen gas. It can power internal combustion engines, solid oxide fuel cells, and turbines. Internal combustion engines (ICEs) powered by ammonia can be modified to accommodate ammonia either on its own or in a blend with petroleum fuel.[8] However, the downside to ammonia is that it is relatively less energy-dense than hydrogen, with roughly one-half the energy density of gasoline, presenting significant volume and storage issues. However, due to the pressure characterization of ammonia combustion, it can provide close to 20% more power than conventional ICEs.

[6] US Department of Energy. Office of Energy Efficiency and Renewable Energy. Hydrogen Storage. https://www.energy.gov/eere/fuelcells/hydrogen-storage. Accessed May 13, 2020.
[7] Delbert, Caroline. “The First International Hydrogen Supply Chain is a Big Deal”. Popular Mechanics. April 29, 2020. https://www.popularmechanics.com/science/a30338137/first-international-hydrogen-.supply-chain/. Accessed May 13, 2020.
[8] Clean Air Task Force. “Fuels Without Carbon: Prospects and the Pathway Forward for Zero-Carbon Hydrogen and Ammonia Fuels”. December 2018. p. 5.

Figure 2-2: Hydrogen production costs using natural gas in selected regions, 2018[9]



Current State of Ship Technology

The marine sector consumed 3.8 million barrels/day of fuel oil in 2017 and is responsible for half of global fuel oil demand.[10] Most of the current ocean-going shipping fleet uses conventional internal combustion engines that rely on cheap but highly polluting bunker oil that emits carbon dioxide, sulphur dioxide, and nitrogen oxide. The IMO 2020 regulation has created an incentive for shipping fleets to switch to cleaner fuels, and the least expensive and technologically fungible of these fuels is liquefied natural gas (LNG).

Only a few thousand vessels are running on LNG today. Vessels can live 30-50 years, and the older the ship is, the more profitable it is. Retrofitting a ship engine to accommodate alternative fuels is a difficult and costly undertaking. As a result, there is little incentive to switch to LNG unless it becomes cost-competitive with fuel oil. However, the downward trends in LNG fuel prices in combination with IMO 2020 regulations indicate that LNG is becoming increasingly attractive as a fuel source more broadly in the marine shipping sector.

Marine LNG engines are dual-fuel engines that can use both natural gas and petroleum fuel. Although most LNG engines are used on LNG transport ships, large container ships are beginning to adopt LNG engines as well. The conversion of LNG engines to support hydrogen fuel would be costly and complex, as higher pressure standards require different engine specifications. The energy in 2.2 pounds (1 kilogram) of hydrogen gas is about the same as the energy in 1 gallon (6.2 pounds, 2.8 kilograms) of gasoline. Hydrogen has a low volumetric energy density, and so it must be stored onboard a vehicle as a compressed gas, with most

9 IEA. "Hydrogen production costs using natural gas in selected regions". 2018. https://www.iea.org/data-and-statistics/charts/hydrogen-production-costs-using-natural-gas-in-selected-regions-2018-2. Accessed May 13, 2020

10 Wood Mackenzie. "IMO 2020: Mayhem or opportunity?". 2020. https://www.woodmac.com/nslp/imo-2020-guide/. Accessed May 13, 2020.

current applications using high-pressure tanks capable of storing hydrogen at either 5,000 or 10,000 pounds per square inch (psi).

However, ammonia could be readily used in a dual fuel engine, with either a blend of petroleum, natural gas, or on its own. While testing is still at the lab stage, the retro-fitting of LNG engines to support ammonia fuel would not be costly or complex. However, the main challenge for the transition to ammonia fuel is the large amount of storage capacity needed onboard, given ammonia's lower energy density in relation to petroleum-based fuels.[11]

Regulations and Collective Efforts

International standards to reduce emissions from marine diesel engines and their fuels have developed significantly over the last twenty years. The most recent development is the January 1, 2020 International Maritime Organization (IMO) implementation of the ruling that limits the amount of emissions from heavy bunker fuels. Under IMO 2020, the marine sector will have to reduce sulphur emissions by over 80% by switching to lower sulphur fuels. The current maximum fuel oil sulphur limit of 3.5 weight percent (wt%) will fall to 0.5 wt%. IMO 2020 regulations represent the largest reduction in the sulphur content of a transportation fuel undertaken at one time.[12] Most importantly for our study, IMO 2020 categorized ammonia as a transport fuel.

Emission Control Areas (ECAs) play a part in emissions curbing as well. ECAs are sea areas in which controls have been established to minimize airborne emissions from ships as defined by Annex VI of the 1997 MARPOL Protocol.[13]

Countries around the world have different regulations regarding emissions standards and zero-carbon initiatives. For example, European ports tend to be run by state governments, and can take certain financial risks by implementing new technologies without feeling the pressure of profit loss. Norwegian and Danish ports and organizations are very advanced in terms of their thinking on integrating hydrogen into their economies as a result of strong governmental support.

On the other hand, the United States does not have a robust national energy policy, and the responsibility to enforce emissions standards largely falls to states. For example, the states of New York, Texas, and California have varying regulations policies. U.S. ports themselves are fairly powerless in the formal regulation process, as states and ECAs play direct roles. However, several ports analyzed within this report, including the Port of Los Angeles and the Port of New York and New Jersey, participate in collective engagements such as the Environmental Shipping Index (ESI) that incentivizes ships to voluntarily reduce emissions. While modest in scale, programs such as the ESI are advantageous to ships making regular stops along regional coastlines.

The Poseidon Principles are another important step in the financial backing of sustainable energy development. The Poseidon Principles establish a framework for assessing and disclosing the climate alignment of ship finance portfolios, with large and impacting signatories held accountable for their investments in the maritime sector. The Principles provide actionable

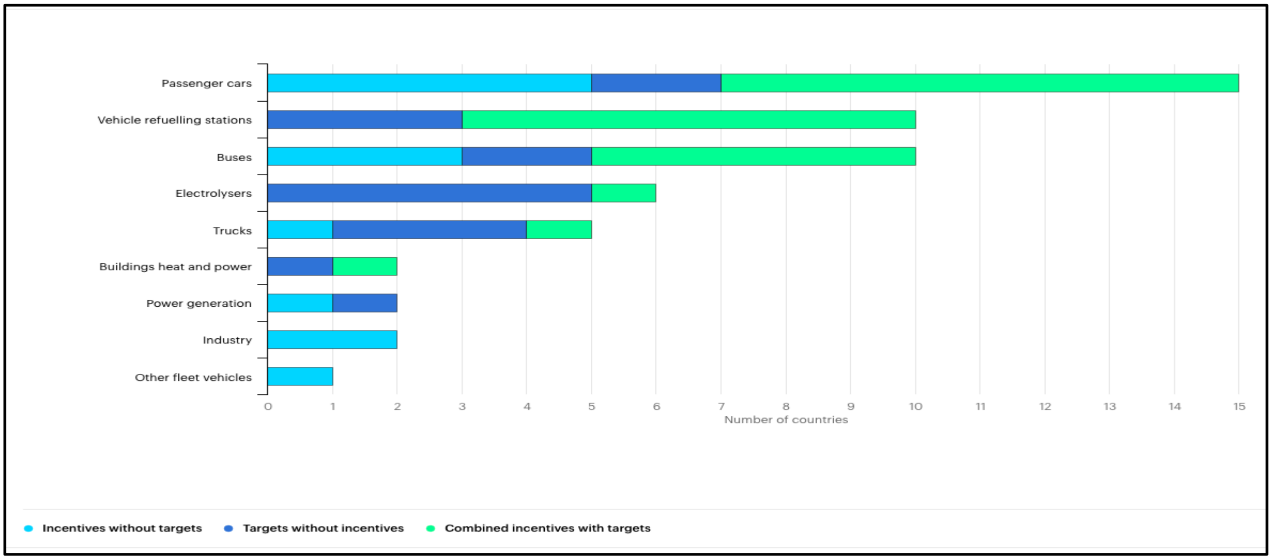
[11] Koivumaa, Vesa. Interview by phone. Conducted by Lauren Kastner, March 25, 2020.
[12] Wood Mackenzie. "IMO 2020: Mayhem or opportunity?". https://www.woodmac.com/nslp/imo-2020-guide/. Accessed May 13, 2020.
[13] International Maritime Organization. "New rules to reduce emissions from ships enter into force". Briefing 23. May 18, 2005. http://www.imo.org/blast/mainframe.asp?topic_id=1018&doc_id=4884. Accessed May 13, 2020.

guidance on how to achieve the goals of the IMO to reduce shipping's total annual GHG emissions by at least 50% by 2050.[14]

Challenges to Adoption

A significant challenge facing hydrogen and ammonia fuel adoption is their present costs. Hydrogen and ammonia are far from global commodities, creating situations where the price of fuel will vary from one port or fueling station to another, conditional on regional and national political and economic realities. Without policy-driven initiatives to mitigate the financial risks to long-term investment in ships, engines, infrastructure, and technologies related to

Figure 2-3: Current policy support for hydrogen deployment, 2018[15]



hydrogen-based fuel adoption, a situation emerges where LNG is a less risky and more affordable choice than zero-carbon fuels. To complicate the situation, shipping companies are not transparent by nature, have very low public visibility, and are slow to adopt new technologies without sizable economic incentives given the long lives of their assets and the difficulty in significantly modifying ship engines once ships have been deployed.

The other significant challenge to hydrogen-based fuel adoption is technological, specifically regarding engine specifications and liquefying hydrogen. Gaseous hydrogen exists in the natural environment, but requires extremely cold temperatures to exist as a liquid. Gaseous hydrogen is liquefied by cooling it to below −253°C (−423°F). Only then can it be stored in large insulated tanks. With today's technology, liquefaction of hydrogen consumes more than 30% of the energy content of the hydrogen, presenting a significant cost. Additionally, some amount of stored hydrogen will be lost through evaporation, or "boil off," especially when using small tanks with large surface-to-volume ratios.[16] Improved liquefaction technology in concert with improved economies of scale could help lower the energy required and the cost.

[14] Rocky Mountain Institute. The Poseidon Principles. 2020.https://www.poseidonprinciples.org/. Accessed May 13, 2020
[15] IEA. "Current policy support for hydrogen deployment". 2018. https://www.iea.org/data-and-statistics/charts/current-policy-support-for-hydrogen-deployment-2018. Accessed May 13, 2020.
[16] US Department of Energy. Office of Energy Efficiency and Renewable Energy. *Liquid Hydrogen Delivery*. https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery. Accessed May 13, 2020.

Because the process of extreme cooling is both energy intensive and technically challenging, the cost of hydrogen as a fuel source in the power and transportation sectors is often much higher than conventional fuel sources. LOHCs mitigate the problem, but are themselves hazardous materials.

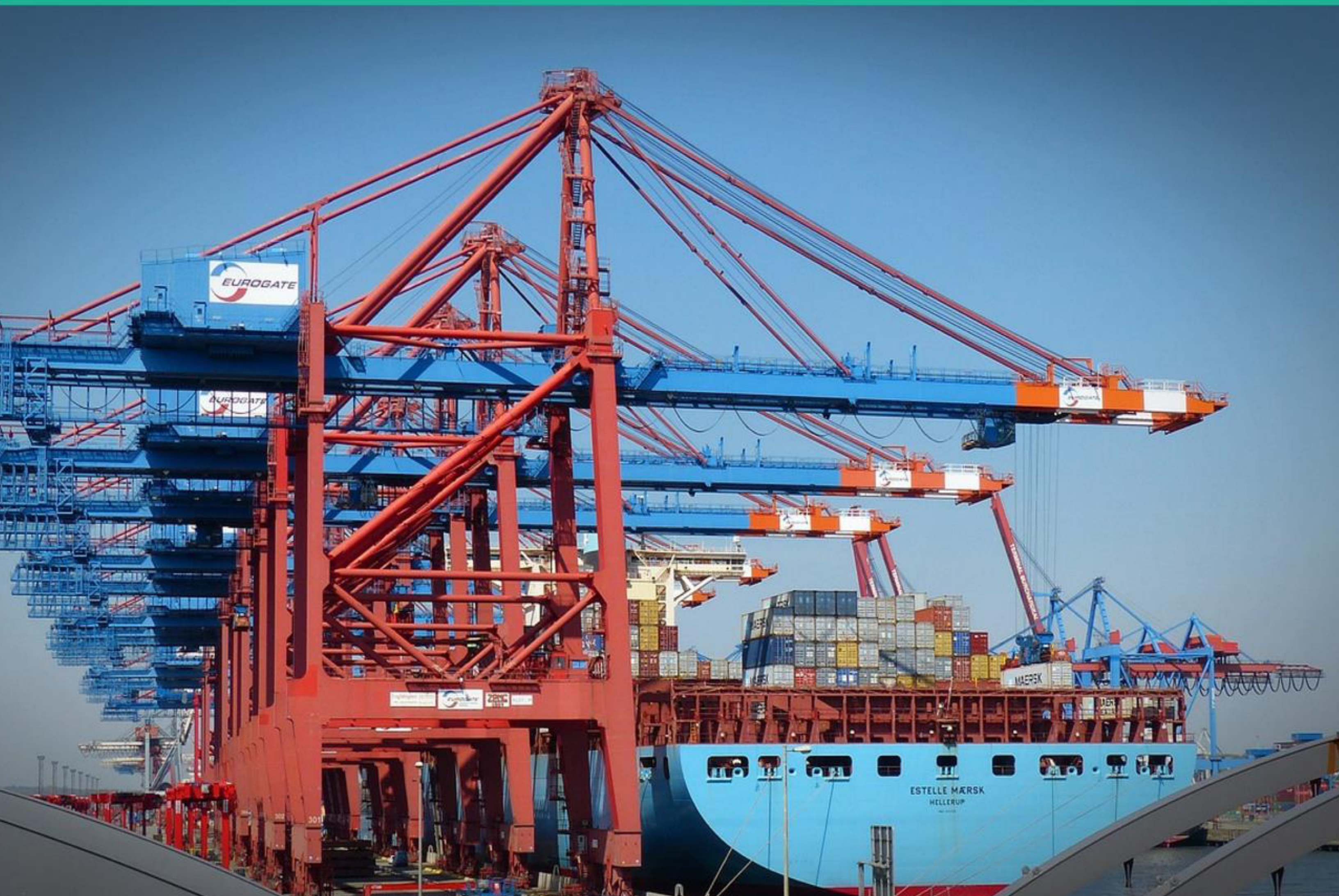
The source of the ammonia is also a challenge, as most of the ammonia produced today is for fertilizer. Because ammonia has an energy density less than half that of petroleum-based fuels, it requires extra storage space, which is in high demand on a container vessel. The ammonia storage tank is one of its biggest hurdles for adoption, rather than the retrofitting of engines.

Additionally, both hydrogen and ammonia have inherent chemical and physical risks. Ammonia is a toxic substance, and hydrogen is extremely flammable. A ship-to-ship collision with hydrogen fuel on board would create a risk of rupture and release of hydrogen into the atmosphere with a potential ignition point.[17] Not only would this situation present risks to human safety, but may also carry significant political and security implications. Fleets will want strict safety measures and testing in place before moving to adopt hydrogen-based fuels.

[17] Pendray, John. Interview by phone. Conducted by Lauren Kastner, March 4, 2020.

Stakeholder Analysis

Overview of stakeholder landscape including Investors, shipping companies, engine manufacturers, fuel producers, policymakers, multilateral organizations, and ports.



Stakeholder Analysis

In order to achieve the full-scale decarbonization of the shipping sector, a number of technologies, policies, operations, and investment decisions must be aligned. In such a complex global sector, no single company or institution can switch to zero-carbon fuels without the support of other stakeholders.

While shipping companies and operators at ports around the world are the primary institutional decision- makers for zero-carbon shipping adoption, there is a rich landscape of stakeholders who have a role to play in order to achieve the long-term objective of a decarbonized shipping sector. The following stakeholder analysis identifies the scope of influence and likely position for each stakeholder involved in zero-carbon shipping. The relationships between stakeholders are depicted in Figure 3-1.

Figure 3-1. Shipping Sector Stakeholder Map

Secondary Stakeholders

While lacking direct decision-making authority over ships, ports and their local governments, the IMO, ship manufacturers, and fuel producers can make decisions to enable the transition to zero-carbon ships. These stakeholders may have different priorities from the shipping companies and can significantly accelerate or hinder progress.

Port Authorities: Ports are the land-to-sea gateways for global marine shipping, meaning and port authorities and the geographic areas that they govern are also critical to the transition to zero-carbon shipping. For the transition to occur, ports would need to enable hydrogen-based fuels to be delivered, bunkered, and permitted within the port environment. While ports around the world are governed differently, they have the ability as pseudo-governmental entities to set some regulations and environmental standards that may positively or negatively impact a shipping fleet’s ability to transition to hydrogen-based fuels. Ports are significant economic drivers for a given region and are primarily interested in remaining competitive and growing trade throughput at the port.

Port City Governments: Regardless of how ports may be governed, local governments adjacent to seaports often have a significant interest in how ports operate, particularly with regard to trade relations, job creation, and environmental performance. Because of the large source of GHG emissions and air pollution associated with ports, the city governments may set regulations or policies targeting emissions at ports that could directly impact shipping fleets and their fuel choices.

International Maritime Organization (IMO): Given the global and highly interconnected nature of the shipping industry, the IMO is the only international body that is able to directly regulate the industry's safety and environmental standards. While policymaking at the IMO is notoriously slow-moving, the IMO is playing an increasingly important role in international climate policy because the shipping sector - is currently excluded from the Paris Climate Agreement. The IMO has set aspirational decarbonization goals through 2050 and will need to establish a more specific framework for shipping decarbonization if it hopes to achieve its long-term goals.

Ship and Engine Manufacturers: Ship builders and engine manufacturers can support a faster transition to zero-carbon shipping through their ability to deliver new technology and products to the market. Manufacturers influence the rate of adoption depending on the ammonia or dual fuel engine performance, cost of equipment, and reliability. Because ammonia or dual fuel-compatible engines will demand a higher upfront capital cost compared to the incumbent technology, manufacturers shape the perception and availability of zero-emission ships and are not only responsible for selling their product, but also selling a new operating system to shipping fleets.

Fuel Producers: Fuel producers play a critical role by making zero-carbon fuels available to the market at commercial scale. Commercial-scale producers of ammonia and hydrogen-based fuels will most likely be the existing oil majors who have a direct stake in the future of fuels. It is the fuel producer's responsibility to supply fuels at a low cost to the market, close to where the fuel will be used, and to ensure that the fuel is produced with zero-carbon emissions on a lifecycle basis. The inability for fuel producers to deliver fuel reliably to the market is one of the most glaring risks discouraging shipping companies from fully adopting zero-carbon fleets.

Fuel Infrastructure Suppliers: In addition to the critical role that fuel producers play in the shipping supply chain, midstream fuel infrastructure companies are essential to ensuring that a viable supply chain exists to deliver zero-carbon fuels from production plants to seaports for bunkering and fueling. Fuel delivery and storage infrastructure is perhaps the most complex and capital-intensive piece of the supply chain. The lack of infrastructure for hydrogen-based fuels is one of the critical risks that will enable or hinder zero-carbon fuel adoption.

Influencers

Influencers are policymakers, companies, non-governmental organizations, and investors that can affect the rate at which zero-carbon ships are adopted, the financial challenges that may be presented by implementation, the technological options available, and the political feasibility of adoption.

Investment Banks and Institutional Investors: Investment banks and institutional investors (i.e. pension funds) support the deployment of zero-carbon shipping by bringing enormous pools of capital to the sector. There are points of new investment throughout the supply chain, including commercial-scale ammonia and hydrogen production plants, renewable energy projects to power fuel plants, fuel delivery infrastructure, pipelines, storage, CCUS projects, and new clean fleets of ships. The ability to de-risk these investments and find a business model that serves creditworthy companies is essential to making the fuels commercially viable.

Infrastructure Banks: Infrastructure banks serve an important role in delivering low-cost capital for targeted infrastructure priorities such as fuel delivery infrastructure. Infrastructure banks will play a particularly important role in financing ammonia and hydrogen fuels in regions that otherwise do not have sufficient access to capital or where incumbent infrastructure is underdeveloped.

National Ministries of Energy and Environment: National governments and their ministries of energy and environment set the high-level energy priorities and policies in a given country. A country may choose to set a range of policies that would impact zero-carbon shipping, including but not limited to: establishing minimum blend volumes on the production and use of zero-carbon fuels, enacting carbon pricing, setting emissions standards for ports and the shipping sector, setting renewable energy targets, or developing hydrogen production corridors. In some cases, energy and environment ministries may provide upfront low-cost capital for research and development, as well as demonstrations of technology.

Industry Associations: Industry associations or business consortiums allow for many industrial players with shared interests to self-organize with the goal of advancing hydrogen development and deployment. Industry associations serve the purpose of uniting behind a common position or viewpoint on various policies and pathways for hydrogen-based fuels. Members of industry associations commonly include shipping companies, fuel producers, and engine manufacturers. Industry associations are powerful lobbies that can influence the direction of national governments, ports, IMO, and the investment community.

Retailers / Shipping Customers: Shipping customers such as large retailers or consumer goods companies can influence the decisions of shipping companies. Shipping customers that are concerned about GHG emissions in their supply chain may set supplier specifications that force shipping companies to reduce emissions in their supply chain by choosing a hydrogen-based fuel. As large shipping customers increase their focus on environmental social governance (ESG) reporting and investing and supply chain transparency, more pressure may build for shipping companies to voluntarily invest in zero-carbon fuel technologies.

Other Sector Users of Hydrogen: The shipping sector is not the only sector that will demand zero-carbon hydrogen-based fuels. The use of hydrogen is expected to grow in the power sector and other land-based transportation sectors with the advancement of fuel cell technology. For this reason, other users of hydrogen will play a role in shaping both the supply and demand for hydrogen. Additional demand for hydrogen will positively impact the ability for hydrogen production to reach commercial scale. These stakeholders such as truck and auto manufacturers should be engaged by the shipping sector to strategically invest in and deploy hydrogen production where it is most needed.

Research and Development Institutes / Universities: Research organizations are well-positioned to deliver new technology advancements and important basic science findings regarding fuel production methods, fuel performance characteristics, engine and combustion technology, and engineering science for fuel storage and carbon capture. The ability for ship and engine manufacturers, fuel providers, and ports to work with R&D organizations such as universities in their respective countries will be beneficial to the deployment of the best-fit technology.

Environmental Groups and NGOs: Environmental groups and NGOs promote policy and technology changes that will reduce carbon emissions and local air pollution through their advocacy work. These groups have no direct influence on the adoption rate of zero-emission shipping but exert strong grassroots and political influence over policy and can provide expertise and credible views on the market.

Labor Groups: Labor groups such as longshoreman and maritime workers unions that represent workers at ports are influential in any decisions that could change the way that ports operate or require job skill retraining for the port workforce. As ports, shipping companies, and fuel suppliers begin using hydrogen-based fuels at ports, labor groups can play a role in either accelerating or hindering the adoption of such fuels. Labor groups will need to be engaged in shaping the direction of port operations, job requirements, and safety protocols for the use of zero-carbon fuels in shipping.

Technology and Infrastructure Evaluation

Fuel pathways, cost curves, differentiated methods of obtaining ammonia and hydrogen, and a review of what hydrogen-based fuel production might cost.

Technology and Infrastructure Evaluation

To understand the potential pathways for ports and shipping companies to adopt a hydrogen-based fuel, it is also important to analyze and recognize the technological and infrastructure feasibility of the energy transition. Not all ports and port countries have the same engineering capability to produce a hydrogen-based fuel. Some may have the upstream, midstream, and downstream advantage of procuring a hydrogen-based fuel, while others may only have the capacity to play a role in one aspect of the supply chain. Furthermore, not all paths to a hydrogen-fuel are the same, as there are multiple methods to procure the fuel.

Not all Hydrogen created is equal: The Three Methods of Production

The "Grey" Method

In the petrochemical industry, hydrogen is most often derived from natural gas (CH4), commonly known as *grey hydrogen.* This process utilizes steam methane reforming (SMR) technology in which CH4 is passed through a catalyst while reacting with high-temperature steam (700C to 1000C) to produce hydrogen, carbon monoxide (CO), and carbon dioxide (CO2). The process uses CH4 almost exclusively as a feedstock.[18] The CO then goes through another catalyst with steam to produce more hydrogen and CO2.

In order to produce ammonia (NH3), the hydrogen would have to undergo ammonia synthesis, also known as the Haber-Bosch process.[19]The NH3 would then be stored and transported to buyers of the product.

The SMR method of producing ammonia accounts for 95% of U.S. hydrogen, but the process has severe environmental downsides due to the release of CO2 as a by-product. As such, this type of NH3 is labelled as "*grey*."

Steam-methane reforming reaction

$CH_4 + H_2O$ (+ heat) → $CO + 3H_2$

Water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

Carbon Emissions are not reduced

The "Blue" Method

This method of production is very similar to the *grey method*, as it also utilizes the same SMR technology and Haber-Bosch process. However, the *blue method* is greatly different from the *grey method* in that it employs the use of carbon capture, utilization, and sequestration (CCUS) during the procurement process. CCUS would effectively reduce the carbon emission of ammonia production, making it a potential pathway in achieving ZCF. The downside however, is the additional cost associated with CCUS. The capital expenditure to create *blue hydrogen* is financially and energy exhausting.[20] Furthermore, as natural gas is used as the feedstock, some

[18] "Hydrogen Production: Natural Gas Reforming." Energy.Gov, 2019, www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming. Accessed 14 May 2020.
[19] "Hydrogen Production: Natural Gas Reforming." Energy.Gov, 2019, www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming. Accessed 14 May 2020.
[20] Adolf, Jorge, et al. ENERGY OF THE FUTURE? Sustainable Mobility through Fuel Cells and H 2. Shell Deutschland Oil GmbH.

would argue that producing hydrogen with such a method is inefficient, as it would be less expensive to use natural gas as a fuel product instead. Given the technological and financial constraints, policies to force the reduction of GHG emissions in the shipping industry as well as financial incentives for the energy transition would be needed to make *blue ammonia* a competitive fuel source.

Nonetheless, the *blue method* is currently the most likely production method for zero-carbon ammonia from a technology standpoint, as the existing infrastructure is already in place.

Steam-methane reforming reaction

$CH_4 + H_2O$ (+ heat) → $CO + 3H_2$

Water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

Carbon Emissions are reduced through the use of CCUS technology

The "Green" Method

Apart from the SMR and CCUS technology, hydrogen and ammonia could also be produced through renewable energy sources such as solar and wind power. The process starts at an electrolyser plant, where electric current produced by a renewable energy source runs through water, splitting it into hydrogen (H2) and oxygen (O2). This is known as electrolysis, where a negative anode attracts a slightly positively charged hydrogen atom through an electrolyte membrane, while the oxygen remains at the positive cathode of the electrolyser.[21] After separation, oxygen is emitted back to the atmosphere, while hydrogen is collected for further use.

At the same time, nitrogen is produced at an adjacent air separation unit. Both hydrogen and nitrogen are then stored onsite and sent to an ammonia synthesis facility, which utilizes the Haber-Bosch method much like the *grey and blue methods* for ammonia production. The key difference with the *green method* is its net-zero carbon emissions in the hydrogen or ammonia production process.

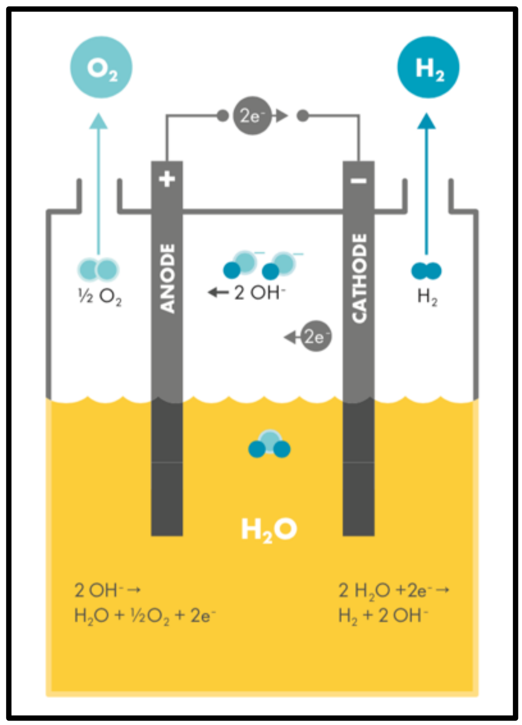


Figure 4-1: Hydrogen Electrolysis Process

Ideally, the *green method* would utilize renewable energy as its electricity source, giving it its "green" status, and the renewable electricity for this process could be sourced in two ways.

[21] "Hydrogen Production: Electrolysis." Energy.Gov, 2019, www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis. Accessed 14 May 2020.

The first is exemplified by a hydrogen or ammonia plant that has renewable energy sources on site such as solar panels that would be used to power the plant. While using renewables to generate electricity would be preferable for the electrical grid system, the process would be costly, with large project financing and upfront investment requirements that many investors and producers would not be willing to undertake given the infancy of the hydrogen market.

The second way that renewable energy could be sourced to produce green hydrogen or ammonia would be from grid electricity. This is with the caveat that it is produced in a country with high renewable deployment in its grid, and that there are high-levels of curtailment from renewable energy during low-demand. As such, hydrogen would be used as a storage option for the curtailed energy.

Figure 4-2: Conceptual Layout of a Green Ammonia Plant [22]

Blue vs. Green: Factors of consideration

While *green* ammonia utilizes carbon neutral feedstock to produce ammonia, *blue* Ammonia also has the potential to be a zero-carbon fuel depending on the efficiency of its CCUS technology implementation. As such, ports do not necessarily have to only explore *green* ammonia pathways. Rather, the decision between the production of *blue* and *green* ammonia would be dependent on a number of factors.

