15. April 2024

Oceans of Opportunity

ZERO-EMISSION SHIPPING MISSION

RMI

GLOBAL MARITIME FORUM

Supplying Green Methanol and Ammonia at Ports

Contents

About

In September 2022, the Zero-Emission Shipping Mission launched its Action Plan, outlining the key actions needed to reach the Mission's goal of having at least 5% uptake of zero-emission fuels in the sector by 2030. The plan identified 43 priority actions across ships, fuel, and bunkering, of which the Mission committed to lead 18 and support a further 25.

The plan also included a vision to develop a "Blueprint for Future Ports" - a 3-year program to envision and help realize the zero-emission fuel-ready ports of the future. The first deliverable from the Blueprint was launched at COP27 – the Green Corridors Hub, a 'one-stop shop' website for information on green shipping corridors, including a library, route tracker, and stakeholder matchmaker tool.

This report represents the second deliverable from the Blueprint. It is intended to support strategic decision-making and action by ports, the marine fuel supply chain, and policymakers to establish bunkering of zero-emission fuels, by providing a fact base on the production and sourcing of these fuels, and priority actions to ensure their availability by 2030.

Read more about the Action Plan and Blueprint here. We welcome enquiries from stakeholders interested in contributing to our work. Please contact shippingmission@dma.dk.

Zero-Emission Shipping Mission

The Zero-Emission Shipping Mission is an ambitious alliance of countries, the private sector, research institutes, and civil society. Our goal is to have at least 5% uptake of zero or near-zero greenhouse gas emission technologies, fuels, and/or energy sources within shipping by 2030, including green hydrogen, green methanol, green ammonia, and/or advanced biofuels.

In support of this goal, the Mission undertakes activities across the entire maritime value chain, with a focus on increasing the coordination of maritime decarbonization research, development, and demonstration, undertaking collaborative projects in urgent and impactful areas, and supporting the dissemination of learnings related to zero-emission solutions.

The Mission is driven by our 16 members from around the globe:

Co-leads

Denmark
Ministry of Industry, Business and Financial Affairs, Ministry of Climate, Energy and Utilities and Ministry of Foreign Affairs

Norway
Ministry of Climate and Environment

The United States
U.S. Department of Energy

Global Maritime Forum
Representing the Getting to Zero Coalition

Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

Core Mission Members

The United Kingdom
Department for Transport

Morocco
Ministry of Energy Transition & Sustainable Development

India
Ministry of Science and Technology

Singapore
Maritime and Ports Authority

Australia
Ministry for Climate Change and Energy

Support Mission Members

France
Ministry of the Sea

Ghana
Ghana Maritime Authority

South Korea
Ministry of Trade, Industry and Energy

European Commission
Directorate-General for Research and Innovation

Canada
Transport Canada

Germany
Federal Ministry for Economics and Climate Action

RMI

RMI, founded as Rocky Mountain Institute in 1982, is an independent nonprofit that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. It works in the world's most critical geographies and engages businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions by at least 50 percent by 2030.

The Climate Aligned Industry Program at RMI is focused on decarbonizing the heavy industry and transport sectors, implementing market mechanisms and supporting policy implementation to limit global warming to 1.5°C. It currently brings together heavy industry sectors (steel, shipping, aviation, cement, and chemicals) with our cross-cutting green hydrogen initiative (The Green Hydrogen Catapult). RMI's work on shipping decarbonization focuses on key pathways for impact including: (1) Examining future trade flows of zero-emission maritime fuels; (2) Implementing green shipping corridors aimed at catalyzing uptake of zero-emission fuels and (3) Creating Market Based Mechanisms (such as Book and Claim) to create a market for differentiated green transportation products.

Global Maritime Forum

The Global Maritime Forum is an international not-for-profit organization committed to shaping the future of global seaborne trade. It works by bringing together visionary leaders and experts, who through collaboration and collective action strive to increase sustainable long-term economic development and human wellbeing.

The Forum is a founding member and co-lead of the Zero-Emission Shipping Mission, where it represents the Getting to Zero Coalition – an industry platform bringing together leading stakeholders from across the maritime and fuels value chains with the financial sector and others committed to making commercially viable zero-emission vessels a scalable reality by 2030, towards full decarbonization by 2050. In its capacity as co-lead, the Global Maritime Forum heads up the Mission Fueling Infrastructure Pillar.

Acknowledgments

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Sounding board

The team would like to thank the following sounding board members for their active participation in helping shape this report:

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DANISH MARITIME AUTHORITY

We would like to thank the Danish Maritime Authority for their support in funding the design of this report.

Endorsements

“As one of the Core Members of the Zero-Emission Shipping Mission, MPA is pleased to have contributed to the findings of the report as a sounding board member. The report is a useful reflection of the production trends and possibilities for green methanol and ammonia, information which is very important for bunkering hubs such as Singapore. We look forward to working closely with RMI, GMF and fellow ZESM partners in the future to support the supply and uptake of such zero and near-zero fuels at scale to accelerate maritime decarbonisation.”

TEO Eng Dih,
Chief Executive

MPA
SINGAPORE

“The report helps us understand port strategies for the bunkering of green methanol and ammonia. These questions are essential for addressing the classic 'chicken and egg' dilemma for sustainable fuel production for international shipping. The report is the culmination of a project under the auspices of Zero-Emission Shipping Mission and as a member of the Mission, I believe that the report will contribute to international knowledge sharing and cooperation across ports and the maritime value chain to bunker these fuels”

Rikke Wetter Olufsen,
Deputy Director General

DANISH MARITIME AUTHORITY

“UMAS participated in the stakeholder feedback sessions and reviewed the final report. Our purpose is to lead and support the decarbonisation of the shipping, maritime, and related energy sectors worldwide. Therefore, we support RMI's efforts to convene these industries around the practical implementation of a decarbonisation pathway and look forward to contributing and undertaking further work in this important area.”

Chris Thorne,
Director of Strategy and Operations

UMAS

“The segment of renewable fuels is gaining momentum and a decent overview of the various projects worldwide was much needed. The Port Fuel Supply Study therefore is a very helpful document that provides us with essential insights, not only on the status of the projects but also the industry's challenges and opportunities. Moreover, the categorization of other ports in different fases of maturity serves as a great benchmark for Porto do Açu and is as a source of inspiration to optimize our growth strategy looking at our peers' best practices”

Maartje Driessens,
International Relations Manager

PORTO DO AÇU

Glossary

Green fuels: Refers to e-ammonia, e-methanol, and bio-methanol in this report.

Green hydrogen-based fuels: Refers to e-ammonia and e-methanol in this report.

Green hydrogen: Hydrogen with very low to zero production emissions. Made via renewable electricity-powered electrolysis.

E-ammonia/ green ammonia: Ammonia with very low to zero production emissions. E-ammonia is produced using hydrogen from renewable electricity-powered electrolysis and nitrogen. This report uses green ammonia and e-ammonia synonymously.

Green methanol: Methanol with very low to zero production emissions. Green methanol includes e-methanol and bio-methanol.

E-methanol: Methanol produced using hydrogen from renewable electricity-powered electrolysis and sustainable carbon.

Bio-methanol: Methanol produced using waste or residual biomass feedstocks.

Very low sulfur fuel oil (VLSFO): One of the conventional fuels currently used in the shipping sector.

VLSFO equivalent units: These units are used in this report to compare cost of green methanol and ammonia on an energy density basis.

Delivered cost of fuel: The total cost of fuel supplied to a vessel. It includes the cost of production, storage, transport, and port infrastructure associated with bunkering the fuel.

International Maritime Organization (IMO): The specialized agency of the United Nations responsible for regulating international shipping.

Twenty-foot equivalent units (TEU): A standard unit for counting containers of various capacities and describing the capacities of container ships or terminals.

Final investment decision (FID): The point where an investment decision is made to go ahead with a fuel production project.

Expression of interest (EOI): An EOI is released by a party interested in purchasing a product from supplier(s) and invites supplier(s) to submit proposals to the interested party.

Capital expenditures (CAPEX): Costs incurred to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment.

Operating expenses (OPEX): Costs incurred during the operation and/ or maintenance of produced goods or services.

Inflation Reduction Act (IRA): A US federal law passed in 2022. The IRA is commonly referenced in this report because of the Credit for Production of Clean Hydrogen (section 45V) and Clean Electricity Production Tax Credits (section 45Y).

EU Emissions Trading Scheme (EU ETS): The EU's cap and trade emissions trading scheme, which covers emissions from the shipping sector since January 2024.

Executive summary

Shipping is beginning to shift to new fuels as the sector's journey to net zero becomes clearer. The International Maritime Organization's 2023 Greenhouse Strategy sets a target for shipping to hit net-zero emissions by or around 2050 and an interim milestone of reaching at least 5-10% uptake of zero or near-zero greenhouse gas (GHG) emission technologies, fuels, and/or energy sources by 2030.

Among the multiple fuels and technologies being considered, green methanol and green ammonia[1] are seen as promising options for achieving the decarbonization goals set forth by the IMO.

While the potential cost and performance of green methanol and ammonia are the subject of significant industry research and demonstration activities, there are large uncertainties around their availability. These uncertainties have been highlighted by shipowners and operators as obstacles to investment in zero-emission ships. To help provide greater clarity about the availability of green methanol and ammonia, this study explores where these fuels may come from, whether there will be enough, what their full cost will be, and what must be done by when to ensure their availability by 2030, to meet the fuel uptake targets set by the IMO for this time. Focus is placed on ports and the bunkering ecosystem centered around them, as the actors best positioned to unlock the supply of new fuels.

1 Green methanol and green ammonia refer to methanol and ammonia with very low to zero production emissions, including e-methanol and e-ammonia (produced using hydrogen from renewables-based water electrolysis and sustainable carbon or nitrogen) and bio-methanol (produced using waste or residual biomass feedstocks). The phrase "green methanol and ammonia" is used through the report as a shorthand to refer to green methanol and green ammonia. Green methanol and ammonia are two of the four focus fuels of the Zero-Emission Shipping Mission and the primary focus of this report.

Green methanol and ammonia supply dynamics

Fuel supply dynamics will change dramatically as the maritime industry decarbonizes.

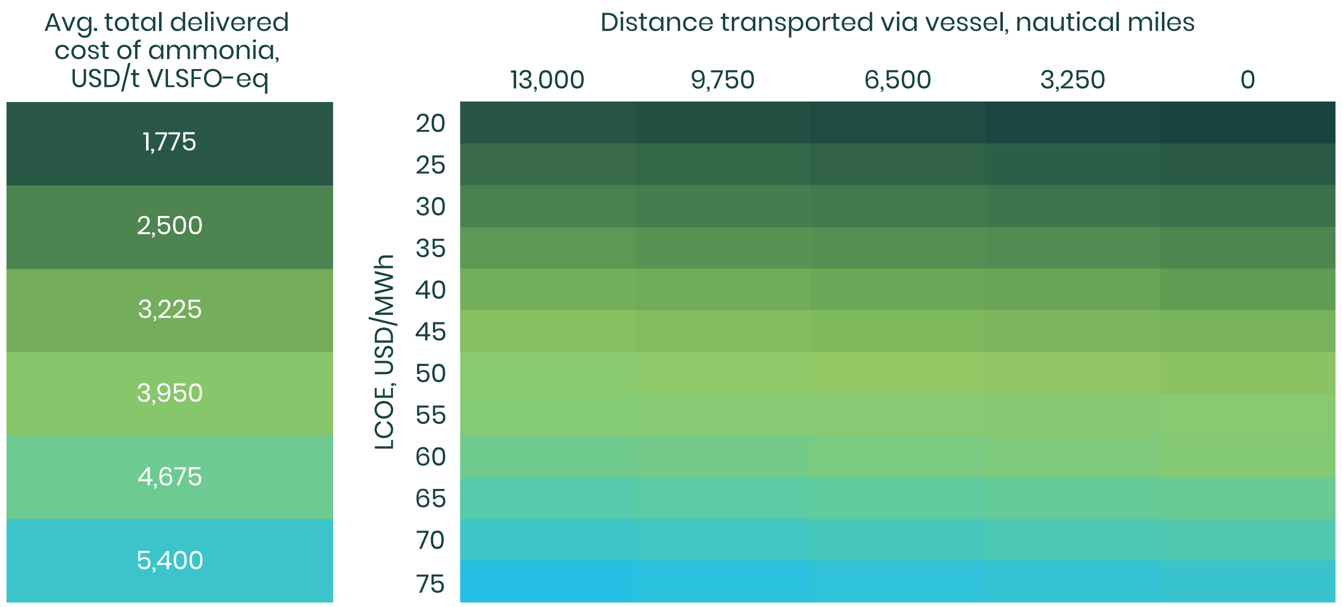
The economics of green ammonia and methanol production and transport, assessed in the report, suggest there will be extensive trade in these fuels, linking low-cost production regions with key ports.

While the cost of transporting ammonia and methanol to ports is relatively immaterial, with even the longest possible routes adding no more than 15% to the delivered cost of the fuel, production costs for e-ammonia and methanol vary significantly between regions. Areas with good renewable energy resources, low capital costs, and access to hydrogen production support mechanisms will produce e-ammonia and methanol several times cheaper than other regions.

Exhibit ES 1

The cost of renewable energy impacts the delivered cost of e-methanol and ammonia significantly more than the cost of transport

Relative impact on delivered cost of e-ammonia from levelized cost of renewable electricity (y-axis) compared to seaborne transport (x-axis)
USD per metric ton VLSFO equivalent



Source: RMI analysis.

Many ports have favorable conditions to produce e-ammonia or methanol. In the medium to long-term, local production will be the most economical option for these ports to source e-ammonia or methanol bunkers. This includes many smaller ports, several in the Global South, for which the transition will create new opportunities to both build a hydrogen production economy and participate in the global bunker market. Ports that have less favorable production conditions will instead be able to benefit from the trade of green methanol and ammonia, making them significant end-use markets for hydrogen exporters and project developers.

In the immediate term, especially the period to 2030, constraints on the availability of green methanol and ammonia will also shape trade flows between producers and ports. To explore these dynamics, the study inventories global projects aiming to produce green methanol and ammonia by 2030 and considers scenarios for how several bunker ports would secure supply if they aligned with IMO targets and supplied 5% green methanol and/or ammonia by this time. The results suggest that supply patterns for the two fuels may differ significantly.

For green methanol, limitations in availability may result in a concentration of supply in major bunkering hubs and European ports, which are likely to see higher demand for low-emission fuels this decade due to the FuelEU Maritime regulation and inclusion of shipping in the EU Emissions Trading Scheme. The results suggest there are opportunities for developers to further expand green methanol production to meet demand from shipping and enable supply at more ports.

In contrast, green ammonia trade could be more diversified and feature long-distance transport from projects in low-cost production regions, including the US, South America, Australia, and Sub-Saharan Africa, to key bunkering hubs. While there could be more than enough green ammonia to supply potential first-mover ports, competition for the lowest-cost volumes could be fierce and reward those able to move early in securing supply. Green ammonia from the US, which can benefit from the tax credit package associated with the Inflation Reduction Act (IRA), may be particularly sought after, since it will be the most cost-competitive green ammonia globally by a considerable margin.

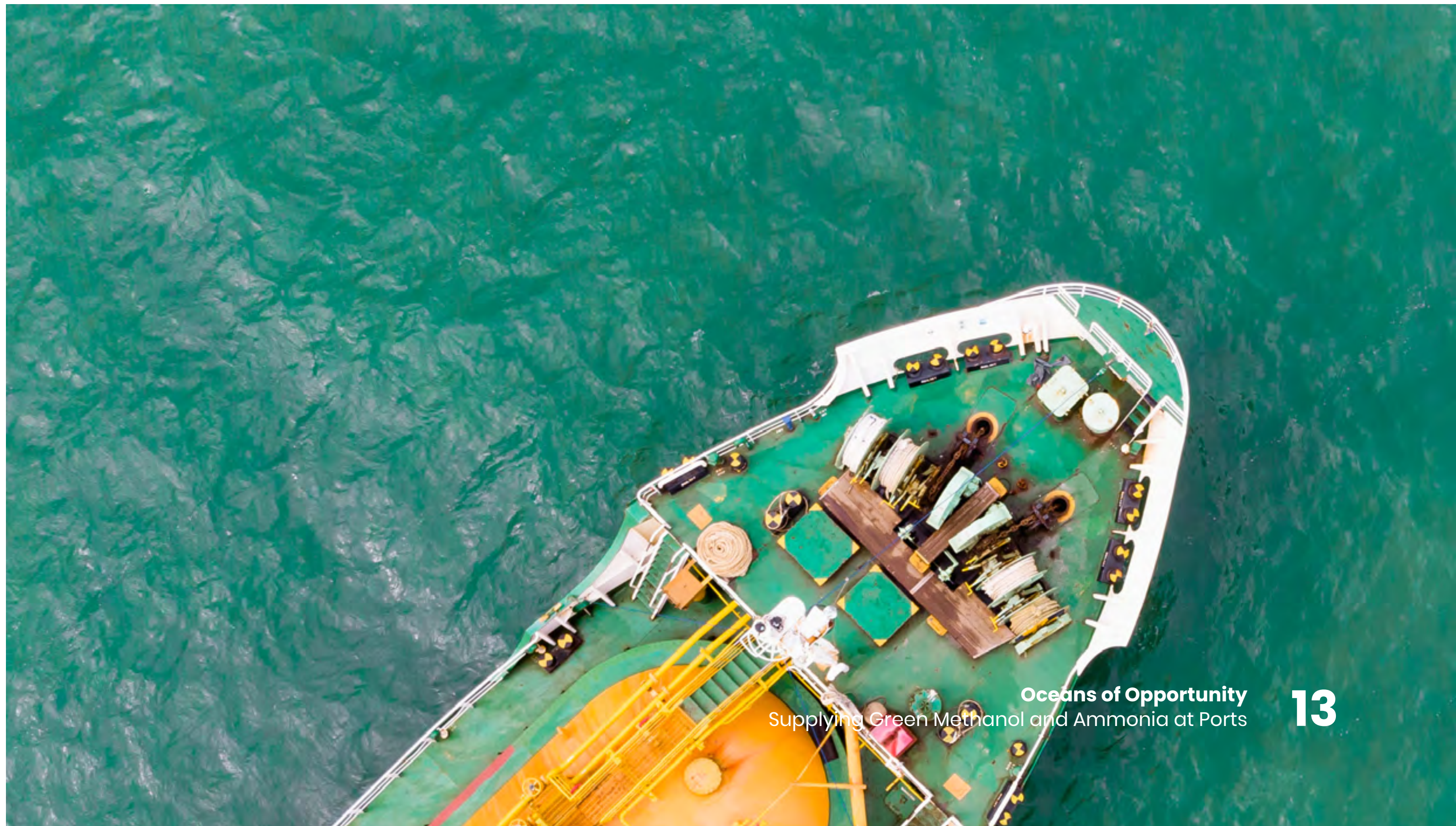


Exhibit **ES2**

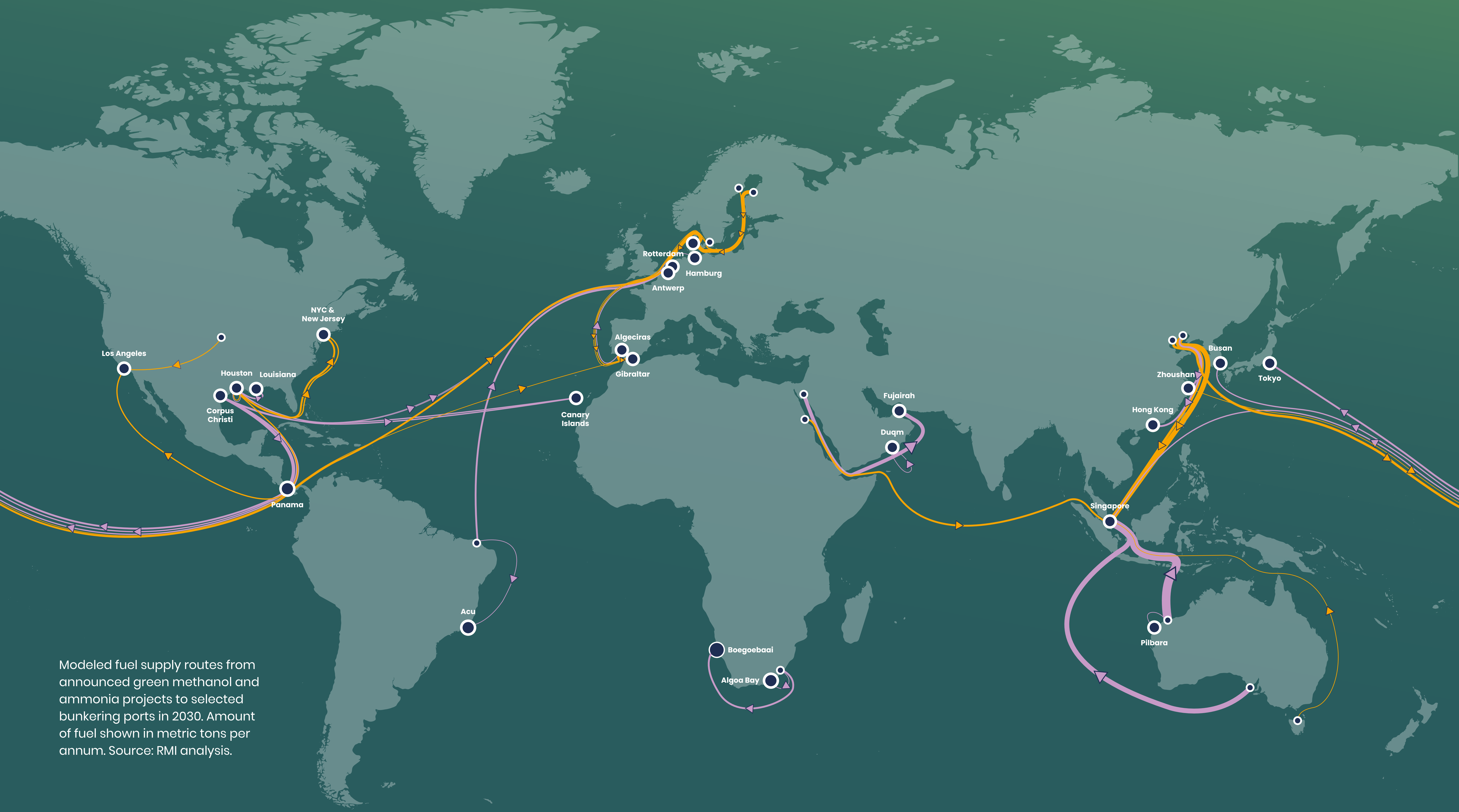
Potential green methanol and ammonia trade flows by 2030 if all announced volume is realized.