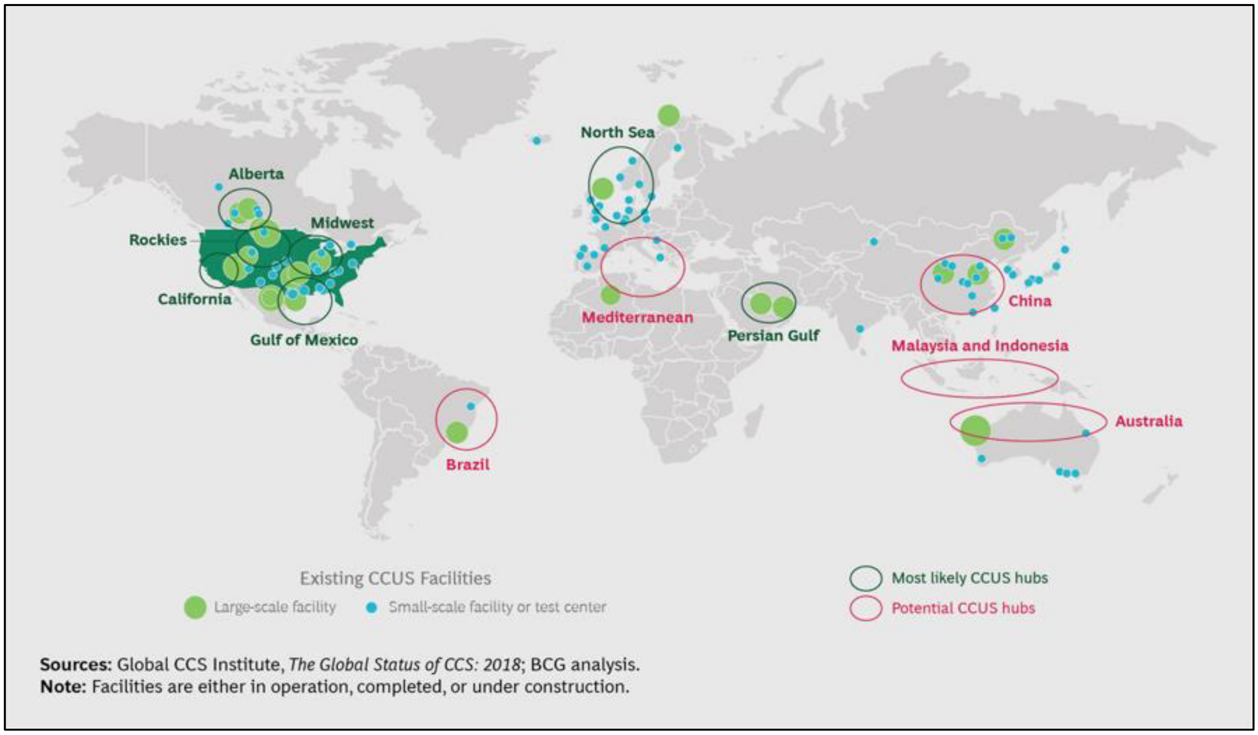
Geographic Advantage

As with any energy source, geography plays a key factor in the procurement process of a hydrogen-based fuel. Firstly, not all ports will have the same geographic advantage for producing hydrogen and ammonia onsite, and will therefore have to source their hydrogen-based fuel from their country or trade routes. The geographic criteria in producing *blue* or *green* ammonia therefore pertain to a region that could be easily accessed by ports.

[22] Dewar, Alex, and Bas Sudmeijer. “The Business Case for Carbon Capture.” Boston Consulting Group, 24 Sept. 2019.

For *blue* ammonia, the geographic requirements are less restrictive than for *green* ammonia. The natural gas feedstock for *blue* ammonia is easily transportable, unlike the renewable energy infrastructure needed to produce *green* ammonia. *blue* ammonia could be procured as long as infrastructures such as pipelines for transporting natural gas, steam methane reforming facilities, and CCUS technology are available. However, in the case of CCUS, it would be geographically limited as it is heavily dependent on the region's geological capability to store carbon safely and cost-efficiently. To date the central and mountain regions of the US, the North Sea, China, Australia, and the Persian Gulf have been leading carbon capture with large scale CCUS facilities. Other regions such as Japan have slowly adopted the technology, but at smaller capacities.

Figure 4-3: CCUS Capacity, Potential Regional Hubs [23]



Green Ammonia would depend on the renewable energy used for the electrolysis process. If the green ammonia plant plans to utilize solar power, the facility would need to be located in a region with ample sunshine and large tracts of land. For wind power, the ammonia plant would have to be constructed in a region with significant wind energy.

Storage for Transportation of Hydrogen and Ammonia

For a port to effectively adopt a hydrogen-based fuel as one of its main fuel supplies for deep sea shipping, it would need to invest in storage and transportations. Since hydrogen and ammonia both pose potential risks, the storage and transportation infrastructure must meet standardized safety requirements. Hydrogen is a highly volatile and extremely flammable molecule in its natural state. There are currently four specialized storage methods for hydrogen.

[23] Dewar, Alex, and Bas Sudmeijer. "The Business Case for Carbon Capture." Boston Consulting Group, 24 Sept. 2019.

Compressed Gaseous Hydrogen, CGH_2. At the downstream level, when transporting hydrogen to end-users, the fuel would have to be stored in a reinforced steel composite pressure vehicle that could withstand up to 1000 bars of pressure.[24] Furthermore, the storage vessels would have to be able to withstand the heat induced by the pressure due to Boyle's Law. Industrially, tube trailers (withstand up to 250 bars) and container trailers (withstand up to 500 bars) are already transporting hydrogen in small- to medium-amounts.

Storing hydrogen in a standard low-pressure storage tank (50 bars) would be inefficient because of hydrogen's low density. To make storage and transportation efficient from a cost-per-trip perspective, hydrogen fuel companies will need reinforced steel-composite pressure vehicles, so that they can transport the maximum volume of hydrogen in a single trip. The risk associated with this method of storage and transportation is that in an accident, the hydrogen could easily ignite.[25] To date, it takes the equivalent of 9 to 12 percent of the energy from the produced hydrogen to compress a storage tanker to 350 to 700 bars, carrying 25 g/l and 40g/l, respectively.[26]

Liquefaction Hydrogen, LH_2. In this storage process, the supplier would need to freeze the hydrogen to -253 degrees Celsius. In contrast to CGH_2, LH_2 requires highly insulated storage vessels along with a technical plant to carry out the freezing process, requiring additional financial costs.[27] Currently, liquid trailers specialized for cryogenic logistics could transport up to 4000kg in one trip.

Additionally, the storage would not have to account for the same level of pressure as CGH_2, since the LH_2 process would only amount to 1 bar of pressure in the tanker. However, the amount of hydrogen transported would be denser at 70 g/l, in comparison to the compressed state. Furthermore, the benefit of this method is its wide-scale application in space travel, making it a safe form of hydrogen storage. The downside, however, is the 30 percent loss in energy yield when freezing the hydrogen to -253 degrees Celsius.[28]

Cold and Cryo-Compressed Hydrogen (CcH_2). In this storage process, the two previous storage methods are employed, first with freezing and then compressing.

The freezing process occurs first due to Gay-Lussac's Gas Law, which states that the volume of a gas held at constant pressure changes proportional with temperature. As such, if the hydrogen is frozen, the volume of the gas in the storage tank would decrease. More hydrogen would then be injected while undergoing the freezing process. The cycle would continue until the storage tank is full. In comparison to CGH_2 and LH_2, the CcH_2 process has the highest energy density but is not presently industrially utilized.

Slush Hydrogen (SH_2). This storage process freezes hydrogen to its solid state at -259 degrees Celsius, making it 16 percent denser than liquid hydrogen. This method is currently in its R&D phase.

Apart from the four main methods of physically storing hydrogen, there are chemical reactionary processes as well. The predominant method is feeding hydrogen into a catalyst that bonds three hydrogen atoms to one nitrogen atom, effectively creating ammonia. As a result, ammonia is industrially considered to be a storage medium for hydrogen.

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[24] Adolf, Jorge, et al. ENERGY OF THE FUTURE? Sustainable Mobility through Fuel Cells and H 2. Shell Deutschland Oil GmbH.
[25] Ibid.
[26] Ibid.
[27] Ibid.
[28] Ibid.

In contrast to hydrogen, ammonia is currently being transported in bulk globally either in its liquid or gaseous state. Liquified Petroleum Gas vessels are used for maritime transport of ammonia, a well-established trading practice.[29]

Cost Evaluation for Hydrogen-Based Fuels

Cost Outlook for Hydrogen

Although hydrogen has been used in the petrochemical industry for decades, its use as a commercial fuel for transportation is still in its infancy, and there is not yet an established commodity market for *blue* and *green* hydrogen. Additionally, the cost for each hydrogen production pathway varies, dependent on location and method of procurement.

As of 2020, the cost for producing *green* hydrogen sits between $2.50 and $6.80 per kg. *Blue* hydrogen, by contrast, costs between $1.40 to $2.40 per kg.[30] $2 per kg of hydrogen is roughly equivalent to $15/MMbtu.[31] In contrast, the spot market price for natural gas in May of 2020 was between $1.6 to $2.1/ MMbtu. Based on these costs, it is evident that both *green* and *blue* hydrogen are not cost-competitive with natural gas in the current market. A scaled-up hydrogen industry would drastically push down the cost of production.

Bloomberg New Energy Finance predicts that the cost of green hydrogen in China, India, and Western Europe, would meet $2/kg in 2030 and $1/kg (equivalent of $7.4/MMbtu) in 2050.[32] Furthermore, costs would be 20 to 25 percent lower in countries with cheaper renewable and hydrogen storage, such as the US, Brazil, Australia, Scandinavia, and the Middle East.[33] On average, global green hydrogen could be $0.7 to $1.6/kg (equivalent of $6 to $12/MMbtu of natural gas) by 2050.

The Hydrogen Council had a more aggressive outlook as they forecasted *green* hydrogen to cost $1.20/kg in regions such as Australia and Saudi Arabia. Alternatively, the council believes that Northern Europe would be producing green hydrogen at $2.5/kg.[34] *Blue* hydrogen may be cost-competitive more quickly and reach $1.20/kg by 2025 in the US and in the Middle East.[35]

Cost Outlook for Ammonia

While hydrogen is a needed chemical for producing *blue* or *green* ammonia, the ammonia market is already fully developed for agricultural and industrial purposes. Between 2015 and 2017, the International Fertilizer Association estimated that 175 million tonnes of ammonia were produced in the US.[36] As of April 2020, the price of ammonia on the spot market was approximately $500 per ton (while the price for April 2019 was $600 per ton).[37] Given the maturity of the ammonia market and the established trading guidelines in chemical's handling, ammonia would be an easier logistical transition as a ZCF for maritime sectors.

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[29] *Ash, Nick, and Tim Scarborough. Sailing on Solar: Could Green Ammonia Decarbonise International Shipping.*
[30] Collins, Leigh. "A Wake-up Call on Green Hydrogen: The Amount of Wind and Solar Needed Is Immense | Recharge." Recharge | Latest Renewable Energy News, 19 Mar. 2020, www.rechargenews.com/transition/a-wake-up-call-on-green-hydrogen-the-amount-of-wind-and-solar-needed-is-immense/2-1-776481. Accessed May 14, 2020.
[31] Hydrogen Economy Outlook Key Messages. Bloomberg New Energy Finance, 20 Mar. 2020.
[32] Ibid.
[33] Ibid.
[34] Ibid.
[35] Hydrogen Council, and McKinsey. Path to Hydrogen Competitiveness A Cost Perspective. Hydrogen Council, Jan. 2020.
[36] Ash, Nick, and Scarborough, Tim. *Sailing on Solar: Could Green Ammonia Decarbonise International Shipping.*
[37] Widmar, David. "Fertilizer Prices Fall to Lowest Levels in a Decade, Economist Says." Successful Farming, 6 Apr. 2020, www.agriculture.com/news/crops/fertilizer-prices-fall-to-lowest-levels-in-a-decade-economist-says. Accessed May 14, 2020.

Although ammonia is already widely produced, it would require further investments and growth to meet the demand of shipping companies, should 100 percent of deep-sea ships transition to using ammonia. This would lead to an approximate 1.4 million tonnes of ammonia consumption per day, or 511 million tonnes per year. To achieve this level of production, there would need to be an increase of *blue* and *green* ammonia facilities.

The cost to build a green ammonia plant that could produce 700 tons per day is estimated to be between $620 and $791 million.[38] It would be able to provide the daily fuel consumption for 4 post-Panamax size vessels.[39]

It should also be noted that since *blue* and *green* ammonia are dependent on the production cost and method of *blue* and *green* hydrogen, ammonia will be cheaper as the hydrogen industry scales up. To achieve the production level of 511 million tonnes per year, there would be multiple factors to consider to determine the cost of *blue* or *green* ammonia (and hydrogen).

Factors for Consideration for Calculating Costs

I. **Levelized Cost of Storage (LCOS)**: Apart from the production cost, future hydrogen and ammonia suppliers will have to account for the LCOS, the additional costs of which manufacturers will assume when delivering ammonia to ports.

Figure 4-4: Current LCOS Prices[40]

	Gaseous state				Liquid state			Solid state
	Salt caverns	Depleted gas fields	Rock caverns	Pressurized containers	Liquid hydrogen	Ammonia	LOHCs	Metal hydrides
Main usage (volume and cycling)	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small volumes, daily	Small - medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks	Small volumes, days-weeks
Benchmark LCOS ($/kg)[1]	$0.23	$1.90	$0.71	$0.19	$4.57	$2.83	$4.50	Not evaluated
Possible future LCOS[1]	$0.11	$1.07	$0.23	$0.17	$0.95	$0.87	$1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

II. **Levelized Cost of Electricity (LCOE) and Power Purchasing Agreements (PPA)**: The development of electrolyzers for *green* hydrogen production is highly dependent on the renewable energy source. If the *green* ammonia plant uses the main grid as its electricity source, its cost of production will correlate with the LCOE of renewable energy within the country. Australia, for example, would have lower costs in production due to its low LCOE.[41] Furthermore, the *green* ammonia plant would need to purchase a form of renewable energy credit to ensure that the electricity used from the grid is from a renewable source, compounding additional costs.

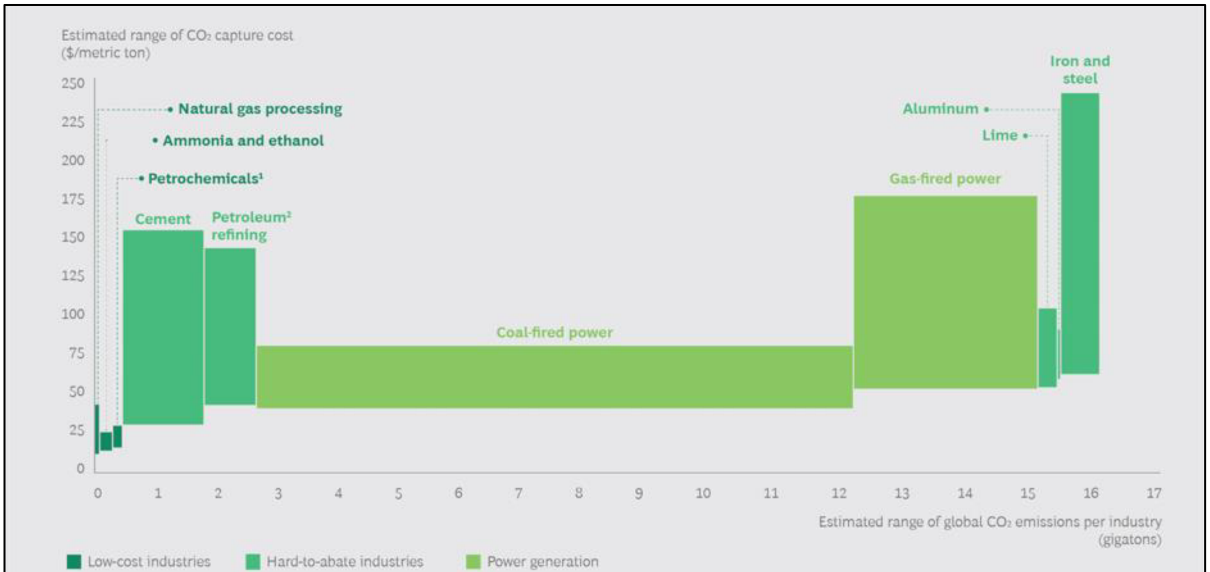
[38] Ash and Scaborough
[39] Refer to Appendix
[40] Hydrogen Economy Outlook Key Messages. Bloomberg New Energy Finance, 20 Mar. 2020.
[41] Hydrogen Economy Outlook Key Messages. Bloomberg New Energy Finance, 20 Mar. 2020.

If the green ammonia plant is constructing its own renewable energy sources onsite as distributed generation, its cost of production would then be correlated to the PPA prices of the country. The lower the PPA price, the lower the production cost. Australia, to continue the example, would likely be able to produce low-cost hydrogen due to its low PPA prices.[42]

III. Cost of CCUS:

The cost of *blue* hydrogen production would correlate to the cost of CCUS, and how efficient the carbon capture technology could be paired with ammonia production. To date, the dollar per metric ton of carbon captured varies depending on the refining and burning process of the distillate. In the case of ammonia, it costs less than $25/metric tons to store carbon. By comparison, carbon capture for natural gas costs between $35 to $45/ metric ton. Carbon capture for ammonia production is already competitive in current markets as a result, and the price will only decrease as CCUS technology is scaled in conjunction with *blue* hydrogen production.

Figure 4-5: Three Market Segments for Carbon Capture[43]

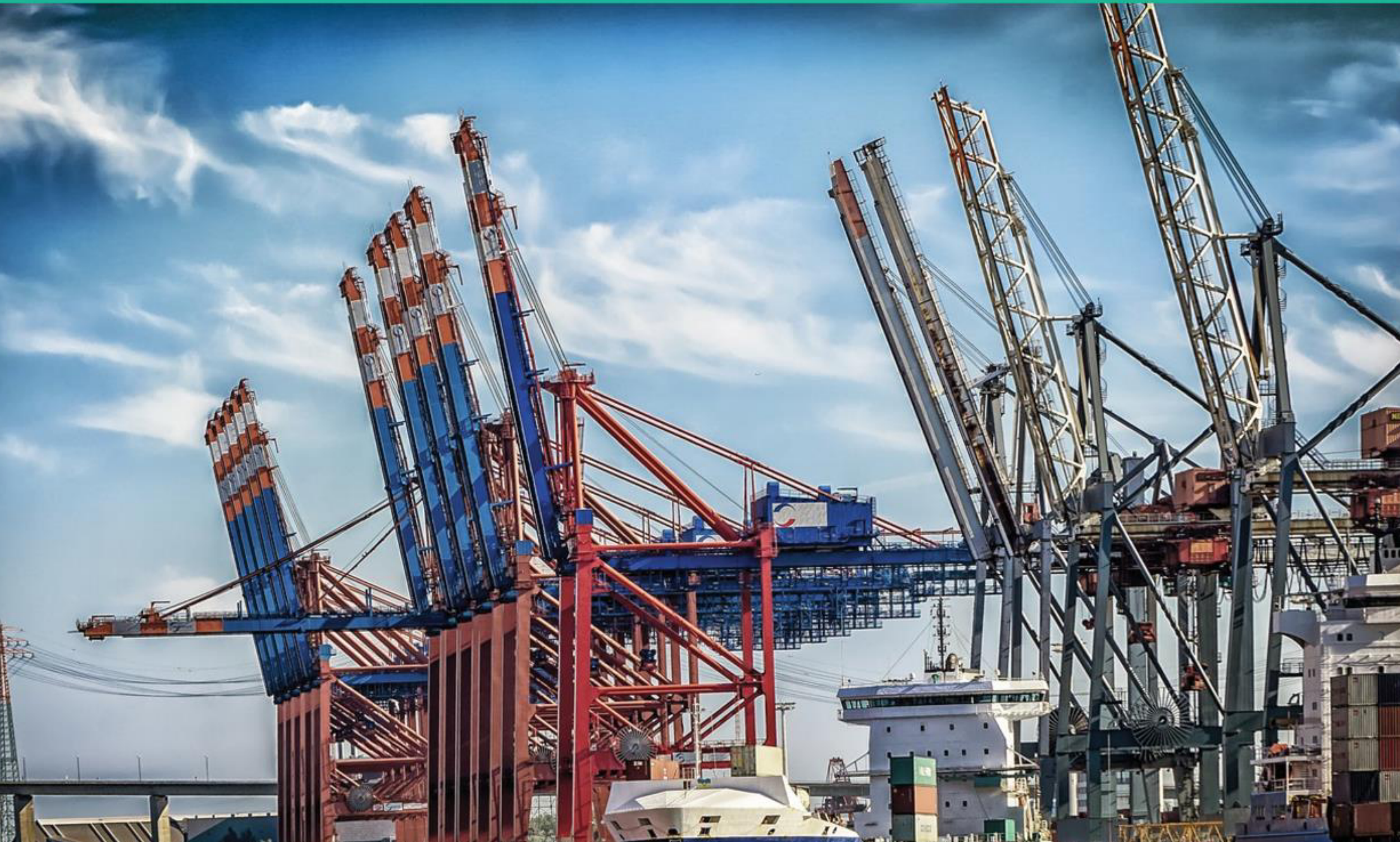


Sources: BCG proprietary carbon capture model–estimated cost ranges are based on published literature and public statements; sector-specific emissions data is based on International Energy Agency estimates.
Note: Exploration and production (E&P) is excluded from curve owing to lack of cost estimates. Cost curve reflects range of estimates and excludes some outliers, so it should be considered illustrative.
¹Only includes high-concentration CO_2 streams.
²Includes emissions from fossil-based hydrogen production (i.e., from steam methane reforming).

[42] Wood Mackenzie. "The Future for Green Hydrogen." Www.Woodmac.Com, Wood Mackenzie, 25 Oct. 2019, www.woodmac.com/news/editorial/the-future-for-green-hydrogen/. Accessed May 14, 2020.
[43] Dewar, Alex, and Bas Sudmeijer. "The Business Case for Carbon Capture." Boston Consulting Group, 24 Sept. 2019.

Port Evaluation

Metrics and profiles of over 10 international ports.



Port Evaluation

Port Metrics

This report examines a representative set of major international shipping ports to assess their ability to catalyze a transition to hydrogen-based fuels in the shipping sector. While ports cannot unilaterally force a shipping fleet to fuel-switch, ports are a critical connection point between the supply and demand of hydrogen-based fuels. Because of the inherent global nature of the shipping industry, multiple ports around the world will need to be able to deliver hydrogen-fuel to complete the shipping value chain. The ability for a port to produce or bunker hydrogen-based fuel sources from both conventional and renewable feedstocks may be the deciding factor for a shipping company to invest in hydrogen-based fuel ships with certainty that a ship will have end-to-end access to fuel.

In order to provide a clearer picture of the current state and assess the future potential of a port to transition to hydrogen-based fuels, a uniform set of metrics was applied to each major port. Ports were selected and analyzed using the metrics described below. The subsequent section presents a profile of each port analyzed and assesses the feasibility for the port to be a first-mover.

Metric 1: Trade with Critical Shipping Routes

Well-connected ports are essential to minimize shipping costs and foster sustainable development. Trade with critical shipping routes is an important metric when evaluating the potential for an international port to be a first-mover in the global markets. The intuition behind this conclusion is simple: the more trade there is with critical shipping routes, the better an international port can push the entire industry to adopt zero-carbon shipping regulations when the switch to hydrogen and ammonia fuel source is possible.

The analysis begins by determining the largest markets served by the continent and then determining the magnitude of trade in those markets, looking at a particular international port's global connectivity score as ranked by the UNCTAD.

Metric 2: Port's Technological Accessibility of Hydrogen and Ammonia

As this project assesses the feasibility of using ammonia as the primary fuel source for the maritime industry, it is important to evaluate each port's technological accessibility to hydrogen and ammonia. In other words, do the major ports (examined in Section 6) display the fundamental engineering elements to provide ammonia for ships? When analyzing the ports, this paper recognizes that countries are not equal in their geography, energy access, and vision in terms of producing hydrogen. As such, this report will break down two different pathways and standards to evaluate a shipping port's technological ability to be an energy hub of hydrogen and ammonia.

Capacity to Procure and Transport Hydrogen and Ammonia

When evaluating each port in their feasibility to become a hub for hydrogen and ammonia, we look toward the region's potential to produce and transport the energy source. The procurement and supply chain is measured by its capability to produce *grey, blue, or green hydrogen.* Once hydrogen is procured, it undergoes synthesis, creating ammonia. The ammonia would then be used as the final fuel source for trans-oceanic shipping.

Role of Storage and Distribution of Hydrogen and Ammonia

As mentioned, not all port countries have the geographic and energy accessibility to procure hydrogen. For example, Singapore is constrained by its land size and energy import, and therefore would not necessarily have the engineering ability to produce hydrogen and ammonia. Given this fact, Singapore is unlikely to meet the aforementioned pathway to become a hydrogen hub.

Instead, ports such as Singapore could become hydrogen importing hubs, storing and distributing the fuel. This would also be exceptionally beneficial in establishing a global supply chain for hydrogen, as many of the potential hydrogen producers, such as Tasmania, do not necessarily have the trade routes in place for distribution.[44]

Metric 3: Hydrogen Policy Support

Policy support for hydrogen-based fuel policy is evaluated by the presence and strength of the following factors:

1. **Published hydrogen development roadmaps**
2. **Funding Initiatives**
3. **Government Regulations**
4. **Private Business Initiatives**
5. **Port Specific Initiatives**

1. **Published hydrogen development roadmaps:**
   Hydrogen development roadmaps provide the most concrete evidence that the target country, business, or port is exploring the integration of hydrogen into its operations. These roadmaps would take the form of reports published by the government, business, or the port itself. These reports should outline the specific organization's thinking on the impacts, opportunities, and risks presented by the transition to a hydrogen-based economy or operations. However, not all reports are created equal. An ideal report would present three broad categories of considerations that identify a) the hydrogen procurement source, b) the uses of the hydrogen, and c) policy considerations to achieve the hydrogen goals.

2. **Funding initiatives:**
   Committed funding from government sources is also concrete proof of policy support for hydrogen energy solutions. Specifically, these funds should come from government or public sources, as opposed to business investments. Governments allocating taxpayer money to fund the hydrogen transition would transform plans into action. Thus, the ideal funding initiative would outline the amount of money committed, whether or not the money is being disbursed, and which organizations are receiving the funds.

3. **Government regulations:**
   Government regulations act to encourage greater adoption of hydrogen solutions, and fall into two broad categories:

[44] Tasmanian Renewable Hydrogen Action Plan. https://www.stategrowth.tas.gov.au/__data/assets/pdf_file/0003/207705/Draft_Tasmanian_Hydrogen_Action_Plan_-_November_2019.pdf. Accessed May 14, 2020.

- Targets for hydrogen production or procurement. The government can set a specific volume of hydrogen to be produced or imported by a certain date in order to give organizations guidance on the country's priorities for energy solutions.
- Renewable fuel policies (or low carbon fuels) or mandates that compel companies within the country's borders/under the country's flag to incorporate renewable fuels into their vehicle fleet. In addition, incorporating hydrogen or ammonia as a renewable fuel solution (as opposed classifying it as a chemical) would further strengthen policy support for hydrogen fuels.

4. **Private business initiatives:**
   Private businesses have a strong role to play in the transition to hydrogen-based fuel solutions. Companies in the fuel, automotive, shipping, and power industries are looking to integrate hydrogen into their operations. Metrics including the amount of investment, company roadmaps, or identification of potential partners would demonstrate how much each company values hydrogen solutions and the concrete steps that they are taking. The presence of any procurement plan for hydrogen would be a good reflection of private business engagement in the target country.

5. **Port-Specific Initiatives:**
   Port specific initiatives give an idea of the localized development goals of each port and the expected trajectories of investment decisions over medium- and long-term time horizons. With international trade zones, ports can often have objectives and policies that differ substantially from their home country's general policies. Ports with stated clean energy development plans are rated more highly because they are reasonably more likely to initiate plans and act more quickly than those with no stated intentions. Ports within collective initiatives are also rated more highly due to the strategic partnerships and shared goals those initiatives create. Essential criteria for port-specific initiatives are:

   - Specific and enforceable policies already in place at ports: Emission control areas (ECAs)
   - Stated initiative that is part of a port's development plan and that it intends to see through
   - Collective initiative between national/international ports that guides its development goals

Metric 4: Economic Data at Port

Seaports perform many critical services for adjacent cities and coastal countries, and the most significant of those services is acting as a major economic driver. Ports enable the movement of goods and raw materials in and out of a given region by serving as a hub for various modes of transport including shipping vessels, container railways, and over the road trucking. The ability for industry to easily and predictably move goods in and out of a port is one of the essential requirements of a strong commercial sector in any country.

In a globally competitive economy, ports are often competing to grow trade activities by attracting new shippers to do business at the port. To measure this growth, ports often measure their success through a number of metrics that generally describe the throughput of goods at the port and the scale of operations occurring at the port. When considering the ability of a port to transition to alternative fuels for ships that are entering and refueling at a given port, the following economic measures are assessed to determine if a port is viable:

1. **Sub-Metric: Twenty-foot-equivalent (TEU) per year (container cargo)**
   This metric is the foundational measure of a port's productivity for cargo

2. **Sub-Metric: Million Metric Revenue Tons (bulk cargo)**

3. **Sub-Metric: Ships entering a port per year**

4. **Sub-Metric: Maximum ship size (not scored)**

5. **Sub-Metric: Connection to rail**
   - Rail intermodal moves
   - Number of connections
   - Generally, trucks are the primary mode within a 500-mile radius of a port. Rail connectivity at a port becomes increasingly important in attracting containerized cargo when the origin-destination pairs are more than 500 miles apart.

Port of New York and New Jersey

Busiest on the Eastern Seaboard

The Port of New York and New Jersey is a major economic driver for the New York metropolitan area, and is the largest and busiest container port on the East Coast of the United States.

New York is well-suited to become an importer of hydrogen-based fuels. The New York metro area has small-scale but developing infrastructures of hydrogen fuel, with several large companies presently invested in operations. New York's Offshore Wind plan could provide ample renewable energy for fuel production. The Port does not presently bunker fuel.

No coordinated policies or efforts from industry have focused exclusively on hydrogen-based fuels in the marine shipping sector, however conditions are ripe for market activation in the United States, and shipping fleets originating from Northern European ports may drive initial demand.

Port of New York and New Jersey: Busiest on the Eastern Seaboard

Introduction:

The Port of New York and New Jersey serves the largest metropolitan economy in the United States. New York Harbor is one of the world's largest natural harbors, and the Port is the largest and busiest container port on the East Coast of the U.S. It is the third largest port in North America behind Los Angeles and Long Beach, serving a local population of over 27 million people.

The Port's 2018 container cargo volumes were 7.2 million twenty-foot equivalent units (TEU) and its container facilities account for approximately 70% of the Port Authority's port land acreage. The port's primary trading partner by volume is China, taking up 25% of total trade. India, Germany, and Italy follow, with trade volumes in the high single-digits. Container volumes are projected to double or triple over the next 30-year time frame. Its terminals are located throughout the New York metropolitan area including in Newark, New Jersey.

Access to Hydrogen:

The Port of New York and New Jersey has established hydrogen fueling stations near JFK International Airport for vehicles. However, their scale is still currently small. The private company Air Liquide has established a hydrogen fueling station in Southern Brooklyn to support the initial employment of FCEVs.[45] Several other private companies including Shell and Toyota have begun investment and deployment of hydrogen refueling stations. New York does not have any large hydrogen manufacturing facilities.

Government Policies:

The 2015 New York State Energy Plan integrates Governor Andrew M. Cuomo's major new energy initiative, known as Reforming the Energy Vision (REV), and other energy policies and initiatives. The 2015 State Energy Plan establishes three statewide clean energy targets to be met by 2030:

- Reducing greenhouse gas (GHG) emissions from the energy sector—power generation, industry, buildings, and transportation - by 40 percent from 1990 levels.
- Increasing the share of renewable energy sources to 50 percent of total state electricity generation
- Increasing statewide energy efficiency by 600 trillion British thermal units (Btu) to reduce energy consumption in buildings by 23 percent from 2012 levels.

In January 2017, NYSERDA made a $360 million investment to support utility- scale clean energy projects, which included hydropower, onshore wind, solar, and a fuel cell project. The Long Island Power Authority also recently selected three fuel cell projects with a total capacity of 40 megawatts to power hydrogen vehicles. 33 Fuel cells operating on both renewable and non-renewable fuel are classified as a renewable resource in New York.

Most recently, New York State has a Municipal Zero-Emission Vehicle (ZEV) & ZEV Infrastructure Rebate Program that provides "rebates to cities, towns, villages, and counties (or

[45] New Energy New York. "Hydrogen and Fuel Cell Development Plan". 2018. http://neesc.org/wp-content/uploads/2015/01/2018_NY_H2_-Fuel_Cell_Dev_Plan_final4.pdf. Accessed May 13, 2020.

boroughs of New York City) for costs associated with the purchase or lease (for at least 36 months) of eligible clean vehicles, and installation of eligible infrastructure which supports public use of clean vehicles," including hydrogen refueling equipment.

NY Hydrogen Fuel Cell Policy Incentives:

- Mandatory Renewable Portfolio Standards (RPS)
- Interconnection Standards
- Net Metering
- Public Benefits Fund
- Fuel Cell Rebate and Performance Incentive
- New York Green Bank
- ZEV Purchase Targets/Incentives
- Public / Private Infrastructure Partnerships
- ZEV Refueling Infrastructure Program.

Port-specific policies and initiatives:

The Port Authority is committed to the long-term sustainability of the region while meeting the critical infrastructure needs of New York and New Jersey. It was the first public transportation agency in the United States to embrace the Paris Agreement, setting aggressive interim greenhouse gas (GHG) reduction targets that call for a 35 percent reduction by 2025 and reaffirming the agency's commitment to an 80 percent reduction by 2050.[46]

The decision to embrace the Paris Agreement is consistent with the pledges made by New York and New Jersey as part of the U.S. Climate Alliance. The Port Authority convened the cross-stakeholder Sustainable Aviation Fuels Working Group with the intention to bring sustainable aircraft fuels to the East Coast as a bridge to fully decarbonize aviation.

The Port has partnered with organizations such as Below 50, whose Transforming Heavy Transport program is geared towards reducing emissions from freight and logistics operations including air, sea, land and trans-shipment centers. The Port supports energy sectors with marine facilities for alternate fuels (offshore wind, LNG bunkering). According to its 30-year development plan, the Port Authority will lead by example as it progressively moves to low- and zero-emissions operations across its terminal facilities, including converting to electric port vehicles and equipment at all its facilities. The Port Authority has pledged to develop pilot programs and initiatives, including potential for continued rollout of hybrid-power electrified port vehicles and container handling equipment, as well as explore potential for expanding shore power beyond its initial location at Brooklyn PAMT.

Offshore Wind:

- As part of the States' sustainability plans, the Governors of New York and New Jersey have together committed to install nearly 12.5 gigawatts of wind-energy capacity by 2030. The Port is uniquely situated to provide critical support to the offshore wind needs.
- Port facilities in Howland Hook, Elizabeth, and Brooklyn have been identified as suitable locations to install wind capacity. The Port is also expected to support the supply chain (import of raw materials, parts, components, etc.) associated with offshore wind.

[46] Port of New York and New Jersey. Port Master Plan 2050. 2020. https://www.panynj.gov/port/en/our-port/port-development/port-master-plan.html. Accessed May 15, 2020.

- The PANYNJ will assess site feasibility and compatibility in support of LNG bunkering operations.

LNG Bunkering:

- LNG supply replenishment alternatives could consist of onsite liquefaction or delivery by truck, barge, small ship, or rail. Further infrastructure development will likely depend on LNG suppliers, end users, and involved stakeholders.

Clean Vessel Incentive Program

The Port Authority of New York & New Jersey Clean Vessel Incentive (CVI) Program is a special first-come, first-served program that provides financial incentives to encourage operators, charters, and agents of ocean-going vessels calling at Port Authority marine terminals to make voluntary engine, fuel, and technology enhancements that reduce emissions beyond the regulatory environmental standards set by the International Maritime Organization (IMO).

Economic Data at Port

Container demand at Port Authority facilities is projected to increase from 7.2 million twenty- foot equivalent units (TEU) in 2018 to between 12 million and 17 million TEU by 2050. Average annual growth ranges from 2.1 percent under low forecast assumptions to 3.4 percent under high forecast assumptions. Approximately 85 percent of inbound container activity is currently destined for the local truck market. Achieving long-term growth above and beyond the organic growth in local consumption (12 million) hinges on capturing a larger share of imports destined for inland distribution centers. To accomplish this, Port Authority facilities must compete on price and service reliability with other Atlantic Coast ports.

The NY-NJ throughput grew at a compound annual growth rate (CAGR) of 2.8 percent over the past five years. It has been a beneficiary of the nearly two-decade shift in container cargo from the West Coast to East and Gulf coasts, in part due to a history of longshore labor peace. Its growth is not as strong as ports in the Southeast, particularly Savannah and Norfolk. It competes heavily with those ports for discretionary cargo moving inland via rail. Its share of the East Coast container market was 29.01 percent in the first half of 2019, down from 33.5 percent in 2010.

Feasibility to bring hydrogen to port

Given the Port's high economic activity and heavy throughput, but relatively low momentum for hydrogen-based fuel adoption and necessary infrastructure, the Port will likely not be a primary mover of hydrogen fuel adoption. However, the Port may experience rapid knock-on effects from European hydrogen fuel adoption and will move quickly to capitalize on demand. Its commitment and access to clean energy in the form of offshore wind gives the port a ready feedstock for green hydrogen. The Port also possesses the capacity for rapid hydrogen fuel adoption given its manufacturing and infrastructure capabilities. Ultimately, the port's commitment to and capacity for LNG bunkering and the characteristics of LNG marine engines to work with hydrogen sources make the port more attractive as a hydrogen-based fuel adopter.

From a policy perspective, there has not been as much movement as in other U.S. cities like Los Angeles to create economic incentives for adoption of hydrogen-based fuels. Given these characteristics, it is likely that the Port will play a limited role in the bunkering of hydrogen-based fuels in the short-term and act as an importer of hydrogen-based fuels in the medium- to long-term until its green hydrogen production solutions scale up.

PORT PROFILE

Port of Houston

America's distribution hub

The Port of Houston is the busiest in the United States in terms of foreign tonnage, energy, and petrochemical manufacturing. Situated on the Gulf of Mexico, the Port is both a domestic and international shipping hub.

The Port is primed to be a major hydrogen-based fuels production hub and one of the first adopters in the country for the marine shipping industry, with potential for both bunkering and export. Texas is one of the top-three hydrogen producing states in the U.S., with excellent natural gas resources, carbon, capture, utilization, and storage (CCUS) infrastructure, and energy experience.

The Port's mission does not presently prioritize zero-carbon fuels, however Texas has great potential for production using renewable energy, and leads the nation in wind power capacity.

Port of Houston: America's Distribution Hub

Introduction

The Port of Houston is one of the world's largest ports and serves the metropolitan area of Houston, Texas, the fourth-largest city in the United States. It is the busiest U.S. port in terms of foreign tonnage, energy, and petrochemical manufacturing, second in the U.S. in terms of overall tonnage, sixth in the U.S. by total TEUs, and sixteenth-busiest in the world. It is the largest port on the Gulf Coast, and handles about two-thirds of all the containerized cargo in the Gulf of Mexico. The Port is also in close proximity to the Mississippi River, thus serving as a hub for both domestic and international shipping.

The Port is a 52-mile-long complex of nearly 200 public and private terminals extending inland along the Houston Ship Channel from the Gulf of Mexico. Located at the mouth of Galveston Bay, the Barbours Cut Container Terminal is about 3.5 hours sailing time from the Gulf, and is the Port's busiest terminal. Many of the Port's private terminals handle energy-related commodities. The Port moves more than 250 million tons of cargo annually. Mexico is the Greater Houston region's top foreign trading partner, followed by China, Brazil, the Netherlands and South Korea. The Port is a major gateway for US trade in petroleum products, such as petrochemical resins used by industry.

Connection to Rail

The Port of Houston Port Terminal Railroad Association connects many of the Port's terminals to Class I railroads, connecting Texas to the southeast, midwest, and southwest United States. Houston offers shippers direct connections by Interstate highways to both east and west coasts; and northwards to the midwest.

Access to Hydrogen and Ammonia

Texas is one of the three major hydrogen-producing states, along with California and Louisiana, and is the largest producer of hydrogen in the nation. It has accumulated excellent knowledge of the production, storage, transport and safe handling of hydrogen as a result. Almost all of the hydrogen currently produced in the United States is used for refining petroleum, treating metals, producing fertilizer, and processing foods. Texas has ready access to hydrogen through its existing infrastructure, as most hydrogen is produced at or close to where it is used—typically at large industrial sites.

Texas also has excellent resources of natural gas, the main feedstock for manufacturing hydrogen. Its developing solar and substantial wind energy infrastructures give Texas the advantage of eventually using renewables to create green hydrogen. This green hydrogen and ammonia pathway exists because renewable energy can be produced to the extent that it has to be curtailed, and so renewable energies could be used to create hydrogen in order to store energy or to produce ammonia. In addition, hydrogen production and storage in Texas could help to stabilize the electricity grid as more intermittent renewables come on line.[47]

[47] Lloyd, Alan C. and Webber, Michael E."Texas positioned to lead hydrogen revolution". Express News. March 19, 2017. https://www.mysanantonio.com/opinion/commentary/article/Texas-positioned-to-lead-hydrogen-revolution-11010208.php. Accessed May 13, 2020.

The corporation Air Liquide operates the world's largest hydrogen storage facility in an underground cavern in Beaumont, Texas, on the Gulf Coast. Air Liquide also operates a steam-methane reformer in La Porte and has other hydrogen projects along its Gulf Coast Pipeline. It also has plans to build a $150 million liquid hydrogen plant.

The Port will have ready access to ammonia, with infrastructure development planned for completion by 2023. Gulf Coast Ammonia LLC (GCA), Air Products, and Eastman Chemical Company reached final financing agreements to build the world's largest single-train ammonia synthesis loop in Texas City, TX, which is 26 miles from Barbours Cut Container Terminal. The facility will provide roughly 1.3 million tons of ammonia per year (about 9% of the world's supply) when it opens in 2023.[48]

In terms of carbon capture, utilization, and sequestration (CCUS), oil majors including Chevron have invested in research and development of this technology, resulting in a vast CCUS capability that is poised to be developed in the region. Texas holds the best position in the U.S. to lead in CCUS. The state possesses vast underground formations suitable for storing carbon dioxide, and is located near major drilling, refining, chemicals and other energy-intensive industries, meaning that it will require less pipeline and transport vessels to move carbon from production source to storage.[49] Texas is also home to many operational CCUS facilities. One such facility exists at Air Products' Port Arthur hydrogen production facility, with a carbon capture capacity of 1 Mtpa. The captured CO2 is transported to oil fields in Texas for enhanced recovery. 4 million tonnes of CO2 have been captured since the facilities became operational in 2013. Petra Nova Carbon Capture has been operational since 2017 and is the world's largest post-combustion CO2 capture system presently in operation. A production unit near Houston was retrofitted with a 1.4 Mtpa capture facility, which is transported via pipeline to an oil field near Houston for enhanced oil recovery. The Century Plant facility has CO2 capture capacity of around 8.4 Mtpa and also transports captured CO2 to oil fields for enhanced recovery. Finally, a facility currently in early stage development by Occidental Petroleum Corporation and White Energy will store captured CO2 in oil fields in the Permian Basin.[50]

Additionally, Texas has long been home to a large number of U.S. oil and gas companies with the technical and industrial know-how to tackle the hurdles of capturing, transporting and storing gases thousands of feet underground. [51]

Government Policies

Texas has historically been heavily dependent on its fossil fuel production, but renewables are an increasing and significant part of its energy mix. The state set its renewable-energy policy in 1999 with its Renewable Portfolio Standard legislation, which restructured the electricity market. Currently, Texas has more than 10,000 wind turbines with 21,450 megawatts of installed capacity, the most of any state in the nation and with more than one fourth of the nation's total in 2018. It is the sixth-largest wind-energy producer in the world. Retail electricity prices have decreased well below the U.S. average, to about 8.4 cents per kWh in 2017,

[48] Blum, Jordan. "Nearly $1B Gulf Coast Ammonia plant in Texas City to begin construction". Houston Chronicle. January 8, 2020. https://www.houstonchronicle.com/business/energy/article/Nearly-1B-Gulf-Coast-Ammonia-plant-in-Texas-City-14958561.php. Accessed May 13, 2020.

[49] Beck, Lee. "Carbon capture and storage in the USA: the role of US innovation leadership in climate-technology commercialization". Clean Energy, Volume 4, Issue 1. March 2020. https://doi.org/10.1093/ce/zkz031. Accessed May 13, 2020.

[50] Global CCS Institute. Core2 Facilities Database. 2020. https://co2re.co/FacilityData. Accessed May 13, 2020.

[51] Tracy Hester and Elizabeth George. "The Top Five Legal Barriers To Carbon Capture And Sequestration In Texas". Forbes. November 19, 2019. https://www.forbes.com/sites/uhenergy/2019/11/19/the-top-five-legal-barriers-to-carbon-capture-and-sequestration-in-texas/#38153e375085. Accessed May 13, 2020.

compared with the U.S. average of 10.5 cents. Energy facilities in the state produced 21.5% of energy from wind, solar, hydro and biomass, and 20.3% from coal. The state still makes more energy from gas than from any other form of energy. Texas has no specific policy related to hydrogen-based fuels in the marine sector.

Port-specific policies and initiatives

In January 2020, Port Houston adopted its next five-year strategic plan. The plan did not prioritize renewable fuels or energy development. In October 2019, Port Houston was set to purchase renewable electricity port-wide, entering a 10-year contract that is expected to save the port about $240,000 a year compared to its current three-year contract. Sourcing the electricity from 100 percent renewable generation will eliminate about 25,000 tons of carbon dioxide from Port Houston's carbon footprint per year, or a quarter of a million tons over ten years.

Private Sector Drivers of Hydrogen-based fuel adoption

Ammonia's operational capability within LNG infrastructure makes existing or upcoming LNG infrastructure promising for ammonia's eventual adoption, especially for bunkering. Kinder Morgan's Natural Gas Pipeline Company of America will start construction of its Gulf Coast Southbound project in Texas. The compression-based expansion of NGPL's Gulf Coast Mainline natural gas system will boost supplies to Cheniere Energy's LNG terminal near Corpus Christi. It will enable the system to provide 300,000 Dt/d of firm southbound transportation capacity to Corpus Christi Liquefaction, and allow NGPL to make 28,000 Dt/d available to the market.

Of the major international companies in the Hydrogen Council, at least three have significant operations in Texas - Air Liquide, Shell, and Toyota. Air Liquide is a major producer of hydrogen in Texas already. Shell has its U.S. corporate headquarters in Houston and has major oil and gas production and exploration, refinery and gas station network operations in Texas. Toyota has a manufacturing plant in San Antonio and recently moved its U.S. corporate headquarters to Plano, Texas.

Economic Data at Port

The Port has been growing quickly. It exceeded growth targets, with its TEU volumes up 38% to 2.7 million and operating revenue up 41% between 2014-2018. The Greater Port of Houston's impact on Texas' economy increased by 28% to $339 billion over four years. The Port has invested a total of $540 million on capital assets since January 2015.

The Port has a strong market base with established supply chains and proximity to a large industrial base with a growing population. The diversity of container cargo mitigates downturn risk. The Port also has consistent and reliable labor, and physical and financial ability to grow capacity. Some of its weaknesses emerge in its aged assets and channel limitations, lack of full control of channel funding, insufficient stakeholder engagement, and perceived lack of transparency and diversity.

Feasibility to bring hydrogen-based fuels to port

Given the Port's international trade relationships, its strategic location near oil and gas industries, and its proximity to developing ammonia infrastructure, the Port of Houston stands to be a relatively early adopter of hydrogen-based fuels in the United States. Its potential for storage and bunkering is high, and its ready access to inexpensive renewable energy sources as well as access to hydrogen and ammonia itself makes it a contender for early production of grey and blue hydrogen and the eventual production of green hydrogen and ammonia.

Port of Los Angeles

Busiest port in the western hemisphere

The Port of Los Angeles (POLA) is a significant economic driver for the City of Los Angeles and is currently the largest container port in the United States.

Given California's ambitious emissions reduction goals and development of hydrogen production for use in on-road vehicles, POLA could be an early-adopter of hydrogen-based fuels in shipping. California has ample natural resources and a favorable policy and investment environment to commercialize fuel production at scale.

While no coordinated policies or efforts from industry have focused exclusively on hydrogen in the marine shipping sector, the conditions are ripe for market activation. Shipping fleets originating from East Asian ports may drive initial demand for ammonia at POLA.

Port of Los Angeles: Busiest Port in the Western Hemisphere

Introduction

The Port of Los Angeles is a significant economic driver for the City of Los Angeles and is currently the largest container port in the United States. In 2018, POLA had a 9.5 million Twenty-Foot Equivalent Units (TEUs) throughput, the most cargo moved annually by a Western Hemisphere port. In California alone, nearly 1 million jobs are related to trade through the Port of Los Angeles.

The Port of Los Angeles is governed by the Los Angeles Board of Harbor Commissioners, a panel appointed by the Mayor of Los Angeles. POLA serves as a landlord for more than 300 port tenants and generates revenues from those leases and shipping service fees. Given POLA's close proximity and shared shoreline as the Port of Long Beach (POLB), the two ports often jointly make policy decisions as the San Pedro Bay Ports, although maintaining separate harbor commissions.

Existing Hydrogen Projects

The state of California, and Los Angeles in particular, have set a number of ambitious targets around decarbonization. California has committed to reduce its greenhouse gas emissions to 80% or more below 1990 levels by 2050, with an ambitious interim target of 40% below 1990 levels by 2030.

In Southern California and at the Port of Los Angeles (POLA), the focus on hydrogen has currently been limited to its use on-road trucking, cargo handling equipment, and power generation. POLA has partnered with a major terminal operator to demonstrate the use of hydrogen in cargo handling equipment and yard-tractors. Fuel for these vehicles is currently being brought into the terminal by mobile fuel trucks that can efficiently fuel many parked trucks in an orderly fashion. This process has been received favorably because the hydrogen fueling operations require the same footprint and work requirements as the incumbent diesel fueling operations. Given the sensitivities with union labor contracts, it is important at POLA that workers are performing similar type tasks without requiring extensive job retraining.[52]

Toyota's "Shore to Store" pilot will operate at POLA through a $41 million grant from the California Energy Commission.[53] The pilot involves 10 hydrogen trucks that are performing drayage routes between POLA and Toyota facilities. Shell is a partner to the project to provide fuel by building two new hydrogen fueling stations, completing a network of five end-to-end fueling stations.[54] Shell is currently producing approximately 2000 kg of hydrogen per day for this truck pilot and it is expected that other fuel providers are prepared to scale up quickly if hydrogen truck adoption accelerates.[55]

The Los Angeles Department of Water and Power (LADWP), the municipal government run utility serving LA, recently announced the construction of a new 840-megawatt power plant capable of running on both LNG and hydrogen. The goal would be to phase in the use of

[52] Goldberg, Jacob. Interview by Lauren Kastner. Port of Los Angeles. 7 May, 2020.
[53] Society of Motor Manufacturers and Traders. "Hydrogen powered Toyota tractor enters service at Port of LA." 13 November, 2019. https://www.smmt.co.uk/2019/11/hydrogen-powered-toyota-tractor-enters-service-at-port-of-la/
[54] Port of Los Angeles. "Port of Los Angeles Preliminarily Awarded $41 Million [...]." 14 September, 2020. https://www.portoflosangeles.org/references/news_091418_carb_toyota
[55] Goldberg, Jacob. Interview by Lauren Kastner. Port of Los Angeles. 7 May, 2020.

hydrogen at the plant until it is burning 100% hydrogen by 2045. Critical to that plant's success will be the availability and use of green hydrogen in order to meet the state's decarbonization goals.[56]

Port Environmental Policies

POLA and the San Pedro Bay Ports have implemented a number of environmental policies that are largely targeted at reducing pollution from port operations in order to achieve federal air quality standards. While most of the regulations are targeted at land-based sources of port emissions, the policies are increasingly focused on maritime emissions.[57]

The San Pedro Bay Ports Clean Air Action Plan (CAAP) is a comprehensive air quality plan for reducing port-related air pollution in attainment with the National Ambient Air Quality Standards (NAAQS) administered by the South Coast Air Quality Management District (SCAQMD). Jointly adopted by POLA and POLB, the plan includes a number of strategies including the Clean Truck Program, vessel pollution reduction programs, and advanced new technology. The plan was originally adopted in 2006, with updates in 2010 and 2017. Since 2005, air pollution from the San Pedro Bay Ports have dropped 87% for diesel particulate matter, 56% for nitrogen oxides, and 97% for sulfur oxides. Greenhouse gas emissions were added to the scope of the CAAP in 2017.[58] In the next iteration of the Port's CAAP, it may consider implementing a similar rate for ships similar to the existing Clean Truck Rate.[59] It is possible that ships below a certain emissions level would be required to pay a rate to enter the Port, which would be reinvested through a fund to finance future clean ship deployment.[60]

In response to the California Air Resources Board at-berth emissions regulations, POLA developed the Alternative Maritime Power (AMP) program to address emissions from stationary shipping container vessels docked at-berth. Docked shipping vessels typically run onboard power with diesel generators, creating a significant amount of air pollution in the port environment. As an alternative to running the generators, POLA routed electrical power to the dock so that ships can plug-in to cleaner electrical power from shore.[61]

The Ports of Los Angeles and Long Beach have developed the Technology Advancement Program (TAP) to support development and demonstration of new, clean air technologies in the port environment. The TAP provides an incentive for existing ocean-going vessels that are demonstrating an emission reduction technology that reduces diesel particulate matter and nitrogen oxide emissions. In alignment with the Environmental Ship Index (ESI), POLA developed a voluntary ESI Program to recognize shipping fleets that are using cleaner technology and practices in advance of regulations.[62] The multi-port scheme provides a cash incentive to clean ships that make a call to the Port. For ships that score 40-49 points on the ESI, a $750 incentive is paid to the ship while ships scoring 50 points or higher receive a $2500 incentive each time they make a call to the port. While this incentive is unlikely to unilaterally drive a change in shipping fleet environmental performance, it may be attractive for a ship to

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[56] Roth, Sammy. "Los Angeles wants to build a hydrogen-fueled power plant. It's never been done before." LA Times. 10 Dec., 2019.
https://www.latimes.com/environment/story/2019-12-10/los-angeles-hydrogen-fueled-intermountain-power-plant
[57] Port of Los Angeles. "Ocean-Going Vessel Emission Reduction." Accessed 7 May, 2020.
https://www.portoflosangeles.org/environment/air-quality/ocean-going-vessel-emission-reduction
[58] Port of Los Angeles. "Clean Air Action Plan." Accessed 7 May, 2020. https://cleanairactionplan.org/
[59] https://www.portoflosangeles.org/environment/air-quality/clean-truck-program
[60] Goldberg, Jacob. Interview by Lauren Kastner. Port of Los Angeles. 7 May, 2020.
[61] Port of Los Angeles. "Ocean-Going Vessel Emission Reduction." Accessed 7 May, 2020.
[62] Ibid.

improve its environmental performance if it can collect a series of incentives by making calls at multiple ESI participating ports on a single route.

Access to Hydrogen

While there is no single zero-carbon fuel of the future for California, the state has begun investing heavily in hydrogen as a future zero-carbon fuel for a number of energy services including electricity generation and on-road transportation. In general, California is well-positioned to produce hydrogen because of the clean energy policy environment, access to natural resources to produce hydrogen, available infrastructure for the transport of fuels, a strong fuels production industry in the state, and growing demand for hydrogen in several use cases.

Existing hydrogen production in California occurs close to the point of fueling for end customers clustered in large metropolitan areas in California. California currently has 31 active hydrogen fueling stations for on-road vehicles, with 100 more stations planned over the next 10 years. The top fuel providers are Shell, First Element Fuel, Air Liquide, and Air Products, along with several other small station network owners. In some cases, the fuel delivery value chain is vertically integrated and the fuel producer also owns the station network, such as Shell. In other cases, a hydrogen fuel station provider such as First Element Fuel has partnered with a fuel producer such as Air Products to deliver fuel.[63]

The California Energy Commission (CEC) has committed $20 million per year for the next 10 years to help support the initial construction and operations of hydrogen fueling stations. The state's goal is to have 200 fueling stations across the state by 2025. California requires that at least one-third of hydrogen supplied to state-funded fueling stations must be renewable hydrogen.[64] Today, most renewable hydrogen in the state is produced using biogas from agricultural waste, but it is expected that wind and solar resources will be required to meet the state's renewable hydrogen goals in the years to come.

According to the latest projections, "capital costs in California, where hydrogen infrastructure is being built out today, are estimated from $0.9 million, for a 100- to 170 kg/day station, to $1.4 million for a 250 kg/day station for early (2013) market fueling. For stations built in 2015 to 2017, the capital cost is estimated to be $0.9 million for a 250 kg/day station and $1.5 to $2.0 million for a 400 to 500 kg/day station."[65]

While most of the production in California is to meet demand for hydrogen in fuel cell cars, new plans for large-scale production facilities are emerging that offer a promising path to scale that could potentially serve the marine shipping sector. Air Liquide announced that it plans to start construction in 2020 on a renewable hydrogen production facility outside of Las Vegas, Nevada. The $150 million plant will have a production capacity of 30 tons of liquid hydrogen a day to meet demand in California.[66]

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[63] FirstElement Fuel. "FirstElement Fuel's $25.5 Million Deal with Air Products is Largest Ever of Its Kind [...]." 6 October, 2014. https://www.businesswire.com/news/home/20141006005176/en/FirstElement-Fuel%E2%80%99s-25.5-Million-Deal-Air-Products#.VDLIFildWlo

[64] Voelcker, John. "CA Renewable Hydrogen Rule: Forcing the Carbon Numbers to Work." 7 August 2015. https://www.greencarreports.com/news/1099459_ca-renewable-hydrogen-rule-forcing-the-carbon-numbers-to-work

[65] California Hydrogen Business Council. "Hydrogen FAQs." Accessed 7 May, 2020. https://www.californiahydrogen.org/resources/hydrogen-faq/#S32

[66] Air Liquide. "Air Liquide committed to producing renewable hydrogen for the West Coast mobility market with new liquid hydrogen plant." 8 October, 2019. https://energies.airliquide.com/hydrogen-day-2019?utm_source=hootsuite&utm_medium=facebook&utm_term=spring&utm_content=rocket&utm_campaign=

Another noteworthy planned project is Mitsubishi Hitachi Power Systems plans to build hydrogen storage facilities in Utah. The company plans to use hollowed out underground salt domes as impermeable storage caverns to store hydrogen fuel.[67] The company claims this is the world's largest hydrogen storage facility. While the storage facility will not be complete until 2045, the development of storage capabilities will be critical to helping California produce and deliver hydrogen fuel at scale.

Feasibility Assessment

Given California's ambitious emissions reduction goals and the early demonstrations of hydrogen fuel in other applications, it is quite possible that the Port of Los Angeles could be an early-mover on hydrogen-based fuels in the North American market. While no coordinated policies or efforts from industry have focused exclusively on hydrogen in the marine shipping sector, the present conditions could be ripe for market activation.

California not only has a robust environmental fuels policy environment including the mature Low Carbon Fuel Standard, but it also has environmental and carbon markets which can reasonably integrate marine emissions into those programs. California also has access to significant natural resources that can help it develop low carbon fuels for shipping. California has ample solar irradiance to produce hydrogen through electrolysis and it has natural gas reserves, which paired with CCUS, could lead to a green hydrogen and ammonia fuels market. California's ports are also very well-connected by land and sea, so bringing new fuels into the port is possible.

California has made more progress than any other part of the U.S. at developing a hydrogen economy. While the efforts have been focused on on-road vehicles, more vehicle applications within the transportation sector successfully transitioning to hydrogen will help prime the market for marine shipping. Should a major shipping company decide to transition their fleet to hydrogen-based fuels and require new fuels to be delivered at the port, the shipping company could issue an RFP for fuel services from suppliers in California. It is expected that many fuel suppliers and engineering, procurement, and construction companies would be ready to respond to the RFP quickly and competitively.

[67] Compton, Jason. "In Utah, Hydrogen And A Massive Salt Dome Are Winning The West For Renewable Energy." Forbes. 13 March, 2020.
https://www.forbes.com/sites/mitsubishiheavyindustries/2020/03/13/in-utah-hydrogen-and-a-massive-salt-dome-are-winning-the-west-for-renewable-energy/#12a530be5c52

Port of Rotterdam

Europe's biggest port

As the biggest port in Europe and one of the most connected ports in the world to the global trade network, the Port of Rotterdam can contribute to setting the standard that shipping companies must follow in terms of emissions and carbon reduction.

The Netherlands is the second largest producer of hydrogen in Europe, with hydrogen coming from five industrial clusters. It also produces 13% of Europe's ammonia. Although CCUS and green hydrogen technologies are still undeveloped or in their infancy in the Netherlands, both the Dutch government and the EU have unveiled detailed plans to ramp up the production of hydrogen, as well as do so in a carbon-neutral manner. Northern Netherlands plans to create a "hydrogen valley" to supply the rest of Europe, serving as the "hydrogen backbone" of production and fuel delivery infrastructure.

All of these factors combined lead to the conclusion that the Port of Rotterdam is well-suited to be a hydrogen-based fuel production hub that can lead both Europe and the rest of the world in the same direction.