LEGEND

Ammonia
- Port
- Production Location
- Supply route

Methanol
- Port
- Production Location
- Supply route

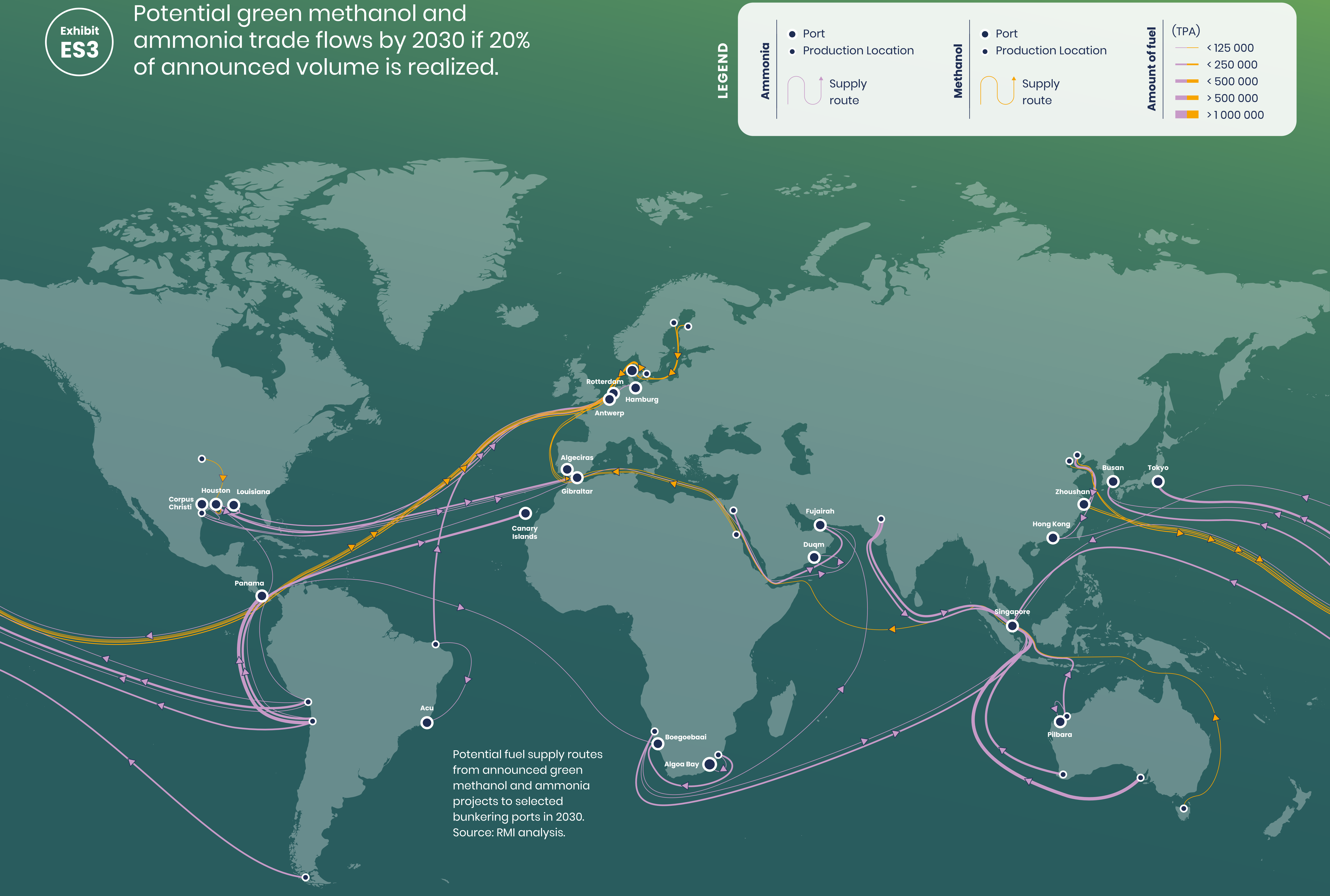
Amount of fuel (TPA)
- < 125 000
- < 250 000
- < 500 000
- > 500 000
- > 1 000 000



Modeled fuel supply routes from announced green methanol and ammonia projects to selected bunkering ports in 2030. Amount of fuel shown in metric tons per annum. Source: RMI analysis.

Exhibit **ES3**

Potential green methanol and ammonia trade flows by 2030 if 20% of announced volume is realized.



Potential fuel supply routes from announced green methanol and ammonia projects to selected bunkering ports in 2030. Source: RMI analysis.

Strategies for ports to become first movers in green methanol and ammonia bunkering

Future green methanol and ammonia supply dynamics are not predetermined but will be shaped by the real-world action taken by stakeholders over the coming years. The second part of the report examines strategies that ports and the bunkering ecosystem can take to be first movers in establishing green methanol and ammonia bunkering by 2030.

It identifies four distinct groups of ports, called "archetypes", that might emerge during the transition – Importing Incumbents, Producing Incumbents, Future Exporters, and Bespoke Players. They are based on the expected cost of producing e-methanol and ammonia near the port and their current level of bunkering demand, which are the factors expected to have the greatest impact on delivered cost of green methanol and ammonia at ports.

Exhibit ES 4

Ports can be divided into four archetypes by their bunkering volumes and the cost of local fuel production. Archetypes are associated with certain opportunities and risks

Illustrative mapping of ports. Spacing between these ports is not fully representative of reality. The intention of this graph to show various ports who are currently representative of the four archetypes.

Importing Incumbents

Opportunities:

- **Leveraging existing demand** to **lower** port **infrastructure costs**
- Obtaining lower fuel costs due to **demand aggregation**

Risks:

- **Losing bunkering share** to more **assertive** ports

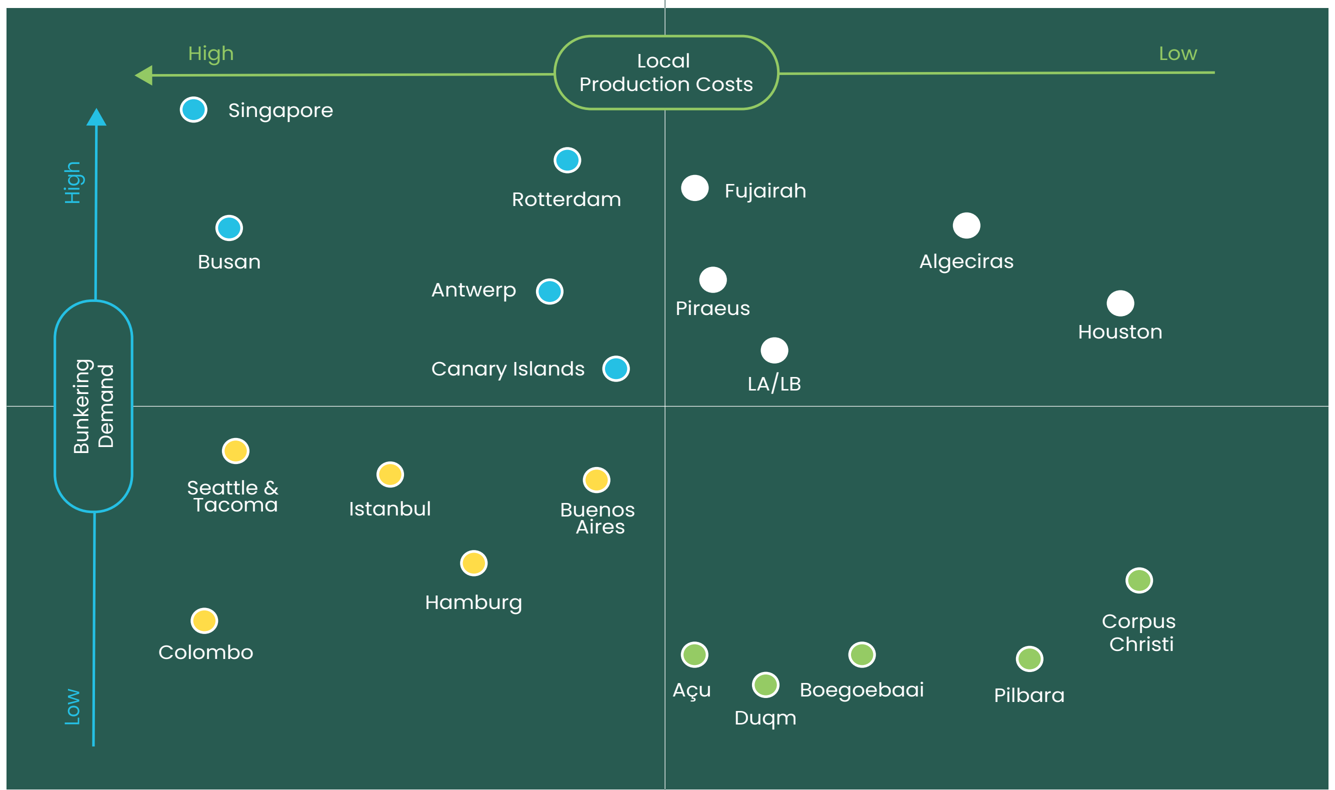
Producing Incumbents

Opportunities:

- **Leveraging existing status** as bunkering hub
- Becoming a **major exporter** in future

Risks:

- **Moving slowly** on infrastructure, regulations, and permitting



Bespoke Players

Opportunities:

- Becoming a **"first mover"** in the **Zero-emission fuel bunkering space**
- **Investing swiftly in bunkering infrastructure**
- Creating **enabling ecosystem** for fuel procurement

Risks:

- **Losing status as bunkering hub without proactivity**

Future Exporters

Opportunities:

- Can take advantage of **excellent renewables**
- Becoming a **major exporter** in future, open door to **bunkering**.

Risks:

- **Infrastructure cost** can be prohibitive at **low demand**

Source: RMI analysis.

Importing Incumbents

Represented by the likes of Singapore and Busan, these ports have a high level of existing bunker demand, but high local e-methanol and ammonia production costs, meaning they would need to import large amounts of the fuels for bunkering. They can leverage their position as existing bunkering (and, in some cases, industrial) hubs to avoid high last-mile infrastructure costs and support the sourcing of low-cost imports. However, they risk losing market share to more aggressive ports if they are slow to act, necessitating proactive efforts to procure the fuels.

Producing Incumbents

This archetype is exemplified by ports like Algeciras and Houston. They have both high existing bunker demand and favorable production conditions. These ports have the readiest opportunity to become first movers in green methanol and ammonia bunkering. By leveraging their existing status as bunkering hubs, their low production costs, and the synergies between bunkering and potential fuel exports, they can quickly establish low-cost green methanol and/or ammonia supply.

Constraints on their potential growth include slow movement in activating demand for the new fuels, building out infrastructure, and developing regulations, standards, and permitting. Proactive collaboration within their networks can help to sidestep these constraints.

Future Exporters

Represented by Corpus Christi in the US, the Pilbara ports in Australia, and many ports in the Global South, ports in this archetype have low-cost production conditions but low (or no) existing bunker demand. Their low-cost production potential means they have opportunities to produce e-ammonia or methanol for bunkering but also export. This can help de-risk infrastructure investments and minimize otherwise high last-mile costs, making them competitive bunkering locations. But they must swiftly activate demand from shipping and other sectors, while establishing a bunkering ecosystem from a low or non-existent base.

Bespoke Players

This archetype includes ports like Seattle and Tacoma, Colombo and Hamburg. They are characterized by low existing bunkering demand and high e-ammonia and methanol production costs. While the transition to zero-emission shipping will bring these ports opportunities, they must adopt a highly proactive and holistic approach to developing green methanol and ammonia bunkering, including moving fast to obtain low-cost imports and taking action to attract demand/ bring down last mile costs.

Action and recommendations for ports

Ports can use the archetypes as a starting point for developing their zero-emission bunkering strategies. Five case studies in the report explore the existing actions being taken by Singapore, Algeciras, Corpus Christi, Seattle and Tacoma, and Rotterdam to establish methanol and/or ammonia bunkering. The case studies provide packages of suggested actions that ports in each of the archetypes can take with actors in the bunkering supply chain to become first movers in green methanol and ammonia bunkering.

Exhibit ES 5

Recommended actions ports and the bunkering ecosystem should take to seize their green bunkering opportunity especially relevant to each archetype

	Importing Incumbents	Producing Incumbents	Future Exporters	Bespoke Players
Establish partnerships with low-cost regions to earmark low-cost fuel volumes	✓			✓
Participate in **hydrogen import/ export corridors**	✓			
Coordinate green methanol and ammonia bunkering standards with other ports	✓	✓		
Engage first mover customers within shipping to activate green methanol and ammonia fuel demand	✓	✓	✓	✓
Set up **export routes** for the supply of green methanol and ammonia to other ports to scale infrastructure and production		✓	✓	
Consider focusing efforts on **establishing bunkering for one zero-emission fuel** in the near-term			✓	✓
Implement **incentives**, such as discounted harbor dues and preferential berthing **for zero-emission ships**			✓	✓
Consider setting a **target of 10% zero-emission fuel sales** by 2030			✓	✓
Explore the availability of **capital grants** or **preferential loans for methanol and ammonia bunkering infrastructure**			✓	✓
Explore **collaborative offtake opportunities**			✓	✓

Introduction

The IMO's 2023 Greenhouse Gas Strategy leaves no question, shipping must rapidly decarbonize, with a firm target now set for the industry to reach net-zero "by or around, i.e. close to, 2050"[i].

While improvements in the technical and operational efficiency of ships have significant untapped potential[ii] to reduce the sector's emissions, the industry will need to adopt new fuels to reach net-zero by 2050. Multiple potential fuels and pathways are being considered. However, there is increasing consensus that green hydrogen-based fuels – particularly green methanol and green ammonia – will play a key role in delivering the rapid emissions reductions the sector needs to deliver on these ambitions[iii,iv,v,vi].

If green methanol and ammonia are to live up to their potential to decarbonize international shipping, action must be taken today. Trends from other sectors suggest that relatively limited uptake of new technologies can activate tipping points, after which their use rapidly increases[vii,viii]. These trends are reflected in the IMO strategy, which also sets a near-term target of 5-10% uptake of zero-emission fuels by 2030[ix]. Getting to the tipping point for zero-emission fuel will require three key conditions to be in place: affordability, attractiveness, and accessibility.

Exhibit 1

Affordability, attractiveness, and accessibility are needed for zero-emission fuels to reach a technology tipping point

	Affordability	Attractiveness	Accessibility
Definition	Price parity between incumbent and new technology	Equal or better performance across quality, reliability and convenience etc.	Supply chain for large-scale adoption in place

Source: Adapted from Systemiq/Bezos Earth Fund, "The Breakthrough Effect in ASEAN"

While several studies have explored the actions needed to close the cost gap between zero-emission and conventional fuels[x] (affordability), and pilot projects are underway to validate the feasibility and performance of zero-emission vessels (attractiveness)[xi], accessibility remains a relatively neglected area of research. There is a particular knowledge gap around zero-emission fuel supply chains – where the fuel will come from, whether there will be enough, what the delivered cost will be, and what must be done by when. Uncertainties in this area have been highlighted by shipowners and operators as blockers to investment[xii].

The objective of this report is to help create clarity for stakeholders in shipping, the bunkering ecosystem and public sector, by explaining the dynamics that will influence the supply of green methanol and green ammonia as marine fuels and suggesting strategies ports can take to establish to establish green methanol and ammonia bunkering by 2030.

The report emphasizes green methanol and ammonia in alignment with the Shipping Mission's focus on green hydrogen, green ammonia, green methanol, and advanced biofuels for the maritime sector. It should be noted that, the United States Department of Energy and NREL, with advisory support from RMI, are collaborating on a companion piece centered on advanced biofuels, slated for publication later this year. This report's emphasis on green methanol and ammonia does not exclude or imply that they are the sole solutions for decarbonizing the maritime industry.

Our approach

To understand these supply dynamics and suggest strategies for ports, the report models the delivered cost of green methanol and ammonia – including the cost of production, transport, and bunkering infrastructure of the fuels - and presents scenarios for how announced green ammonia and methanol projects could connect to key global ports.

An industry sounding board group consisting of 14 stakeholders from across the bunkering ecosystem – including ports, bunker suppliers, fuel producers, and regulators – provided qualitative insights and helped validate the modeling results.

Hydrogen cost modeling approach

The e-methanol and ammonia cost modeling in this report relies on green hydrogen cost modeling.

As a nascent industry, green hydrogen costs are subject to uncertainty and modeling efforts depend on assumptions. The model considers hydrogen production systems that will reach a final investment decision (FID) around 2030, once the green hydrogen industry is expected to have matured significantly. The costs calculated here are likely to vary from the costs realized by specific project developers.

Important assumptions in the model include:

- **Electrolyzer costs:** Since electrolyzer deployment is nascent, green hydrogen projects currently face a number of first-of-a-kind costs and risks, including lack of streamlined production processes, technology integration risk, higher engineering, procurement, construction, and labor costs. First-mover developers are still managing these costs and risks, which directly affect the point-of-sale costs they can achieve. As electrolyzer systems are deployed at scale, many of these costs and risks will be reduced, with the pace of cost decline likely to be dependent on the quantity of electrolyzers installed over time. Exhibit 2 shows how different assumptions on electrolyzer capacity buildup and learning rates can affect final levelized cost of hydrogen calculations.

- **Financing:** The model does not account for dynamic project financing parameters that will affect the final cost of hydrogen for producers and consumers. We have calculated delivered costs by assuming a steady, baseline set of financial parameters that will determine how project developers secure access to capital, ultimately determining the levelized cost of hydrogen they can achieve. However different project financing structures will yield different costs of hydrogen. Exhibit 2 also shows the impact on the levelized cost of hydrogen (LCOH) of different debt-to-equity ratios and weighted average cost of capital assumptions for electrolyzer projects.

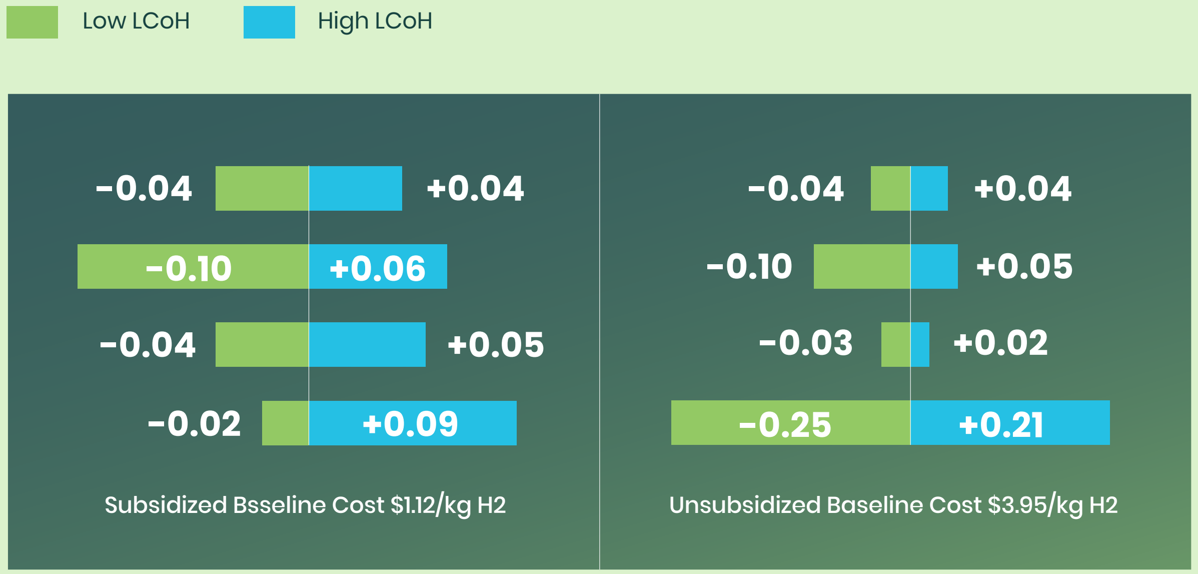
- **Renewable electricity:** The model analyzes the dynamics of a behind-the-meter plant (not connected to grid power) producing a constant supply of green hydrogen (which is usually needed to produce hydrogen derivatives, especially ammonia). This requires plants to build up sufficient renewables and storage for continuous supply over the course of a typical year.