Port of Rotterdam: Europe's Biggest Port

Introduction

The Port of Rotterdam holds a crucial place in both the European and global trade network. Operated by the Port Authority of Rotterdam, it is the biggest port in Europe with a total port area of 12,606 ha, a total quay length of 74.5 km and a port depth of 24m. The Port can handle the world's biggest ships, including the 400m long and 62m wide MSC Gülsün.

The Port serves as one of the most important nodes in European and global trade. In 2019, it handled 14,810,804 TEU of containers, carried by 29,491 seagoing vessels. The Port of Rotterdam mainly facilitates trade throughout Europe, with connections to 300 destination terminals in Europe, as well as 50 in the Americas, 40 in the Middle East and Africa, and 40 in Asia. To further prove the port's robust global connectivity, the UNCTAD gave the port a score of 92.75, ranking the port among the top ten most connected in the world.

In terms of ancillary services, the port also boasts robust bunkering and other energy services. As Europe's largest bunkering port, as well as one of the top three bunkering ports worldwide, the Port of Rotterdam processes 11 million meters cubed of bunker fuel per year. The port also offers 3 permanent LNG bunker vessels, as well as 4 licensed LNG bunker specialists. In addition, the port is also home to 5 oil refineries, 6 refinery terminals, 11 independent tank terminals for oil products, 1 natural gas terminal, and 86 wind turbines (194MW). Crude oil storage: 14.5 million meters, and 3 LNG storage tanks, each with 180,000 m3 capacity[68] All in all, the Port of Rotterdam is one of the best places to facilitate change throughout the global shipping industry due to its critical place in the European and global trade network.

Access to Hydrogen and Ammonia

The Netherlands is the second largest producer of hydrogen in Europe, at approximately 820,000 tons/year in 2018.[69] The vast majority of this hydrogen production uses natural gas as its feedstock. Hydrogen production represented about 10% of natural gas consumption in the Netherlands in 2018.[70] Most of this hydrogen comes from 5 industrial clusters spread throughout the Netherlands, namely at Eemshaven, Maasdelta, Zeeuws-Vlaanderen, Limburg, and Ijmond.[71] In terms of geographic distance, the clusters of Maasdelta, and Ijmond are the nearest to the port of Rotterdam. Hydrogen is mainly transported by around 1100km of dedicated pipelines both within the Netherlands and to other countries, with Rotterdam as a crucial node within this pipeline network.[72] Thus, Rotterdam has ready access to domestically-produced hydrogen to facilitate a transition to hydrogen-based shipping fuels.

However, almost all of the hydrogen produced by the Netherlands is considered "grey" hydrogen, meaning that the steam-methane reforming (SMR) production process releases carbon into the atmosphere. Although the Netherlands sequesters around 10,000 tons of CO2 annually as of 2017, it is unclear how much of the sequestered carbon came from hydrogen

[68]RoRo, Maud Eijgendaal Business Manager, et al. "LNG Terminal." Port of Rotterdam, 12 June 2015, www.portofrotterdam.com/en/doing-business/logistics/cargo/lng-liquefied-natural-gas/lng-terminal. Accessed 15 May 2020.
[69]Energie, Topsector. TKI NIEUW GAS Outlines of a Hydrogen Roadmap.
[70]Energie, Topsector. TKI NIEUW GAS Outlines of a Hydrogen Roadmap.
[71]"Filling the Data Gap: An Update of the 2019 Hydrogen Supply in the Netherlands." DNV GL, 26 Nov. 2019, www.dnvgl.nl/news/filling-the-data-gap-an-update-of-the-2019-hydrogen-supply-in-the-netherlands-162721. Accessed 15 May 2020.
[72] Mulder, Machiel, et al. Outlook for a Dutch Hydrogen Market. Mar. 2019.

production.[73] Rotterdam was meant to host a large-scale carbon capture, utilization, and sequestration (CCUS) demonstration project at a nearby coal plant, but the project was cancelled in 2017 when the two project developers Uniper and Engie withdrew, citing cost concerns.[74] Nevertheless, the Netherlands claims it can exploit former gas fields to store 2700-3200 megatons of CO2, with around 2000 megatons of capacity underground and 1000 megatons of capacity under the sea.[75] Additionally, other CCUS capacity may be available elsewhere in Europe that the Netherlands can take advantage of. For example, Norway has begun demonstrating CCUS capabilities with their plans to inject captured carbon into oil fields in the North Sea. Norway's own ports such as the Port of Grenland may be able to take advantage of this CCUS capacity as their hydrogen production grows or make CCUS available to nearby countries such as the Netherlands.[76] As a result, the Netherlands has abundant carbon storage sites to facilitate increased use of CCUS technology in its economy.

The only "green" source of hydrogen production in the Netherlands is the 1MW of hydrogen electrolysis capacity at Hystock.[77] Nevertheless, the Netherlands has set a goal of establishing 500MW of hydrogen electrolysis capacity by 2025, and 3-4GW of capacity by 2030.[78] In particular, the companies Shell Netherlands, Gasunie and Groningen Seaports have formed a consortium to begin a feasibility study on the NortH2 project in 2020.[79] The NortH2 project aims to leverage a mega offshore wind farm to produce its first hydrogen by 2027, and expand to 3-4 GW of hydrogen by 2030.[80]

In terms of ammonia production, the Netherlands can produce 3 million tons of ammonia/year as of 2017. This production comes from 2 major ammonia plants at Yara Sluiskil (1.8 million tons of capacity) and OCi Nitrogen (1.2 million tons), representing 13% of European Union (EU) ammonia production capacity (2017)[81] Taking both hydrogen production capacity and ammonia production capacity into account, the Netherlands appears well placed to emerge as a hydrogen-based fuel production hub, with the potential for these fuels to be zero-carbon if the Netherlands fully develops both its CCUS and green hydrogen capacities.

General hydrogen policies

The Netherlands has published multiple hydrogen development roadmaps through public and private channels. One of the most prominent plans is an investment agenda to transform the Northern Netherlands (specifically the Groningen and Drenthe provinces) into a "hydrogen valley."[82] Other plans include a study on the socio-economic impacts of transitioning to a hydrogen economy from Gasunie - a state-owned natural gas storage and transport company,[83]

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[73] Hellemans, Alexander. "The Netherlands Confronts a Carbon Dilemma: Sequester or Recycle?" IEEE Spectrum: Technology, Engineering, and Science News, 26 Dec. 2017, spectrum.ieee.org/energy/fossil-fuels/the-netherlands-confronts-a-carbon-dilemma-sequester-or-recycle. Accessed 15 May 2020.
[74] "Projects | NLOG." Www.Nlog.Nl, www.nlog.nl/en/projects. Accessed 15 May 2020.
[75] "CO2-Storage." Noordzeeloket UK, www.noordzeeloket.nl/en/functions-and-use/co2-opslag/. Accessed 15 May 2020.
[76] Tore Orvik, Bjorn. Interview conducted by Lauren Kastner and Ethan Tsai. Port of Grenland, Norway. 16 April, 2020.
[77] "Netherlands." Iphe, Nov. 2019, www.iphe.net/netherlands. Accessed 15 May 2020.
[78] Ibid.
[79] Macola, Ilaria. "Dutch Power Consortium to Produce Green Hydrogen through Renewables." Power Technology | Energy News and Market Analysis, 28 Feb. 2020, www.power-technology.com/news/dutch-power-consortium-green-hydrogen-renewables/. Accessed 15 May 2020.
[80] "Europe's Largest Green Hydrogen Project Starts in Groningen." Gasunie, 27 Feb. 2020, www.gasunie.nl/en/news/europes-largest-green-hydrogen-project-starts-in-groningen. Accessed 15 May 2020.
[81] Batool, M, and W Wetzels. DECARBONISATION OPTIONS FOR THE DUTCH FERTILISER INDUSTRY Manufacturing Industry Decarbonisation Data Exchange Network Decarbonisation Options for the Dutch Fertiliser Industry. 3 Oct. 2019.
[82] INVESTMENT AGENDA HYDROGEN NORTHERN NETHERLANDS Heading for Emission-Free Hydrogen at Commercial Scale. Feb. 2019.
[83] Jepma, Catrinus, et al. The Dutch Hydrogen Economy in 2050 An Exploratory Study on the Socio-Economic Impacts of Introducing Hydrogen into the Netherlands Energy System. Mar. 2019.

and a roadmap to bring hydrogen production and distribution to the Netherlands, published by Topsector Energie - an advocacy group dedicated to facilitating the transition to sustainable energies.[84]

The investment agenda for the Northern Netherlands lists 33 different and concrete projects with a total price tag of 2.8 billion euros.[85] These projects vary from plans to build both small and large-scale electrolysers ranging from 1MW to 1GW of capacity, to transforming natural gas pipelines and creating sequestration sites for both hydrogen and carbon dioxide, respectively.[86] Ultimately the goal of this plan is to make emissions-free hydrogen cost competitive by 2030. To achieve this goal, the plan lists the most immediate priority as filling a 100 million euro/year financing gap between 2020 to 2024.[87] Nevertheless, the plan claims that companies in the Northern Netherlands are ready to cover part of the investment gap, while at the same time seeking public support from the Dutch federal government and the EU for the rest."[88]

The Netherlands also receives policy and financial support for its hydrogen agenda from the EU. In November 2019, the Northern Netherlands won a 20 million euro grant from the EU to fund its hydrogen valley investment agenda, with another 70 million euros matched by public and private funds.[89] The 20 million euro grant came from the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a European research and development partnership under the Horizon 2020 initiative.[90] Furthermore, the Netherlands plays a crucial role in the envisioned hydrogen future for the whole EU, as documented in its Hydrogen Roadmap Europe published in 2019,[91] as well as its upcoming Clean Hydrogen Alliance set for launch in summer 2020.[92] The Netherlands has already begun consultations with Germany on linking their envisioned hydrogen pipeline infrastructure,[93] with the ultimate aim of establishing an "EU hydrogen backbone" that would stretch 2000km across northern France and central Germany.[94] Thus, these Dutch and EU-wide hydrogen engagement initiatives demonstrate that the Netherlands currently receives strong policy support to build a hydrogen-based economy, and this support will only grow stronger as both the Netherlands and the EU strive to achieve their 2050 climate targets.

Port-specific initiatives

In addition to policy support from both the Dutch government and the EU, the Port of Rotterdam is also making strides in advancing its own decarbonization plan. According to its port-wide decarbonization plan, the Port Authority of Rotterdam has set a goal of reducing the emissions of the port and its industrial complex by 50% by 2025 and by 60% by 2030, compared to 1990 levels as part of the Rotterdam Climate Initiative"[95] Furthermore, the plan

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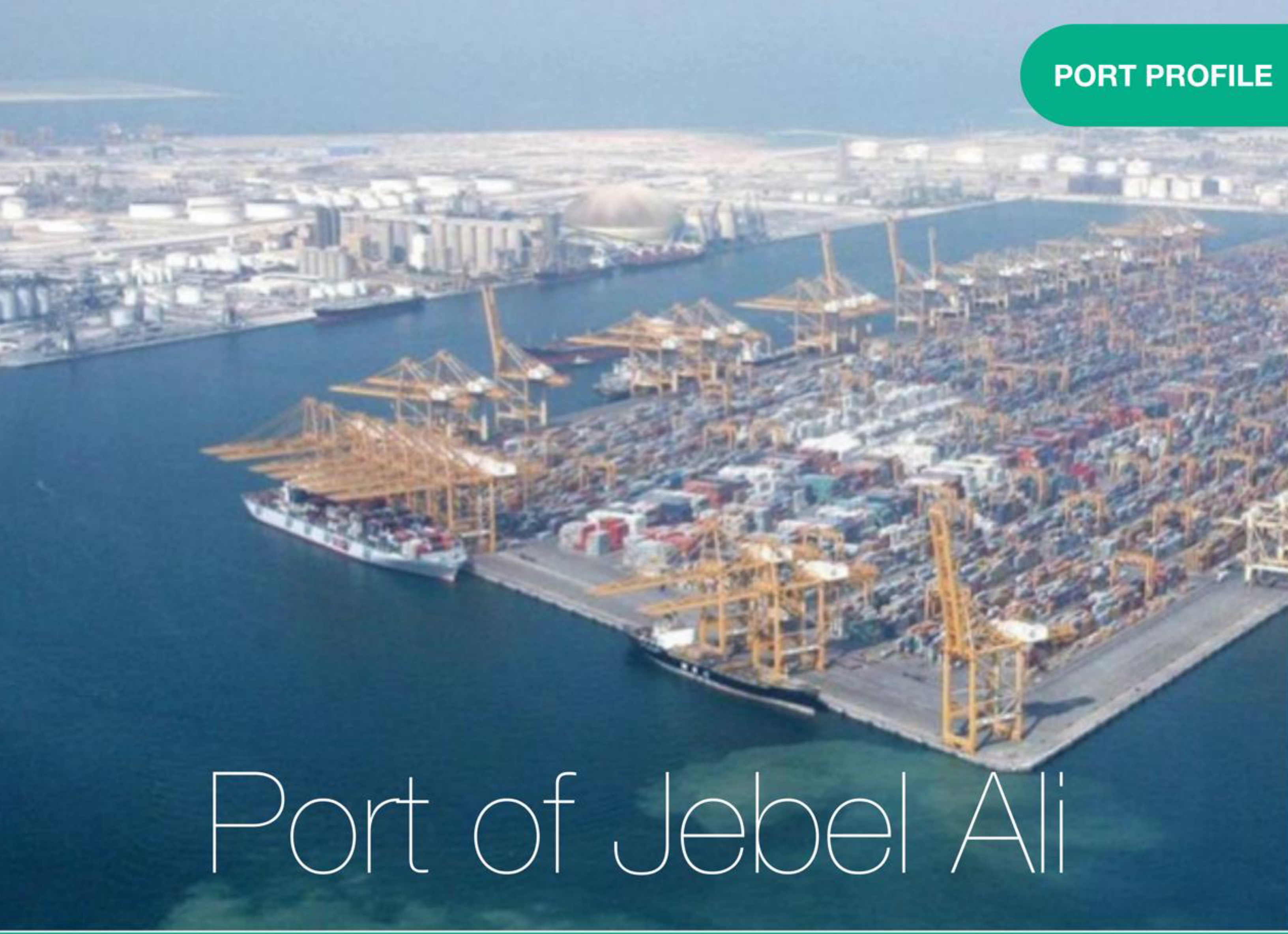
[84]Gigler, Jörg, and Marcel Weeda. Outlines of a Hydrogen Roadmap.
[85] "Foresight | Hydrogen: The Northern Netherlands Is Ready." Foresight, 3 May 2019, foresightdk.com/hydrogen-northern-netherlands-is-ready/. Accessed 15 May 2020.
[86] Ibid.
[87] Ibid.
[88] Ibid.
[89] FORESIGHT Contributor. "Hydrogen: Northern Netherlands Leads Europe and the World | Energy Central." Energycentral.Com, 4 Nov. 2019, energycentral.com/c/ec/hydrogen-northern-netherlands-leads-europe-and-world. Accessed 15 May 2020.
[90] Ibid.
[91] A SUSTAINABLE PATHWAY FOR THE EUROPEAN ENERGY TRANSITION HYDROGEN ROADMAP EUROPE. Jan. 2019.
[92] Simon, Frédéric. "EU Announces 'Clean Hydrogen Alliance' for Launch in the Summer." Www.Euractiv.Com, 10 Mar. 2020, www.euractiv.com/section/energy-environment/news/eu-announces-clean-hydrogen-alliance-for-launch-in-the-summer/. Accessed 15 May 2020.
[93] Eriksen, Freja. "Netherlands Highlights Hydrogen Cooperation with Germany." Clean Energy Wire, 24 Feb. 2020, www.cleanenergywire.org/news/netherlands-highlights-hydrogen-cooperation-germany. Accessed 15 May 2020.
[94] Hulst, Noé. Hydrogen Market in The Netherlands. 5 June 2019.
[95] Samadi, Sascha, et al. Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam On Behalf Of. 2016.

specifically mentions the role of hydrogen by acknowledging that “Hydrogen... produced with renewable electricity – could play a significant role in the transport sector by 2050. In such a future, the port would be well-suited to become a major producer, as its existing delivery infrastructure for fossil transport fuels could be used, while the required carbon and hydrogen could be sourced via ship. Hydrogen could also be produced from electricity at the port, provided the already strong interconnection to the electricity grid is further expanded.”[96] The final goal of the decarbonization plan is to achieve zero-emissions by 2050.[97] Thus, these plans demonstrate that Port of Rotterdam is eyeing to become a major node in the supply of hydrogen both for the rest of the Netherlands as well as the EU, and has already invested time and energy to lay out a pathway to achieving this goal.

Feasibility to Bring Hydrogen to Port

The Port of Rotterdam is a prime candidate to serve as a first-mover that facilitates the transition to hydrogen-based fuels for the global shipping industry. As the biggest port in Europe and one of the most connected ports in the world to the global trade network, the Port of Rotterdam can contribute to setting the standard that shipping companies must follow in terms of emissions and carbon reduction. In terms of hydrogen, the Port of Rotterdam can take advantage of the multiple hydrogen production clusters in the Netherlands. Although CCUS and green hydrogen technologies are still undeveloped or in their infancy in the Netherlands, both the Dutch government and the EU have unveiled detailed plans to ramp up the production of hydrogen, as well as do so in a carbon-neutral manner. Finally, the Port of Rotterdam itself has published its own port decarbonization plans that feature hydrogen in a prominent role in addressing carbon emissions in the transport sector. All of these factors combined lead to the conclusion that the Port of Rotterdam is well-suited to be a hydrogen-based fuel production hub that can lead both Europe and the rest of the world in the same direction.

[96] Samadi, Sascha, et al. Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam On Behalf Of. 2016.
[97] “Carbon Neutral in 3 Steps.” Port of Rotterdam, 11 Oct. 2018, www.portofrotterdam.com/en/doing-business/port-of-the-future/energy-transition/carbon-neutral. Accessed 15 May 2020.



Port of Jebel Ali

The Largest Port in the Middle East

The Port of Jebel Ali is situated in one of the best environments to take advantage of cost-competitive green hydrogen and ammonia production and re-export potential, thanks to the abundant supplies of both natural gas and solar power for the UAE. Jebel Ali is highly connected to South Asia, Southeast Asia, and East Asia, as well as the coasts of Africa and the Mediterranean.

The UAE has enormous reserves of natural gas, both from Abu Dhabi, off the shore of Dubai (newly discovered), and from Qatar. More importantly, the UAE has a commercial-scale CCUS plant in operation with the possibility of scaling up.

Nevertheless, the port itself lacks any meaningful commitment to transitioning to providing low-carbon fuels, but would be a prime candidate to pitch the ramp-up of hydrogen-based shipping fuel infrastructure and production solutions.

Port of Jebel Ali: The Largest Port in the Middle East

Introduction of Port of Jebel Ali

The port of Jebel Ali is the world's largest man-made harbor, as well as the largest port in the Middle East. In addition, it is commonly ranked as the 11th largest container port in the world.[98] As the biggest port in the region, Jebel Ali is considered the gateway to both the UAE, the Gulf Cooperation Council (GCC), and the wider region - including Eastern, Western and Southern Africa and South Asia. As a result, the port of Jebel Ali gives shipping companies market access to over 3.5 billion people and $2.1 trillion of GDP.[99] Although the port of Jebel Ali has the most direct connections with ports in the Far East and the Mediterranean (18 and 14 direct ports of call, respectively), the most popular shipping destinations in terms of weekly sailings are the Indian subcontinent, Southeast Asia, and the Far East.[100]

Surprisingly, the port of Jebel Ali does not possess any rail connections, even though Abu Dhabi's Etihad Rail is planning on building the first rail link soon. As such, a part of the cargo that comes into the port is shipped throughout the UAE and the GCC by road, but a vast majority of the cargo is re-exported. The Port is instrumental in making Dubai the world's 3rd largest re-export market. As such, the Port serves as a critical stop-over point for ships engaged in world trade, and would be an instrumental part of any marine shipping fuel transition.

In addition, the Port is only slated to grow in importance for world shipping. DP World is currently building Terminal 4 (out of a planned 15 terminals in total) of the Jebel Ali port. This expansion will bring the Port to 22.4 million TEU. Once all 15 terminal expansions are completed, the Port is predicted to be the world's largest, with a 55 million TEU capacity.[101] Engaging the Port on the fuel transition as early as possible is critical to decarbonizing the shipping fuel sector.

Access to Hydrogen and Ammonia

There are no concrete or immediately obvious numbers on the total volume of hydrogen that the UAE produces. But given the presence of several major refineries in the UAE, such as that at Ruwais, it is safe to assume that the UAE has robust hydrogen production capabilities for use in the petroleum product distilling process.

Nevertheless, the UAE's hydrogen production potential can be estimated by looking at its natural gas supplies. The UAE is a major producer of natural gas, and could potentially use its vast reserves for hydrogen production through steam-methane reforming (SMR). According to the International Energy Agency, the UAE produced 66.48 bcm of natural gas in 2017, and imported 19.23 bcm.[102] Most of UAE's natural gas imports come from Qatar (though the UAE has been trying to diversify its natural gas sources in light of its diplomatic spat with Qatar starting in June 2018). In addition, the UAE just discovered a massive natural gas field in February 2020 at the Jebel Ali gas field off the coast of Dubai, with over 2.26 trillion bcm of

[98] DP World UAE Region. June 2019.
[99] Ibid.
[100] Ibid.
[101] "Jebel Ali Port, Dubai - Ship Technology." Ship Technology, 2013, www.ship-technology.com/projects/jebel-ali-port-dubai/.
[102] "Data Tables – Data & Statistics." IEA, www.iea.org/data-and-statistics/data-tables?country=UAE&energy=Natural%20gas&year=2017. Accessed 15 May 2020.

gas.[103] Thus, the UAE has plentiful supplies of natural gas in order to generate hydrogen using SMR.

For Dubai in particular, the emirate relies on Abu Dhabi and Qatar for its supply of natural gas (at least before the Jebel Ali field discovery).[104] Specifically, Dubai imports natural gas through long-term contracts that ship the LNG from Abu Dhabi, as well as through the Dolphin pipeline from Qatar's North Field, to the Port of Jebel Ali.[105] This gasfield discovery could allow Dubai to end its dependence on natural gas imports by 2025. Thus, the port of Jebel Ali therefore already has the infrastructure in place to transport the natural gas needed to create ammonia or other hydrogen-based fuels onsite.

In addition, the UAE has begun developing its carbon capture, utilization, and sequestration (CCUS) capabilities. The Abu Dhabi state-owned company ADNOC established its first commercial-scale CCUS project in 2016 at the Emirates Steel facility at Mussafah, with 800,000 tonnes/year of CO2 capture capacity.[106] Most of this CO2 goes toward enhanced oil recovery (EOR), which replaces natural gas and thus further boosts Abu Dhabi's capacity to sell its natural gas.[107] ADNOC plans to expand its CCUS capacity to 5 million tonnes/year by 2030, and is already undertaking efforts to achieve this goal.[108] As a result, the UAE already possesses the technical capacity to operate CCUS, but needs to scale up these operations in order to generate zero-carbon hydrogen.

The UAE is both a major ammonia producer and situated near one of the largest ammonia producers in the world. The Ruwais Fertilizer Industries (FERTIL) plant and its expansion can produce up to 2 million tonnes of ammonia per year, with most of its production exported to the US and Australia.[109] In addition, Saudi Arabia produced 15 million tonnes of ammonia in 2017, over 90% of which was exported.[110] The ammonia plants of the Saudi Arabian Fertilizer Company (SAFCO) are some of the largest in the world, with the SAFCO IV plant producing 1.1 million tonnes of ammonia per year.[111] Thus, the UAE has emerged as one of the strongest hubs for the production and distribution of ammonia, especially if the shipping sector begins adopting ammonia to replace its current fuel mix.

The UAE also possesses vast potential for renewable energy, especially solar. The UAE's electricity mix has enormous potential to shift away from natural gas, which provides 98% of UAE electricity generation.[112] In early 2020, the UAE's first nuclear plant (5.6 GW of capacity)

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[103] Dipaola, Anthony. "UAE Finds 80 Tcf Gas Field, the World's Biggest since 2005." Www.Worldoil.Com, 6 Feb. 2020, www.worldoil.com/news/2020/2/6/uae-finds-80-tcf-gas-field-the-world-s-biggest-since-2005. Accessed 15 May 2020.
[104] "Meeting Demand: Attention Turns to Diversifying the Energy Mix and Developing Infrastructure." Oxford Business Group, 11 Feb. 2014, oxfordbusinessgroup.com/overview/meeting-demand-attention-turns-diversifying-energy-mix-and-developing-infrastructure. Accessed 15 May 2020.
[105] Ibid.
[106] Ibid.
[107] "Carbon Capture and Sequestration Technologies @ MIT." Mit.Edu, 2016, sequestration.mit.edu/tools/projects/esi_ccs.html. Accessed 15 May 2020.
[108] Saadi, Dania. "Adnoc to Expand Carbon Capture Projects to Reduce Emissions and Boost Oil Recovery." The National, 28 Nov. 2018, www.thenational.ae/business/energy/adnoc-to-expand-carbon-capture-projects-to-reduce-emissions-and-boost-oil-recovery-1.796756. Accessed 15 May 2020.
[109] Thapliyal, Deepika. "UAE's FERTIL to Start Urea, Ammonia Production at New Plant in June." ICIS Explore, 13 May 2013, www.icis.com/explore/resources/news/2013/05/13/9667976/uae-s-fertil-to-start-urea-ammonia-production-at-new-plant-in-june/. Accessed 15 May 2020.
[110] Wouters, Frank, and Ad Wijk. Feature | The New Oil: Green Hydrogen from the Arabian Gulf. 19 Apr. 2019, revolve.media/the-new-oil-green-hydrogen-from-the-arabian-gulf/. Accessed 15 May 2020.
[111] Ibid.
[112] IEA, www.iea.org/data-and-statistics/data-tables?country=UAE&energy=Electricity&year=2017. Accessed 15 May 2020.

was supposedly ready to commence operations.[113] With regard to solar power, supposedly 32% of the UAE's territory is "highly suitable" for solar power deployment.[114] In addition, the UAE began operating the world's largest solar plant in 2019 at Sweihan, with 1.17 GW of generation capacity. This adds to the 487 MW of solar PV and 100 MW of CSP already installed in the UAE.[115] Finally, solar energy in the UAE is some of the cheapest in the world. The aforementioned Sweihan solar plant can offer solar power at 2.42 cents/kWh, while the DEWA III 800MW solar plant at Dubai can offer 2.99 cents/kWh.[116] Thanks to the UAE's enormous solar power potential and cheap solar electricity prices, the country is in prime position to leverage these resources to create green hydrogen.

In fact, a study has already shown the potential of the UAE to become a cost competitive producer of green hydrogen and ammonia. The study assumes that producing 1kg of hydrogen requires 50kWh of electricity. Given that the UAE offers solar electricity prices of less than 3 cents/kWh, it would cost only $1.5 to produce one kg of hydrogen. Assuming a 10-year lifespan and linear depreciation of a 1MW hydrogen electrolyser that cost $400,000, the overall cost of green hydrogen could reach $1.75/kg in the UAE.[117] The same logic applies for green ammonia. According to the Power to Ammonia study by the ISPT in the Netherlands, the low cost of solar could enable the UAE to cost-competitively produce green ammonia as well. In fact, the UAE environment minister claimed that green hydrogen produced in the UAE could reach cost competitiveness within five years.[118] In other words, the UAE is one of the best-positioned countries to become the first adopters of cost-competitive green hydrogen or ammonia fuels, especially for the shipping sector.

General hydrogen policies

The UAE government lacks a unified and integrated plan to convert to a hydrogen-based economy. The UAE has committed to a few plans of hydrogen adoption, but none are integrated with each other. One such plan is a memorandum of understanding signed in 2020 between the Abu Dhabi Department of Energy and the power project developer Marubeni on developing a hydrogen-based society, but lacks any details on timeline or financial commitment.[119] Another plan comes through the UAE Vision 2021 framework, which mentions hydrogen as a potential source of energy that can contribute towards achieving a 50% clean energy mix in the UAE by 2050. Thus, the UAE lacks a "roadmap" that guides the country towards attaining a hydrogen-based future.

However, the UAE government has already kicked off multiple pilot projects to explore the potential role of hydrogen in diversifying away from its economic reliance on oil and gas. Construction for the UAE's first green hydrogen project commenced in February 2019 at Seih Al

[113] "UAE's Nuclear Plant 'ready' to Begin Operations." The National, 28 Jan. 2020, www.thenational.ae/uae/uae-s-nuclear-plant-ready-to-begin-operations-1.970946. Accessed 15 May 2020.
[114] Gherboudj, Imen, and Hosni Ghedira. "Assessment of Solar Energy Potential over the United Arab Emirates Using Remote Sensing and Weather Forecast Data." Renewable and Sustainable Energy Reviews, vol. 55, Mar. 2016, pp. 1210–1224, 10.1016/j.rser.2015.03.099. Accessed 8 Feb. 2020.
[115] RENEWABLE ENERGY MARKET ANALYSIS: GCC 2019. 2019.
[116] Wouters, Frank, and Ad Wijk. Feature | The New Oil: Green Hydrogen from the Arabian Gulf., revolve.media/the-new-oil-green-hydrogen-from-the-arabian-gulf/.
[117] Ibid.
[118] Franke, Andreas. "Green Hydrogen Could Be Cost Competitive in Five Years: UAE Minister | S&P Global Platts." Www.Spglobal.Com, 13 Jan. 2020, www.spglobal.com/platts/en/market-insights/latest-news/electric-power/011320-green-hydrogen-could-be-cost-competitive-in-five-years-uae-minister. Accessed 15 May 2020.
[119] "MOU to Establish Hydrogen-Based Society Concluded Between Marubeni, Abu Dhabi Energy Department of UAE | Energy Central." Energycentral.Com, 20 Jan. 2020, energycentral.com/news/mou-establish-hydrogen-based-society-concluded-between-marubeni-abu-dhabi-energy-department-uae.

Dahl.[120] This project aims to pilot an integrated electrolyser plant with 1 MW of capacity, and is aiming to be completed by 2020.[121] In addition, the French industrial gases company Air Liquide and the UAE's Khalifa University have partnered to conduct extensive studies on the potential of establishing a hydrogen mobility network in the UAE. The study reported that the UAE has a number of fuel cell vehicles in operation in Abu Dhabi, with one refueling station already established and another currently being constructed.[122] Even with the lack of policy or a hydrogen roadmap, the UAE is already taking tentative steps in exploring its role in a hydrogen-based world economy.

Port-specific initiatives

In terms of specific hydrogen initiatives from the port of Jebel Ali, the port has not published any commitments to integrating hydrogen into its operations. So far, the port operator DP World has installed enough solar panels at its global headquarters at Jebel Ali to render the building carbon neutral.[123] In addition, DP World has signed an agreement with SirajPower to install a 15MW solar plant in the Jebel Ali Free Zone next to the Jebel Ali port.[124] Other than these two initiatives, the port has not implemented any other sustainability initiatives, much less commitments to begin integrating hydrogen into its operations.

Feasibility to Bring Hydrogen to Port

The port of Jebel Ali has enormous underlying potential to become a hydrogen-based fuel hub for the shipping sector. The abundant natural gas resources of the UAE, coupled with how a commercial-scale CCUS project is already in operation in Abu Dhabi, places the UAE in prime position to generate large volumes of blue hydrogen. The same argument applies for green hydrogen. The abundance of solar potential and the commissioning of major solar energy projects in the UAE have lowered the cost of solar power to less than 3 cents a kWh, which makes the production of both green hydrogen and green ammonia cost-competitive.

Coupled with the UAE's own hydrogen production capacity and its proximity with Saudi Arabia - one of the largest ammonia producers in the world, the port of Jebel Ali could be a prime candidate for both the production and trade of hydrogen-based shipping fuels. The fact that the port of Jebel Ali does not have any concrete commitments or policies that support hydrogen uptake can even be an advantage, because advocacy groups can take this chance to design an ideal hydrogen-based shipping fuel procurement and delivery plan from scratch.

[120] Leon, Janice. "First Green Hydrogen Project Breaks Ground in Dubai." Gulfnews.Com, 3 Feb. 2019, gulfnews.com/uae/first-green-hydrogen-project-breaks-ground-in-dubai-1.1549175502065. Accessed 15 May 2020.
[121] Ibid.
[122] Awad, Maram. Hydrogen Mobility in the UAE. Oct. 2018. Accessed 14 May 2020.
[123] "Sustainability." DP World UAE Region, dpworld.ae/sustainability/. Accessed 15 May 2020.
[124] "DP World Contracts SirajPower for JAFZA Solar Plant Installation." Logistics Middle East, 20 Nov. 2018, www.logisticsmiddleeast.com/business/31709-dp-world-contracts-sirajpower-for-jafza-solar-plant-installation. Accessed 14 May 2020.

Ports of Keihin

Japan's highest-traffic port network

The Ports of Keihin, and the Port of Tokyo in particular, are considered to be one of the key shipping locations in Asia. Japan has significant ambitions to develop a hydrogen economy for both land-based transportation, power generation, and shipping. Although Japan's hydrogen market is not yet operational, there are already many joint ventures, projects, and developments, all backed by the government, taking place. Once these infrastructure and developments are completed, Japan could have the technological feasibility to produce hydrogen-based fuels within the country. Japan has also formalized hydrogen trade agreements with Australia as a major part of the country's plan to access green hydrogen.

Given the government and company investment in developing a hydrogen-fuel based economy, and the policies and pilot projects enacted, the Port of Tokyo has the full capability to move forward as a hydrogen and ammonia energy hub for shipping.

Ports of Keihin: Japan's highest-traffic port network

Introduction

The Port of Tokyo is considered to be one of the key shipping locations in Asia. It is the largest and most important port in Japan, handling a total of 4.57 million TEU in 2018. It shares the Tokyo Bay Area with two other major ports as well: Port of Yokohama and Kawasaki. Collectively, Tokyo, Yokohama, and Kawasaki are known as the Ports of Keihin, and together, they are one of the highest-traffic ports.[125] This relationship between the three ports will be a key factor in the transition towards zero-carbon fuel sources. Should the Port of Tokyo transition to a hydrogen-based fuel source, it would be likely that the other two ports would follow suit or lead in its development.

Individually, the Port of Tokyo has a massive influence over Japan's Tohoku Region, which serves a population of over 40 million people. This commercial port is responsible for the distribution of goods throughout the Metropolitan area of Tokyo and surrounding regions such as Shinetsu region and southern Tohoku area.[126]

Looking ahead, the Port of Tokyo has recognized the need to improve their facility to meet the future international standards of trade. In essence, the Japanese government plans to reorganize, expand, and improve the functionality of the port. Furthermore, the port is slowly implementing environmental plans to make the harbor greener. This includes the installation of solar panels and the expansion of hydrogen stations.[127]

Accessibility to Hydrogen and Ammonia

As an island nation, Japan has been heavily reliant on fossil fuel for its energy demand, and even more so since the wake of the Fukushima Incident of 2011. As of 2017, Japan's energy mix is 87.4 percent fossil fuel, with 39 percent from petroleum.[128] Given it's high dependence on fossil fuel, Japan has started to explore other potential fuel sources. As such, Japan has adopted a "Basic Hydrogen Strategy" due to the potential market growth of hydrogen in the coming years.[129] Furthermore, hydrogen has the capability of reducing energy supply risk as it could be procured in various methods. Japan forecasts that the hydrogen market within the country could grow to 408.5 Billion Yen or $3.79 Billion USD. Given this projection, the government has been willing to engage in R&D and fund major producers, such as Toyota, in developing pathways to achieve a hydrogen fuel-based transportation economy.[130]

The Port of Tokyo's feasibility of adapting a hydrogen-based fuel from a technology and procurement perspective could be analyzed at three different levels: the utilization of existing

[125] "Port of Keihin." Www.Joc.Com, www.joc.com/port-news/asian-ports/port-keihin. Accessed 14 May 2020.
[126] Port of Tokyo 2020: Bureau of Port and Harbor, Tokyo Metropolitan Government. BUREAU OF PORT AND HARBOR, TOKYO METROPOLITAN GOVERNMENT, Mar. 2020.
[127] Ibid.
[128] "2019 – Understanding the Current Energy Situation in Japan (Part 1)." Agency for Natural Resources and Energy,METI, 13 Aug. 2019, www.enecho.meti.go.jp/en/category/special/article/energyissue2019_01.html. Accessed 15 May 2020.
[129] Makino, Hanna. "Japan, the New Hydrogen Nation." S-GE, 23 Jan. 2020, www.s-ge.com/en/article/global-opportunities/20201-c5-japan-hydrogen-market. Accessed 15 May 2020.
[130] Dawson, Chester. "For Toyota, Hydrogen Still the Route Forward." The Japan Times, 11 Oct. 2019, www.japantimes.co.jp/news/2019/10/11/business/corporate-business/toyota-hydrogen-mirai-sedan/. Accessed 15 May 2020.

hydrogen development by Japanese industrial companies, the development of hydrogen and ammonia facilities in the Keihin Port area, and the capability of importing hydrogen-based fuel.

I. *Utilizing existing hydrogen projects by Japanese industrial companies*

Although Japan's hydrogen market is not yet operational, there are already many joint ventures, projects, and developments, all backed by the government, taking place.[131] As such, once these infrastructure and developments are completed, Japan could have the technological feasibility to produce hydrogen and hydrogen-based fuels within the country. In effect, the Port of Tokyo would be able to shift to a hydrogen and ammonia hub, should deep sea shipping demand for hydrogen-based fuel grow.

To date, Japan has started to develop a number of projects that will help grow the hydrogen supply chain within the country. Such projects range from upstream, midstream, and downstream of the supply chain. While many of the business initiatives will be further explored in the "Port of Tokyo's Relevant Hydrogen and Ammonia Policies" section, there are a few current developments that are noteworthy to explore.

The first is the Fukushima Hydrogen Energy Research Field (FH2R). In construction since 2018, this is a renewable energy-powered-10MW class hydrogen production unit, which is currently the largest in the world.[132] The purpose of this hydrogen plant is for transportation use, including cars, buses, and with other sectors in consideration. Furthermore, this pilot project will be instrumental in developing the strategy and mechanisms in balancing the electricity produced by the installed renewables with the current Japanese grid.

The second project is a pilot ammonia production plant constructed by the Tsubame BHB Co. at the Kawasaki Factory of Ajinomoto Co., located 17km south of the Port of Tokyo. Completed in 2019, this plant will procure several dozen tons of ammonia per year for transportation use. While this is still a pilot project, it is a stepping stone towards their goal of building more on-site ammonia manufacturing facilities throughout Japan, with the objective of producing tens of thousands of ammonia per year.[133]

II. *The Development of Ammonia and Hydrogen Facilities in Keihin Port Area*

To date, the Keihin Port area has adopted hydrogen-based fuel technology and pilot projects. While many of these developments are not in the Port of Tokyo, the introduction of hydrogen-based technology in the Keihin Port area as pilot projects would indicate that there is potential to access hydrogen in the Port of Tokyo.

Within the Keihin Port area, the Port of Yokohama and Kawasaki will introduce hydrogen fuel cell tugboats by 2022.[134] Although the hydrogen fuel cell would be unfeasible for deep sea shipping, it is still significant in this context as it signifies that there will be hydrogen fuel at the Keihin Port area to help refuel the tugboats. Furthermore, the Port of Yokohama, in partnership with Toshiba, will be introducing pilot projects to install

[131] Makino, Hanna. "Japan, the New Hydrogen Nation." S-GE, 23 Jan. 2020, www.s-ge.com/en/article/global-opportunities/20201-c5-japan-hydrogen-market. Accessed 15 May 2020.

[132] "Japanese Launch World's Largest-Class Hydrogen Production Unit." Renewable Energy World, 16 Mar. 2020, www.renewableenergyworld.com/2020/03/16/japanese-launch-worlds-largest-class-hydrogen-production-unit/. Accessed 15 May 2020.

[133] Ltd, Tsubame BHB Co. "Completed Construction of Pilot Plant for On-Site Ammonia Manufacturing at the Tsubame BHB Kawasaki Branch." Tsubame BHB Co., Ltd., 7 Oct. 2019, tsubame-bhb.co.jp/en/2019/10/07/pressrelease/. Accessed 15 May 2020.

[134] Wingrove, Martyn. "Japan Takes a Leap into Hydrogen Fuel." Riviera, 30 Oct. 2019, www.rivieramm.com/news-content-hub/news-content-hub/japan-takes-a-leap-into-hydrogen-fuel-56658. Accessed 15 May 2020.

water electrolysis hydrogen generators and hydrogen storage tanks.[135] Although this is meant as back-up generators for the Port of Yokohama, it proves that it would be feasible to build hydrogen-based facilities in the Keihin Port area.

III. Capability of Importing Hydrogen-Based Fuel

Japan's forecast of a $3.79 Billion USD hydrogen economy has pushed the government and companies to develop facilities and infrastructure to procure hydrogen-based fuel domestically. However, Japan has recognized the constraint that comes from energy dependence given its current fossil fuel demand. As such, Japanese companies have looked to diversify their hydrogen supply chain by looking for external sources.

One of the largest projects for sourcing hydrogen internally, is HySTRA (Co2-Free Hydrogen Energy Supply-chain Technology Research Association).[136] This association, backed by companies such as Shell, Kawasaki Heavy Industries, and Iwatani Corporation, aims to create a complete supply chain to import hydrogen from Australia. Through this development, the HySTRA association will develop a gasification facility in Australia, liquified hydrogen carrier vessel, and storage and unloading facilities in Japan. Although the downstream of the supply chain will be located in Kobe, the HySTRA aims to expand its storage and unloading facilities to multiple ports around the world.

Port of Tokyo's Relevant Hydrogen and Ammonia Policies

While the Port of Tokyo has not enacted specific policies in applying hydrogen-based fuel to deep sea shipping, the Tokyo Metropolitan Government has taken steps to develop its green strategies. This will pave the way for the introduction of hydrogen and ammonia as fuel sources. Among its goals, there are two harbor specific development plans and policies that will support the future introduction of hydrogen-based fuels to the port.

The first is the Eighth Revised Port and Harbor Action Plan. This plan comes with a wide array of visions, including the reorganization and expansion of terminal facilities, increased tourism to the harbor, and increased maintenance of port security. Among its goals, the most significant is the aim to establish green projects such as the solar power and hydrogen stations.[137] At the moment, most of the pilot projects for hydrogen stations are situated in Yokohama and Kawasaki as previously mentioned. However, the Action Plan indicates the openness to hydrogen developments at the port.

The second policy that will usher the development of hydrogen-based fuel is the Basic Agreement. Signed in 2008, this agreement accelerated the collaboration between the Keihin Ports with the goal of increasing their competitiveness in international shipping. Through this, the Keihin Ports will work together to improve their facilities and functionality. As such, should hydrogen infrastructure develop in one of the ports, it will likely be used in another as well.

[135] "Toshiba : News Release (4 Nov, 2015): Toshiba Wins Order to Supply Independent Hydrogen Energy Supply System to the City of Yokohama's Port & Harbor Bureau." Toshiba.Co.Jp, 4 Nov. 2015, www.toshiba.co.jp/about/press/2015_11/pr0402.htm. Accessed 15 May 2020.
[136]"Hydrogen Energy Supply Chain Pilot Project between Australia and Japan." HYDROGEN SUPPLY CHAIN - HySTRA, www.hystra.or.jp/en/project/. Accessed 15 May 2020.
[137] Port of Tokyo 2020: Bureau of Port and Harbor, Tokyo Metropolitan Government. BUREAU OF PORT AND HARBOR, TOKYO METROPOLITAN GOVERNMENT, Mar. 2020.

Feasibility in bringing hydrogen-based fuel to the Port of Tokyo

Given the government and company investment in developing a hydrogen-fuel based economy, and the policies and pilot projects enacted, the Port of Tokyo has the full capability to move forward as a hydrogen and ammonia energy shipping hub. The Port of Tokyo is aware of the need to make this energy transition, and they have historically been working closely with other Keihin Ports in developing their infrastructure.

However, the shift to hydrogen-based fuel for deep sea shipping is contingent on the demand from shipping companies. Additionally, Japan would also need to make their hydrogen as cost-competitive as current fuel sources such as VLSFO and LNG. Even so, Japan's vision of a hydrogen-based economy will play an essential role in developing the supply of hydrogen and ammonia.

Port of Hong Kong

One of the busiest and most efficient international container ports in the world

Port of Hong Kong is one of the most connected ports in the world. China's Belt and Road Initiative highlights the critical position of Port of Hong Kong in the world.

However, Hong Kong is an example of a port that lacks the first-mover potential for hydrogen fuel adoption. The city lacks both production capacity and policy support for hydrogen, and ongoing political unrest discourages meaningful investment by major companies.

At best, Port of Hong Kong could serve as a refueling hub for Asian-Pacific trade routes, but recent economic and political trends indicate an ongoing decrease in the port's competitiveness.

Port of Hong Kong: One of the busiest and most efficient international container ports in the world

Trade with Critical Shipping Routes

The Port of Hong Kong is one of the busiest, the most connected, and the most efficient international container ports in the world. The port provides about 330 frequent and comprehensive container liner services per week, connecting to around 470 destinations worldwide.[138]

China's Belt and Road Initiative (BRI) - a massive trade and infrastructure network buildout - covers about 60 countries. Among these participating countries, the Port of Hong Kong trades with about 45 of them. As a result, the Port of Hong Kong is becoming a key node for trade between China and other emerging economies around the world.

Assessing the Port's Hydrogen and Ammonia Potential

Hong Kong has limited hydrogen production capacity and projected hydrogen demand, which poses a key challenge for the Port of Hong Kong to switch to hydrogen or ammonia fuel source before 2050.

In terms of hydrogen production capacity, Hong Kong cannot become a major hydrogen producer, as it lacks both the resources for hydrogen production and the geological capacity for carbon capture, utilization and sequestration (CCUS). According to a study by the Institute of Energy Economics Japan, Hong Kong does not have adequate CCUS capacity. In order to procure zero-emission hydrogen, Hong Kong needs to import from economies where CCUS is available, or where renewable energy is abundantly deployed. Thus, Hong Kong would most likely be a hydrogen importer to meet any future demand.

However, the projected hydrogen demand in Hong Kong accounts for only 2.8% of the projected hydrogen demand in mainland China in 2050. An additional sign of weak hydrogen demand growth is how there is hardly any anticipated reduction in Hong Kong's fossil fuel demand by 2040. As a result, Hong Kong does not appear to be a demand driver for hydrogen in the region.

Bunkering

Hong Kong could have potential as a hydrogen bunker and refueling hub. More than 30 companies in Hong Kong are bunker suppliers and traders, ranging from oil majors and leading international and regional bunkering groups to Chinese and local companies.[139] In 2013, about 500,000 to 600,000 tonnes of marine fuels were delivered to vessels each month in Hong Kong. Total fuel storage capacity is estimated to be around 450,000 tonnes.[140] Nevertheless, bunker volumes sold are thought to have decreased slightly since 2012 and were believed to be somewhere between 6 million and 6.5 million mt in 2018. Although Hong Kong offers strong bunkering facilities, it is unlikely to make the first move on switching to hydrogen given how the lack of growth in its bunkering industry would render any hydrogen investments unprofitable.

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[138] "HKMPB - Port." Hkmpb.Gov.Hk, 2018, www.hkmpb.gov.hk/en/port.html.
[139] Lampert, Edwin. "Hong Kong Bunkering Attracts Newcomers." Riviera, 8 Nov. 2013, www.rivieramm.com/news-content-hub/news-content-hub/hong-kong-bunkering-attracts-newcomers-39633. Accessed 14 May 2020.
[140] Ibid.

Hydrogen Policy Support

In 2017, the Hong Kong government published Hong Kong's Climate Action Plan 2030+ report, pledging to reduce 65 to 70 percent of its carbon intensity by 2030 using 2005 as the base year.[141]

Looking ahead, however, the Hong Kong government currently does not have a long-term decarbonization strategy or target beyond 2030. The absence of any policy support to encourage either hydrogen production or consumption further emphasizes Hong Kong's weak hydrogen adoption potential. This lack of long-term policy support will become the main obstacle for the Port of Hong Kong to conduct the successful transition to hydrogen or ammonia fuel sources.

Feasibility in Switching to Hydrogen-based Fuel

At best, the Port of Hong Kong could serve as a refueling hub for Asian-Pacific trade routes, but recent economic and political trends indicate an ongoing decrease in the port's competitiveness. Hong Kong is one of the most connected ports in the world, especially with developing countries along the Belt and Road Initiative. The port is also a regional bunkering and refueling hub, but nowhere close to the scale of Singapore. Although these factors would place the port in a prime position to push hydrogen adoption among its numerous trading partners, Hong Kong is starting to lose its influence among global ports. Bunkering volumes have fallen since 2012, and other Mainland Chinese ports are overtaking Hong Kong in terms of global connectivity. The ongoing political unrest since June 2019 have also forced companies to consider decreasing their exposure to the city. Thus, Hong Kong does not appear to play a big role in promoting hydrogen adoption in the Asia-Pacific network, and may only switch to hydrogen solutions once the rest of the ports in the region do so.

[141] Jiang, Xiaoqian, and Mengpin Ge. "Hong Kong Energy Policy SimulatorLATOR: Methods, Data, and Scenario Results For 2050." World Resources Institute.

Port of Shanghai

World's best connected and largest cargo port

China is the world's largest hydrogen producer, accounting for ⅓ of the world's total production. Shanghai's status as the world's most connected port gives it enormous leverage in pushing other ports to adopt hydrogen solutions. As countless shipping companies use the port as both a final destination and a refueling station, Shanghai's adoption of hydrogen-based fuels would usher in a wave of subsequent adoptions in other ports.

Port of Shanghai could be a major hydrogen supply, demand and refueling hub for the entire Asia-Pacific region

Nevertheless, this is contingent upon the Chinese government recognizing hydrogen as a policy priority. So far, interest in hydrogen as a dominant fuel source is low, particularly for the shipping sector.

Shanghai has enormous potential to drive hydrogen adoption in the Asia-Pacific network, but currently lacks the policy support to do so.

Port of Shanghai: World's largest cargo port and best-connected port

Trade with Critical Shipping Routes

Container liner services from the Port of Shanghai connect to nearly all the major ports around the world. More than 2,000 container ships depart from the port every month, en route to North America, Europe, the Mediterranean, Persian Gulf, Red Sea, Black Sea, Africa, Australia, Southeast Asia, Northeast Asia, and other regions.[142]

The Port of Shanghai currently tops the United Nations Conference on Trade and Development's (UNCTAD) 2019 ranking of the world's best-connected ports, with a connectivity score of 134 points in UNCTAD's port Liner Shipping Connectivity Index.[143]

Assessing the Port's Hydrogen and Ammonia Potential

I. Hydrogen

China is the world's largest hydrogen producer, with an annual production of 22 million tons, accounting for over 1/3 of the world's total production. Hydrogen supply comes from high local demand for chemical production and oil refining.[144]

The Chinese hydrogen fuel sector has made substantial progress in the production and application of fuel cells and related components, but still lags behind in terms of storage, transportation, and infrastructure.[145] These deficiencies hold China back in terms of transitioning to a hydrogen-based economy and raising its overall hydrogen demand..[146]

Looking ahead, hydrogen energy is expected to see a wide application in China's transportation and industrial sectors if the high cost of hydrogen production and lack of hydrogen infrastructure can be tackled in the near future.[147]

II. Ammonia

China is the world's largest producer and consumer for ammonia. China accounts for nearly 40% of the world's ammonia production capacity.[148] In 2018, China produced about 54 million metric tons of ammonia.[149]

On the one hand, China has been closing down millions of tons of annual ammonia production capacities, as a result of industry consolidation and the campaign against air pollution. On the other hand, China has been building many new coal-based ammonia

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[142] Portshanghai.Com.Cn, 2014, www.portshanghai.com.cn/en/channel1/channel11.html.
[143] "Unctad.Org | Shanghai Tops Ranking of World's Best-Connected Ports." Unctad.Org, unctad.org/en/pages/newsdetails.aspx?OriginalVersionID=2163&Sitemap_x0020_Taxonomy=UNCTAD%20Home. Accessed 13 May 2020.
[144] Brasington, Louis. "Hydrogen in China | Cleantech Group." Www.Cleantech.Com, 24 Sept. 2019, www.cleantech.com/hydrogen-in-china/. Accessed 13 May 2020.
[145] Liu, Yuanyuan. "Hydrogen Is Expected to Account for 10% of China's Energy Network by 2050." Renewable Energy World, 26 Aug. 2019, www.renewableenergyworld.com/2019/08/26/hydrogen-is-expected-to-account-for-10-of-chinas-energy-network-by-2050/#gref. Accessed 13 May 2020.
[146] Ren, Xusheng, et al. "Challenges towards Hydrogen Economy in China." International Journal of Hydrogen Energy, 14 Feb. 2020, www.sciencedirect.com/science/article/pii/S0360319920303414, 10.1016/j.ijhydene.2020.01.163. Accessed 13 May 2020.
[147] Ibid.
[148] Zeng, Cai. Overview of China Ammonia Industry.
[149] Brown, Trevor. "Ammonia in China: Change Is Coming." Ammonia Energy Association, 7 Nov. 2019, www.ammoniaenergy.org/articles/ammonia-in-china-change-is-coming/. Accessed 13 May 2020.

projects in recent years.[150] Currently, about 70% of China's ammonia is derived from coal, 10% from oil products and 20% from natural gas.[151]

According to the Ammonia Energy Association, key questions to consider will be the timing of when China builds its green ammonia demonstration plant and when the country will recognize green ammonia as a valuable storage and distribution technology within China's clean energy portfolio.[152]

III. Renewables

China is the top country in the world for the deployment of renewable power, with almost 30% of the world's renewable power capacity within its borders. This deployment is still growing, as almost half the renewable power capacity added globally in 2017 was in China.[153] More than 1/3 of China's power capacity is renewable, with the energy mix split into roughly 19 percent hydro, 10 percent wind, and 9 percent solar in 2018.[154]

China is especially active in its deployment of wind and solar energy. China has abundant wind power resources, particularly in its northern and western provinces. In 2018, China had installed roughly 185 GW of wind power, which provided roughly 5% of China's electricity generation.[155] China's major solar energy capacity is also primarily located in the western part of the country.[156] In 2018, China had deployed 175 GW of solar power, which provided roughly 3 percent of China's electricity generation[157]

Nevertheless, China faces high rates of renewable energy curtailment, and must increasingly rely on ultra-high voltage (UHV) technology to send electricity from remote regions with excess supply to areas of higher demand. An example of an UHV-transmission line project is a 1,100-kV transmission line from its far northwest to the heavily populated east in 2016.[158] Built by the State Grid Corp. of China, this line stretches 3,293 km (2,046 miles) and can transmit 12 GW of power.[159] The company claims that this line can supply 66 billion kWh of electricity to eastern China annually, meeting the power demand of 50 million households and reducing coal use by 30.24 million tons.[160] Thus, Shanghai could greatly benefit from the transmission of renewables from China's western regions as the buildout of UHV transmission lines continues.

IV. CCUS

Shanghai currently has a CCUS demonstration project in operation at a local coal plant, and uses the carbon to support the local beverage bottling industry. China also has

[150] Zeng, Cai. Overview of China Ammonia Industry.
[151] Qadir, Zara. "Exploring the Economics and Sustainability of the Ammonia Industry in China | Sustainable Gas Institute." Sustainable Gas Institute, www.sustainablegasinstitute.org/exploring-the-economics-and-sustainability-of-the-ammonia-industry-in-china/. Accessed 13 May 2020.
[152] Brown, Trevor. "Ammonia in China: Change Is Coming."
[153] "RENEWABLE POWER | Guide to Chinese Climate Policy." Columbia.Edu, 2017, chineseclimatepolicy.energypolicy.columbia.edu/en/renewable-power. Accessed 14 May 2020.
[154] Ibid.
[155] "Wind Power | Guide to Chinese Climate Policy." Columbia.Edu, 2018, chineseclimatepolicy.energypolicy.columbia.edu/en/wind-power. Accessed 14 May 2020.
[156] "Solar Power | Guide to Chinese Climate Policy." Columbia.Edu, 2018, chineseclimatepolicy.energypolicy.columbia.edu/en/solar-power.
[157] Ibid.
[158] "World's Biggest Ultra-High Voltage Line Powers Up Across China." Www.Tdworld.Com, 2 Jan. 2019, www.tdworld.com/overhead-transmission/article/20972092/worlds-biggest-ultrahigh-voltage-line-powers-up-across-china. Accessed 14 May 2020.
[159] Ibid.
[160] Ibid.

multiple other CCUS projects either completed or in the works. Nevertheless, theFrench Institute of International Relations claims that CCUS is still in its infancy stage in China. Although the first large scale CCUS project was commissioned in 2018, CCUS still faces many challenges, such as an adequate regulatory framework, suitable storage sites for CO2, and financial incentives for projects.[161]

Hydrogen Policy Support

I. **Chinese Government Level-Develop H2 Fuel and Fuel Cell**

Hydrogen energy has recently been listed as one of the disruptive technologies for the industrial revolution by the central government in several key documents.[162]

In 2015, the Chinese government published the Made in China 2025, a 10-year plan to upgrade China's manufacturing industry. This initiative highlights hydrogen as a key energy source to develop in the energy vehicle market.

In 2016, the first Hydrogen Fuel Cell Vehicle Technology Roadmap was released. Later that same year hydrogen new energy vehicles and hydrogen infrastructure were added to the 13th Five-Year Plan outlining targets for mass application of hydrogen in the transport sector.[163]

The Chinese government recently issued a whitepaper on the status and prospects of the hydrogen fuel and fuel cell sectors, indicating that energy derived from hydrogen will become an important part of the Chinese energy network. [164]

By 2050, hydrogen fuel is expected to account for 10 percent of the Chinese energy system. Demand for hydrogen fuel is expected to grow to nearly 60 million tons and annual economic output is expected to surpass 10 trillion yuan. [165]

II. **Shanghai City Government Level-H2 Energy Harbor for EV**

The Shanghai city government plans to build a world-class "Hydrogen Energy Harbor" in its Jiading District, the center of its automobile industry, to cultivate a sound industrial chain for hydrogen fuel cell vehicles. The Hydrogen Energy Harbor will form an industrial cluster in a planned space of 2.15 square kilometers, with a production value of 50 billion yuan annually, according to the Xinhua News Agency.

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[161] l'Ifri, Etudes de. "Carbon Capture, Storage and Utilization to the Rescue of Coal? Global Perspectives and Focus on China and the United States." Www.Ifri.Org, June 2019, www.ifri.org/en/publications/etudes-de-lifri/carbon-capture-storage-and-utilization-rescue-coal-global-perspectives. Accessed 14 May 2020.

[162] Ren, Xusheng, et al. "Challenges towards Hydrogen Economy in China." International Journal of Hydrogen Energy, 14 Feb. 2020, www.sciencedirect.com/science/article/pii/S0360319920303414, 10.1016/j.ijhydene.2020.01.163. Accessed 13 May 2020.

[163] Brasington, Louis. "Hydrogen in China | Cleantech Group." Www.Cleantech.Com, 24 Sept. 2019, www.cleantech.com/hydrogen-in-china/. Accessed 13 May 2020.

[164] Liu, Yuanyuan. "Hydrogen Is Expected to Account for 10% of China's Energy Network by 2050." Renewable Energy World, 26 Aug. 2019, www.renewableenergyworld.com/2019/08/26/hydrogen-is-expected-to-account-for-10-of-chinas-energy-network-by-2050/#gref. Accessed 13 May 2020.

[165] Ibid.

Feasibility in Switching to Hydrogen-based Fuel

The Port of Shanghai could be a major hydrogen supply, demand and refueling hub for the entire Asia-Pacific region, but only once the Chinese government provides meaningful policy support.

China has abundant potential to supply both domestic and external demand for blue and green hydrogen. China is already the largest producer of hydrogen in the world. CCUS could decarbonize this production, and Shanghai could use the captured carbon for local manufacturing industries to compensate for its lack of nearby sequestration geology. Shanghai could also benefit from enormous amounts of excess renewable energy from China's western regions, if the country continues with its ultra-high voltage transmission line buildout. This renewable energy could power green hydrogen production around Shanghai.

Shanghai would also be a large consumer of hydrogen, which could further spur both production and imports. The Chinese government has highlighted hydrogen as a key vehicle fuel source in its Made in China 2025 industrial policy. In Shanghai's case, the city plans to build a "world-class" industrial supply chain for hydrogen vehicles. This robust demand would help establish the need for more domestic hydrogen supply, and perhaps even imports from abroad.

Finally, Shanghai's status as the world's most connected port gives it enormous leverage in pushing other ports to adopt hydrogen solutions. As countless shipping companies use the port as both a final destination and a refueling station, Shanghai's adoption of hydrogen-based fuels would usher in a wave of subsequent adoptions in other ports.

Nevertheless, every development described above depends on Chinese government recognition of hydrogen as a policy priority. So far, interest in hydrogen as a dominant fuel source is low, particularly for the shipping sector. Hence, Shanghai has enormous potential to drive hydrogen adoption in the Asia-Pacific, but currently lacks the policy support to do so.