Exhibit 2

Levelized cost of hydrogen is sensitive to various technological and financial parameters

LCoH sensitivities are for an archetypical production plant in the Port of Houston, 2030.

	Baseline Value	Sensitivity Analysis
Electrolyzers deployed by 2030 (GW)	320	± 70
Learning Rate (%)	5%	-2.5%/+5% pp
Debt to Equity Ratio (%)	70%	± 10% pp
WACC (%)	7.8%	± 2.3% pp



Source: RMI analysis.

- **Compliance costs:** The model does not include project-specific implementation costs, like those associated with regulatory compliance or legal fees, or the costs of drawn-out permitting processes.

Bio-methanol is not produced using green hydrogen and, as such, cost estimates do not rely on green hydrogen cost modeling. Bio-methanol production costs in this report are instead taken from the IRENA 2021 Renewable Methanol report[xiii]

Further details on the cost modeling assumptions used are included in the Appendix.

The report consists of two parts. The first section explores how flows of green methanol and ammonia from producers to ports might play out on a global level. The second section examines implications for specific port "archetypes", including through five case studies on the Ports of Singapore, Algeciras, Corpus Christi, Seattle and Tacoma, and Rotterdam.

The report does not include case-by-case analyses of green methanol and ammonia bunkering infrastructure costs or risk assessments for implementing green methanol and ammonia bunkering at give ports.

Successful validation of the safety of methanol and ammonia bunkering is of paramount importance for green methanol and ammonia to become widespread solutions to decarbonizing the sector. The following fact box provides a summary of progress in this area.

Emerging learnings on methanol and ammonia bunkering safety

Methanol

Methanol is a toxic and highly flammable chemical. It is more flammable than ammonia and burns with a flame that can be hard to see in daylight, creating a risk of fires. Its toxicity means robust safety protocols must be in place to protect seafarers and port operatives from coming into contact with the fuel.

Following the first methanol-powered ship – the Stena Germanica – hitting the water just under a decade ago, experience in handling methanol as a marine fuel has grown. Truck-to-ship bunkering of methanol was successfully demonstrated in 2015, shore-to-ship bunkering in 2016, and barge-to-ship bunkering in 2021. Methanol bunkering has since been validated in several different locations and types of conditions, with 10 global ports now offering methanol bunkering and a further 11 planning to establish capability in the near term[xiv].

From a regulatory standpoint, several resources for methanol bunkering are available. The IMO's IGC Code, which applies to bunker vessels, has provisions for ships carrying methanol, and port-specific guidelines, operational checklists, and class rules have been published[xv,xvi].

Ammonia

Ammonia is a highly toxic chemical. While its strong odor makes small leaks easy to detect, a sudden loss of containment or spill would have serious implications for human health and sea life. The likelihood and potential impact of ammonia releases will therefore need to be carefully managed to enable safe ammonia bunkering.

There is significant experience safely handling ammonia. Due to the ongoing development of ammonia marine engines, bunkering pilots are still in early stages, with little regulatory guidance currently available. However, the world's first ammonia bunkering was completed in Singapore in March 2024 and several studies have been undertaken, providing initial datapoints on the risks and potential mitigations required to ensure safety.

Further work is required to enable ammonia as a solution in the sector's transition. This includes risk assessments, the development of operational safety materials, port guidelines, and real-world trials and pilots. An overview of emerging learnings on ammonia bunkering safety can be found in Annex 8.

Finally, it should be noted that many port authorities have a landlord role, focused on creating an enabling environment for bunkering through planning, providing space, developing suitable regulation. Other actors in the bunkering ecosystem, such as bunker suppliers, barge operators, and terminal operators, will have key roles in implementing green methanol and ammonia bunkering. The term "port" is used in this report as shorthand to encapsulate this broader ecosystem involved in bunkering at ports, rather than just port authorities.

1. Green methanol and ammonia fuel supply dynamics

This section explores where green methanol and ammonia bunkers are most likely to be produced and how they may be sourced by ports. An understanding of these dynamics can help provide clarity about the availability of green methanol and ammonia at ports and support the development of strategies for implementing green methanol and/or ammonia bunkering.

a. The economics of green methanol and ammonia production and trade

The low cost of transporting green methanol and ammonia will lead to extensive trade in ammonia and methanol bunkers, linking low-cost production regions to key ports.

There are several possible scenarios for where green methanol and ammonia could be produced and how they could be sourced. At a high level, they could be produced near each bunker port or production and bunkering could be "decoupled", with green methanol and ammonia produced in low-cost locations and transported to ports where they are then bunkered[2].

While several factors will be relevant, economics are expected to be the key driver of the bunker market and determine the most likely scenario. The extent to which the cost of producing the fuels differs in different regions and the cost of transporting the fuels are particularly key; if transportation costs are lower than the geographical difference in production costs, decoupling is likely.

Production costs

Regional differences in the cost of producing green methanol and ammonia are significant. For e-methanol and ammonia, these differences are driven by three elements – renewable energy resources, cost of capital, and hydrogen production subsidies.

While the cost of the sustainable carbon used to produce e-methanol also impacts on the cost of e-methanol, the level of variation in the cost of sustainable carbon is expected to be limited[3].

2 In reality, supply chain configurations would sit on a spectrum between these two poles and include i) the fuels being produced locally, at or around the ports where they are sold; ii) produced domestically and transported to the port by truck, rail or ship; iii) produced regionally and transported to the port by either rail or ship; or iv) produced in global locations and traded.

3 See Annex 2: "Carbon costs" for further information about the cost of sustainable carbon.

Renewable energy resources

E-methanol and ammonia are produced using green hydrogen. The biggest driver of the cost of producing green hydrogen is the renewable electricity used to split the water into hydrogen through electrolysis.

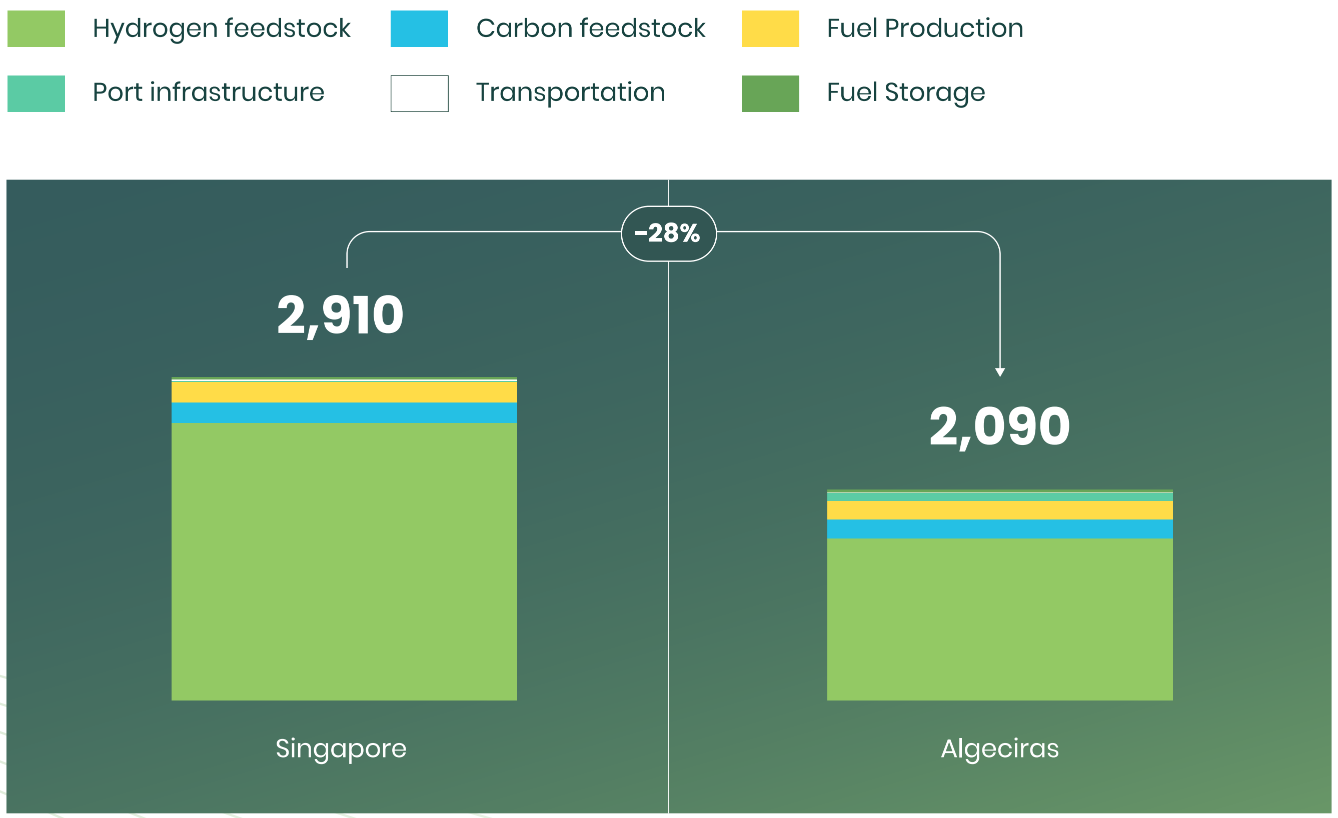
Renewable electricity costs depend on renewable capacity factors, a measure reflecting how often a renewable energy generation unit, like a solar or wind farm, operates at peak capacity. The high cost of the equipment for green hydrogen plants means that it is important to run electrolyzers at high capacity, to reduce the cost per unit of production. This makes high renewable capacity factors crucial for producing low-cost e-methanol and ammonia.

Global variation in renewable capacity factors is substantial, influenced by differing climate conditions and the duration of sunlight in different locations throughout the year. For example, Singapore has relatively low renewable energy capacity factors of 16% for solar and 12% for wind, while Algeciras in Southern Spain has relatively high capacity factors of 27% for solar and 34% for wind[4]. This leads to a ~28% difference in the cost of e-methanol produced in the two locations.

Exhibit 3

Solar and wind resources are key factors for determining the cost of green hydrogen

Delivered cost of locally-produced e-methanol in Singapore versus Algeciras
USD per metric ton VLSFO equivalent



Source: RMI analysis.

4 Capacity factors were obtained using a latitude and longitude and Renewables Ninja's API.

Cost of capital

E-methanol and ammonia projects are multibillion-dollar endeavors. Because of the large scale of investment required, the cost of capital available to project developers can significantly affect project financing costs. This has a domino effect on production costs.

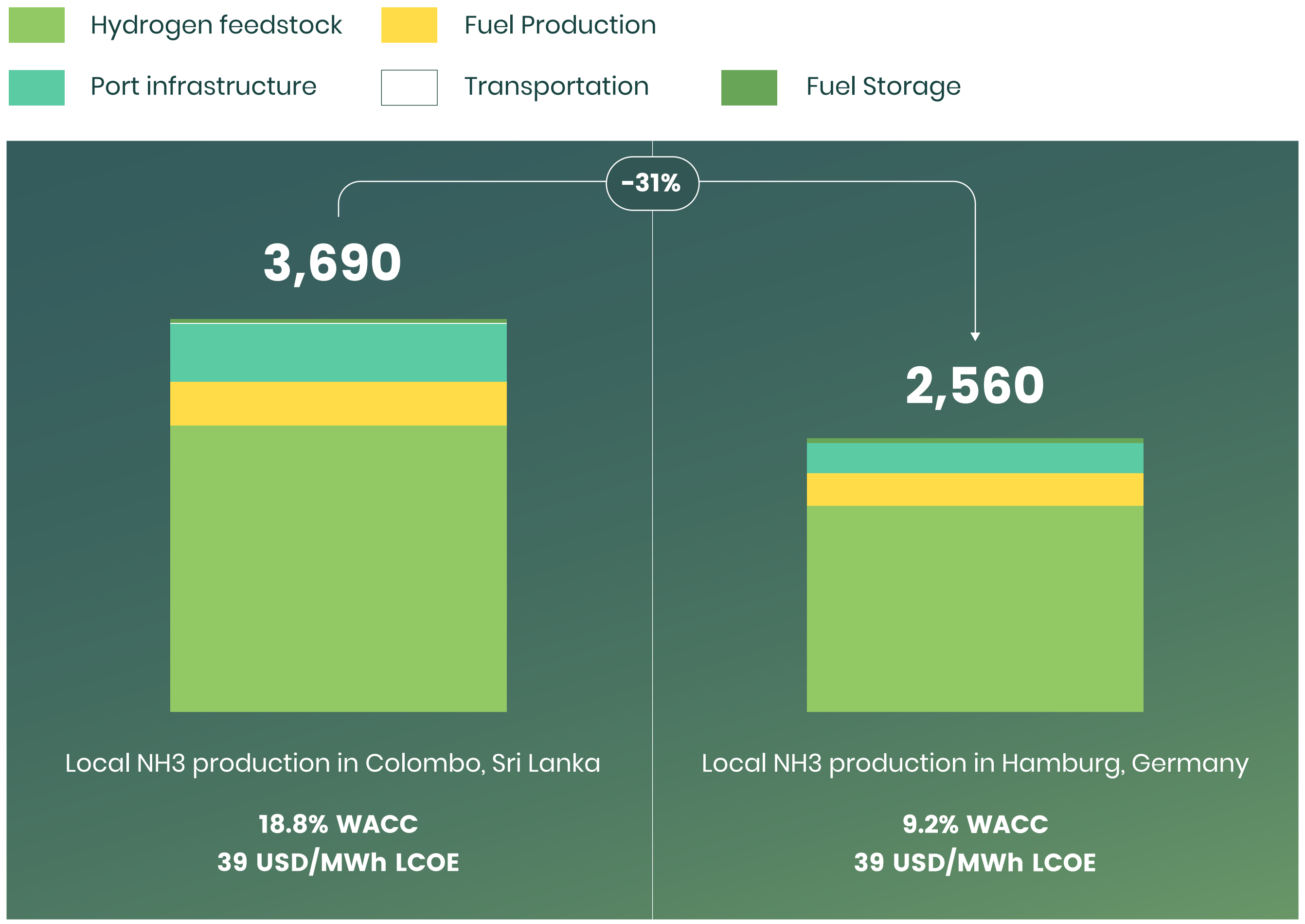
Developed countries in the Global North tend to have a relatively low cost of capital, while many developing countries in the Global South have a high cost of capital, due to perceived investment risks[xvii].

The impact of this disparity is demonstrated in Exhibit 4, which compares the cost of green ammonia in Hamburg, Germany and Colombo, Sri Lanka. These two locations have similar renewable energy capacity factors but a difference of almost 10% in the cost of capital. This difference results in e-ammonia production in Colombo being ~31% more expensive than equivalent production in Hamburg[5].

Exhibit 4

Financial parameters are another key factor in the total delivered cost of e-methanol and ammonia

Impact of differences in the cost of capital on the cost of e-ammonia produced in Colombo and Hamburg
USD per metric ton VLSFO equivalent



Source: RMI analysis.

5 Hamburg also benefits from greater economies of scale in port infrastructure than Colombo, but this accounts for just ~15% of the cost difference between the two locations.

Hydrogen production support

Hydrogen production support mechanisms also have the potential to create geographical differences in the cost of producing e-ammonia and methanol.

While there are support mechanisms in place or under development in other parts of the globe[xviii], the tax credit package offered under the US Inflation Reduction Act (IRA) is the most ambitious such scheme announced to date.

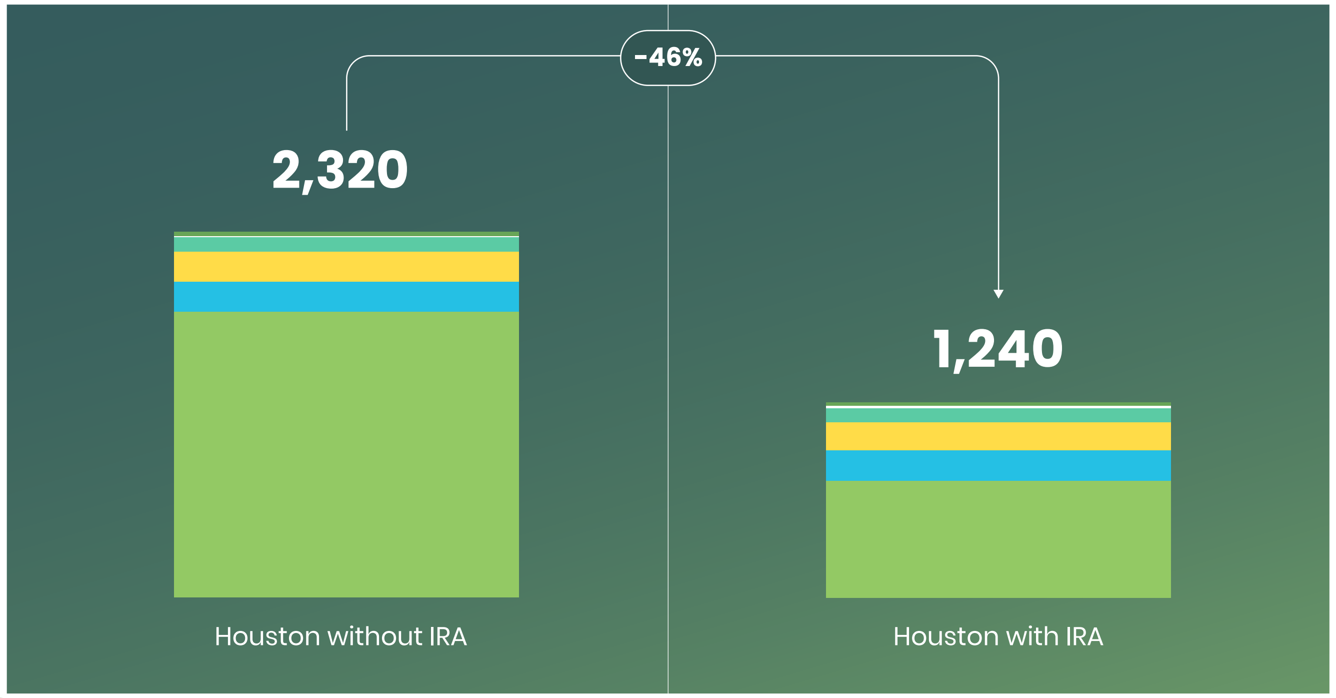
Exhibit 5 shows the expected impact of the IRA on the cost of e-methanol. The renewable electricity and hydrogen production tax credits under the IRA are estimated to reduce the cost of e-methanol produced in Houston by 46%.

Exhibit 5

Hydrogen support mechanisms, like the IRA, can significantly reduce the cost of green fuels at ports

Delivered cost of e-methanol at Port of Houston with and without IRA tax credits
USD per metric ton VLSFO equivalent.

Hydrogen feedstock | Carbon feedstock | Fuel Production
Port infrastructure | Transportation | Fuel Storage



Source: RMI analysis.

Transportation costs

Compared to the regional differences in the cost of e-methanol and ammonia production, the cost of transporting these fuels is relatively negligible.

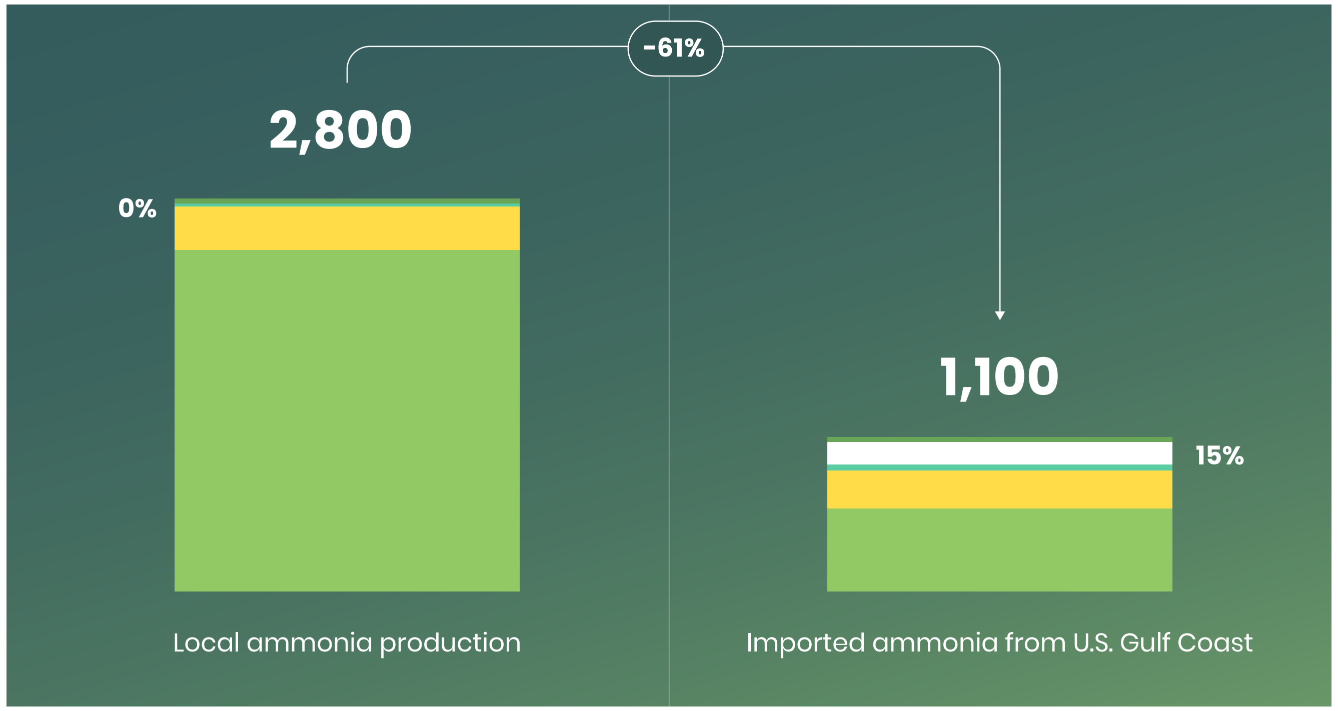
On one of the longest possible seaborne transport routes in the world, from Houston to Singapore, transportation of green ammonia is estimated to cost $166 per metric ton VLSFO equivalent, or 15% of the delivered cost of the fuel. In contrast, the difference in production costs between locally sourced e-ammonia and imports from Houston is almost $1,900 per ton VLSFO equivalent.