Ports of Australia

All-in on hydrogen

The Ports of Australia could be the first major sources of both blue and green hydrogen supply for the Asia-Pacific region. Australia looks to rapidly ramp up its production of hydrogen during the coming decades to meet future regional demand, as defined in its National Hydrogen Strategy. The country boasts of abundant resources and capacity to export both blue and green hydrogen.

These factors could enable Australia to export green hydrogen, once the renewable energy inputs and electrolysis technology becomes both cost competitive.

Given Australia's major trade links with China, Hong Kong, Japan and Singapore, the Australian ports can further encourage hydrogen adoption in other ports in the Asia-Pacific region by acting as the first major stable and abundant source of supply. Thus, any step by Australia to increase hydrogen capacity is a step towards further hydrogen adoption in the Asia-Pacific network.

Australian Ports: All-in on Hydrogen

Australia Overview

The national government of Australia has taken an ambitious approach to position itself as a major player in the world as a hydrogen producer. In 2018, the country's Council of Australian Governments Energy Council began to define a national hydrogen strategy for Australia. Since 2015, the Australian Government has committed over $146 million to hydrogen projects and it plans to continue investing in the areas of R&D, commercial deployment, infrastructure, and demand creation. Australia is primarily motivated to develop its hydrogen industry in order to utilize its ample supply of renewable energy, meet domestic energy needs, become a net exporter of hydrogen, create new jobs, and achieve carbon reduction targets.

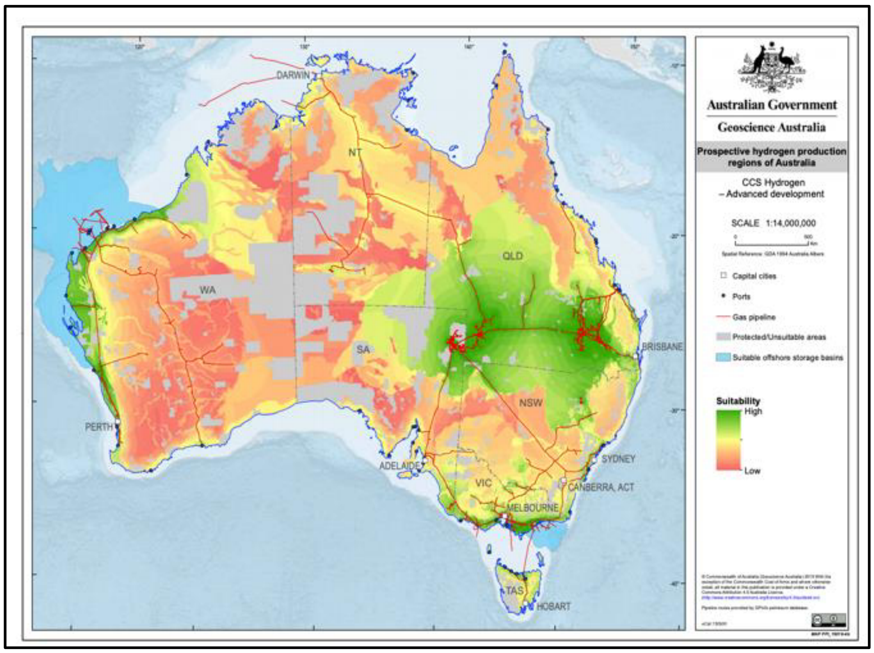


Figure 5-1: Fossil Fuel with CCS Production Potential, Based on Proximity to Advanced CCS Sites

A key element of Australia's approach will be to create hydrogen hubs – clusters of large-scale demand. These may be at ports, in cities, or in regional or remote areas, and will provide the industry with its springboard to scale. Hubs will make the development of infrastructure more cost-effective, promote efficiencies from economies of scale, foster innovation, and promote synergies from sector coupling. The hubs are generally clustered around key resources for hydrogen including access to renewable energy, access to geographic locations favorable to CCUS as shown in Figure 5-1,[166] access to rail and seaports, and access to water. Water scarcity in Australia will be a unique resource constraint for the industry, but advances are being made to make desalination of seawater possible at hub locations. CCUS is one of the most attractive resources that Australia has at its disposal, especially for the early commercialization of hydrogen when natural gas feedstocks will likely be an important part of bringing costs down initially.

The main driver of Australia's ambition to become a hydrogen economy is due to its relationships and proximity to the Asia Pacific region. Japan, Korea, and Singapore in particular are major sources of demand for Australia's hydrogen because of those countries' goals to deploy hydrogen vehicles for on-road transportation as well as for shipping. As recently as

[166] [166] COAG Energy Council. "Australia's National Hydrogen Strategy." November 2019. https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf

January 2020, the trade ministers of Japan and Australia met to sign the Joint Statement on Cooperation on Hydrogen and Fuel Cells at the Australia-Japan ministerial Economic Dialogue.[167] Australia has considerably more land, natural resources, and infrastructure in place to produce hydrogen fuels than any of these other countries.

Today, Australia's annual production of hydrogen is .5 million tonnes of hydrogen, which represents .7% of global hydrogen production. Under an aggressive scenario published under the National Hydrogen Strategy, Australia could produce as much as 11% of global hydrogen by 2050, assuming a more than doubling of global hydrogen by 2050. Under its more conservative estimate of hydrogen demand globally, Australia could produce as much as 24% of the world's hydrogen. These production scenarios would require 918 TWh and 188 TWh of additional electricity, respectively, by 2050.[168] The value of Australia's potential low-emissions hydrogen exports could reach $2.2 billion by 2030 and $5.7 billion by 2040. For this reason, Australia will be a net-exporter of hydrogen with the ability to meet demand for ships making calls at Australian ports and to export to meet demand throughout the Asia Pacific region.

At the national level, the Australia Renewable Energy Agency (ARENA) has been the central government research agency responsible for promoting and accelerating most of the hydrogen pilots and demonstrations. In April 2020, ARENA announced a round of new funding of $70 million for green hydrogen projects that support the goals in the national hydrogen strategy. ARENA's role in the hydrogen ecosystem is to ensure that foundational resources such as renewable energy are in place in order to get projects to commercial scale. For this reason, ARENA has stated that its funding priorities are for commercial projects with more than 100 MW of electrolysers.[169] In addition to ARENA, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has been a leader in driving innovation on hydrogen and ammonia production. While most of the hydrogen in Australia is made with natural gas feedstock and sometimes uses CCUS, CSIRO is developing new technologies to convert hydrogen to ammonia and back again with vanadium membrane technologies which are expected to improve the process and bring down costs.[170]

For the purpose of this report, Australia is analyzed at the country level because its hydrogen strategy plans to leverage the strengths of all of Australia's major ports. While some ports will take the lead on hydrogen exports, all of the major ports in Australia have been incorporated in the national strategy. To illustrate the potential for hydrogen-based fuels at Australian ports, two of the top 10 ports in Australia have been selected for evaluation. Because they have many attributes in common, they are evaluated together.

Top 10 Ports in Australia

1. Port of Brisbane
2. Port of Sydney
3. **Port of Fremantle (Perth)**
4. Port of Melbourne
5. Port of Hedland
6. Port of Dampier

[167] Matich, Blake. "Australia and Japan agree to hydrogen future." PV Magazine Australia. 24 January, 2020. https://www.pv-magazine-australia.com/2020/01/24/australia-and-japan-agree-to-hydrogen-future/
[168] COAG Energy Council. "Australia's National Hydrogen Strategy." November 2019.]
[169] Australian Renewable Energy Agency. "Hydrogen Energy." Accessed 7 May, 2020. https://arena.gov.au/renewable-energy/hydrogen/
[170] Commonwealth Scientific and Industrial Research Organisation. "National Hydrogen Roadmap." 13 November, 2019. https://www.csiro.au/en/Do-business/Futures/Reports/Hydrogen-Roadmap

7. Port of Wellington, NZ
8. **Port of Darwin**
9. Port of Adelaide
10. Port of Newcastle

Port of Fremantle (Perth), Western Australia

Western Australia has been working both at the territory level and the national level to develop its hydrogen ambition. The Port of Fremantle is well-positioned as a hydrogen focal point for the territory because it is not only the third largest port in the country, but it also has existing infrastructure for fuel exports at the port.

Western Australia has a well-established LNG industry and has been able to develop a collaborative and globally competitive supply chain with many of the world's largest oil and gas companies nearby. In 2018, Western Australia was the second largest exporter of LNG in the world. Port of Fremantle has two significant terminals that can potentially be utilized in the future for hydrogen and ammonia export. The Kwinana Bulk Jetty is currently used to handle bulk cargo including fertilizer, making the terminal ready for ammonia export. Similarly, the BP Oil Refinery Terminal is the home of Australia's largest oil refinery, with a capacity of 138,000 barrels per day. The terminal is a significant export hub with existing fuel infrastructure, which could be foundational for other bulk liquids at the port.[171]

Additionally, Western Australia has one of the world's best offshore CCUS resources, which will be critical for blue hydrogen and ammonia production. In 2019, Chevron Australia and other partners launched the Gorgon Joint Venture, a carbon dioxide injection system at the Chevron-led Gorgon natural gas facility on Barrow Island, off the northwest coast of Western Australia. Chevron claims that the project will be the largest storage facility of its kind in the world and it will reduce emissions at the natural gas facility by 40 percent.[172]

The region has many advantages for hydrogen production including some of the highest solar irradiance in the world and wind resources off the western coast. Western Australia also has significant amounts of unpopulated land that can be developed for solar, pipelines, and storage. The Asian Renewable Energy Hub is one example of a joint project being developed by a consortium consisting of InterContinental Energy, CWP Energy Asia, Vestas and Macquarie Group. The proposed project consists of 15 gigawatts of renewable generation and is suited for both solar and wind generation on the 6,500 square kilometer project site with access to both the Port of Hedland and Port of Fremantle. The bulk of the power will enable large scale production of green hydrogen products for domestic and export markets, notably Japan and Korea.[173] The Western Australian Government has also pledged to establish a $10 million Renewable Hydrogen Fund to facilitate private sector investment and leverage financial support for projects like the Asian Renewable Energy Hub.[174]

[171] Fremantle Ports. "Port Facilities." Accessed 7 May, 2020. https://www.fremantleports.com.au/the-port/port-facilities
[172] Chevron. "Safe start up and operation of the carbon dioxide injection system at the Gorgon natural gas facility." 8 August, 2019. https://australia.chevron.com/news/2019/carbon-dioxide-injection
[173] The Asian Renewable Energy Hub. "About the Asian Renewable Energy Hub." Accessed 7 May, 2020. https://asianrehub.com/
[174] Government of Western Australia. "Western Australia Renewable Hydrogen Strategy." July 2019. http://www.drd.wa.gov.au/Publications/Documents/wa_renewable_hydrogen_strategy.pdf

Port of Darwin, Northern Territory

Darwin Port is operated by Darwin Port Operations Pty Ltd which is part of the Landbridge Group. The Landbridge Group is a large private company based in Rizhao city in Shandong Province in China, operating businesses in China and Australia. The Darwin Port operates commercial wharf facilities at East Arm Wharf and the cruise ship terminal at Fort Hill Wharf.

The Port of Darwin is strategically positioned as Australia's nearest port to Asia and the nation's 'northern gateway' for Oceania trade. It is also a key support hub for the expanding offshore oil and gas fields in the Arafura Sea, Timor Sea and waters off the coast of Western Australia. It is the only port between Townsville and Fremantle with full access to multi-modal transport services. Port of Darwin is a strategic trade port with all of Asia because it is the northernmost port in Australia. In particular, China, Hong Kong, Japan, and Singapore are major trade routes.

Darwin Port is well-connected to natural gas infrastructure through local gas reserves in the Timor Sea and through land-based pipelines running through the Northern Territory toward Darwin. Bayu-Undan, in the Timor Sea, has estimated gas reserves of 3.4 trillion cubic feet. Processing of this natural gas takes place at the Darwin LNG facility, which was commissioned in February 2006 and delivered the first cargo of LNG to Tokyo Electric and Tokyo Gas. The LNG plant features:

- A 92m-diameter, 47m-high LNG storage tank to hold up to 188,000m^3 of gas
- LNG process area – for treating and liquefying raw gas
- Marine jetty for delivering liquefied gas to cargo ships for transportation

Darwin is the only port between Townsville and Fremantle with full access to multi-modal transport services. Well planned road transport corridors and close proximity to the Adelaide to Darwin rail terminal provides ease of access to Darwin Port for users to or from all parts of Australia. The port has existing capacity and this, coupled with a port development strategy driven by a determination to take advantage of projected trade growth, sees it well positioned to be able to partner with operators from a wide variety of business sectors.

Port of Darwin has a high likelihood of succeeding as a hydrogen exporting port because of its ample access to natural resources to produce hydrogen, its proximity to Asia, and integration with Australia's energy corridor through intermodal transport that make the Territory an attractive location for renewable hydrogen investment. In addition to the national hydrogen strategy, the Northern Territory has committed to a renewable energy goal of 50% renewable energy in the power sector by 2030. The Northern Territory is seeking investment and collaborative partnerships to develop projects that are aligned with strategic areas of focus including: Exports, enhancing renewable energy access and energy security in remote areas, blending of hydrogen to provide low-carbon gas, green ammonia production, and combined desalination and solar electrolysis systems.[175]

[175] COAG Energy Council. "Australia's National Hydrogen Strategy." November 2019.

Port of Singapore

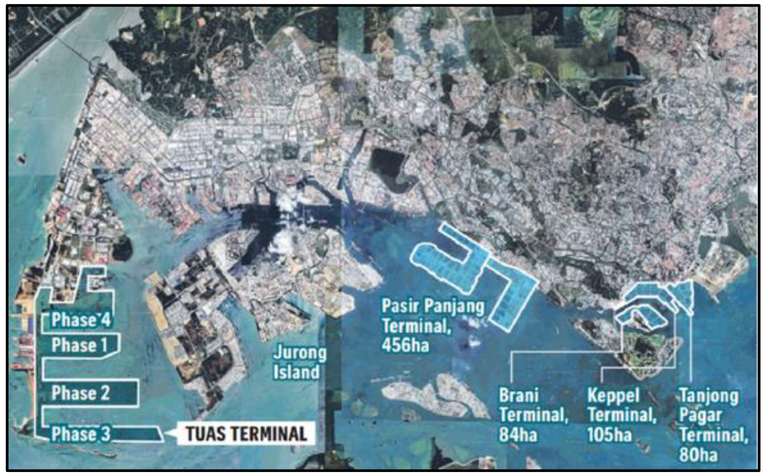
Second largest container port in the world, major bunkering hub

As of last year, the Port of Singapore was ranked as the second-busiest port of the world and is one of the world's major fuel bunkering hubs. While Singapore does not have significant demand for hydrogen-based fuels for domestic consumption, it will likely develop capabilities to bunker fuels for the global shipping industry, building off of existing infrastructure.

Singapore will likely import hydrogen-based fuels from other major producers such as Indonesia, Malaysia, and Australia. With its inbuilt infrastructure, abundance of petroleum and natural gas imports, and political will, the Port of Singapore has the full capability to move towards a hydrogen and ammonia based trading hub for maritime shipping. Additionally, the preexisting, vast trading routes will be advantageous for Singapore, as it will allow them to import and export hydrogen and ammonia in the future.

Singapore: 2nd Largest Container Port in the World

Introduction



The Port of Singapore is widely considered to be one of the largest and most important ports in the world. Singapore has historically played a significant role in providing shipping and trading services between the East and the West. It's key geographic location in Southeast Asia allows for the easy access of maritime companies to engage in commerce with clients from around the world. In many ways, the Port of Singapore has situated itself as a Hub Port for global trade. As of last year, the Port of Singapore was ranked as the second-busiest port of the world, only being beaten by Shanghai, China.

Singapore attained its status as a key trading hub thanks to its prioritization of three factors: connectivity, capacity, and competitiveness.

1. **The connectivity** of this port with international ports around the world is one of the crucial factors that allows for Singapore to secure shipments. Furthermore, there are up to 200 connection vessels at Singapore at any moment, and as such, containers and goods could be passed onto other vessels for delivery.
2. **The capacity**, meaning its deep berth areas, quay lengths, and depth of the harbor allows for all types of ships to enter the port. Furthermore, shipping lines are organized efficiently, thus maximizing the amount of ships that comes through per year.
3. Finally, the Port of Singapore is dedicated to maximizing **the competitive** edge of their port users. By utilizing the most up-to-date technology, AI, Big Data, and other tools, the port aims to maximize the efficiency of their ports, making it one of the premier locations for international shipping.

Accessibility to Hydrogen and Ammonia

As of 2020, Singapore has been a net importer of natural gas and petroleum and has positioned itself as an energy hub within Southeast Asia, thanks to its world-class refining, storage, and distribution infrastructure. Within the region, the country is known to produce vast amounts of petrochemicals, as well as other refined petroleum products. Thus, Singapore is a key player in the world of fossil fuels. Furthermore, Singapore is heavily constrained by its natural resources due to its geography. They need to look outwards to meet their energy demands. As of 2015, Singapore's energy consumption mix was 87 percent petroleum products, with 13 percent natural gas, and the remaining 1 percent from other fuel sources, and the city's electrical grid's feedstock is 95 percent natural gas.[176]

Due to its current status as a major oil trading hub, the Port of Singapore is technically well-positioned to make the transition towards a hydrogen and ammonia-based economy. Singapore could potentially access a steady stream of supply to hydrogen and ammonia in two different pathways.

The first is by increasing the import of natural gas and utilizing it in the production of hydrogen, which would later be used to create ammonia. Given the current infrastructure and trading routes in place for natural gas, this procurement process is feasible. However, the greatest drawback to this pathway is that the produced hydrogen would likely be carbon-intensive, as Singapore lacks the geographic ability to conduct carbon capture, utilization and sequestration (CCUS). It would be possible for Singapore to capture the emissions and utilize them for the city's petrochemical industry, but the costs would outweigh the benefits of this operation.

The second pathway for Singapore to transition to hydrogen and ammonia is to leverage its preexisting status as an oil trading hub.[177] Given its bunkering infrastructure capacity, the Port of Singapore already has the capability to store ammonia. As such, the Singaporean government should explore their existing shipping routes to find countries and ports that have the capacity and political-will to produce and export ammonia. Such countries could be Australia, Indonesia, or Malaysia, all of which are in the Southeast Asia vicinity.

Port Specific Policies

Since signing the Paris Agreement in 2015, Singapore has aimed to reduce their carbon emission levels by 36 percent below their 2005 levels by 2030.[178] While the Port of Singapore does not have official policies in place for the trade and distribution of hydrogen or ammonia, the Singaporean government has made significant strides in developing its efforts that could help pave the way in bringing the two fuels to their ports. Among its sustainable developments, the two key government movements are the Maritime Singapore Green Initiative, and the sponsorship of feasibility reports on hydrogen and ammonia by the Singaporean Government.

I. Maritime Singapore Green Initiative

The Maritime Singapore Green Initiative is a financial goal by the Maritime and Port Authority of Singapore (MPA), where they pledged to invest up to $100 million Singapore Dollars (approximately $70 million USD)[179] in the reduction of carbon emissions as a whole. This initiative was first conceived in 2011 and has since been extended to the end of 2024.[180]

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[176] "International - U.S. Energy Information Administration (EIA)." Eia.Gov, July 2016, www.eia.gov/international/analysis/country/SGP.
[177] "International - U.S. Energy Information Administration (EIA)." Eia.Gov, July 2016, www.eia.gov/international/analysis/country/SGP.
[178] "Singapore Seeking Assistance to Transition to a Cl." Australian Trade and Investment Commission, 24 Apr. 2019, www.austrade.gov.au/news/latest-from-austrade/2019-latest-from-austrade/singapore-seeking-assistance-to-transition-to-a-clean-energy-future. Accessed 14 May 2020.
[179] Average Interest rate of April 2020: 1 Singapore Dollar = 0.7 US Dollar
[180] "Maritime Singapore Green Initiative." Mpa.Gov.Sg, 2018, www.mpa.gov.sg/web/portal/home/maritime-singapore/green-efforts/maritime-singapore-green-initiative.

There are four main aspects of this initiative that would help incentivize the transition to hydrogen or ammonia fuel:[181]

1. **Green Ship Program (GSP)**: This objective is to encourage Singapore-Flagged ship owners to voluntarily adopt solutions that go beyond the IMO environmental regulatory standards. In doing so, the MPA will provide tax rebates and reduction of Initial Registration Fees, or costs that ship owners undertake in order to park their vessels. The levels of the financial incentives are as follows.[182]

   Note: The GSP is effective from January 1, 2010 to December 31, 2024

Criteria	**Incentives**	
	Initial Registration Fee	**Annual Tonnage Tax**
Adoption of ships that exceed the IMO's Energy Efficiency Design Index (EEDI)[183]	50 percent Reduction	20 percent Rebate
Adoption of LNG as a fuel	75 percent Reduction	50 percent Rebate
Adoption of Fuel with lower carbon content than LNG (without the adoption of EEDI)	50 percent Reduction	20 percent Rebate
Adoption of ships that exceed EEDI and utilizes fuel with lower carbon content than LNG	75 percent Reduction	50 percent Rebate

2. **Green Port Program (GPP)**: This objective is similar to the GSP, except that the GPP targets ships and vessels that are calling in the Port of Singapore. In other words, this policy is aimed at ships that will dock at the Port of Singapore for the purpose of trade, fuel, or resupply. Vessels could meet the financial incentives in the following ways:[184]

Note: The GPP is effective from January 1, 2010 to December 31, 2024

Criteria	**Port Dues Concession**
Use of LNG bunker during port stay	25 percent reduction for the port stay
Calling to port vessels exceed IMO's EEDI	
Using the services provided by the LNG-fueled harbor craft during port stay	Additional 10 percent reduction

[181] "Maritime Singapore Green Initiative." Mpa.Gov.Sg, 2018, www.mpa.gov.sg/web/portal/home/maritime-singapore/green-efforts/maritime-singapore-green-initiative.
[182] Maritime Singapore. Adoption of Ship Designs Ex IMO EEDI Req. MPA Singapore, 2019.
[183] Please Refer to Appendix
[184] Maritime Singapore. Adoption of Ship Designs Ex IMO EEDI Req. MPA Singapore, 2019.

3. **Green Energy and Technology Program**: This objective is a joint program between the Maritime Singapore Green Initiative and local maritime companies to research and develop green technology that will help ships meet IMO2030 standards.[185]

4. **Green Awareness Program**: In contrast to the GSP and GPP, this program does not provide financial incentives. Instead, the MPA is dedicated in providing workshops and training for local maritime companies in green skills, such as carbon accounting. The purpose is to encourage companies to pursue advanced sustainability reporting for carbon emissions and pricing. This will allow for companies to better track their carbon emissions in accordance with IMO2020, and will help smooth the transition towards a zero-carbon fuel.[186]

In essence, the Maritime Singapore Green Initiative is an effort by the MPA that incentivizes local maritime companies and vessels using the Port of Singapore to adopt greener strategies. This current program is significant because it demonstrates that Singapore has the fundamental policy mechanisms in place to allow for the transition towards the use of hydrogen and ammonia at their port.

II. Singapore's Official Sponsorship for Feasibility Study on Hydrogen

Within the past two years, the Singaporean government, as well as the PSA, have pushed for the study of hydrogen on two separate occasions.

The first was a partnership between Singapore, KBR, and Argus on a feasibility study on "Hydrogen Imports and Downstream Application."[187][188] This study aimed to assess the cost-competitiveness of transitioning to hydrogen from a fossil fuel-based economy and the social marginal benefits that could be derived from such a shift.

The second study on hydrogen in recent years was between the Singaporean terminal operator, PSA, Singapore LNG Corporation, City Gas, Chiyoda Corporation, and Mitsubishi Corporation. This partnership formed a Memorandum of Understanding (MOU) in developing ways to utilize hydrogen as a zero-carbon fuel source.[189] In particular, this study aims to develop the technology to import, transport, and store hydrogen in Singapore, effectively making it a large energy hub in the future. More specifically, the PSA hopes to apply this transition not only to its maritime shipping industry, but to also contribute towards electrical demand in the country.[190]

Connection to Other Modes of Logistics Transportation

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[185] Maritime Singapore. Adoption of Ship Designs Ex IMO EEDI Req. MPA Singapore, 2019.
[186] Maritime Singapore. Adoption of Ship Designs Ex IMO EEDI Req. MPA Singapore, 2019.
[187] "Singapore Seeking Assistance to Transition to a Cl." Australian Trade and Investment Commission, 24 Apr. 2019, www.austrade.gov.au/news/latest-from-austrade/2019-latest-from-austrade/singapore-seeking-assistance-to-transition-to-a-clean-energy-future. Accessed 14 May 2020.
[188] "Singapore Selects KBR and Argus for Major Hydrogen Feasibility Study | KBR." Www.Kbr.Com, 23 Sept. 2019, www.kbr.com/en/insights-events/press-release/singapore-selects-kbr-and-argus-major-hydrogen-feasibility-study. Accessed 14 May 2020.
[189] "PSA, Jurong Port, Others to Launch Hydrogen Import Study." Offshore Energy, 31 Mar. 2020, worldmaritimenews.com/archives/293434/psa-jurong-port-others-to-launch-hydrogen-import-study/. Accessed 14 May 2020.
[190] "PSA, Jurong Port, Others to Launch Hydrogen Import Study." Offshore Energy, 31 Mar. 2020, worldmaritimenews.com/archives/293434/psa-jurong-port-others-to-launch-hydrogen-import-study/. Accessed 14 May 2020.

The Port of Singapore is often nicknamed the “Gateway of Asia”, due to its immense connectivity in and out of Asia. Beyond its vast shipping routes to 600 ports across the world, the port is also closely connected to Singapore Changi International Airport, which is linked to 300 cities in 70 countries.[191] While this does not necessarily seem to pertain to the maritime shipping industry, it is important to note as there are many cargoes that go between flights and ships at this city.

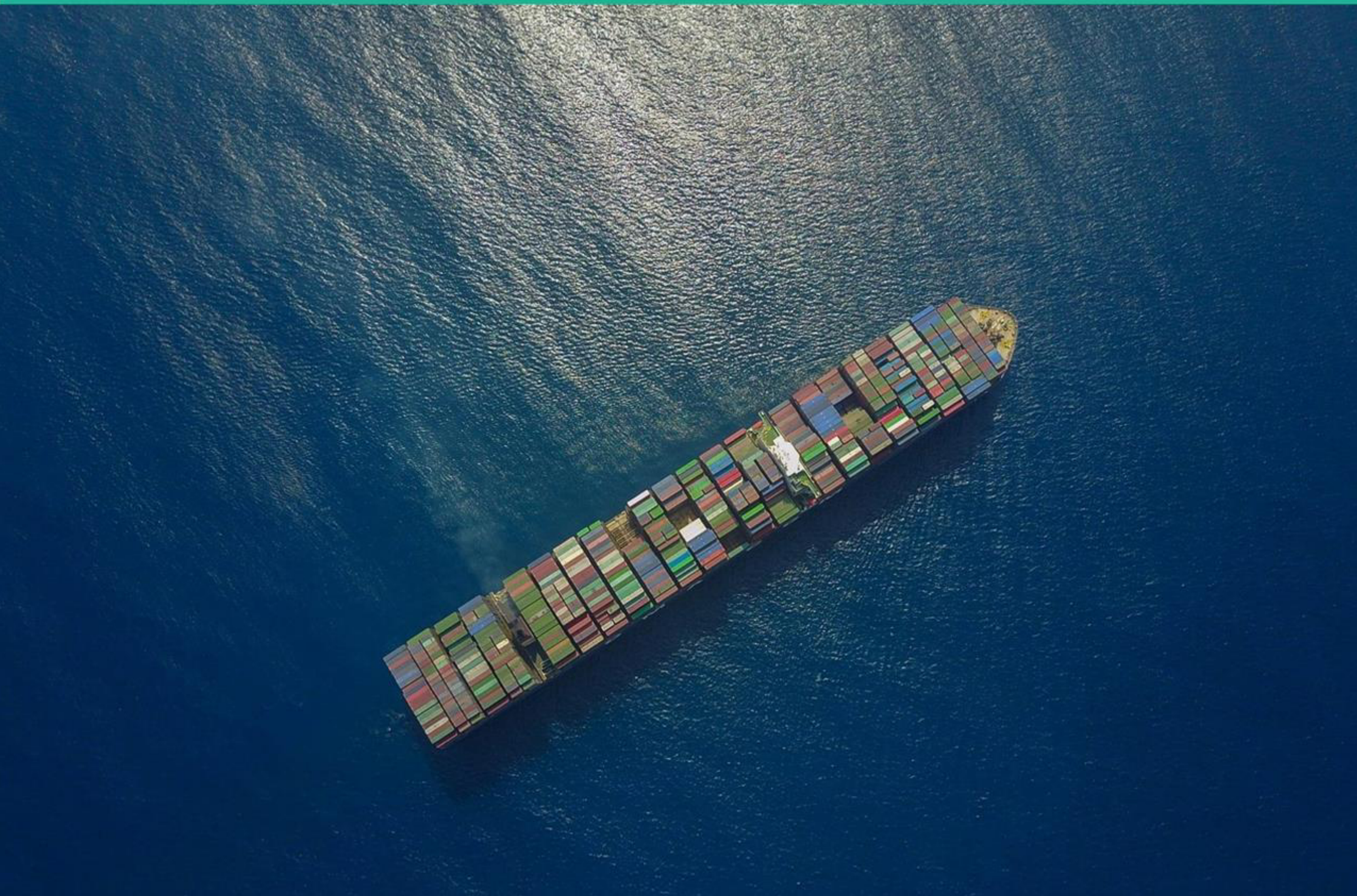
Feasibility to bring hydrogen and ammonia to the Port of Singapore

The MPA and PSA are both cognizant of the need to promote environmental policies, and are aligned with the Paris Agreement of 2015. Furthermore, they are currently working with the government of Singapore and other large multinational companies, such as Mitsubishi Corporation. Such partnerships will help push forward the developments to bunker ammonia for ships. Additionally, Singapore’s preexisting and vast trading routes will allow the country to import and export hydrogen and ammonia in the future. The neighboring countries of Indonesia and Malaysia would be strategic partners in creating blue hydrogen. Australia would also become a key player in supplying hydrogen for Singapore as well. In conclusion, the Port of Singapore is currently on track to becoming a critical hydrogen and ammonia hub for the entire Asia-Pacific region.

[191] “Gateway to Asia.” Mpa.Gov.Sg, 2018, www.mpa.gov.sg/web/portal/home/maritime-singapore/introduction-to-maritime-singapore/gateway-to-asia.

Macro Level Analysis of Adoption Pathways

Key linkages, agreements, and routes that should form based on the port analysis to create a global port network for hydrogen-based fuels.



Macro Level Analysis of Adoption Pathways

This section draws together all the points discussed in the previous sections into a unified overview of how the shipping sector can transition to zero-carbon hydrogen fuel solutions.

Our research and our engagement with the relevant stakeholders suggest that the biggest challenge to hydrogen fuel adoption is overcoming the chicken-or-egg dilemma regarding investments in the necessary infrastructure and technology. The risk of demand not materializing always accompanies investment in the necessary infrastructure to produce hydrogen for zero-carbon shipping at commercial scale. Producers would be left with stranded assets - meaning no revenue to recoup their investments due to the lack of consumer demand. On the other hand, shipping companies hesitate to invest in the technology to power ships using hydrogen because they fear the risk of lack of fuel supply, which would render their investment uneconomical. As a result, neither producers or consumers have incentives to make the first move for investment in hydrogen-fuel solutions. Thus, this section identifies the transition pathways for the supply, transport, utilization, and financing of zero-carbon shipping fuels.

Hydrogen production pathway

The first step to resolving this chicken-or-egg dilemma for hydrogen fuel solutions is to identify the cheapest potential sources of hydrogen production. These sources would correspond to countries or regions that have both the natural resources and the technological capability to produce hydrogen on a large scale at cost-competitive terms. Ramping up hydrogen supply can follow either blue or green production pathways, neither of which are mutually exclusive.

The blue production pathway uses steam-methane reforming (SMR) with natural gas as a feedstock, paired with CCUS. The most cost-effective producers of hydrogen would usually be countries/regions with abundant natural gas resources, or at least have access to this resource through imports. Nevertheless, natural gas-based hydrogen producers must incorporate carbon capture, utilization, and sequestration (CCUS) solutions into their operations in order to qualify as a zero-carbon fuel producer. Since the current cost of carbon is not high enough to spur widespread adoption of CCUS technology, the blue hydrogen production pathway is limited to producers that already have CCUS commercial or demonstration projects in operation, or at least have roadmaps outlining their CCUS development plans. Thus, this pathway would be viable for countries such as the UAE, the Netherlands, the US, Australia, and China.

On the other hand, the green hydrogen pathway hinges on the availability of renewable energy and electrolysis technology. Green hydrogen production shifts the focus to countries or regions with abundant renewable energy resources such as wind or solar. However, the cost of the still-immature electrolysis technology renders green hydrogen uncompetitive in every single country except the UAE. Thus, the green hydrogen production pathway does not appear to be an attractive investment until the cost of both renewable energy and electrolysis technology falls further.

In summary, blue hydrogen is still the most realistic pathway for large-scale production of zero-carbon hydrogen fuels. Hydrogen producers could eventually transition to the green hydrogen pathway once electrolysis technology becomes more cost competitive and renewables increase in deployment.

Hydrogen transport pathway

The transport and storage of hydrogen presents a relatively easier challenge to solve compared to the hydrogen production pathway, given that the necessary technology and standards already exist for the ammonia market.

Ammonia stands out as a more viable hydrogen carrier for transoceanic shipping. Not only does ammonia offer much lower requirements for the cryogenic and pressurization capacities of its storage tanks, but also has codified standards for its safe transportation both on land and at sea. Although new studies have shown that liquid organic hydrogen carriers (LOHCs) reduce the cryogenic and pressurization challenges of transporting pure hydrogen, this technology does not enjoy widespread deployment at the moment.

Therefore, the hydrogen transport pathway could leverage the pre-existing transportation and storage networks and standards for ammonia to facilitate the widespread distribution of hydrogen fuels. This pathway favors countries that are already major ammonia producers and exporters, such as Australia, the UAE, China, the Netherlands and the US.

Hydrogen fuel utilization pathway

Ammonia emerges as the best medium to utilize hydrogen as a fuel source for transoceanic shipping, due to its lower requirements for onboard storage and its applicability in traditional ICE engines. Nevertheless, the dearth of commercial-scale hydrogen fuel supply and the resulting prohibitive cost of these fuels mean that shipbuilders/engine developers such as Thyssenkrupp are only exploring ammonia-powered engines at very small scales. The cheap supply of LNG further complicates the adoption of hydrogen fuels for widespread use. Given the already established market for LNG and its abundant supply at the moment, LNG-powered ships appear as a much more attractive investment for shipbuilders looking to develop cleaner transoceanic shipping solutions both at present and for the foreseeable short term.

As a result, three potential hydrogen fuel utilization pathways emerge. The first is to explore the potential and the costs of retrofitting LNG-powered ships to burn hydrogen. If LNG-powered ships can be retrofitted to burn hydrogen at a cost-competitive rate, then companies could invest in LNG-powered ships before eventually converting them to burn hydrogen once the fuel source becomes cost-competitive. This pathway would entail a longer waiting period before full decarbonization of the shipping sector, but may be more in line with current shipping industry trends.

Another pathway is for leader-position shipping companies to invest early in ammonia retrofits to their ship engines due to their corporate sustainability goals, government mandates, and demand by sustainability-minded customers. This means that they might pay a premium to secure fuel supply contracts, but will meaningfully achieve corporate sustainability goals and be well-positioned once the rest of the industry transitions. Organizations such as the IMO may play a strong role in establishing regulations to push out cheaper (and dirtier) diesel options, but these organizations require multiple years of deliberations and compromises to reach an agreement. Thus, this pathway requires far more ambition from all actors, but would eliminate the intermediate LNG stage in this fuel transition.

The final pathway would see shipping companies transition from HSFO to ships powered by batteries or fuel cells, for two distinct reasons: First, they could operate shorter-range routes and thus are more tolerant of shorter battery ranges. Second, long-distance shippers could wait to be late adopters in the 2045-2050 timeframe when battery or fuel cell technology can deliver cost-competitive long routes.

Financing the adoption

Every pathway mentioned above requires financing in order to become a reality. However, the sources of funds differ depending on the type of pathway. In terms of financing the production pathways, local and national governments are best suited to bear the financial burden. Given that CCUS and electrolysis technologies are still immature, government funds are necessary to undertake the risk of further developing these technologies until they reach commercial viability. In addition, governments can also craft policies to further incentivize the deployment of renewable energy, such as tax credits or subsidies. This kind of public investment sends a policy signal that can crowd-in private sector investment in both blue and green hydrogen production pathways, thus accelerating progress towards widespread commercial-scale zero-carbon hydrogen supply solutions.

On the hydrogen fuel utilization side, the financing for the initial hydrogen-powered ships would come from a major shipping company. Given that hydrogen-capable engine technology is not a developed market, banks and other lending institutions would usually refuse to take this investment risk. As a result, any first-mover company must have a robust balance sheet in order to cover the financing costs in developing hydrogen-powered ships - in other words, a major shipping company with worldwide operations. Although governments can play a role in providing policy support, ultimately the commitment to developing hydrogen-powered ships must make sense from a business perspective for these major shipping companies.

Signposts indicating pathway progress

The zero-carbon hydrogen fuels industry may develop in a number of ways depending on advances in technology, policy, and energy supply, as well as on external events that force the world to change their perspectives regarding the viability of one fuel over another. Nevertheless, the appearance of certain signposts in the various adoption pathways can indicate whether the hydrogen fuels industry is making progress towards widespread acceptance in the transoceanic shipping sector.

Hydrogen production

1. Continued decreases in the cost curves for renewable energy, CCUS and electrolysis technology.
2. Increased investments in blue hydrogen and green hydrogen demonstration projects.
3. More and more government publications of national hydrogen plans and corresponding policies to procure zero-carbon hydrogen either through domestic production or imports.

Hydrogen transport

1. Further buildout of ammonia transportation and storage facilities at major ports

Hydrogen utilization

1. Commitments by a major shipping company to convert 10-15% of their fleet to hydrogen-powered ships, or at least when a company converts its hydrogen unit from R&D project to part of the business model.
2. Further development and deployment of dual-use engines for diesel/ammonia or LNG/hydrogen

3. Recognition by IMO/other standard-setting organizations that hydrogen fuels are viable choices for low-carbon fuels.

Hydrogen Financing:

1. Announcement of government funds available for R&D into green hydrogen production and the establishment of “hydrogen hubs”
2. Financiers see lowered risk in investing in hydrogen, thanks to more guarantees of both stable supply and demand

Global Port Networks

Drawing together the individual port analyses and identifying the role of each port in the establishment of a global/regional hydrogen fuel network.

Global Port Network

Due to the inherent global nature of the shipping industry, multiple ports around the world will need to develop hydrogen-based fuel supply chains simultaneously in order to complete end-to-end zero-carbon fuel shipping routes. Rather than ports transitioning spontaneously, clear patterns are forming where strategic regional networks and port-to-port connections may emerge. This section draws together the individual port analyses and identifies the role of each port in the establishment of global and regional hydrogen-based fuel networks.

The benefit of identifying key port networks is to enable the focused development of investment channels, strategic partnerships, and aligned markets. First-mover ports within a given network can establish the model and ease the transition for secondary ports. Potential port networks will emerge where strong trade relationships already exist, shipping companies already have major regular routes, and countries have complementary interests in developing major commercial hydrogen industries. Furthermore, port networks provide certainty to the market and signal to shipping companies and fuel providers that a region is primed to transition and that fleets are ready for investment.

Some of the ports that were analyzed may not naturally fit into a network for a variety of reasons. For example, a port may be geographically isolated from other major ports or may not have significant domestic ambition for hydrogen. For these ports, alternative pathways may exist for developing hydrogen-based fuel supply chains outside of a network.

The following port networks describe the likely patterns and relationships that will emerge in the transition to zero-carbon fuels.

Asia-Pacific Regional Network

The Asia-Pacific regional network links the ports of Tokyo, Singapore, Shanghai, Singapore, and Australia. This network has the potential to be the first to incorporate hydrogen-based fuels into their maritime shipping links, as a result of abundant potential supply, emerging demand, and extensive trade routes among the major economies in the region.

On the supply side, Australia would emerge as a prime candidate to serve as the regional hydrogen producer, thanks to its abundant natural gas and renewable energy resources, active policy support, and its trade linkages with major Asia-Pacific economies. Shanghai could also supplement this supply due to China's status as the world's biggest producer of both hydrogen and renewable energy, though converting production to zero-carbon processes will only happen if this goal aligns with Chinese government policy priorities.

The Port of Kyoto would be the main demand driver for hydrogen imports, particularly from Australia, as dictated by Japan's continued efforts to transition toward a hydrogen-based economy. Shanghai also emerges as another potential demand driver if Chinese government support of fuel cell vehicles spurs wider hydrogen integration in China's economy. Singapore could also drive hydrogen imports, but mainly to provide refueling services.

Finally, Singapore and Shanghai could act as the primary bunkering and refueling hubs for Asian trade routes, given their positions as the number two and number one most connected ports in the world, respectively. The guarantee of hydrogen bunkering and refueling services at the ports of Singapore and Shanghai would spur hydrogen adoption in other smaller East Asian ports. Singapore emerges as a stronger candidate for early adoption than Shanghai due to its explicit policy support for hydrogen. Hong Kong, in contrast, does not hold strong influence in driving hydrogen adoption in the Asia-Pacific as a result of its lack of hydrogen production capacity and hydrogen demand as well as the heightened political tensions surrounding its relationship with Mainland China.

In sum, the Asia-Pacific network would see Australia as the main exporter of hydrogen to the demand center of Tokyo, while Singapore would serve as the primary refueling hub for regional trade. Shanghai could greatly supplement the supply, demand and refueling operations of this hydrogen network if the Chinese government commits to incorporating hydrogen in its economy.

Americas Regional Network

The Americas regional network encompasses the ports of New York and New Jersey, Los Angeles, and Houston, all of which have potential to become major production centers for blue or green hydrogen.

Regarding hydrogen supply, Houston is the prime candidate to be the first large-scale blue hydrogen producer in the network, given its abundant natural gas resources and extensive development of CCUS technology. Texas also has extensive wind power capacity for eventual green hydrogen production. Houston could export primarily to its main trading partners in Europe, South America, and East Asia, but the port's main obstacle to hydrogen adoption is the lack of policy support for zero-carbon fuels. Los Angeles and New York are more likely to become major green hydrogen producers due to strong state support for renewable energy deployment. LA could export to its main trade markets in Northeast Asia, while New York could also service its primary trade partners of China, India and Europe.

Los Angeles looks to be the main demand driver for hydrogen, considering California's robust support for developing hydrogen vehicles. New York and Houston could see increases in hydrogen demand if their respective states follow California's lead on hydrogen vehicle adoption. However, their hydrogen supply would have to come from local production or foreign imports as a result of the Jones Act that restricts shipping merchandise between US ports unless the ship was built and owned by American firms.

Finally, all three ports can serve as bunkering and refueling stations once they have established their zero-carbon hydrogen supply chains. Each port would service the same markets as their aforementioned potential export destinations.

In summary, the major ports in the Americas network would not be integrated with each other due to the Jones Act, but could push ports in countries outside of the US to adopt hydrogen fuel solutions, especially for their major trading partners. Houston would supply blue hydrogen to Europe, South America, and East Asia, while LA and New York would supply green hydrogen either for local use or for their primary trade partners in East Asia and Europe.

Europe-Middle East Regional Network:

The Europe-Middle East regional network comprises the ports of Rotterdam in the Netherlands and Jebel Ali in the UAE. Both ports would serve as major hydrogen supply hubs for their respective trade partners but move at different speeds for hydrogen adoption.

The ports of Rotterdam and Jebel Ali are some of the largest hydrogen producers in their respective regions. The Netherlands could supply the rest of Europe with zero-carbon hydrogen thanks to its large-scale existing production capacities, ideal geology to conduct CCUS, and enthusiastic policy support for both blue and green production pathways. Jebel Ali also shares the first two traits with Rotterdam but lacks an integrated plan for zero-carbon hydrogen production. However, the UAE boasts of some of the cheapest renewable energy in the world, positioning Jebel Ali as a potential large-scale global exporter of cost-competitive green hydrogen if the policy support materialized.

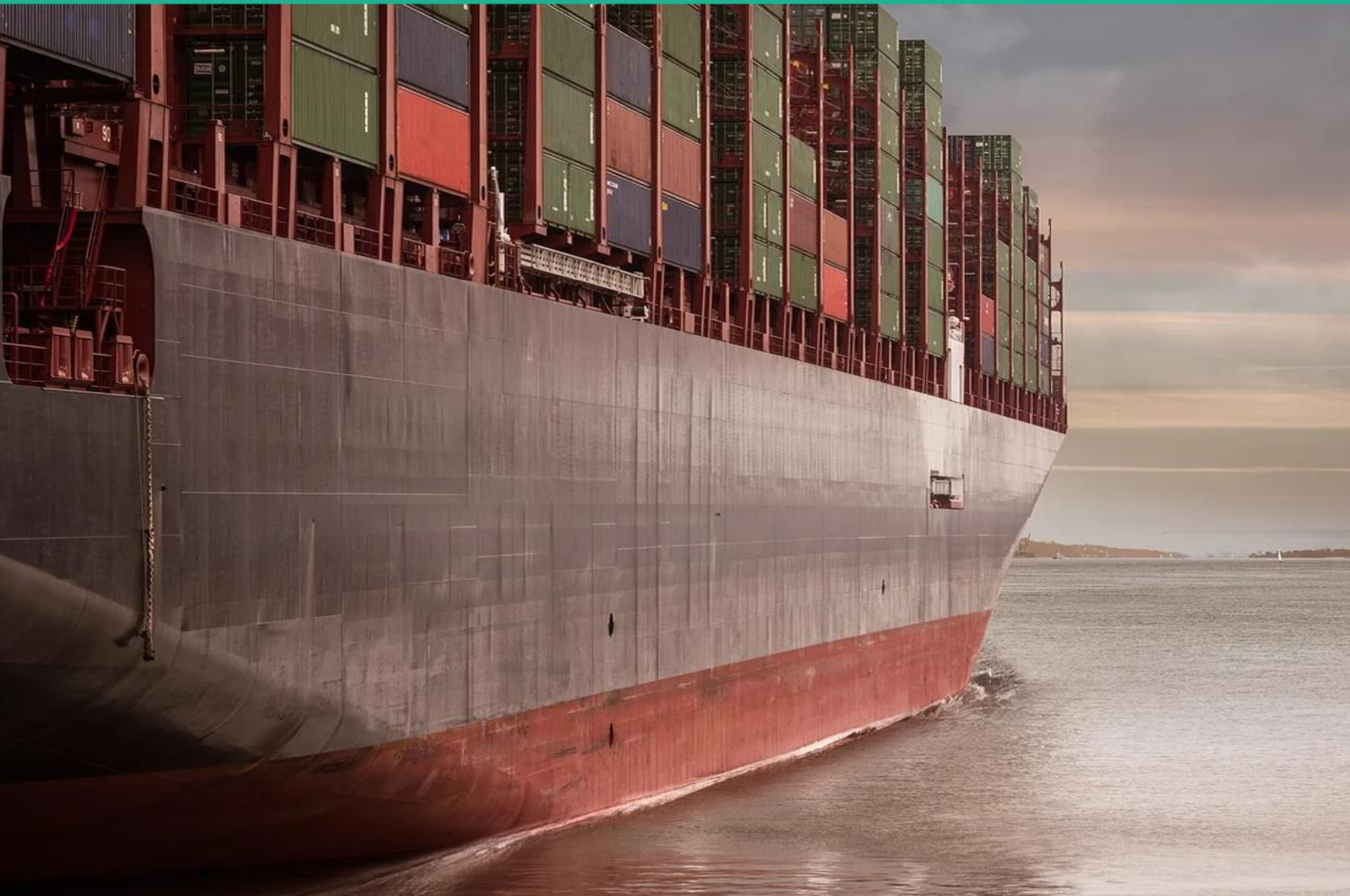
Rotterdam also looks to be a robust center of hydrogen demand, alongside the rest of Europe. The Netherlands is one of the most advanced countries in the world in terms of policy support for transitioning towards a hydrogen-based economy, thus boosting its potential future hydrogen imports from other production centers such as Norway. The European Union has also published its own “hydrogen roadmaps,” which could create a continent-wide source of import demand. The UAE, however, lacks meaningful policy to spur greater domestic hydrogen demand, notwithstanding a relatively small number of demonstration projects featuring hydrogen fuel cell vehicles.

The extensive trade networks of Rotterdam and Jebel Ali give these ports enormous leverage in encouraging hydrogen-based fuel adoption elsewhere. As the most interconnected port to the rest of Europe, Rotterdam represents a major gateway for commerce in the region. Thus, other major European ports would most likely follow Rotterdam’s lead if it shifted over to hydrogen-based fuels, and the same would be true for Jebel Ali, which services high-traffic trade routes to South Asia, Southeast Asia, East Asia, the Mediterranean, and the coasts of Sub-Saharan Africa. Concrete policy support to help convert Jebel Ali to providing hydrogen-based fuels for bunkering and refueling would likely begin a domino effect in hydrogen adoption in ports worldwide.

In conclusion, the Europe-Middle East regional network sees Rotterdam as its first mover in terms of zero-carbon hydrogen supply, demand, and as a catalyst for hydrogen adoption elsewhere. If policy support appeared in the UAE, Jebel Ali would have a much greater impact on both supply and global adoption, thanks to its position at the crossroads of worldwide trade links.

Recommendations

What the industry and stakeholders can do and what decisions need to be made.



Recommendations

Framework and Criteria for Recommendations

Shifting to a hydrogen-based fuel shipping industry in the near future could yield numerous long-term economic, environmental, and marine benefits. Like any transitional technology, the adoption of hydrogen-based fuel is posed as a chicken-and-egg situation. Demand is reliant on the reliability and existence of the supply, and any development or investment for the supply chain is dependent on consumer demand. To break the cycle, this report recommends the following actionable steps that major market movers – shipping companies, oil and gas, policy-makers, etc. – could take to ensure that the shipping industry will adopt either blue or green ammonia.

The key criteria used in analyzing the shift toward hydrogen-based fuel include: existing market demand and supply, technological feasibility, political will, transit routes of ports, port logistics, and trading capacity. While the adoption of ammonia for deep sea shipping will require many components of the energy and commodity market to move simultaneously, it would still be possible through the following recommendations.

***Recommendation 1**: Shipping regions, such as Europe, Southeast Asia, Asia-Pacific, or Northeast Americas, should establish trans-oceanic coalitions between government, energy-industry companies, shipping companies, and financial institutions.*

The energy transition toward a hydrogen fuel-based shipping industry will require many key stakeholders working together to create a zero-carbon hydrogen supply chain. While each major market mover could enact investments and policies individually, their actions would be highly dependent on the news and transparency of other industry stakeholders. To mitigate this problem, this report recommends that key regional shipping areas such as the Asia-Pacific create coalitions to allow stakeholders to gather together and create a unilateral vision to pursue a hydrogen fuel-based shipping industry.

While many business consortiums and industry associations related to hydrogen technology have already emerged, more can be done through formal and informal coalition building to deploy commercial projects at scale.

An example of an industry coalition is Japan's Hydrogen Energy Supply-Chain Technology Research Association (HySTRA) - an association between major Japanese companies such as Kawasaki Heavy Industries, Shell Japan, and Nippon Oil and Energy Corporation. The purpose of the association is to create a hydrogen supply chain that integrates each stage of production, transport, and utilization processes. This vertically integrated supply chain would facilitate communication to assure the availability of a market for each major market mover. This operation would start in Australia, where hydrogen is created from the gasification of brown coal. The refining and liquefaction process of this hydrogen would occur 150km from the nearest Port Facility (Hastings), and then be delivered across the Pacific to Japan for end-use. This vertically integrated supply chain would be under the supervision of the HySTRA, while the companies involved would manage each portion of the operation.

While there is minimal government involvement in the HySTRA development, it is a prototype example of how a coalition between key stakeholders could nurture the establishment of a complete hydrogen-based fuel supply chain.

***Recommendation 2**: Shipping companies must partner with fuel suppliers from ports that are aligned along major trade routes.*

Shipping companies and fuel suppliers along relevant trade routes must provide concrete signals to each other in order to ensure the alignment of hydrogen supply and demand.

Shipping companies would not build and use ships with engines compatible with hydrogen-based fuels unless they can recoup their investment in the relevant technologies within an acceptable timeframe. Thus, leveraging the high traffic of critical shipping lanes is crucial to accelerating the decarbonization of the shipping sector. High traffic trade routes facilitate higher ship utilization rates that could contribute to better returns on investments. Such trade routes include those between East Asian countries themselves, those between East Asia and North America, or those among European countries.

In order to create a hydrogen fuels market, suppliers must communicate information regarding the availability of reliable and affordable hydrogen procurement solutions at each end of the relevant trade routes. Shipping companies can issue Requests for Proposals (RFPs) to better understand market conditions at their desired ports of call. RFPs are applications that outline a company's proposed volume, pricing, and overall business structure to deliver a desired input - in this case hydrogen. The number and quality of RFPs both requested and submitted can not only give suppliers an estimate of the potential demand for hydrogen fuels, but also give shipping companies an estimated availability of hydrogen procurement solutions. Therefore, RFPs can leverage the power of markets to help the supply side and demand side communicate with each other.

Another method of communication could take the form of hosting regional shipping forums, attended by the relevant shipping companies and fuel suppliers along critical trade routes in the area. By creating a platform for these parties to exchange information on their progress in adopting hydrogen or ammonia fuel solutions, shipping companies and fuel suppliers can build confidence to invest in creating a zero-carbon shipping ecosystem. The coalitions mentioned in Recommendation 1 would be the ideal organizer of these regional forums.

***Recommendation 3:** First-Mover ports must work within their country or region to aggregate economy-wide demand for hydrogen fuels.*

Ports that are best suited to facilitate the adoption of a hydrogen fuel ecosystem can link their fuel needs with that of their country or region. Although ports themselves are not as influential in determining government policy, they can still emphasize their role in spurring demand for hydrogen and in decarbonizing the whole economy.

A handful of countries or regions have strategies to integrate hydrogen into their economies, such as Japan, the Netherlands and even California. These strategies align with how increasing numbers of consumers, retailers, and corporates are working to reduce or offset their carbon emissions from the entire lifecycle of their goods or operations. Thus, ports can integrate into this carbon emissions reduction trend by portraying themselves as the prime actors for decarbonizing the maritime transport of goods and services. In other words, ports require hydrogen fuel solutions just as much as the rest of the economy, especially in order to fulfill the demand for zero-carbon fuels by shipping companies that want to retain market share among increasing numbers of environmentally-conscious clients.

Given the sheer amount of fuel that container ships consume, ports can demonstrate that they can play a huge role in increasing the aggregate demand for hydrogen throughout the economy. This increase in aggregate demand can increase the market opportunities for fuel producers if they can scale up production of zero-carbon hydrogen in a short period of time. Ultimately, this report recommends that ports further lobby their national or regional governments to be included as a key demand center in any proposed hydrogen roadmaps for their respective economies.

Recommendation 4*: Fuel producers must coalesce around standard production methods for green hydrogen /ammonia while continuing to innovate.*

Fuel producers should coordinate to establish a standard production and operating procedure for green hydrogen and ammonia, in order to produce at scale.

A future green ammonia plant would require advanced technological capacity to build the infrastructure needed for the supply chain. Such a plant would require its own air separation unit, electrolyser plant, ammonia synthesis, desalination unit, and storage tanks for all petrochemicals. Ideally, the plant would also have its own renewable energy installed onsite, so that all electricity used for the production of hydrogen and ammonia is zero-carbon. This way the green ammonia plant could avoid tapping into the electricity grid, which circumvents the issue of purchasing renewable energy credits to meet the plant's zero-carbon standards. While 100% on-site renewable energy could be an option for sourcing electricity, this would only work in areas with a high amount of installed capacity from renewable energy. Thus, each step in establishing a green ammonia production chain requires proper sequencing and planning.

Establishing a standardized procedure for building green hydrogen plants would lower the barriers for new entrants in this market. This standardized procedure would allow green hydrogen production to scale up more quickly thanks to the cost-reducing effects of constant repetition of a certain process (i.e. moving along the experience curve).

Recommendation 5: *Private and public capital must work with fuel producers to de-risk investments and lower the cost of capital for new fuel production and infrastructure.*

Financing the transition faces an enormous uphill battle, as the market for hydrogen fuel solutions is still unproven. On the one hand, a study by the Hydrogen Council estimated that the world requires over $70 billion in investment to bring hydrogen to cost-competitiveness with other low-carbon solutions.[192] But on the other hand, institutional capital markets such as investment banks or pension funds have no appetite to take on the risk of financing the development of hydrogen-compatible ship engines or large-scale zero-carbon hydrogen production infrastructure.

[192] Path to Hydrogen Competitiveness: A Cost Perspective. 20 Jan. 2020.

Thus, the key recommendation is to leverage public finances to de-risk the cost of investing in hydrogen fuel solutions. Governments and development finance institutions (DFIs) banks are best suited to provide initial financing for further hydrogen R&D and infrastructure buildout. In particular, governments or DFIs can give either direct financing for hydrogen projects, or can guarantee the loans related to developing hydrogen as a fuel source. This way, companies/organizations can freely experiment with lowering the cost of zero-carbon hydrogen without having to worry about delivering financial returns on their investment.

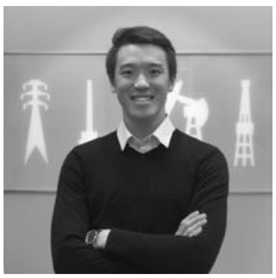
Governments/DFIs can also indirectly finance hydrogen fuel solutions by crowding-in private sector investment in more mature markets, especially in renewables. By implementing policy incentives that encourage more private investment in either renewables or CCUS, governments/DFIs can further lower the cost of energy inputs in the creation of zero-carbon hydrogen. In addition, government financing of hydrogen initiatives could encourage major shipping companies with strong balance sheets to start investing more in hydrogen-capable engine technology. Ultimately, public finance is meant to lay the foundation for zero-carbon hydrogen solutions to become cost-competitive with current shipping fuel options, and spur private investment in hydrogen market creation.

Appendix

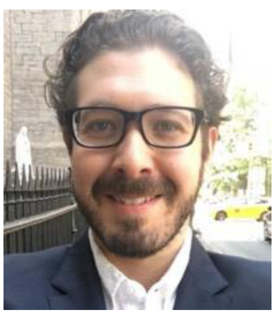
TTNU 106765 0
22G1
MAX. GROSS 30.480 KGS 67.200 LBS
TARE 2.100 KGS 4.630 LBS
NET 28.380 KGS 62.570 LBS
CU. CAP. 33.2 CU.M. 1.172 CU.FT.
PONU 009531 5
22G1
MSKU 769 753 0
22G1
MRKU 734 355 6
22G1
SUDU 769689 9
maerskline.com

Appendix I. Project Team

Lauren Kastner is a second-year MPA candidate, concentrating in Energy and Environment and Management. In addition to her studies, she is also a Director of Policy and Mobility for Build Edison, a cleantech advisory firm based in NYC. In 2019, Lauren served as an EDF Climate Corps Fellow supporting the Los Angeles Mayor's Office of Sustainability on its zero-emission transportation strategy. Prior to SIPA, she was an Environmental Policy Manager for Cummins, Inc.



Leo Luo is a second-year Master of International Affairs (MIA) Degree Candidate at Columbia SIPA, concentrating in Energy and Environment, with a focus on energy finance. Before SIPA, he worked as a downstream oil analyst at an oil and gas consulting firm the Rapidan Energy Group. Leo aims to enter the energy and infrastructure finance space after SIPA, in particular for developing nations.



Steve Maroti is a second-year Master of International Affairs (MIA) Degree Candidate at Columbia SIPA, concentrating in International Security Policy and Energy Policy with an emphasis on advanced quantitative methods. His interests lie in renewable energy development, energy security, conflict management, and big data analysis. Steve's background is in business and education. He enjoys outdoor sports, and he is an avid musician.

Ethan Tsai is a second-year Master of International Affairs candidate concentrating in energy and environment. After spending years working on climate change and energy efficiency policies, as well as sustainable development, he has a newfound vision to mold the energy sector towards a sustainable future. Ethan is particularly interested in renewable energy, storage, energy market, and sustainability solutions. Moving forward, he aims to work with like-minded individuals, especially in energy consulting, market analysis and policy.

Wenting Zhang is a second-year MPA Candidate at Columbia SIPA, concentrating in energy and environment with an emphasis on management. Prior to SIPA, she worked as an auditor at KPMG China and interned for China Huadian Corporation. Her interests lie in renewable energy, energy economics and quantitative analysis.