Exhibit 6

Production costs are more significant than transport costs for the total delivered cost of green methanol and ammonia

Delivered cost of locally-produced e-ammonia versus e-ammonia imported from the US Gulf to Singapore
USD per metric ton VLSFO equivalent

Hydrogen feedstock | Fuel Production
Port infrastructure | Transportation | Fuel Storage



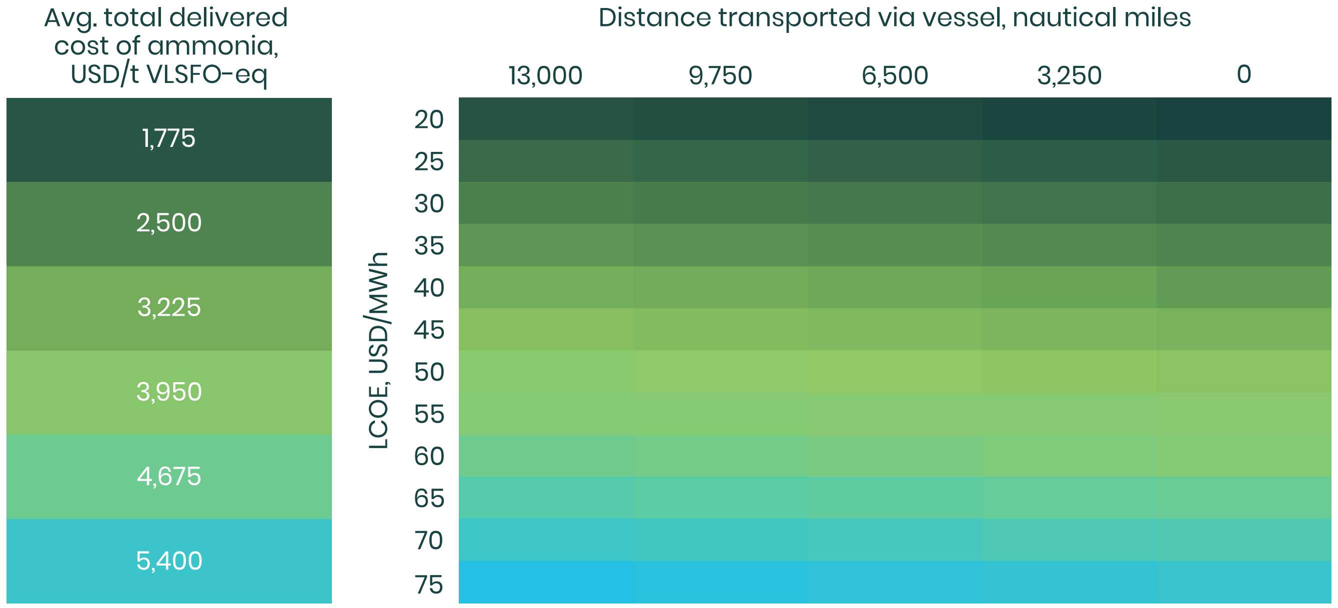
Source: RMI analysis.

This effect holds across all transport distances. Exhibit 7 shows the relative impact of ship transportation and renewable electricity on the delivered cost of green ammonia. While increases or decreases in the cost of renewable electricity have significant impact on the delivered cost of the fuel (read from up to down in the graphic), there is comparatively little change across transport distances (read from side to side).

Exhibit 7

The cost of renewables impacts the total delivered cost of green fuel more than the distance fuel is transported

Relative impact on delivered cost of e-ammonia of LCOE (y-axis) compared to seaborne transport (x-axis)
USD per metric ton VLSFO equivalent



Source: RMI analysis.

This strongly suggests there will be trade in green methanol and ammonia, linking low-cost production regions with certain ports. This, in turn, creates an opportunity for a wide range of ports to access e-methanol and ammonia and establish green methanol and ammonia bunkering, even if they are not situated in locations with the potential for low-cost production of these fuels.

b. Exploring green methanol and ammonia supply and trade in 2030

The analysis in the last section demonstrated that trade in e-methanol and ammonia bunkers is likely. This raises the questions of where the main exporting regions may be and which ports are most likely to be beneficiaries.

In this section, these questions are taken up for the year 2030. Because green methanol and ammonia projects take multiple years to develop, most green methanol and ammonia projects that will be operational by 2030 have already been announced. This makes it possible to build a picture of what supply flows between green methanol and ammonia production locations and ports could look like by 2030. This can provide insights about the feasibility of and opportunities associated with meeting the IMO's target for 5% uptake of zero-emission fuels by this time.

Location and cost of announced green methanol and ammonia production projects

The pipeline of announced green methanol and ammonia projects suggests there will be variation in how much fuel is available, where it is produced, and how much it may cost in 2030.

As a first step, the quantity, location, and cost of green methanol and ammonia that could be available for use in shipping are assessed.

Indications about the quantity and location of the fuel available are based on data on announced projects from the International Energy Organization (IEA)'s Hydrogen Production Projects database[xix] and Rystad Energy's hydrogen database. To account for the fact that several other sectors, beyond shipping, will have demand for green methanol and ammonia, projects that are aiming to secure offtakers in other sectors have been excluded from the estimates. While, in practice, the offtakers targeted by projects can change during the course of their development, this assumption enables a rough estimate of the amount of green methanol and ammonia that could be available to shipping. Estimates of the cost of the announced production are based on RMI modeling. More information about the data sources and assumptions used can be found in Annex 4.

Ammonia

Project announcements suggest that up to 32 million metric tons of green ammonia per year could be available to shipping by 2030.

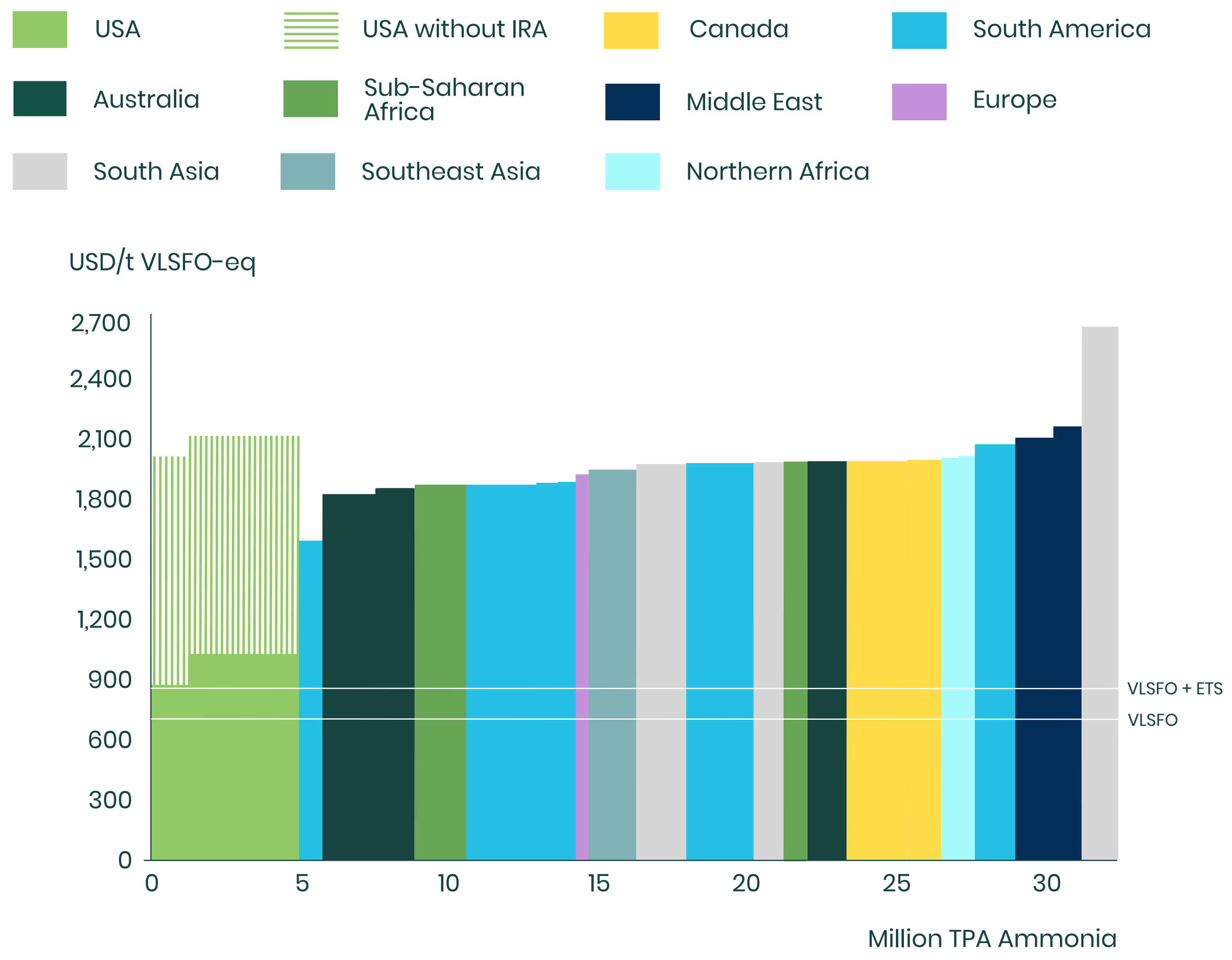
These projects are likely to be able to produce green ammonia at a cost of between $900 and $2,700 per metric ton VLSFO equivalent by 2030, as shown in Exhibit 8. In most cases, this would represent a significant premium compared to conventional bunkers. However, the impact of the generous tax credit package under the US IRA is expected to bring US-produced green ammonia significantly closer to cost parity with VLSFO. This is especially the case for ships regularly sailing between the US and Europe, and therefore subject to the EU Emissions Trading Scheme (EU ETS). Forthcoming IMO mid-term measures are also expected to help close the cost gap when they are implemented in 2027. After 2030, technology learning curves for renewable energy generation and electrolyzers are expected to bring green ammonia production costs down, further reducing the cost gap.

The lowest cost regions for green ammonia by 2030 are estimated to be North America, followed by South America, Oceania, and Sub-Saharan Africa.

Exhibit 8

Significant volumes of green ammonia could be available by 2030

Announced 2030 green ammonia capacity by region in order of cost
USD per metric ton VLSFO equivalent



Source: RMI analysis.

Methanol

The pipeline of announced green methanol projects suggests there could be supply of around 3.5 million tons per year available for shipping by 2030, once projects that are targeting markets other than shipping are excluded.

Compared to vessel orders placed to date[6], there would be a significant supply gap for green methanol by 2030. This may in part be due to constraints on the availability of biogenic CO_2 and its high cost of transportation. These factors could result in higher-than-predicted costs, and limit both the possible sites for and scale of green methanol production[7]. Captured fossil CO2 is more widely available, but its use for methanol production would have negligible emissions reduction benefits.

Green methanol from these projects is expected to range in cost from $900 to $2,500 per metric ton VLSFO equivalent.

The same IRA effect can be observed for green methanol as ammonia, with US-based projects expected to be the most cost-competitive globally. This is followed by bio-methanol volumes in Asia. A major difference from the ammonia project pipeline is the large proportion of announced green methanol production located in Europe; these projects occupy the upper middle of the cost curve. They are followed by Australian and North African volumes, which form the top of the cost curve.

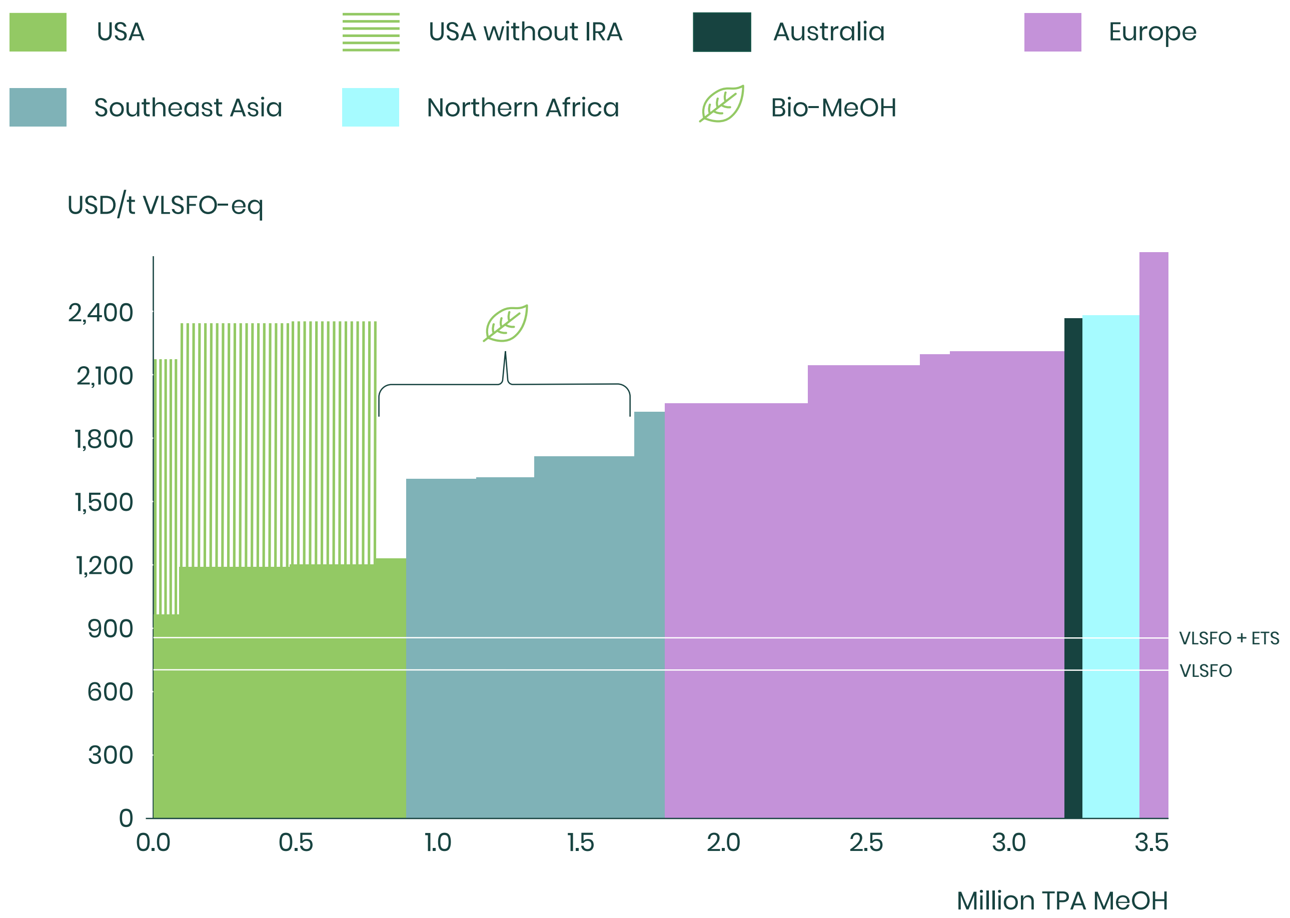
6 Over 240 methanol-capable vessels are on currently order at global shipyards according to the DNV Alternative Fuel Insights (AFI) platform. If these vessels were to exclusively operate on methanol as their primary fuel, this would require roughly 8 million tons of fuel per year.

7 Highlighted by industry experts consulted for the report.

Exhibit 9

The amount of green methanol by 2030 is sizable but may lag behind demand

Announced 2030 bio- & e-methanol capacity by region in order of cost
USD per metric ton VLSFO equivalent



Source: RMI analysis.

While the analysis shows a constrained supply of green methanol, the combined pipeline of green ammonia and methanol projects offers a relatively positive outlook for the supply of green fuels. Together, the announced projects could meet up to 0.674 exajoules of energy demand in shipping, which exceeds the 0.655 exajoules of zero-emission energy required to meet the 2030 IMO's target of 5% uptake of zero-emission fuels by 2030.

Contingent on rapid scale-up of ammonia vessel deployments and an acceleration in methanol projects, the analysis, therefore, suggests there could be enough green fuel to hit the IMO target, even before considering advanced biofuels. To activate this potential supply and push the projects to FID, offtake agreements will need to be signed in the coming few years.

Green methanol and ammonia supply scenarios

Scenarios for how major bunker ports might secure green methanol and ammonia in 2030 suggest supply patterns for the two fuels may differ significantly.

Given the many uncertainties between now and 2030, it is impossible to predict what the flows of green methanol and ammonia to key ports will look like in this period. But scenarios can be generated to provide useful insights about possible trends and patterns. To draw out these insights, scenarios exploring where a selection of global ports might secure supply of green methanol and/or ammonia from by this date are modeled.

To account for uncertainties around how many announced green ammonia and methanol projects will be realized, two scenarios are presented – one in which 100% of announced green methanol and ammonia production materialize in 2030 and another in which only 20% materializes[8].

Flows to 28 ports are considered, consisting of the world's eighteen larger bunkering ports and ten relatively smaller bunkering ports (representing other port archetypes that will be introduced later in the report). Together, these ports account for half of today's bunker market.

The allocation of green methanol and ammonia from announced projects to ports in the scenarios is driven by a set of key assumptions about the ports' sourcing behavior:

- The ports align with the IMO target and supply 5% zero-emission fuels by 2030 in the form of green methanol and/or ammonia exclusively.
- Ports are assumed to favor local supply over import, if available.
- Large bunker ports are expected to be more aggressive in sourcing green methanol and ammonia and have greater purchasing power than smaller bunker ports.
- Ports in geographies with shipping decarbonization regulations, most notably the EU, are also assumed to be assertive in sourcing green methanol and ammonia, given regulations will create demand for lower carbon solutions.
- Ports with large bunker demand are assumed to hedge against supply chain risk by sourcing from at least two green methanol or ammonia projects.
- Large bunker ports are assumed to provide both green methanol and ammonia by 2030. This is modelled at a ratio of two-to-one methanol to ammonia based on an extrapolation of demand for the two fuels in 2030 from existing methanol and ammonia vessel orders[9].
- In contrast, smaller bunker ports are expected to focus on either green methanol or ammonia bunkering, to manage the complexity of implementing methanol and ammonia bunkering and minimize infrastructure costs.

It should be noted that the scenarios are intended to be heuristic and represent a simplification of reality. A multitude of other factors could impact the supply and demand of green methanol and green ammonia. The outputs should thus be treated as illustrative, providing insights rather than prognostications.

Scenario results

For ammonia, the 100% FID scenario sees most fuel supplied by projects in the United States and Oceania. The trade flows remain largely regional, with the ports being supplied by projects located within their region of the world. However, because of its very low cost, ammonia from North America is exported globally.