Faculty Advisor

Jason Bordoff joined the Columbia faculty after serving until January 2013 as Special Assistant to the President and Senior Director for Energy and Climate Change on the Staff of the National Security Council, and, prior to that, holding senior policy positions on the White House's National Economic Council and Council on Environmental Quality. One of the world's top energy policy experts, he joined the Administration in April 2009. At Columbia's School of International and Public Affairs, Bordoff is a professor of professional practice and serves as founding Director of SIPA's Center on Global Energy Policy. Bordoff's research and policy interests lie at the intersection of economics, energy, environment, and national security. Prior to joining the White House, Bordoff was the Policy Director of the Hamilton Project, an economic policy initiative housed at the Brookings Institution. Bordoff graduated with honors from Harvard Law School, where he was treasurer and an editor of the Harvard Law Review, and clerked on the U.S. Court of Appeals for the D.C. Circuit. He also holds an MLitt degree from Oxford University, where he studied as a Marshall Scholar, and a BA magna cum laude and Phi Beta Kappa from Brown University.

Appendix II. Key Terms

Ammonia Catalyst: Ammonia catalyst (usually iron) is used in the synthesis process where nitrogen and hydrogen are transformed into ammonia.

Berth: The place where a ship lies when at anchor or at a wharf.[193]

Blue (hydrogen/ammonia): Blue hydrogen/ammonia is hydrogen/ammonia that meets the low-carbon emission target and it is predominantly created from SMR technology with CCUS technology employed.

Bunkering: To fuel the ships with bunker fuels, either via pipeline or tanker vehicle at berth or with special bunker vessels on the water.[194]

Carbon Capture, Utilization, and Sequestration (CCUS): Carbon capture, utilization, and storage, or CCUS, is an important emission reduction technology that can be applied across the energy system. CCUS technologies involve the capture of carbon dioxide (CO2) from fuel combustion or industrial processes, the transport of this CO2 via ship or pipeline, and either its use as a resource to create valuable products or services or its permanent storage deep underground in geological formations.[195]

Draft Depth: The draft depth of a ship is the vertical distance between the waterline and the bottom of the hull. Draft depth determines the minimum depth of water a ship can safely navigate.[196]

Electrolysis: Also called water splitting. By decomposing water into oxygen and hydrogen with electric current, water electrolysis is the most dominant technology that can be used for hydrogen production from renewables.

Gasification: Gasification is a process that uses high temperatures and a controlled amount of oxygen to convert carbon-containing materials into synthetic gas, which is a fuel.

Green (hydrogen/ammonia): Green hydrogen/ammonia is hydrogen/ammonia that both meets the low-carbon emission target and is generated from renewable energy sources such as solar or wind.

Grey (hydrogen/ammonia): Grey hydrogen/ammonia is hydrogen/ammonia produced using fossil fuels such as natural gas.

High Sulfur Fuel Oil (HSFO): Heavy fuel oils with a maximum sulfur content of 3.5% are categorized as high sulfur fuel oil (HSFO).

Hydrogen Fuel Cell: A hydrogen fuel cell is composed of an anode, a cathode, and an electrolyte membrane. It works by passing hydrogen through the anode of a fuel cell and oxygen through the cathode. At the anode site, the hydrogen molecules are split into electrons

[193] “Definition of BERTH.” Www.Merriam-Webster.Com, www.merriam-webster.com/dictionary/berth. Accessed 15 May 2020.
[194] “Bunkering | Glossary | Marquard & Bahls.” Www.Marquard-Bahls.Com, www.marquard-bahls.com/en/news-info/glossary/detail/term/bunkering-marine-fuelling.html. Accessed 15 May 2020.
[195] “Carbon Capture, Utilisation and Storage - Fuels & Technologies.” IEA, www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage. Accessed 15 May 2020.
[196] “Draft (Hull).” Www.Wikiwand.Com, www.wikiwand.com/en/Draft_(hull. Accessed 15 May 2020.)

and protons. The protons pass through the electrolyte membrane, while the electrons are forced through a circuit, generating an electric current and excess heat. At the cathode, the protons, electrons, and oxygen combine to produce water molecules.[197]

IMO: IMO, the International Maritime Organization, is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. IMO's work supports the UN SDGs.[198]

IMO 2020 regulations: From 1 January 2020, the marine sector will have to reduce sulphur emissions by over 80% by switching to lower sulphur fuels. The current maximum fuel oil sulphur limit of 3.5 weight percent (wt%) will fall to 0.5 wt%.[199]

Liquified Natural Gas (LNG): LNG stands for liquified natural gas, a natural gas that has been cooled to a liquid state at about -260° Fahrenheit for shipping and storage. The volume of natural gas in its liquid state is about 600 times smaller than its volume in its gaseous state. This process makes it possible to transport natural gas to places pipelines do not reach.[200]

Low Sulfur Fuel Oil (LSFO): As of January 1st 2020, IMO requires reducing the maximum sulphur content of marine fuel oil down to 0.5%.

Quay: A structure built parallel to the bank of a waterway for use as a landing place.[201]

Renewable Energy - Wind, solar, geothermal, hydro: Renewable energy is energy produced from sources that do not deplete or can be replenished within a human's lifetime. The most common examples include wind, solar, geothermal, biomass, and hydropower.[202] Renewable energy plays an important role in reducing greenhouse gas emissions.

Steam Methane Reforming (SMR): Steam methane reforming is a method for producing hydrogen by reaction of hydrocarbons with water. Commonly natural gas is the feedstock.[203]

TEU: TEU stands for *twenty-foot equivalent unit*, which measures the cargo-carrying capacity of a container ship. It is based on the volume of a 20-foot-long (6.1m) standard-sized intermodal container.

Zero-carbon energy: Zero carbon energy means there is absolutely no carbon emissions emitted during the production process. Hydro, wind, nuclear, and CCUS are all examples of zero-carbon energy.

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197 "Fuel Cell & Hydrogen Energy Association." Fuel Cell & Hydrogen Energy Association, 2014, www.fchea.org/fuelcells. Accessed 15 May 2020.
198 "About IMO." Imo.Org, 2019, www.imo.org/en/About/Pages/Default.aspx. Accessed 15 May 2020.
199 "IMO 2020: Mayhem or Opportunity?" Www.Woodmac.Com, www.woodmac.com/nslp/imo-2020-guide/. Accessed 15 May 2020.
200 "Liquefied Natural Gas (LNG)." Energy.Gov, www.energy.gov/fe/science-innovation/oil-gas/liquefied-natural-gas. Accessed 15 May 2020.
201 "Definition of QUAY." Www.Merriam-Webster.Com, www.merriam-webster.com/dictionary/quay. Accessed 15 May 2020.
202 Frewin, Chris. "Renewable Energy | Student Energy." Studentenergy.Org, 2014, www.studentenergy.org/topics/renewable-energy. Accessed 15 May 2020.
203 "Steam Reforming - Wikiwand." Www.Wikiwand.Com, www.wikiwand.com/en/Steam_reforming. Accessed 15 May 2020.

Appendix III. Stakeholder Interviews by Organization

Stakeholder Type	Organization Name	Contact Name	Title
Experts / Researchers	Center for Strategic and International Studies	Jane Nakano	Senior Fellow
Experts / Researchers	Center for Strategic and International Studies	Nikos Tsafos	Senior Fellow
Experts / Researchers	Center for Strategic and International Studies	Sarah Ladislaw	Senior Vice President; Director and Senior Fellow
Experts / Researchers	Columbia University Center on Global Energy Policy	Antoine Halff	Adjunct Senior Research Scholar
Experts / Researchers	Columbia University Center on Global Energy Policy	Julio Friedman	Senior Research Scholar
Companies	Citi	Michael Eckhart	Managing Director
Experts / Researchers	Clean Air Task Force	Jonathan Lewis	Senior Counsel
Engine Manufacturers	Cummins	John Pendray	Senior Technical Advisor
Engine Manufacturers	Cummins	Traci Kraus	Director
Experts / Researchers	Environmental Defense Fund	Annie Petsonk	International Counsel
Experts / Researchers	Environmental Defense Fund	Marie Hubatova	Manager - International Climate
Experts / Researchers	Environmental Defense Fund	Natacha Stamitiou	Research Analyst
Shipping Companies	Maersk	Tue Johannessen	Senior Innovation Portfolio Manager
Engine Manufacturers	MAN Energy Systems	Peter Kirkesby	Promotion Manager
Governments	Norwegian Consulate General	Ginni Wiik	Royal Norwegian Consulate General
Port Authorities	Port Authority NJ and NY	Alex Cassidy	Leadership Fellow
Port Authorities	Port Authority NJ and NY	Dana Mecomber	Senior Environmental Specialist

Port Authorities	Port Authority NJ and NY	Vignesh Gowrishankar	Deputy Director of Environmental and Energy Programs
Port Authorities	Port of Grenland, Oslo	Bjørn Tore Orvik	Project Development Manager
Port Authorities	Port of Los Angeles	Jacob Goldberg	Environmental Specialist
Experts / Researchers	Rocky Mountain Institute	Jamie Mitchell	Manager
Shipping Companies	Seaspan	Gerry Wang	Co-Founder, Co-Chairman and Chief Executive Officer
Fuel Infrastructure	Thyssenkrupp	Adam Paschal	Director of Business Development
Engine Manufacturers	Wartsila	Vesa Koivumaa	Business Development Director

APPENDIX IV. Supplemental Port Data

This section contains key statistics to support the evaluation of each port. The data includes economic, physical, geographic, and resource characteristics of each port.

Port of New York and New Jersey

Closest City: New York
Country: United States
Port Operator/Authority: Port Authority of New York and New Jersey
Geography:

- 3,000 acres
- 6 Terminal Locations
- Port Newark Container Terminal
  - Maher Terminals
  - APM Terminals
  - GCT New York Terminal
  - GCT Bayonne Terminal
  - Red Hook Container Terminals
- Quay Lengths - 4400 ft, 10128 ft, 6001 ft, 2300 ft, 2678 ft, 2080 ft/1200 ft
- Port Depth- 50 feet (draft)

Annual Containers Handled: 7.2 million twenty-foot equivalent units (TEU)/year

Total Tonnage: 84,962 TMT

Ships/Year: Approx. 1600

- The largest terminal is operated by Maher Terminals.[204]
- 75–80% of the Port's total capacity is accounted for in the Port Newark and Elizabeth PAMT complex.
- The Port's volume growth is driven by the fact that so many vessels make their first U.S. calls there.
- It receives 72% of first port of calls.
- One-third of the nation's GDP is produced within 250 miles of it.
- Large container ships account for a growing share of vessels at NY-NJ, with a 20 percentage point increase in the share of 10,000 - 14,999 TEU ships from 2018 to 2019.

  Connection to Rail: 645,760 containers. The Port has extended reach into the Midwest, Southern, and U.S. Northeast markets by virtue of the ExpressRail facility at GCT Bayonne terminal in New Jersey. ExpressRail is the rail network supporting intermodal freight transport at the major container terminals of the port.

Trade Routes/Critical shipping routes

The Port scored a 49.52 on the UNCTAD Port liner shipping connectivity index (2019).[205]

[204] Tirschwell, Peter. "NY–NJ port leadership steps up amid heightened competition". JOC. November 18, 2019. https://www.joc.com/port-news/us-ports/port-new-york-and-new-jersey/ny%E2%80%93nj-port-leadership-steps-amid-heightened-competition_20191118.html. Accessed May 13, 2020.
[205] United Nations Conference on Trade and Development. Maritime Transport Indicators. Database. 2020. https://unctadstat.unctad.org/wds/TableViewer/summary.aspx. Accessed May 13, 2020.

Top 5 Trading Partners by Volume:

- China (26.3%)
- India (7.6%)
- Germany (5.6%)
- Italy (4.3%)
- Spain (3.3%)

Top 5 Trading Partners by Value:

- China ($39.5B)
- Germany ($14B)
- India ($12.8)
- Italy ($10.5)
- Japan ($9.0B)

Port of Houston

Closest City: Houston, Texas
Country: United States
Port Operator/Authority: Port of Houston Authority
Geography:

- 50-mile long complex
- 2 Main Cargo Container Terminal Locations plus 10 Multi-Purpose, Breakbulk, And Project Cargo Terminals
  - Barbours Cut Container Terminal
  - Bayport Container Terminal
- Quay Length - 6000 feet, 3500 ft
- Minimum Berth Depth - 46.5 ft[206]

Annual Containers Handled: 2,987,291 TEUs (2019)
Total Tonnage: 41 Million Tons
Ships/Year: 2,033 (2020 YTD)
Trade Routes/Critical shipping routes:

The Port scored a 39.56 on the UNCTAD Port liner shipping connectivity index (2019).[207]

Top 5 Trading Partners by Import Volume - % of Total Import TEUs (2019):
China (PRC): 29.5%
Germany: 7.8%
India: 6.1%
Brazil: 5.7%
Italy: 4.6%

Top 5 Trading Partners by Export Volume - % of Total Export TEUs (2019):
Belgium: 9.2%
China (PRC): 6.5%
Brazil: 6.4%

[206] Bureau of Transportation Statistics. Port of Houston. Database. 2020. https://explore.dot.gov/views/PortPerformance-temp-view2/ProfileDashboard?Port%20ID=2031&:isGuestRedirectFromVizportal=y&:embed=y. Accessed May 13, 2020.
[207] United Nations Conference on Trade and Development. International Trade. Database. 2020. https://unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx?sCS_ChosenLang=en. Accessed May 13, 2020.

Colombia: 3.7%
Turkey: 3.7%

Top 5 Trading Regions by Import Volume - % of Total Import TEUs (2019):
Far East: 43.3%
Europe/Med: 30.2%
India/ME: 10.8%
South Am.: 9.7%
Carib/Central Am.: 4.4%

Top 5 Trading Regions by Export Volume - % of Total Export TEUs (2019):
Europe/Med: 28.4%
Far East: 20.7%
South Am: 19.1%
India/ME: 17.1%
Carib/Central Am.: 7.8%

Port of Los Angeles

Closest City: Los Angeles
Country: United States
Port Operator/Authority: Municipal
Geography
- 7500 acres
- 43 miles of waterfront
- 15 marinas

Key Stats:
- Access to Oil Terminals
- Record Performance
- Port Services

Annual Cargo Handled:
- 9,337,632.40 TEU/year
- 207.3 MMRT

Ships/Yr:
- Approximately 2000 vessels of all types each year

Ship sizing in ports:
- 53 feet deep in main channel

The Port scored a 41.95 on the UNCTAD Port liner shipping connectivity index (2019).[208]

Connection to Rail:
As the largest North American port, the Port of Los Angeles (POLA) is well-connected to extensive rail services to move U.S. imports and exports through the port. Approximately

[208] "Beyond 20/20 WDS." Unctadstat.Unctad.Org, unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx?sCS_ChosenLang=en. Accessed 15 May 2020.

35% of intermodal containers that are moved through the POLA use near-dock and on-dock rail yards serving eight container terminals. The Alameda Corridor, a dedicated rail expressway that connects the docks to the transcontinental rail system, is essential for cargo to move quickly across the continent.[209] According to the POLA, more than $300 million has been invested in the rail network over the last decade to ensure competitiveness.[210]

Trade Routes/Critical shipping routes

- Top 5 Trading Partners in 2018:
  - China/Hong Kong ($153B)
  - Japan ($36B)
  - Vietnam ($19B)
  - South Korea ($15B)
  - Taiwan ($14B)
- Top 5 Foreign Trade Routes in 2018:
  - Northeast Asia (73%)
  - Southeast Asia (21%)
  - India subcontinent (2%)
  - Northern Europe (1%)
  - Middle East (1%)

Port of Rotterdam

Closest City: Rotterdam
Country: Netherlands
Port Operator/Authority: Port of Rotterdam Authority
Geography

- Total quay length: 74.5 km
- Port Depth: 24m
- Total port area: 12,606 ha
  - Land area: 7,796 ha
    - Of which rentable sites: 5,968 ha

Energy services:[211]

- 5 oil refineries
- 6 refinery terminals
- 11 independent tank terminals for oil products
- 1 natural gas terminal
- 86 wind turbines (194MW)
- Crude oil storage: 14.5 million meters
- **LNG storage**: 3 storage tanks, each with 180,000 m3 capacity[212]
  - Current LNG import and re-export capacity: 12 billion m3

Bunkering:

- **Annual bunker fuel delivery volume:** 11 million m3[213]

209"Alameda Corridor Transportation Authority." Www.Acta.Org, www.acta.org/. Accessed 15 May 2020.
210 "Rail | Supply Chain | Port of Los Angeles." Www.Portoflosangeles.Org, www.portoflosangeles.org/business/supply-chain/rail. Accessed 15 May 2020.
211"Annual Reports." Port of Rotterdam, 1 Mar. 2016, www.portofrotterdam.com/en/port-authority/about-the-port-authority/finance/annual-reports. Accessed 15 May 2020.
212RoRo, Maud Eijgendaal Business Manager, et al. "LNG Terminal." Port of Rotterdam, 12 June 2015, www.portofrotterdam.com/en/doing-business/logistics/cargo/lng-liquefied-natural-gas/lng-terminal. Accessed 15 May 2020.
213 "Rotterdam Bunker Port." Port of Rotterdam, 2 Mar. 2016, www.portofrotterdam.com/en/shipping/sea-shipping/other/rotterdam-bunker-port. Accessed 15 May 2020.

    - Ranks as Europe's largest bunkering port, as well as one of the top three bunkering ports worldwide
- **LNG bunkering:** 3 permanent LNG bunker vessels, as well as 4 licensed LNG bunker specialists.[214]

Port Services:

- 4 Industrial gases and water plants
- 1 waste processing plant
- 6 steam and power plants
    - Of which 3 are natural gas, 3 are coal and biomass

Annual Containers Handled: 14,810,804 TEU in 2019[215]

Ships/Yr: 29,491 seagoing vessels in 2019

Ship sizing in port: The port can handle the world's largest ship (the MSC Gülsün), which is 400m long and 62m wide[216]

Connection to Rail: 435 rail connections/week, of which 276 are direct routes[217]

Trade Routes/Critical shipping routes:

- Ships to terminals worldwide,
    - Europe: 300 destination terminals (approx.)
    - Americas: 50 destination terminals (approx.)
    - Middle East and Africa: 40 destination terminals (approx.)
    - Asia: 40 destination terminals (approx.)[218]
- UNCTAD connectivity score: 92.75 points
    - One of the top ten ports in the world in terms of connectivity[219]

Port of Jebel Ali

Closest City: Dubai

Country: United Arab Emirates (UAE)

Port Operator/Authority: DP World

Geography

- Three main cargo terminals[220]
    - Terminal 1: 9 million TEU capacity, 15 berths
    - Terminal 2: 6.5 million TEU capacity, 8 berths
    - Terminal 3: 3.8 million TEU capacity, 5 berths
        - Capable of handling Ultra Large Container Vessels (ULCV), with 18,000 TEU of capacity
- Total number of berths (including general cargo and tank terminals): 67[221]
- Total quay length: 17245m[222]

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[214] "Port of Rotterdam Points to Rise in LNG Bunkering." Offshore Energy, 21 Jan. 2020, worldmaritimenews.com/archives/289716/port-of-rotterdam-points-to-rise-in-lng-bunkering/. Accessed 15 May 2020.

[215] "Annual Reports." Port of Rotterdam, 1 Mar. 2016, www.portofrotterdam.com/en/port-authority/about-the-port-authority/finance/annual-reports. Accessed 15 May 2020.

[216] "World's Largest Container Ship MSC Gülsün to Visit Rotterdam." Port of Rotterdam, 29 Aug. 2019, www.portofrotterdam.com/en/news-and-press-releases/worlds-largest-container-ship-msc-gulsun-to-visit-rotterdam. Accessed 15 May 2020.

[217] "Rail Transport." Port of Rotterdam, 12 June 2015, www.portofrotterdam.com/en/doing-business/logistics/connections/intermodal-transportation/rail-transport. Accessed 15 May 2020.

[218] "Navigate." Rotterdam.Navigate-Connections.Com, rotterdam.navigate-connections.com/destinations. Accessed 15 May 2020.

[219] "Unctad.Org | Shanghai Tops Ranking of World's Best-Connected Ports." Unctad.Org, unctad.org/en/pages/newsdetails.aspx?OriginalVersionID=2163&Sitemap_x0020_Taxonomy=UNCTAD%20Home. Accessed 15 May 2020.

[220] "Jebel Ali Port - DP World UAE Region." DP World UAE Region, 2017, dpworld.ae/our-portfolio/jebel-ali-port/. Accessed 15 May 2020.

[221] http://dpworld.ae/content/files/2017/12/511217201385051PM722-Jabal-Ali-Port-A3-Leaflet_english.pdf

        - Terminal 2: 3000m
        - Terminal 3: 1860m
    - Max Port Depth: 17m
    - Total port area: 13,400ha

Energy services:
- Oil refineries:
    - 1 refinery with 140kbd of refining capacity. By May 2020, this capacity will rise to 210kbd, after the commissioning of refinery expansion.[223]
        - This refinery takes oil condensate (basically super light sweet crude) instead of normal crude oil
- Independent tank terminals for crude oil and oil products: 100+ storage tanks, with over 4 million cubic meters of storage capacity.[224]
- Natural gas terminal
    - Jebel Ali receives LNG using a Floating Storage Regasification Unit (FSRU) - the *Explorer*, which went into service in 2010, and was expanded in 2015.[225]
        - Has the first LNG bunkering service on an FSRU
        - **Storage and bunkering capacity:** 151,000 cubic meters of LNG[226]

Annual Containers Handled: 19.8 million TEU in 2019[227]
Ships/Yr: 10,000 ships
Ship sizing in port: Around 500 ft
Connection to Rail: Zero[228]
- No rail connections so far
- The port is connected to the rest of the UAE and the GCC using highways - 2 to 3 days transit
- Port is also directly connected with the Al Maktoum International Airport, with a dedicated customs-bonded corridor to expedite sea-air transfers of goods

Trade Routes/Critical shipping routes:
Over 80 weekly shipping services
Connects to over 150 ports worldwide
    - Direct ports of call:[229]
        - Far East: 18
        - Mediterranean: 14
        - North Europe: 13
        - Indian Sub-continent: 9
        - West Africa: 9
        - North Africa: 9
        - South Africa: 9
    - UNCTAD connectivity score: 74.55 points

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222 http://dpworld.ae/content/files/2019/03/DPW-Std-Presentation-June-2019.pdf
223 Brelsford, Robert. “ENOC Nears Commissioning of Jebel Ali Refinery Expansion Project.” Www.Ogj.Com, 21 Apr. 2020, www.ogj.com/refining-processing/refining/construction/article/14174488/enoc-nears-commissioning-of-jebel-ali-refinery-expansion-project. Accessed 15 May 2020.
224 http://dpworld.ae/content/files/2019/03/DPW-Std-Presentation-June-2019.pdf
225 “Jebel Ali LNG Import Terminal: Upgraded FSRU to Meet Dubai’s Rising Energy Demand.” Excelerate Energy, excelerateenergy.com/project/jebel-ali-lng-import-terminal/. Accessed 15 May 2020.
226 “Excelerate & DUSUP Perform First Gas-Up Operation in Dubai.” Excelerate Energy, 15 Sept. 2016, excelerateenergy.com/excelerate-energy-and-dusup-perform-first-gas-up-operation-at-jebel-ali-lng-import-terminal/. Accessed 15 May 2020.
227 “Jebel Ali Port - DP World UAE Region.” DP World UAE Region, 2017, dpworld.ae/our-portfolio/jebel-ali-port/. Accessed 15 May 2020.
228 http://dpworld.ae/content/files/2019/03/DPW-Std-Presentation-June-2019.pdf
229 http://dpworld.ae/content/files/2019/03/DPW-Std-Presentation-June-2019.pdf

○ Ranked as the 15th most connected port in the world, after Hamburg, Germany[230]

Ports of Keihin (Port of Tokyo)

Top Five Major Ports: Kobe, Nagoya, Osaka, Tokyo, and Yokohama
Port Authority: Bureau of Port and Harbor, Tokyo Metropolitan Government
Size of Harbor: 5,292 hectares (52.92 sq km)
Land Area: 1,033 hectares (10.33 sq km)
Total Area: 6,325 hectares (63.25 sq km)
Geography and Key Regions:
Aomi Container Terminal: 5 berth areas | 479,079 sq meters with quay length of 1,570 meters
Shinagawa Container Terminal: 3 berth areas | 79,939 sq meters with quay length of 333m
Oil Container Terminal: 7 berth areas | 945,700 sq meters with quay length of 2,354 meters
Kamigumi Container Terminal: 1 berth area | quay length of 260 meters
Other terminals: For food, general cargo (bulk cargo, timber, construction materials)
Key Stats:

- Oil Terminal: Yes
- Port Services: Longshore, electrical repairs, steam, navigation equipment, access to rail
- Supplies: Fuel oil, water, diesel oil

Annual Containers Handled in 2018: 4,570,000 TEU
Total Containers Handled in first half of 2019: 2,440,000 TEU
2017 Record of Performance:
Incoming Vessels: 23,604
Volume of Cargo from vessels: 90.78 million tons
Foreign Traded Value: 17,563 billion yen = 159.118 million USD (1 yen = 0.0091 USD)
Weekly Sailing Distributions[231]:

- North America 11
- Europe 1
- New Zealand 1
- South America 1
- Asia (excluding China and S. Korea) 33
- China 26
- S. Korea 12

Connectivity:

- From Oi Container Terminal, 40 service routes
- From Aomi Container Terminal, 36 service routes
- Shinagawa Container Terminal, 18 service routes

Port of Hong Kong

Closest City: Shenzhen
Country: China

[230] "Beyond 20/20 WDS." Unctadstat.Unctad.Org, unctadstat.unctad.org/wds/ReportFolders/reportFolders.aspx?sCS_ChosenLang=en. Accessed 15 May 2020.
[231] "The Port of Tokyo: Gateway to the World." Www.Tptc.Co.Jp, www.tptc.co.jp/en/guide/advantage/world. Accessed 15 May 2020.

Port Operator/Authority: Hong Kong Maritime and Port Board
Area: 2.7 km²

Annual Cargo Handled:
- Port Container Throughput: 18.3 million TEU
- Port Cargo Throughput: 26.3 million tonnes

Ships/Year: 25,388

Water Deep: 17m

Connection to Rail: Hong Kong West Kowloon Station

The Hong Kong West Kowloon Station is served by both short-distance and long-distance train services.

- Short-distance services

Short-distance services consist of a frequent service to mainland China, including Shenzhen, Dongguan, and Guangzhou.

- Long-distance services

Long-distance services link Hong Kong to at least 16 major destinations in mainland China[232]

Port of Shanghai

Closest City: Shanghai
Country: China
Port Operator/Authority: Shanghai International Port Group (SIPG)
Area: 3,600 km²

Annual Cargo Handled:
- 43.6 million TEU/year
- 542 million cargo tonnage

Ships/Month: 2000

Deep Water Port: Yes

Connection to Rail
- Mainly 2 railways near Port of Shanghai: Tianjin-Shanghai Railway and Shanghai-Hangzhou Railway
- Hardly any direct connection between the Shanghai Railway and the Port of Shanghai.
- On July 12, 2019, Shanghai Municipal Government publicly released the "Shanghai Work Plan for Promoting the Development of Water-Railway Intermodal Transport"

City/Area: Pasir, Panjang
Country: Singapore
Port Operator: Port of Singapore Authority (PSA) International
Port Authority: Maritime and Port Authority of Singapore

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[232] "Hong Kong West Kowloon Railway Station." Wikipedia, 8 May 2020, en.wikipedia.org/wiki/Hong_Kong_West_Kowloon_railway_station. Accessed 13 May 2020.

Geography and Key Regions:

Pasir Panjang Terminals are most advanced and busy

· Terminal 1: 6 berths, 2145m quay length, 85 ha
· Terminal 2: 9 berths, 2972m quay length, 139 ha
· Terminal 3: 8 berths, 2655m quay length, 94 ha
· Terminal 4: 3 berths, 1264m quay length, 70 ha
· Terminal 5: 6 berths, 2120m quay length, 83 ha
· Terminal 6: 6 berths, 2251m quay length, 80 ha
· Automobile terminal: 3 berths, 1010m quay length, 25 ha

Tanjong Pagar Terminal: 7 berths, 2097m quay length, 79.5 ha (note, no quay cranes)
Keppel Terminal: 14 berths, 3164m quay length, 102.5 ha
Brani Terminal: 8 berths, 2325m quay length, 84 ha

Key Stats:

· Handling capacity of 45 Million TEU
· PSA Operates 67 berths
· Capable of handling all types of vessels
· 2017: 4186 MWh of electricity consumption
· 2017: 1776 TCO2
· Oil Terminal: Yes
· Port Services: Electrical repairs, access to rail

Annual Containers Handled in 2018: 36.31 million TEU
Total Containers Handled in first half of 2019: 2,440,000 TEU
Daily Sailing distributions:

- Australia 3
- USA 2
- Japan 3
- Europe 4
- Central and South America 1
- South Asia 8
- Greater China 12
- Southeast Asia 34

Connectivity

- Over 600 ports and access to 120 countries
- 130,000 Vessel Calls per year

Supplies: Fuel oil, water, diesel oil, Engine supplies

Port of Darwin

Closest City: Darwin
Country: Australia
Port Operator/Authority: Privately operated by The Landbridge Group

Annual Cargo Handled:
21279 TEU

Ships/Yr:
1808 vessels

Ship sizing in ports:

Port of Darwin: The East Arm Wharf is able to accommodate Panamax sized ships of a maximum length of 274 meters and a deadweight tonnage of up to 80,000 tonnes.

Appendix V: Hydrogen Properties

Fuel Name	Hydrogen	Ammonia
Chemical Name	Dihydrogen or an equilibrium hydrogen mixture	nitrogen trihydride
Chemical Symbol	H_2	NH_3
Boiling Point (Celsius)	-252.76	-33.5
Critical Temperature for liquefaction (Celsius)	-239.96	132.4
Melting Point (Celsius)	-259.19	-78
Autoignition Temperature (Celsius)	585	630
Critical Pressure (bar)	13.1	112.8
Density at 0 Celsius or Standard temperature and Pressure(g/l)	0.089	0.768
Density in liquid state (g/l)	70.79	681.9
Density in melting point (g/l)	-76.3	817
Gravimetric Energy Density (MJ/kg)	120.1	22.5
Keynotes	Liquification increases the density of hydrogen by around 800 times	Ammonia has higher boiling point than hydrogen, making it easier to transport
Risks	Highly Flammable (If stored in a fail-safe vessel, the flames spout upwards, mitigating any damages).	Flammable and toxic

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