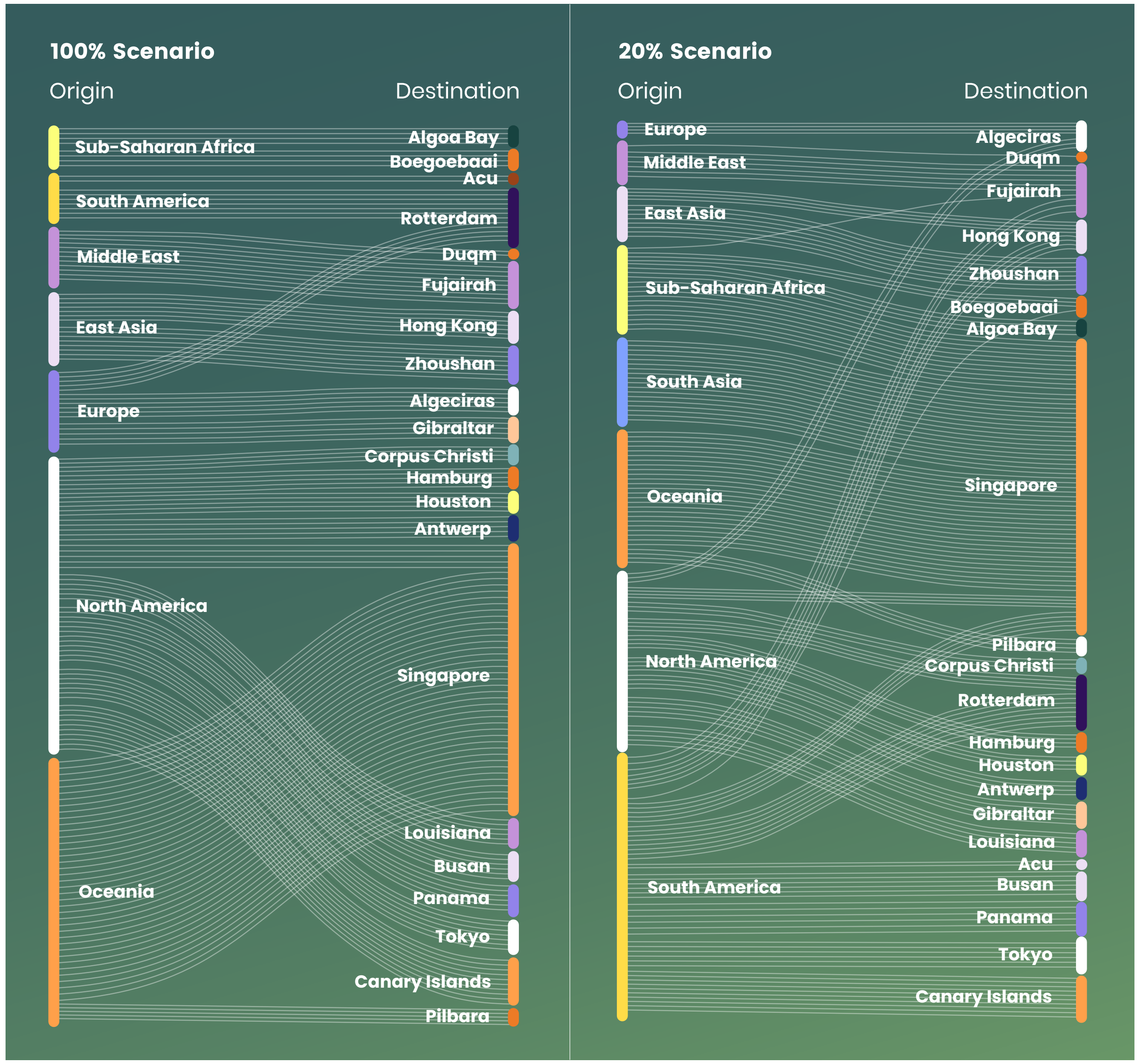
In the 20% FID scenario, South America emerges as the largest source of green ammonia, though North American and Oceanian volumes remain prominent. Trade flows are generally more fragmented and global than in the 100% scenario, with ports drawing on more sources of fuel to meet their needs.

8 It is important to note that there is a distinct difference between "announced" projects and those that have reached a "final investment decision" (FID), which is considered the industry benchmark for a project moving forward. Given the nascent state of the hydrogen industry, the number of projects that have moved to FID are limited.
9 According to an RMI analysis and the orders from the DNV Alternative Fuels Insights (AFI) platform.

Exhibit 10

The supply of green ammonia is diverse, with large supplies expected from North America, Oceania, and South America

2030 e-ammonia mass flows to selected ports
in 100% (left) and 20% (right) FID scenarios[10]



Source: RMI analysis.

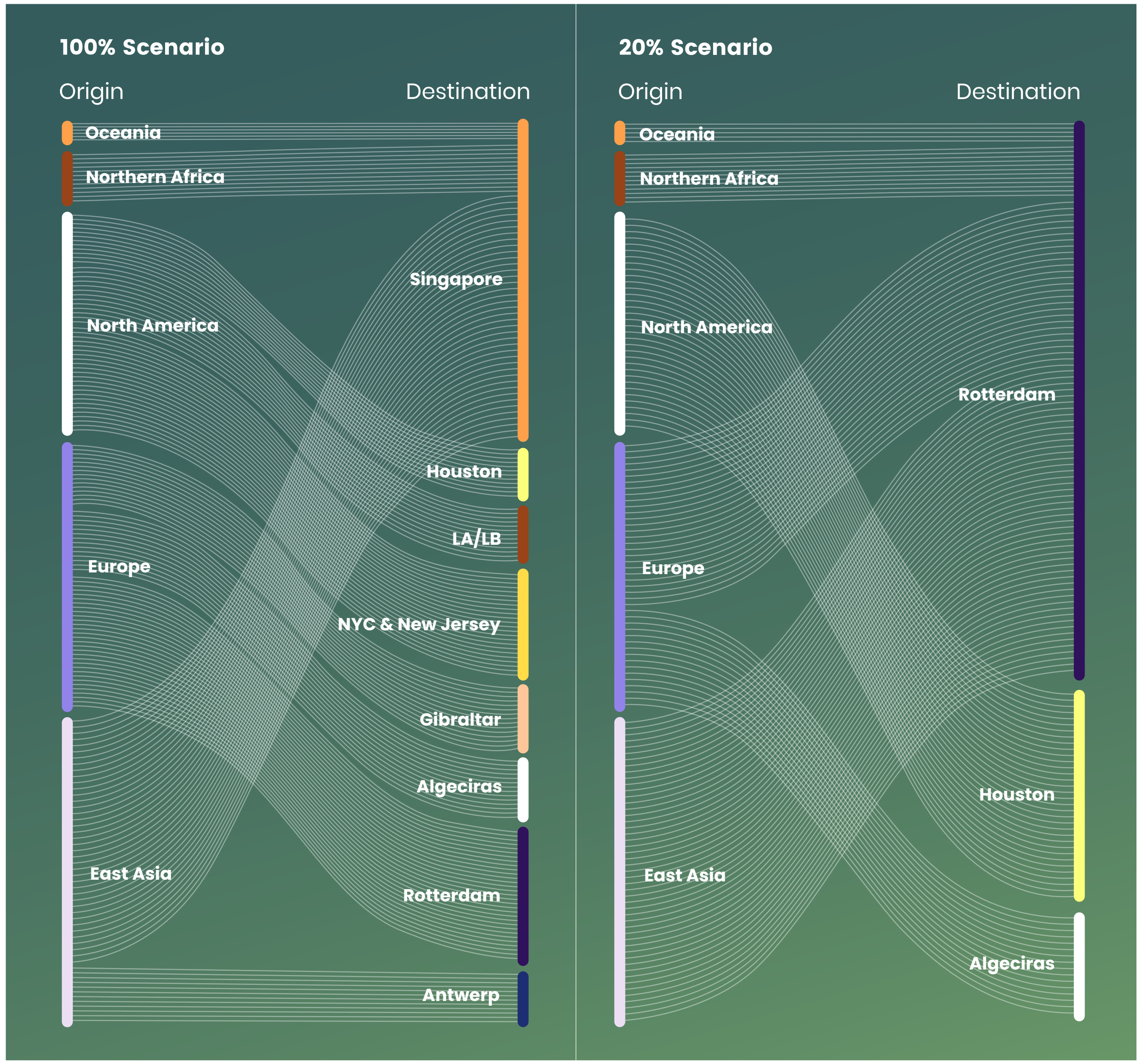
For methanol, the 100% FID scenario shows a smaller number of ports receiving trade flows, with more consolidation around existing bunkering hubs, due to constraints in the availability of green methanol. Regionalization is more pronounced compared to ammonia trade flows. Under the 20% FID scenario, there are very few ports able to supply methanol and regionalized trade flows.

10 Chart based on maritime demand only. Does not include potential industrial demand.

Exhibit 11

Announced e- and bio-methanol volumes will be constrained and primarily come from Europe, China, and North America

2030 e-and bio-methanol mass flows to selected ports
in 100% (left) and 20% (right) FID scenarios[11]



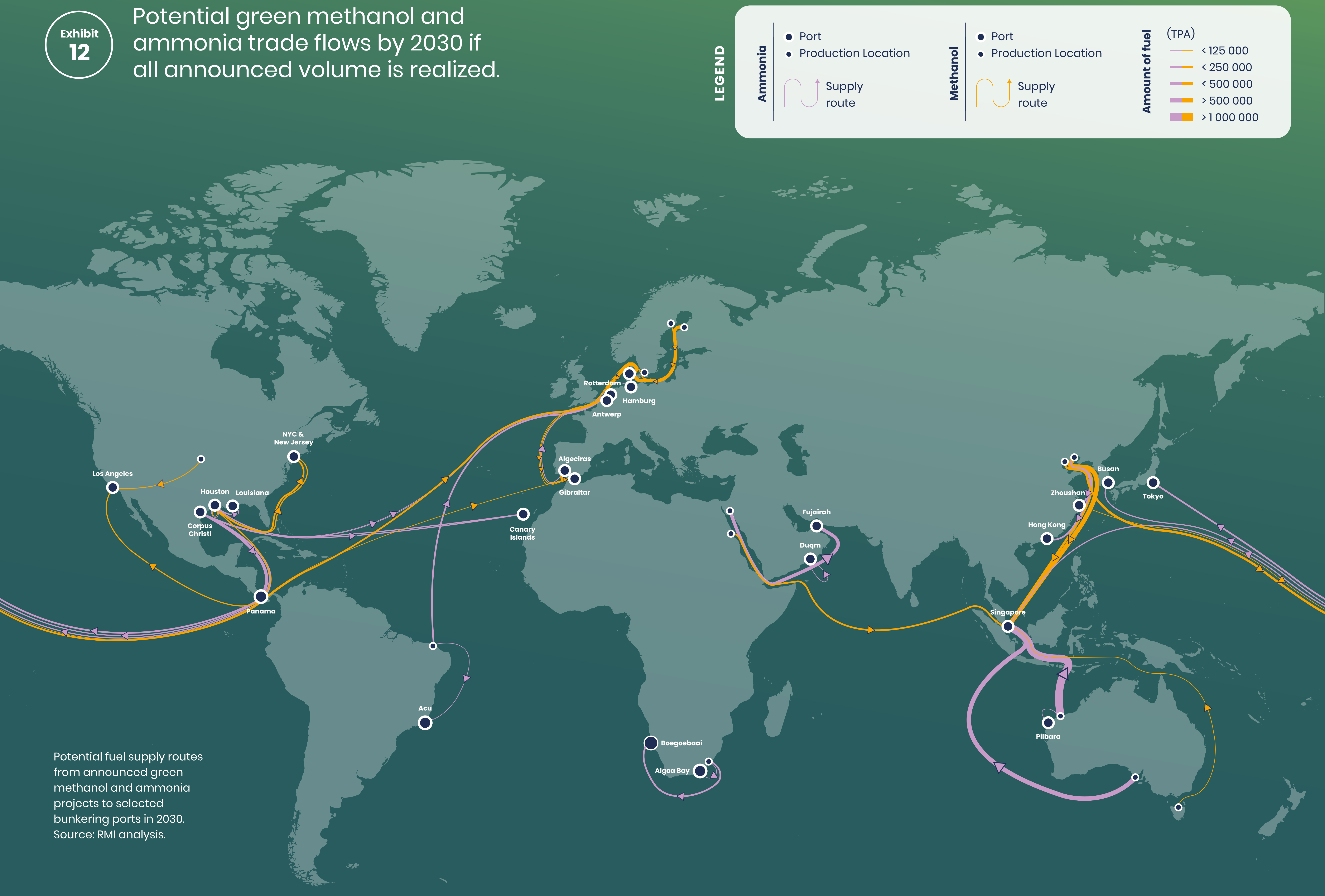
Source: RMI analysis.

The maps below present a picture of what trade in both methanol and ammonia might look like by 2030.

11 Chart based on maritime demand only. Does not include potential industrial demand.

Exhibit 12

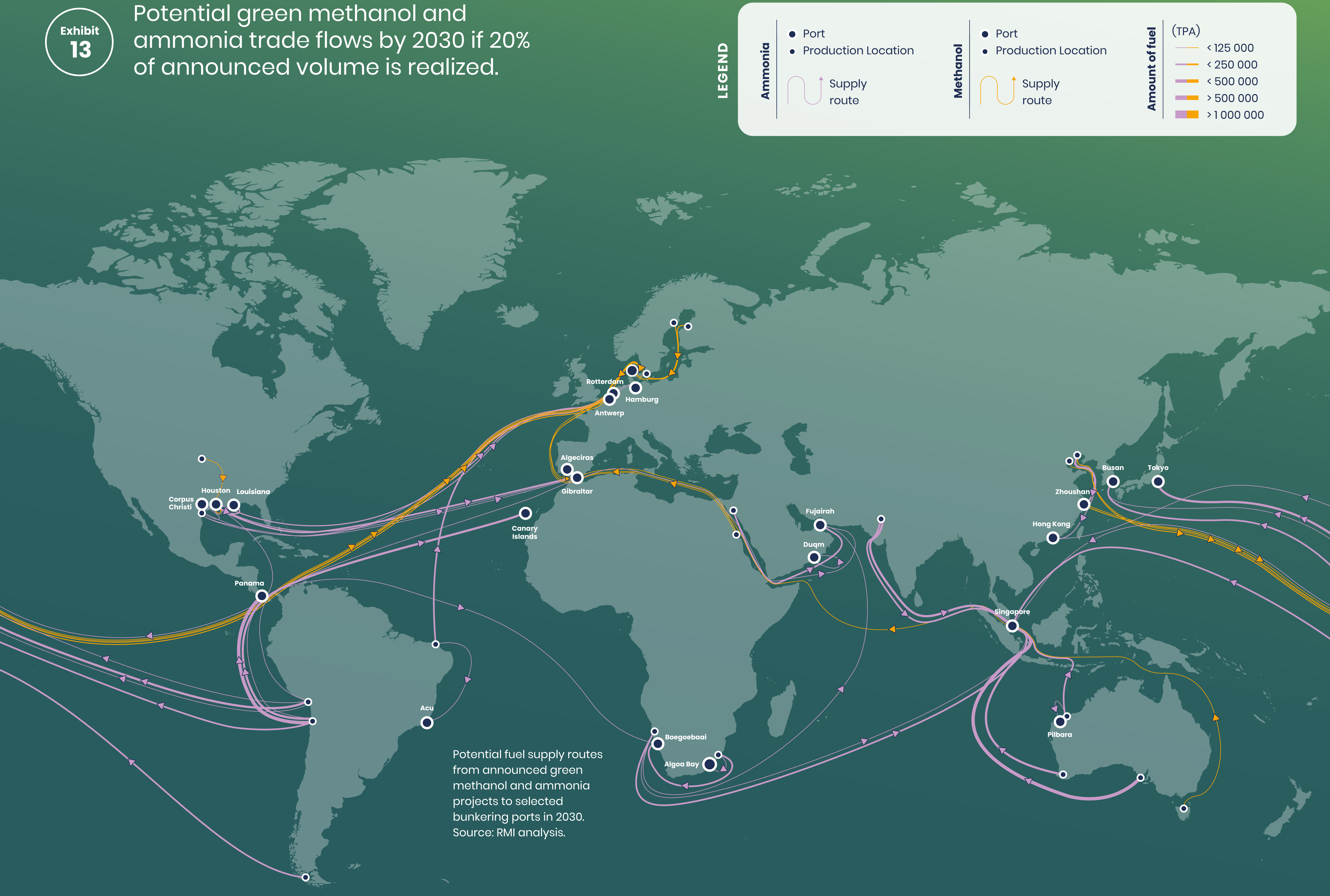
Potential green methanol and ammonia trade flows by 2030 if all announced volume is realized.



Potential fuel supply routes from announced green methanol and ammonia projects to selected bunkering ports in 2030. Source: RMI analysis.

Exhibit 13

Potential green methanol and ammonia trade flows by 2030 if 20% of announced volume is realized.



Potential fuel supply routes from announced green methanol and ammonia projects to selected bunkering ports in 2030. Source: RMI analysis.

Scenario implications

The results have several cross-cutting and overarching implications.

They suggest that many existing bunkering hubs may become large green methanol and/or ammonia importers. Europe may be partially self-sufficient, utilizing domestic production, while North America could retain energy hubs in the Gulf Coast region, leveraging the IRA and good renewable capacity factors, as well as other favorable conditions, such as short permitting timelines[xx], existing infrastructure, and experience with handling, storing, and transporting ammonia. New export hubs could appear in Australia, catering primarily to Singapore.

For both methanol and ammonia, the results show maritime fuel-related economic activity in the Global South – specifically in Sub-Saharan Africa, South America, South and East Asia. This suggests that shipping's transition will present an opportunity for countries that have not traditionally been involved in energy markets to create new commodity markets, supporting the achievement of their development goals.

The scenarios also show the impact that ambitious policy can have on countries' competitiveness in the future global zero-emission marine fuel market, with the United States serving as the prime example of how forward-looking policies can create new markets and commodity flows.

The methanol scenario reveals a clear opportunity for fuel producers to fill the gap in methanol supply, especially in countries with excellent renewable capacity factors, supportive policy conditions, receptive investment environments and biomass availability. This could include countries in the Global South, such as Chile, Brazil, and South Africa. In contrast, the scenarios suggest that ammonia might be a safer option than methanol when it comes to supply availability.

Finally, the results highlight the importance of vessel owners, ports, and the bunkering ecosystem being proactive in ensuring projects materialize by signing offtake agreements to obtain the fuel necessary to be competitive in the 2030 green hydrogen-based fuel market.

2. Port archetypes and strategies

Action at ports to provide zero-emission bunkering this decade is of vital importance. First-mover ports will catalyze zero-emission fuel supply chains, lowering the threshold for first-mover ship operators to adopt these fuels. The resulting positioning will allow them to seize opportunities in the mature zero-emission bunkering market that will emerge in the 2030s.

This section explores how different ports and the bunkering ecosystems centered on them can be first movers within this new landscape.

a. Drivers of green methanol and ammonia supply costs at ports

Two factors – production costs and last-mile costs – are expected to have the biggest influence on ports' green methanol and ammonia bunkering plans.

As a starting point, it was hypothesized that bunkering hubs will continue to compete based on cost in the decarbonized future. This will lead ports to pursue efforts to minimize the cost at which they provide green methanol and ammonia[12].

Following this reasoning, the opportunities, challenges, and approaches needed for ports to become first movers in supplying green methanol and ammonia would be determined by the factors that have the biggest impact on the delivered cost of fuel.

As described in the previous chapter, the production cost of green methanol or ammonia makes up the largest share of the delivered cost of the fuel. For e-methanol and ammonia, this is most influenced by the quality of local solar and wind resources (and access to hydrogen production subsidies). This suggests that the cost of renewable electricity in the area around the ports will be the most significant factor determining their green methanol and ammonia fuel sourcing strategies.

After the cost of local fuel production, demand is expected to be the next biggest driver of ports' sourcing strategies. This is because of the economics of utilization[13]. Bunker suppliers and terminal operators who invest in bunkering infrastructure must generate enough revenue to cover their initial capital and operational expenditures and make a reasonable return on their investment. If they have fewer customers, they must charge these customers more to make the project viable. Fuel demand is therefore relevant in so far as it affects the cost of storage and bunkering – collectively known as 'last-mile' costs.

The level of demand for green methanol and ammonia can have a substantial effect on their delivered cost. As shown in Exhibit 14, last-mile costs can add $300 per metric ton VLSFO equivalent to the delivered cost of green ammonia.

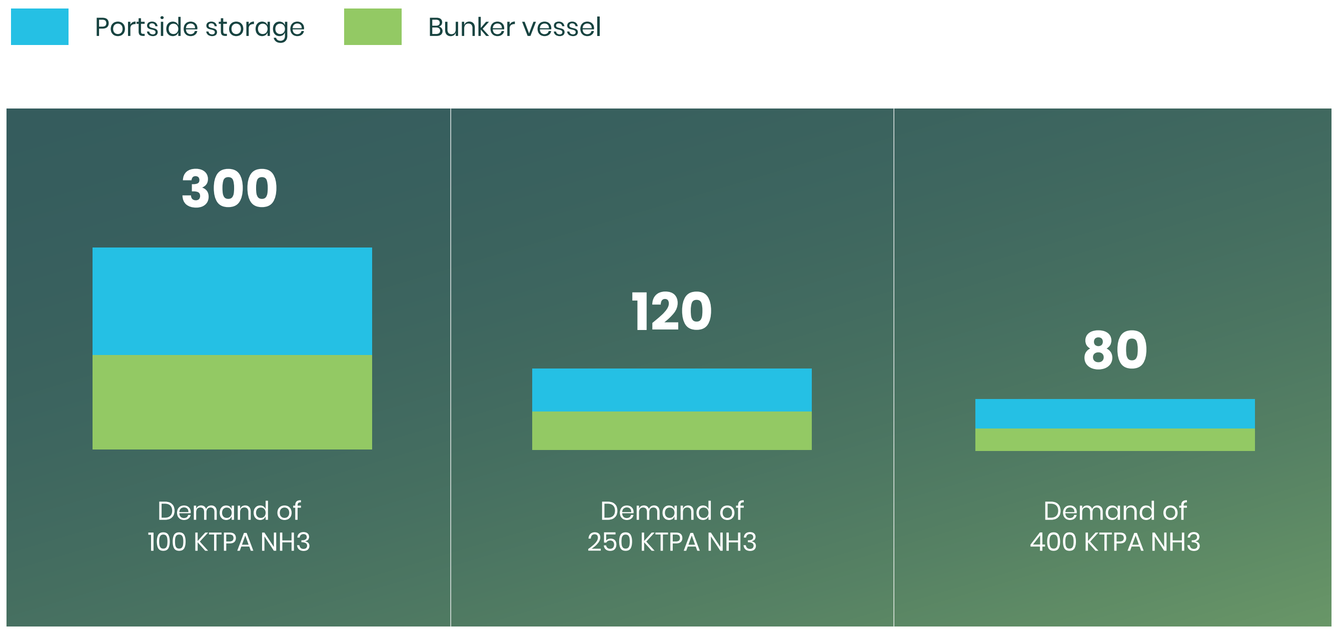
12 This will be especially true in the medium to long term, once the zero-emission fuel market is mature and there are multiple ports that offer zero-emission bunkers in each region. In that context, ports are likely to compete on price to attract bunker demand, as in today's conventional bunker market. However, cost is also likely to be relevant in the short-term. In this period, the cost gap between zero-emission and conventional fuel will be at its highest point, and as such the viability of establishing bunkering will depend on limiting the fuel costs faced by first-mover zero-emission vessel operators.

13 Though not included in this analysis, industrial demand may additionally contribute to reducing last mile costs.

Exhibit 14

Last mile costs are largely impacted by fuel demand

Levelized cost of new ammonia bunkering infrastructure, USD per metric ton VLSFO equivalent[14].
Demand or bunker volumes are shown in units of kilo-metric tons per annum (KTPA)



Source: RMI analysis.

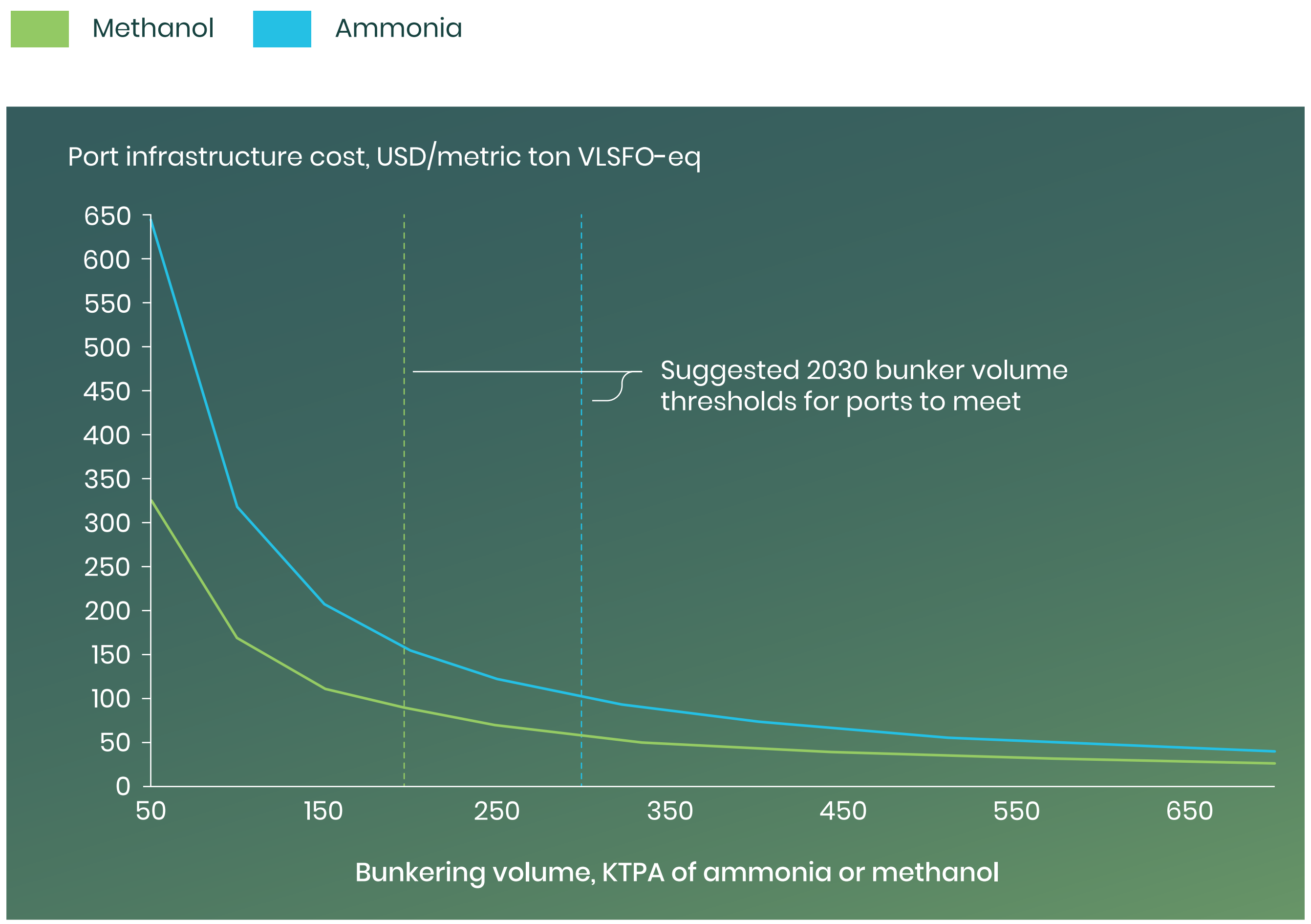
14 US financials and Houston energy costs used for Exhibit. Bunker vessel cost is based on a conventional chemical tanker.

The impact is especially pronounced at lower levels of demand. As shown in the Exhibit, all else being equal, the cost of fuel at a port with 100,000 tons per year of ammonia demand will be roughly two and a half times higher than an identical port with 250,000 tons per year of demand. As the port's fuel demand increases, however, the level of impact decreases, with the cost at 250,000 tons per year of ammonia being only ~40 USD per ton VLSFO equivalent higher than 400,000 tons per year. Indeed, there are thresholds – at around ~200,000 tons per year for methanol and ~300,000 tons per year for ammonia – after which the level of demand has a significantly smaller impact on the cost of fuel.

Exhibit 15

Last-mile costs are significantly smaller once a certain bunker volume is reached

Relative impact of demand on methanol and ammonia last mile levelized costs.



Source: RMI analysis.

This makes demand very relevant in the initial stages of the transition, when zero-emission bunker volumes are low and production costs are at their highest.

Other factors that could influence the delivered cost of green hydrogen-based fuel include:

- Proximity to populated areas, in so far as this may increase safety precautions and costs[15]
- The amount of cargo handled, which may point to the presence of existing infrastructure that can be leveraged
- Geography, which influences labor and capital costs
- Proximity to major trade routes, which may affect the elasticity of demand for green hydrogen-based fuels
- Status of the port, namely whether it is existing or newly built, as this might differentiate permitting and/or leasing costs

b. The four green methanol and ammonia bunkering port archetypes

Ports can be divided into four "archetypes" that shed light on how ports with different characteristics can approach green methanol and ammonia bunkering.

The existence of two main drivers suggests that four distinct groups of ports will emerge in the transition, defined by their bunkering demand, on the one hand, and local cost of fuel production, on the other. We term these groups "green methanol and ammonia bunkering port archetypes".

15 See Annex 1 for further details.

Exhibit 16

Ports can be divided into four archetypes defined by cost of local green fuel production and bunkering demand

Illustrative mapping of ports. Spacing between these ports is not fully representative of reality. The intention of this graph to show various ports who are currently representative of the four archetypes.

Importing Incumbents

Opportunities:

- **Leveraging existing demand** to **lower** port **infrastructure costs**
- Obtaining lower fuel costs due to **demand aggregation**

Risks:

- **Losing bunkering share** to more **assertive** ports

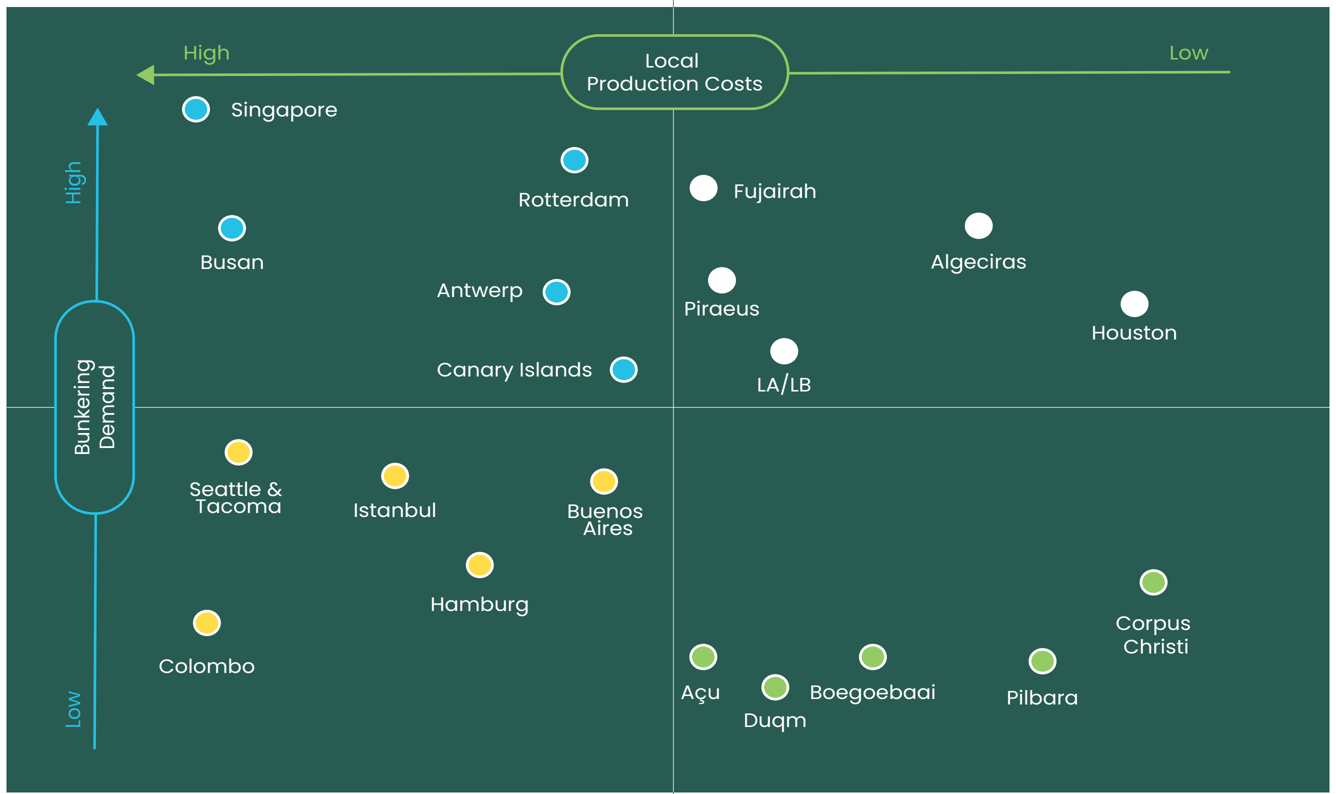
Producing Incumbents

Opportunities:

- **Leveraging existing status** as bunkering hub
- Becoming a **major exporter** in future

Risks:

- **Moving slowly** on infrastructure, regulations, and permitting



Bespoke Players

Opportunities:

- Becoming a **"first mover"** in the **Zero-emission fuel bunkering** space
- **Investing swiftly** in **bunkering infrastructure**
- Creating **enabling ecosystem** for fuel procurement

Risks:

- **Losing status as bunkering hub without proactivity**

Future Exporters

Opportunities:

- Can take advantage of **excellent renewables**
- Becoming a **major exporter** in future, open door to **bunkering**.

Risks:

- **Infrastructure cost** can be prohibitive at **low demand**

Source: RMI analysis.

The archetypes are defined on a scale from high-to-low for both characteristics. High demand ports have bunker volumes above 250,000 tons per year of green fuel, while low-cost of local production ports have a local green hydrogen production cost of less than $4 per kilogram in 2030.

The four archetypes identified are termed Importing Incumbent (high-cost production conditions, high existing demand), Producing Incumbent (low-cost production conditions, high existing demand), Future Exporter (low-cost production conditions, low existing demand), Bespoke Player (high-cost production conditions, low existing demand).

These groups will have similar opportunities, challenges, and priority actions to become green methanol and/or ammonia bunker ports. As such, identifying the archetype that individual ports belong to can provide a useful starting framework for ports' green methanol and ammonia bunkering strategies.

It should be noted that the archetypes represent a simplification of reality. Changes in policy, port-specific regulatory and public acceptance constraints, competition for renewable energy from other sectors, hydrogen/methanol/ammonia demand from other sectors, and many other factors are likely to have impacts on the different archetypes. These factors are mentioned where relevant but are not assessed in detail. This highlights the importance of ports building on the study's framework, using supplementary data sources to fine-tune their strategies.

Importing Incumbent archetype

Example ports: Singapore, Rotterdam, Busan, Antwerp, and the Canary Islands

Ports in this category have a high existing level of bunker demand but also have high costs for local green hydrogen production. This means significant volumes of fuel will need to be imported relatively early in the transition to meet demand and lower the delivered cost of fuel, potentially from multiple sources with a view to mitigating supply risks.

Their large demand gives these ports advantages, helping them avoid prohibitive last-mile infrastructure costs and supporting their fuel sourcing, since this is likely to make them attractive markets for exporters of green hydrogen-based fuels. Several of these ports, which sit within significant industrial areas and/or cities, will also benefit from hydrogen demand from other sectors, further enhancing this appeal and mitigating risks.

Their scale as bunkering hubs should give these ports the capability and, potentially, incentive to offer multiple zero-emission fuels by 2030. This can help them differentiate themselves as one-stop shops for an industry likely to continue to use multiple fuels. It also gives them an important role as testbeds for different fuel pathways and demonstrators of how multi-zero-emission fuel bunkering ports can be organized.

The recommended strategy for these ports is to move fast in securing fuel imports in order to ensure they have sufficient volumes and can access low-cost supply, to avoid losing bunkering market share.

Producing Incumbent archetype

Example ports: Houston, Fujairah, Piraeus, Algeciras, and LA-Long Beach

Ports in this archetype have high existing demand and favorable conditions for producing green hydrogen-based fuels locally, with limited to no need for imports.

These ports have the readiest opportunity to be first-mover green methanol and ammonia bunkering hubs, leveraging both their existing status as a bunkering hub and their local renewable resources. Their low production costs make it likely that these ports will also be exporters of green hydrogen derivatives, both for shipping and other sectors. This creates synergistic opportunities, including building out shared infrastructure, which can bring down last-mile costs.

Similar to the Importing Incumbent ports, Producing Incumbents should have the capability and, potentially, incentive to offer multi-fuel bunkering. This will also help them differentiate themselves as one-stop shops for increasingly multi-fuel fleets and allow them to serve as testbeds for different fuel pathways and demonstrating how a multi-zero-emission fuel bunkering port can be organized.

The main factors that could constrain these ports from achieving their potential are slow movement in activating demand for the new fuels, building out infrastructure, and developing regulations, standards, and permitting.

The recommended strategy for these ports is to lean into their existing demand to scale local production while minimizing last-mile costs.

Future Exporter archetype

Example ports: The Pilbara ports in Western Australia, the planned Boegoebaai port in South Africa, Açu in Brazil, and Corpus Christi in the Gulf of Mexico

Ports in this archetype have low-cost production conditions that make the local production of green hydrogen-based fuels likely, but low (or even no) current demand for bunkering.

Their opportunities are defined by their low production costs. This makes it likely that they will become fuel exporters. In this context, developing bunkering can increase their overall economic opportunity, by supporting a new industry which creates further local value on top of production.

These ports must attract and rapidly scale demand for export while also gradually establishing a bunkering ecosystem – including guidelines, competency, licensing regime, and supplier base – from a low or non-existent base.

However, like the Producing Incumbents, they can leverage the demand and infrastructure from fuel exports to minimize the delivered cost of fuel. If they do not do so, they are likely to face high last-mile costs.

In the short term, it may be wise for these ports to focus on bunkering one zero-emission fuel to avoid fragmenting demand and help manage complexity.

It is important to note that there are likely to be many ports in other renewables-advantaged countries in this category, including in the Global South.

Bespoke Player archetype

Example ports: Seattle and Tacoma, Colombo, Istanbul, Buenos Aires, and Hamburg

Ports in this archetype have comparatively low existing bunkering demand[16] and relatively high local fuel production costs, necessitating small-scale imports of green methanol and/or ammonia.

The transition to zero-emission shipping will bring these ports opportunities, but they will need to adopt the most proactive and holistic approach to develop a facilitating ecosystem for the bunkering of green methanol and/or ammonia This includes moving fast to obtain low-cost imports and bringing down last-mile costs. Slow movement creates a risk of these ports losing market share.

The key recommendation for this archetype is to be first movers in zero-emission bunkering. This can be achieved by investing in infrastructure, aggregating demand with nearby ports, and setting up green corridors. It may also be wise for these ports to focus on bunkering one zero-emission fuel in the short term, to avoid fragmenting demand and help manage complexity.

Several of these ports will benefit from hydrogen demand from other sectors in their hinterland. This demand was not considered in this analysis but should be incorporated in further studies on this topic.

Examples of this archetype include Colombo and Istanbul, which are among the top 20 global bunker ports as of 2022. Many other global ports will be in this archetype.

It is important to note that ports in all four archetypes have opportunities to provide green methanol and/or ammonia. Indeed, it can be argued that there is a need for first movers within each of the archetypes. Not only will the flows of green ammonia and methanol create opportunities for the growth of new bunkering hubs, but different archetypes will face different challenges and therefore generate different learnings about the practical requirements associated with bunkering green methanol and ammonia.

16 It is important to note that some of the "low bunkering demand" ports still have more than a million tons of annual bunkering sales. The term "low bunkering demand" is in the context of the benchmark of 200,000 to 300,000 tons of zero-emission fuel supply to overcome the hurdle of last-mile infrastructure costs.

3. Port case studies

Case studies can help explore how the archetypes play out in real-world contexts and showcase actions ports are already taking to support methanol and ammonia bunkering.

The five case studies in this section draw on a combination of modeling and insights provided by the ports. While care has been taken to ensure the accuracy of the modeling, including via extensive industry validation, the levelized fuel costs provided in this section should not be seen as forecasts or projections, nor an endorsement by the case study ports of these figures. These costs are based on a set of assumptions – including about real-world levels of green methanol and/or ammonia demand – that are highly uncertain. As such, the actual future costs will depend on multiple factors and may differ from the modeling.

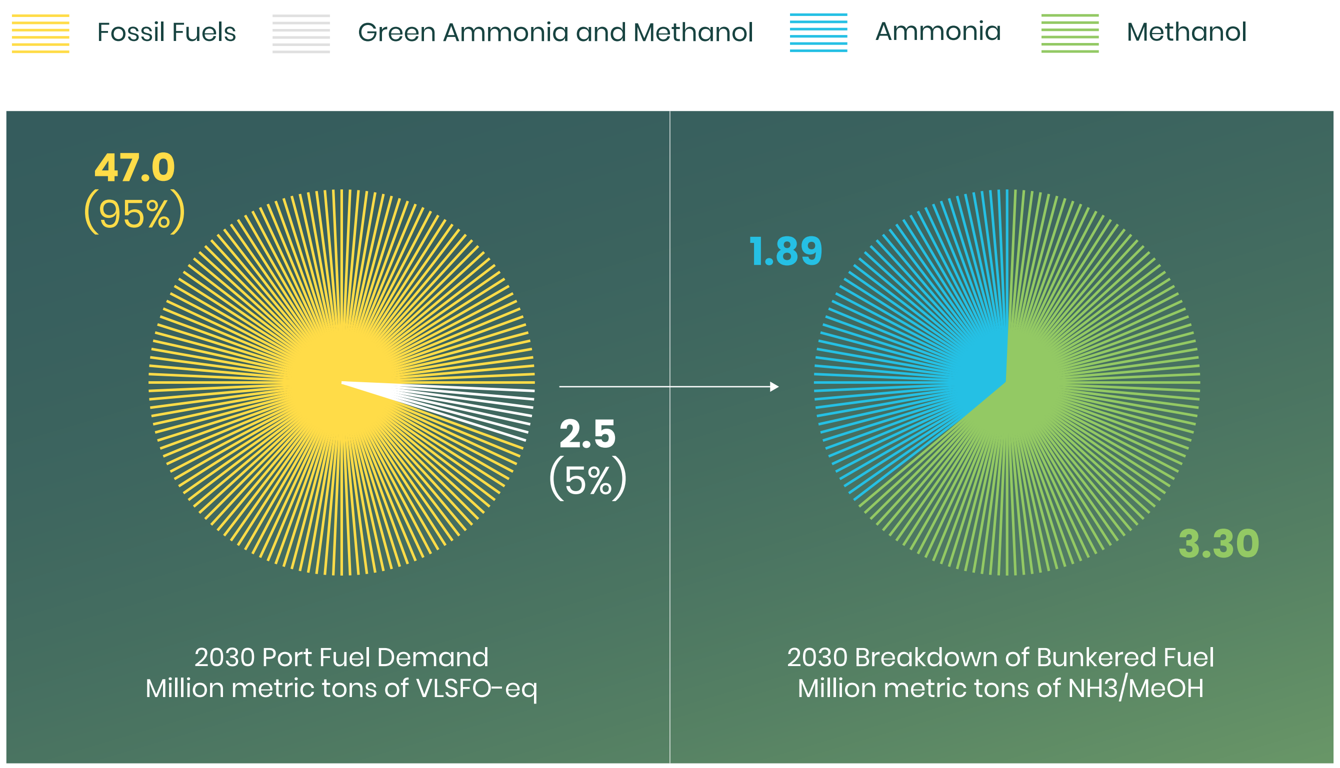
Importing Incumbent: Singapore

Singapore is the world's largest bunkering hub. Strategically located at the intersection of the Indian and Pacific Oceans, the port has seen ~50 million tons of fuel bunkered annually in recent years. This is roughly five times more than the next largest bunkering hub, making Singapore a critical actor in the global landscape.

Exhibit 17

Singapore is the largest bunkering hub globally and will require large amounts of zero-emission fuel

Assumed 2030 fuel demand (left) and modelled methanol and ammonia demand scenario (right) at Singapore.



Source: Ship & Bunker; Xinde Marine News; RMI analysis.

Aligning with the IMO's target of 5% zero-emission fuel uptake by 2030 would require ~2.5 million tons of conventional bunkers to be replaced by zero-emission fuels[17]. If this were met with green hydrogen-based fuels, it would represent the same amount of hydrogen demand as seven hydrogen steel plants[18], making it a globally significant offtake opportunity.

Given its size, status as an existing bunkering hub, and decarbonization commitments, Singapore is seeking to become a multi-fuel bunkering port, offering green methanol and ammonia, among other lower-emission fuels. The contribution of green methanol and ammonia to meeting the 5% target will depend on several factors. For the purposes of the case study, it was assumed that methanol and ammonia meet all 5% of the zero-emission bunker demand. A split between methanol and ammonia is assumed, with two thirds of the 5% target being met with methanol and one third with ammonia, based on an extrapolation from existing methanol and ammonia vessel orders[19].

Green methanol and ammonia supply pathways and costs

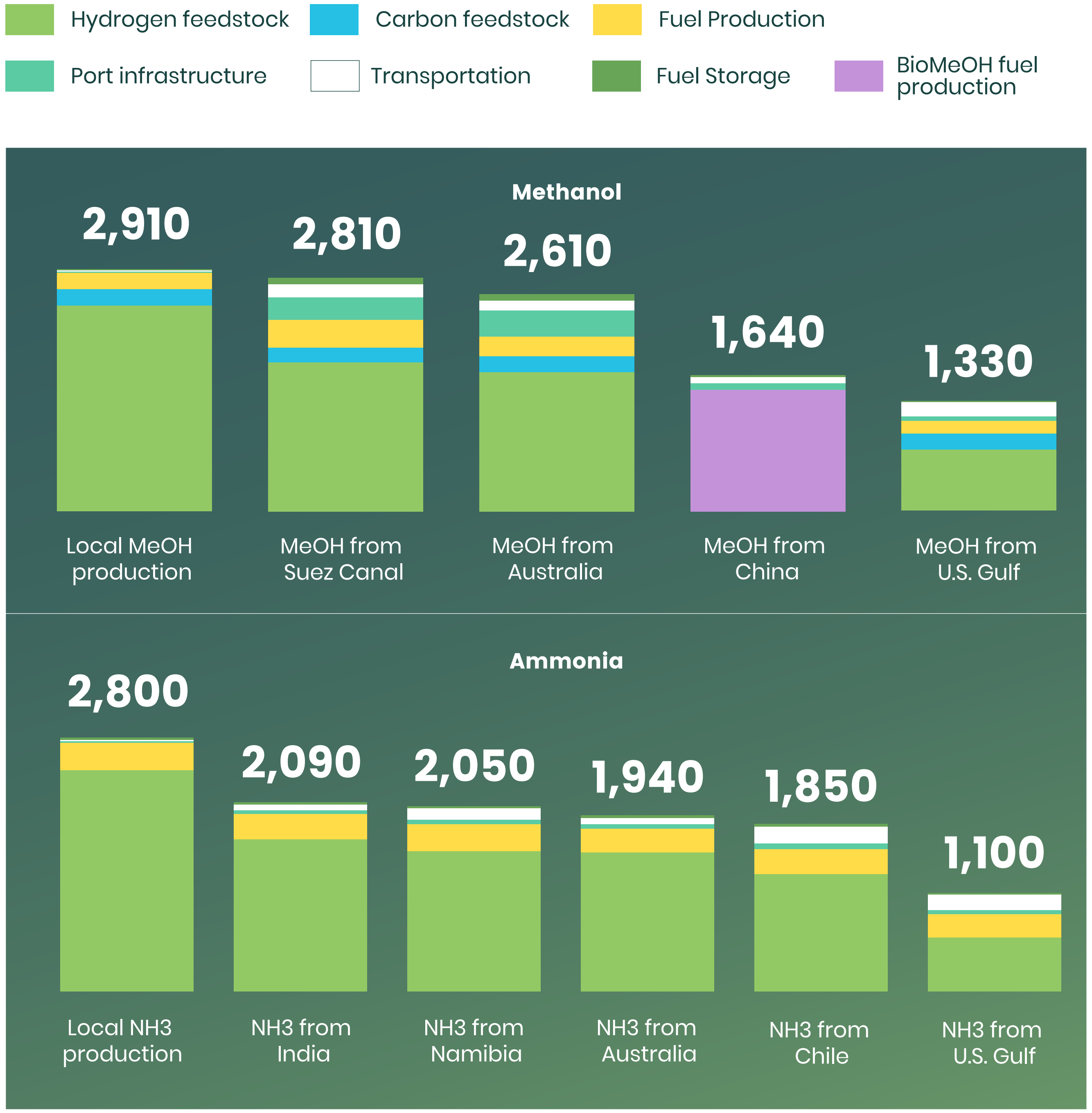
In addition to the space constraints imposed by its geography, Singapore has relatively poor wind and solar energy resources. This makes local production of green hydrogen-based-fuels expensive. As such, importing green methanol and ammonia from low-cost locations will be the most cost-efficient sourcing strategy for the port, even when considering the extra transport and infrastructure costs.

17 Assumed that bunkering volumes will stay largely the same in 2030 compared to current levels, due to efficiency improvements offsetting increased traffic. Assumptions from the Maersk McKinney Moller Center for Zero-Carbon Shipping Industry Transition Strategy 2021 report.
18 Assuming a two-million-ton steel plant. RMI analysis.
19 RMI analysis. Existing vessel order data is from DNV Alternative Fuels Insights (AFI) platform.

Exhibit 18

Singapore will likely source green ammonia and methanol from multiple production locations

Assessed green methanol and ammonia supply pathways for Singapore in 2030[20,21]
in USD per metric ton of VLSFO equivalent



Source: RMI analysis.

20 Existing infrastructure not considered in port infrastructure costs for these scenarios.
21 The Egyptian and Australian methanol projects are relatively small. Their port infrastructure costs could be ~200 USD per metric ton VLSFO equivalent lower if the exporting port reaches the suggested demand threshold of 200,000 tons per year. This threshold is likely to be met if a port participates in other methanol exporting and bunkering activity. For more information on the how bunkering benefits from economies of scale, see Exhibit A2.

Given the overall size of potential demand at the port and competition for fuel volumes, Singapore will likely need to import fuel from several locations.

In a scenario in which a high proportion of announced green ammonia projects reach final investment decisions globally, the modeling suggests that the cheapest available green ammonia imports to Singapore would be from a combination of the US Gulf, Chile, and Australia. This would result in a range of green ammonia costs of between $1,100 and $1,940 per ton, which would be 30-60% cheaper than local production.

Should fewer green ammonia projects reach FID globally, the modeling suggests green ammonia supply to the port would be more fragmented, with imports coming from the US Gulf Coast, Australia, India, Chile, and Namibia.

For green methanol, the trade modeling suggests the cheapest available sources would be bio-methanol from China, while the cheapest e-methanol would come from Egypt and Australia[22]. They would offer green methanol between 44% and 4% cheaper than local production. While e-methanol from the US Gulf Coast would be cheaper than both Chinese bio-methanol and e-methanol from Egypt or Australia, the modeling suggests that high competition could result in the US methanol going to other ports, particularly in Europe, unless the Singaporean port ecosystem moves to proactively secure supply.

In a scenario in which fewer methanol projects reach final investment decision, there is a risk that there may not be enough green methanol for Singapore to fully cover the level of demand assumed here. This is because much of the limited production could be drawn down by European ports, driven by policies such as EU ETS and FuelEU Maritime. The scarcity of methanol highlights the importance of being proactive and undertaking early engagement with fuel developers and offtakers.

Overall, the modeling suggests that Singapore's fuel supply pathways for green ammonia and methanol will differ. Green ammonia sources would likely be more global, while green methanol might be more regional, driven by current supply dynamics. Both show a role for imports from Australia, but there is otherwise limited overlap in import locations.

Methanol and ammonia bunkering readiness and progress

Singapore has been a first mover in developing zero-emission bunkering and positioned itself as a global testbed for methanol and ammonia bunkering. Indeed, momentum is already building to scale the use of both at the port.

22 While e-methanol from the US Gulf Coast is technically cheaper, the modeling suggests that high competition will result in the methanol going to domestic or European ports unless the Singaporean port ecosystem moves to proactively secure the supply. Supply from the US Gulf Coast was shown for comparative reasons.

Exhibit 19

Singapore has developed methanol bunkering capability and is working on ammonia bunkering

Summary of Singapore's progress toward bunkering methanol and ammonia.

	Port readiness	Infrastructure	Regulatory framework	Fuel sourcing	Generating bunker demand
Methanol	• Singapore has reached **Port Readiness Level seven** for methanol bunkering	• Existing chemical terminals in Singapore could be **repurposed for bunkering methanol** • Several methanol-capable **bunker vessels are either in service or on order**	• Efforts to develop a **Technical Reference and licensing framework for methanol bunkering are underway** • Initiatives aim to **establish regulatory requirements and workforce training for methanol bunkering**	• **EOI for proposals to supply methanol as a marine fuel at the port launched in late 2023** • Consortium exploring the feasibility of building a 50 KTPA e-methanol pilot plant locally	• Engaged in **five green shipping corridor** initiatives • Collectively, these could generate hydrogen-based fuel demand at the megaton scale • Via the Green Port Programme, Singapore offers up to **30% on port dues for vessels operating on zero-emission fuels, and 25% on port dues for vessels operating on near zero-emission fuels**
Ammonia	• Singapore has reached **Port Readiness Level six** for ammonia bunkering	• First use of ammonia as a marine fuel in a dual fueled ammonia-powered vessel occurred • Singapore has one **existing ammonia terminal** • **Expanding storage capacity is being explored** • **Development of ammonia bunker vessels is underway** with several orders being placed	• Feasibility studies, safety and operational bunkering protocols have been **rigorously tested** • MPA **has been developing procedures, standards, and regulations** for ammonia bunkering • The **Joint Study Framework for Ammonia Bunkering Safety promotes knowledge sharing,** supporting regulatory development	• An **EOI** was launched with proposals for the **procurement of >100 KTPA of clean ammonia** by 2027	

Port Readiness

In the International Association of Ports and Harbors (IAPH)'s Port Readiness Level (PRL) framework[23], Singapore is estimated to have reached PRL seven of nine for methanol bunkering - bunkering established on a project basis. The Maritime & Port Authority of Singapore (MPA) has stated that it is seeking to position Singapore as a hub for the supply of methanol and demand could exceed one million tons per year before 2030, subject to developments in supply, infrastructure, and regulation[xxi].

The port's first methanol bunker operation took place in July 2023, when the methanol-capable container vessel Laura Maersk received bio-methanol during a stop at Singapore on its way to Copenhagen. This followed an earlier feasibility study by Maersk, Mitsui, and ABS investigating the required operating procedures, fuel storage, and regulatory considerations for the operation.

23 See Annex 7 for further details about the PRL framework.

Meanwhile, the port is estimated to have reached a level six on the IAPH framework for ammonia bunkering - bunkering demonstrated in a protected environment.

In March 2024, Singapore completed the world's first use of ammonia as a marine fuel in a dual-fueled ammonia-powered vessel, the Fortescue Green Pioneer. To enable this, a number of feasibility studies and safety and operational bunkering protocols were rigorously tested at the port.

Notable industry initiatives are advancing further ammonia pilots in Singapore, including:

- The Singapore Ammonia Bunkering Feasibility Study (SABRE) project – involving the MPA, Maersk Mc-Kinney Moller Center, Keppel, ABS, and Sumitomo – aims to implement ammonia bunkering in Singapore before 2030. A technical and commercial feasibility study, and preliminary ammonia bunkering vessel design, were completed in 2022. An initial design, commercial frameworks and bunkering standards are currently being developed, with a view to obtaining a provisional bunkering permit.
- ITOCHU Corporation has launched a joint study framework for ammonia bunkering safety together with 16 companies and organizations, including the MPA. This framework focuses on sharing issues and knowledge related to the safety assessment and bunkering guidelines for the supply of ammonia as a fuel for marine use among port authorities, bunker suppliers, and research institutions.
- The Global Centre for Maritime Decarbonisation and partners are seeking to undertake an ammonia pilot at the port. A feasibility study identifying possible sites and the required safety parameters for the pilot was released in April 2023. The group is now working to operationalize the pilot, which will, in the first instance, involve an ammonia cargo transfer in port waters.

Infrastructure

As an existing chemicals hub, Singapore has several terminals capable of handling methanol, including Vopak Sakra Terminal, Stolthaven Terminal, Petrochemical Corporation of Singapore Terminal, and Chevron Oronite Terminal. While these facilities have primarily been used by the chemicals industry to this point, they would also be suitable for bunkering, subject to mass balancing frameworks being recognized. One methanol-capable bunker vessel is already in service at the port and six more are on order.

The port has one existing ammonia terminal, with capacity of 10,000m3 – Banyan Terminal at Jurong Island. While this could potentially be used for a small-scale pilot, storage would need to be increased for regular bunkering to take place. With this in mind, the terminal owner, Vopak, is exploring adding additional storage capacity. Risk management processes, pre-operations safety checks and tests for ammonia bunkering have already been completed at the terminal. In March 2024, Vopak signed a memorandum of understanding (MOU) with Air Liquide to explore the joint development of low carbon ammonia supply chains in Singapore, including the potential expansion of ammonia storage and handling infrastructure at Banyan Terminal[xxii]. The development of ammonia bunker vessels for use at the port is also underway, with several bunker suppliers and ship operators – including Fratelli Cosulich, Seatrium, and MOL – at different stages of maturity.

Regulatory Framework

Learnings from current operations are being used as part of work to develop a Technical Reference for methanol bunkering. This will establish the operational, safety, crew training and competency requirements for methanol bunkering at the port. It is anticipated to be finalized in 2024 and will enable the port to take its final steps towards large-scale methanol bunkering from a regulatory standpoint, namely the creation of a licensing framework and workforce training.

Meanwhile, MPA has been developing procedures, standards, and regulations for ammonia bunkering, which enabled the Fortescue Green Pioneer operation[xxiii]. In May 2023, MPA, the Embassy of France in Singapore and Innovation Norway held a three-day workshop on managing accidents involving ammonia – the first of a series of exercises held by MPA to develop emergency responses and procedures for ammonia bunkering in Singapore. Subsequently, an ammonia plume model was developed by a number of research bodies to support the safety and incident response planning.

Fuel Sourcing

The MPA has initiated steps to establish supply of green methanol and develop the methanol bunkering ecosystem in the Port of Singapore.

An expression of interest (EOI) for proposals to supply methanol as a marine fuel at the port launched in late 2023. This would include not only storage, sale, and delivery as a marine fuel at scale in Singapore from 2025, but also methanol supply to the port. There are also developments around local production of green methanol, with a consortium exploring the feasibility of building a 50,000 tons per year e-methanol pilot plant in the city, targeted at the bunkering market.

In December 2022, the MPA and Energy Market Authority launched an EOI for proposals to build, own, and operate a low- or zero-carbon ammonia bunkering and power generation solution. This would include procurement, import, storage, and bunkering of at least 100,000 tons per year of low- or zero-carbon ammonia for marine use by 2027. Twenty-six proposals were received under the EOI, and six consortia were shortlisted in October 2023. A process is now underway to select a lead developer for the project[xxiv]. The aim is to start ammonia bunkering on a shore-to-ship basis before scaling to ship-to-ship operations.

It should be noted that Singapore is taking a phased approach to the carbon intensity of ammonia and methanol, with the relevant EOIs initially allowing methanol with a well-to-wake carbon intensity of 1.8 kg CO_2e/kg MeOH and ammonia with a well-to-wake carbon intensity of 0.9 kg CO_2e/kg NH_3 to be imported. The intention is to better activate Singapore's first-mover advantage and slowly move towards net-zero methanol and ammonia once the production of such fuels have scaled up.

Demand

The port has implemented several initiatives that are expected to stimulate demand for zero-emission fuels. It is engaged in six green shipping corridor initiatives involving ten other ports[24]. These include several of the most advanced initiatives globally and have the potential to create significant demand – at the megaton scale – for zero-emission fuels by 2030, depending on the way they are operationalized[xxv].

24 Singapore-Rotterdam Green and Digital Shipping Corridor (GDSC); Singapore-LA-Long Beach GDSC; Singapore-Tianjin GDSC; Singapore-Japan GDSC; Silk Alliance; Singapore-Australia Green and Digital Shipping Corridor

Exhibit 20

Map showing Singapore's activity within announced green corridor initiatives

Source: Global Maritime Forum, "Annual Progress Report on Green Shipping Corridors" 2023.

Under its Green Port Programme, Singapore offers up to a 30% discount on port dues for vessels operating on zero-emissions fuels and a 25% discount on port dues for vessels operating on near-zero-emission marine fuels. Additionally, as part of the Singapore-Rotterdam Green and Digital Shipping Corridor, it has begun coordinating zero-emission bunkering standards with Rotterdam. This can be expected to facilitate shipowner investments on the route.

Finally, the ammonia EOI is expected to help aggregate demand across the maritime and power sectors. This approach has the potential to accelerate investment decisions in both production and infrastructure.

Recommended next steps

Singapore has positioned itself at the forefront of efforts to develop methanol and ammonia bunkering globally, with many of the key elements – including regulation, pilots, infrastructure development, and demand – coming into place. The port will have to manage challenges around the availability of fuel supply if it is to fully realize its potential and drive the sector's transition this decade. To support ongoing efforts and successfully implement green methanol and ammonia bunkering, Singapore could focus on the following next steps:

Catalyzing supply

- Consider setting a **target for up to 5% of fuel sales being zero-emission** by 2030, supporting the delivery of the IMO's targets and increasing shipowners' and operators' confidence in the availability of zero-emission fuel.
- Build on the two existing EOIs by **earmarking low-cost green methanol and ammonia volumes.** This could be pursued through signing Memoranda of Understanding and/or participating in import-export coalitions with expected green methanol and ammonia exporters, such as the US, in the coming years. Early efforts in this space would be particularly relevant for green methanol, given the potential shortfalls in supply.
- Consider implementing a **portfolio approach to fuel sourcing**, like that being taken by Rotterdam, to mitigate geopolitical risks relating to fuel supply. Promising pathways for green methanol imports include China, Australia, and Egypt and for green ammonia include Texas, Chile, Australia, Namibia, and India.

Activating demand

- Set **ambitious 2030 targets** for zero-emission fuel/vessel uptake within its portfolio of **green shipping corridors** and accelerate the green corridor initiatives' operationalization. An effective mechanism could be implementing demand-side incentives for zero-emission fuel use. Given the limited prospect for local production of green methanol and ammonia, zero-emission fuel production incentives are unlikely to be relevant in Singapore. However, there would be an opportunity to piggyback on production incentives being offered by other countries, such as Australia and the US, by offering demand incentives. This would help close the cost gap for their uptake in the maritime sector, accelerating zero-emission fuel uptake, while attracting the lowest-cost fuel volumes to Singapore.
- Build on existing efforts to **aggregate demand for green methanol and ammonia** both within and across end use sectors, as initiated by the EOI for ammonia bunkering and power generation. Opportunities exist to aggregate demand for ammonia and methanol with chemicals. This would support the country's national hydrogen strategy and the Sustainable Jurong Island initiative[xxvi].
- **Continue coordinating standards** for green methanol and ammonia with other ports to facilitate first-mover investments by shipowners and accelerate regulatory developments. This could include harmonizing port guidelines and chain of custody approaches with ports of call for anticipated first-mover ship operators and other global bunkering hubs.

Producing Incumbent: Port of Algeciras

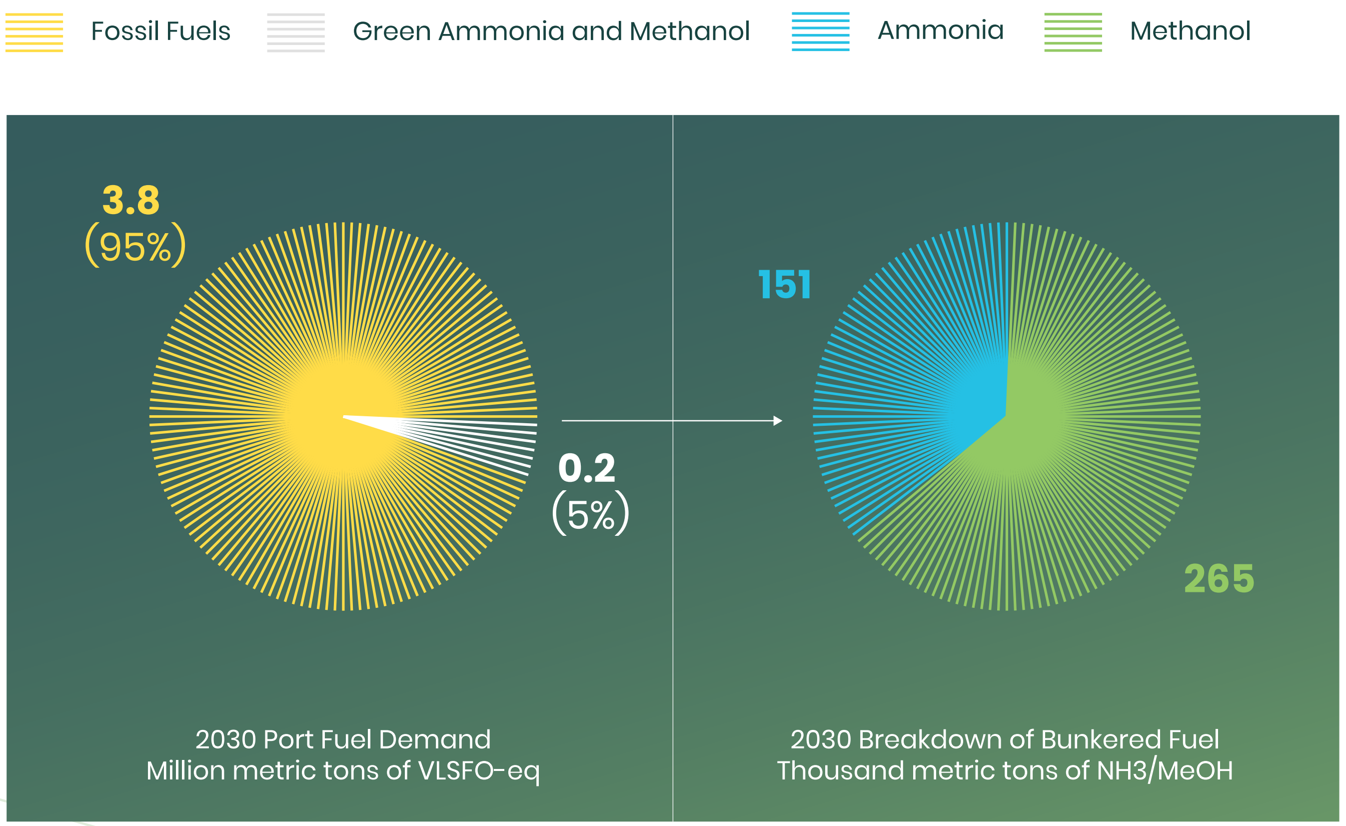
Algeciras is a major port in southern Spain. With the nearby ports of Ceuta and Gibraltar, it forms part of the Gibraltar Strait region, which is the second largest bunkering hub in Europe and third largest in the world, supplying over eight million metric tons of conventional fuel per year[xxvii].

The Port of Algeciras alone is responsible for roughly four million metric tons per year of these bunker volumes. As such, aligning with the IMO's target of at least 5% uptake of zero-emission fuels 2030 would mean replacing ~200,000 metric tons of conventional bunkers with zero-emission fuel by this time.

Exhibit 21

Algeciras is a top global bunkering port and will require sizable volumes of zero-emission fuel

Assumed 2030 fuel demand (left) and modelled methanol and ammonia demand scenario (right) at Algeciras.



Source: Ship & Bunker; RMI analysis.

The port has committed to reach net-zero by 2050 and has ambitions to offer both ammonia and methanol. For the purposes of the case study, it was assumed that methanol and ammonia meet all 5% of the zero-emission bunker demand in 2030. A split between methanol and ammonia is assumed, with two thirds of the 5% target being met with methanol and one third with ammonia, based on an extrapolation from existing methanol and ammonia vessel orders[25]. At Algeciras, this would translate into ~265,000 tons per year of green methanol and ~150,000 tons per year of green ammonia[26].

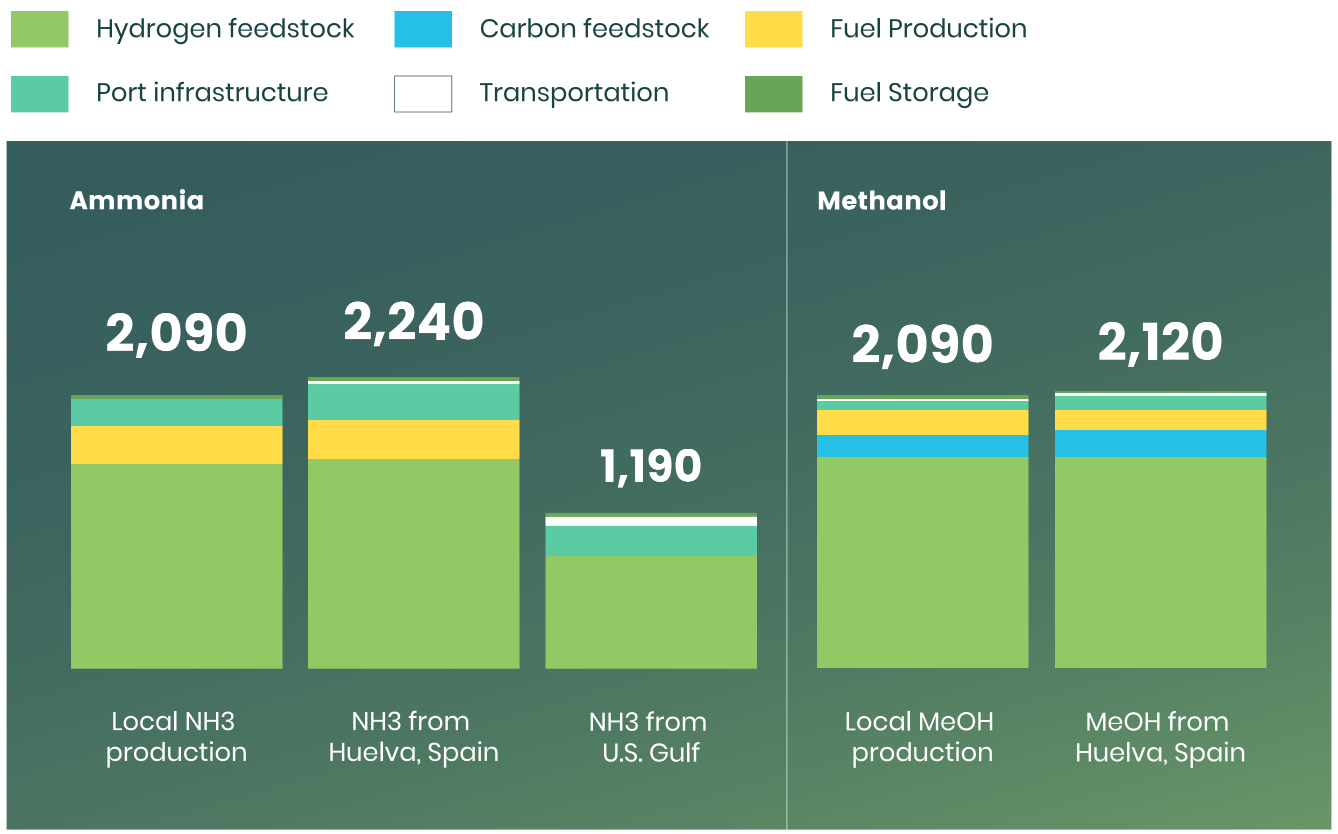
Green methanol and ammonia supply pathways and costs

Thanks to its excellent renewable resources, southern Spain is expected to produce some of the cheapest green methanol and ammonia in Europe. This is true of portside production – with Algeciras having some of the highest local renewable capacity factors of any top twenty bunkering hub globally – and production within the wider region, such as in Huelva to Algeciras' west. Of these two options, supply from portside production at Algeciras is likely to be slightly more economical since less transportation and infrastructure would be needed.

Exhibit 22

Algeciras could source locally-produced green methanol and ammonia

Assessed green methanol and ammonia supply pathways for Algeciras in 2030[27]
USD/metric ton VLSFO-eq of fuel



Source: RMI analysis.

25 RMI analysis. Existing vessel order data is from DNV Alternative Fuels Insights (AFI) platform.
26 Assumed that bunkering volumes will stay largely the same in 2030 compared to current levels, due to efficiency improvements offsetting increased traffic. Assumptions from the Maersk McKinney Moller Center for Zero-Carbon Shipping Industry Transition Strategy 2021 report.
27 Existing infrastructure not considered in port infrastructure costs for these scenarios.

Local production is not the absolute lowest-cost pathway for Algeciras to secure the fuels. This would be imports from US Gulf, which can benefit from the tax credits under the IRA. However, given the favorable local production opportunity and the EU's aim for at least 50% of hydrogen consumed in the bloc to be domestically produced, local supply is considered more likely. Indeed, under the trade model, Algeciras' green methanol and ammonia fuel demand would be fully met by production within the region.

Based on announced hydrogen projects, there should be enough fuel available in the region for the port to supply 5% green methanol and ammonia bunkers in 2030. Planned production is mainly associated with the Andalusian Green Hydrogen Valley initiative, which aims to produce 300,000 tons of green hydrogen per year by the end of the decade. This includes plans for a 300,000 tons per year of green methanol plant near the Port of Huelva and for two major green ammonia plants – one near Huelva, which will produce 400,000 tons per year, and another in San Roque near Algeciras, which will produce 750,000 tons per year.

Exhibit 23

Announced green hydrogen-based fuel projects in Spain expected to come online by 2030

Planned fuel projects as part of the Andalusian Green Hydrogen Valley.

Source: Cepsa.

While some demand is anticipated from the aviation and fertilizer sectors, bunkering and hydrogen exports, particularly to Northwestern Europe, are expected to be the main end-use markets for these projects. This means that there should be more than sufficient fuel available for methanol and ammonia bunkering. At the same time, the green methanol production is being co-developed by C2X – the fuel developer associated with AP Moller-Maersk Holdings – and may be earmarked for use by Maersk. Additional supply may, therefore, be needed if the port intends to offer bunkering to other stakeholders.

Methanol and ammonia bunkering readiness and progress

The port is seeking to be a first mover in zero-emission bunkering, with the aim of having methanol available on an ongoing basis by 2027 and ammonia by 2028.

Exhibit 24

Algeciras is developing methanol and ammonia bunkering capability

Summary of Algeciras' progress toward bunkering methanol and ammonia.

	Port readiness	Infrastructure	Regulatory framework	Fuel sourcing	Generating bunker demand
Methanol	• Algeciras has reached **Port Readiness Level five** for methanol bunkering	• One existing terminal capable of storing methanol • **Inland storage site has been identified to expand storage** • No bunker vessel planned currently	• **Expects to achieve bunkering this year** after • Collaborating with class in updating the port's guidelines • Obtaining required approvals from national regulator	• Andalusian Green Hydrogen Valley Initiative **plans to produce 300 KTPA methanol nearby (Huelva)** • Maersk-affiliated **C2X has invested in methanol production in the region**	• Not currently directly participating in green shipping corridors • Algeciras **planning to export green ammonia to Northwestern Europe**
Ammonia	• Algeciras has reached **Port Readiness Level four** for ammonia bunkering	• No existing ammonia terminal at the port • **Inland storage site has been identified to expand storage** • ITOCHU signed a MOU with bunker supplier, Peninsula, to **develop ammonia bunkering at Algeciras**	• **Ammonia bunkering demonstration being planned and will be performed at anchorage** • Will need to understand mitigation and response measures to fuel spills • Environmental impact assessments needed	• Andalusian Green Hydrogen Valley initiative has plans for: • **400 KTPA ammonia plant near Huelva** • **750 KTPA ammonia** (nominal cap.) **in San Roque**	

Port Readiness

In the IAPH's Port Readiness Level Tool framework, Algeciras is estimated to have reached PRL five of nine for methanol and PRL four for ammonia; it has developed roadmaps for implementing both fuels, which it is progressing through.

Infrastructure

There is one existing terminal capable of storing methanol at the port, owned by EVOS. While small, stakeholder feedback suggests it should be possible to expand the terminal to meet 2030 methanol requirements. At present, no methanol bunker vessel is planned; this would be required to serve containership demand on a regular basis.

In September 2023, ITOCHU signed a MOU with local bunker supplier Peninsula to develop ammonia bunkering at the port. This is one of several ammonia-powered shipping initiatives being spearheaded by ITOCHU, which has ordered ammonia-powered vessels and stated an ambition to create a global ammonia bunkering network.

While there is no existing ammonia terminal at the port, feedback suggests there could be opportunities to adapt Cepsa's existing facilities at the port, while a suitable inland storage site has also been identified. A bunker vessel will be required.

Regulatory Framework

As a next step in its roadmap, the port authority is collaborating with a classification society on updating its port guidelines to include methanol and seeking to obtain approvals for methanol bunkering from the national regulator. It expects to complete these actions and achieve regulatory readiness for methanol bunkering this year.

Substantial work remains to be done to enable ammonia bunkering. With over five million ferry passengers passing through the port annually and high levels of activity in the Bay of Gibraltar – including not only port operations and anchorage areas offering various maritime services, but also beaches and fishing – modeling ammonia spill scenarios and creating suitable mitigation and response measures will be essential. Thorough environmental impact assessments will also need to be completed, quantifying risks to sea life. This is an especially sensitive area for Algeciras, which has a nature reserve located within its bay.

However, these activities are not expected to be blockers to the timely introduction of ammonia bunkering, and an ammonia bunkering demonstration is being planned. This will be performed at anchorage. Once validated at anchorage, work will then be undertaken to enable bunkering at a terminal, including simultaneous operations.

Fuel Sourcing

In the absence of green methanol production projects at the port, the port authority is working to source supply, with a focus on Huelva. The port notes that the availability of biogenic carbon has been a limiting factor for green methanol production in the region, but it is not expected to be a showstopper.

As for ammonia, volumes from the Huelva and San Roque green ammonia plants are expected to be available for bunkering at the port.

Demand

In terms of demand, the port has initiated conversations with shipowners and operators, including bulk carrier operators and container lines, about their first-mover ambitions. As previously noted, Maersk-affiliated C2X has invested in methanol production in the region, suggesting potential for the port to bunker the container line's methanol vessels.

Like Singapore, Algeciras is seeking to coordinate methanol and ammonia bunkering standards with other ports, including Rotterdam, as a means of facilitating vessel investments.

Although several green corridors have routes that pass Algeciras, the port is not currently participating in an initiative.

The port is concerned about synchronizing supply and demand for the fuels, and the impact this could have on production projects reaching FID. To help overcome the issue, the port and developers are exploring synergies with other sectors beyond shipping. For example, two deals have been signed to create a hydrogen corridor for exporting green ammonia to Northwestern Europe[xxviii,xxix]. The port expects this to kickstart green ammonia production and infrastructure development while bunkering is being validated. This highlights the potential of sector coupling in accelerating the move to zero-emission bunkering, and the interaction between exports and bunkering.

Recommended next steps

Algeciras has defined a clear pathway to implementing methanol and ammonia bunkering this decade and is leveraging the synergies between exports and bunkering to accelerate its journey. Activating demand from first-mover ship operators is likely to be the biggest obstacle to Algeciras implementing methanol and ammonia bunkering in a timely fashion. Recommended next steps for the port include:

Catalyzing supply

- Seek to **access subsidies for fuel production**, to further reduce the cost of local production. The port could be well placed, as one of the lowest-cost production locations in Europe, to benefit from initiatives such as the EU Hydrogen Bank and the EU Innovation Fund. This would help accelerate demand by reducing the cost gap between green methanol and ammonia and conventional bunkers.
- **Build out last-mile infrastructure**, coordinating export and bunkering requirements. With ammonia terminals having a four to five-year lead time to operation[xxx,xxxi], action is needed in the next year or two to ensure availability by 2030.

Activating demand

- Consider opportunities to **participate in green shipping corridors** as a means of activating demand for zero-emission fuels. Container routes between Algeciras and the US were shortlisted as a favorable opportunity for the development of a green corridor as part of recent pre-feasibility study on green corridors in Spain[xxxii]. These routes were found to be among the most impactful green corridor opportunities in the country, while also having the potential to benefit from the EU Fit for 55 regulation and the IRA in the US, which would significantly reduce the cost gap for early deployment of green methanol and ammonia-powered vessels[xxxiii,xxxiv].

Exhibit 25

Container routes between Algeciras and the US have been identified as a favorable opportunity for a green corridor

Pre-feasibility assessment of candidate green corridors in Spain. Algeciras-US circled in green.

Very high impact/ feasibility | High impact/ feasibility | Medium impact/ feasibility

Route	Impact	Feasibility			
		Fuels	Demand and cargo	Policy	Stakeholder
Container; Liverpool - Bilbao	High	High	Very high	Very high	Very high
Container; Valencia - Turkey	High	Very high	High	Medium	Medium
Container; Valencia, Algecrias - United States East Coast	Very high	High	Very high	High	High
Container; Barcelona, Valencia - China	Very high	High	High	High	Medium
Ro-ro; Spain - United Kingdom	High	High	Very high	Very high	High
General cargo; Valencia - Italy	Very high	Very high	Very high	Very high	High
Cruise; Barcelona - Spain	High	Medium	Very high	Very high	Very high
Cruise; Spain Atlantic - United Kingdom	Medium	Medium	High	Very high	High

Source: Global Maritime Forum and British Embassy in Madrid, "Green corridors in and out of Spain: Assessing route-based opportunities".

Depending on the scale of exports to Northwestern Europe, there may also be a synergistic opportunity to **turn the planned hydrogen export corridors from the port into green shipping corridors** by powering the vessels transporting green ammonia/methanol on the route with green ammonia/methanol. This would have several benefits, including taking advantage of the low barriers to implementation of ammonia/methanol as a fuel onboard product carriers, while enabling the fuel producer to provide a lowest-GHG value proposition.

- Implement **incentives for zero-emission ships** to attract these vessels to the port, like Port of Rotterdam, which will offer a substantial port fee reduction for ships that bunker sustainable fuels at the port to support the Zero Emissions Maritime Buyers Alliance (ZEMBA) initiative[xxxv]. At Algeciras, this could include reductions in port fees and/or preferential berthing for zero-emission vessels.

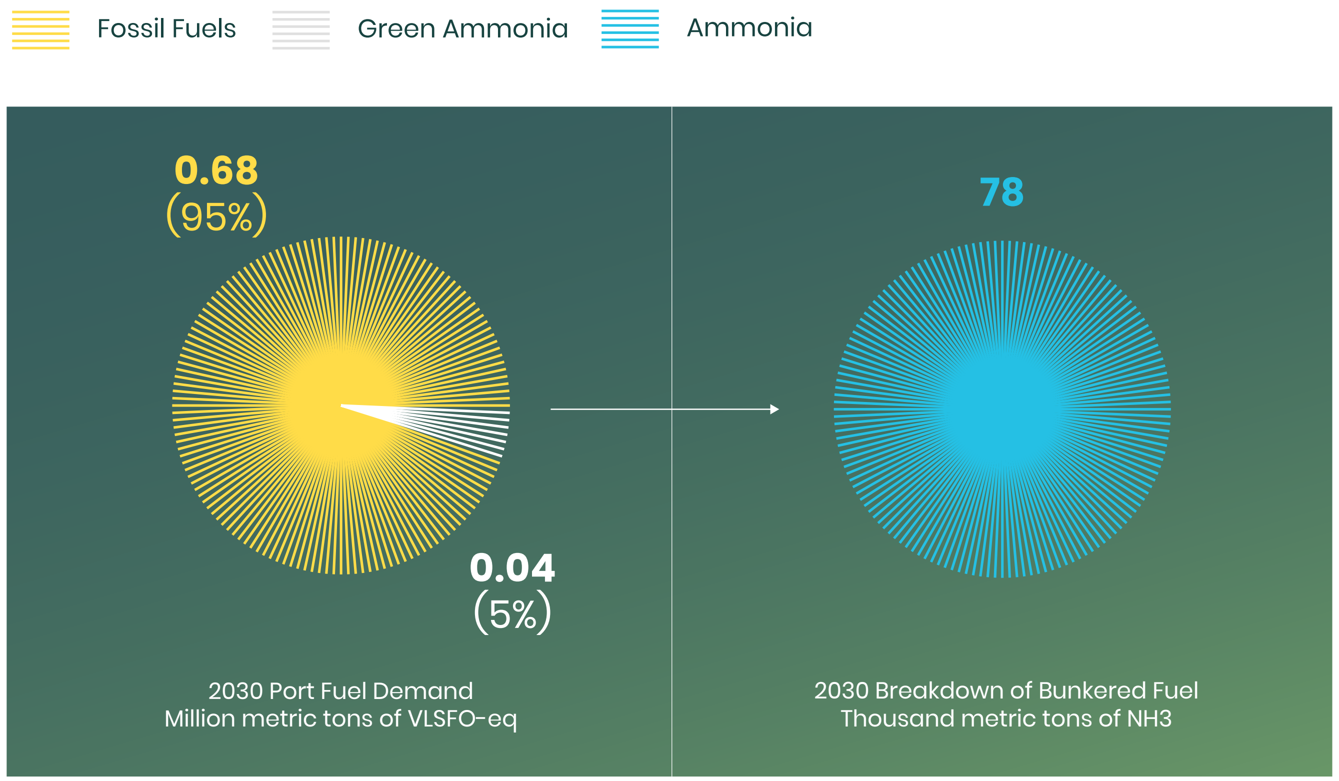
Future Exporter: Port of Corpus Christi

The Port of Corpus Christi is located in the western Gulf of Mexico. It is the largest energy export port in the US, handling over 125 million tons of crude oil and ~16 million tons of liquefied natural gas (LNG) in 2023[xxxvi]. However, as of today, it has a relatively small bunkering market, supplying roughly 700,000 tons of conventional bunkers per year.

Exhibit 26

Corpus Christi is a relatively small conventional bunkering port, but it has opportunities for ammonia bunkering

Assumed 2030 fuel demand (left) and modelled ammonia demand scenario (right) at Corpus Christi.



Source: Ship & Bunker; RMI analysis.

The port is initially focusing on ammonia bunkering opportunities, given the momentum behind ammonia exports from the region. It also sees potential for the production and bunkering of methanol in the future, given the availability of captured carbon in the area.

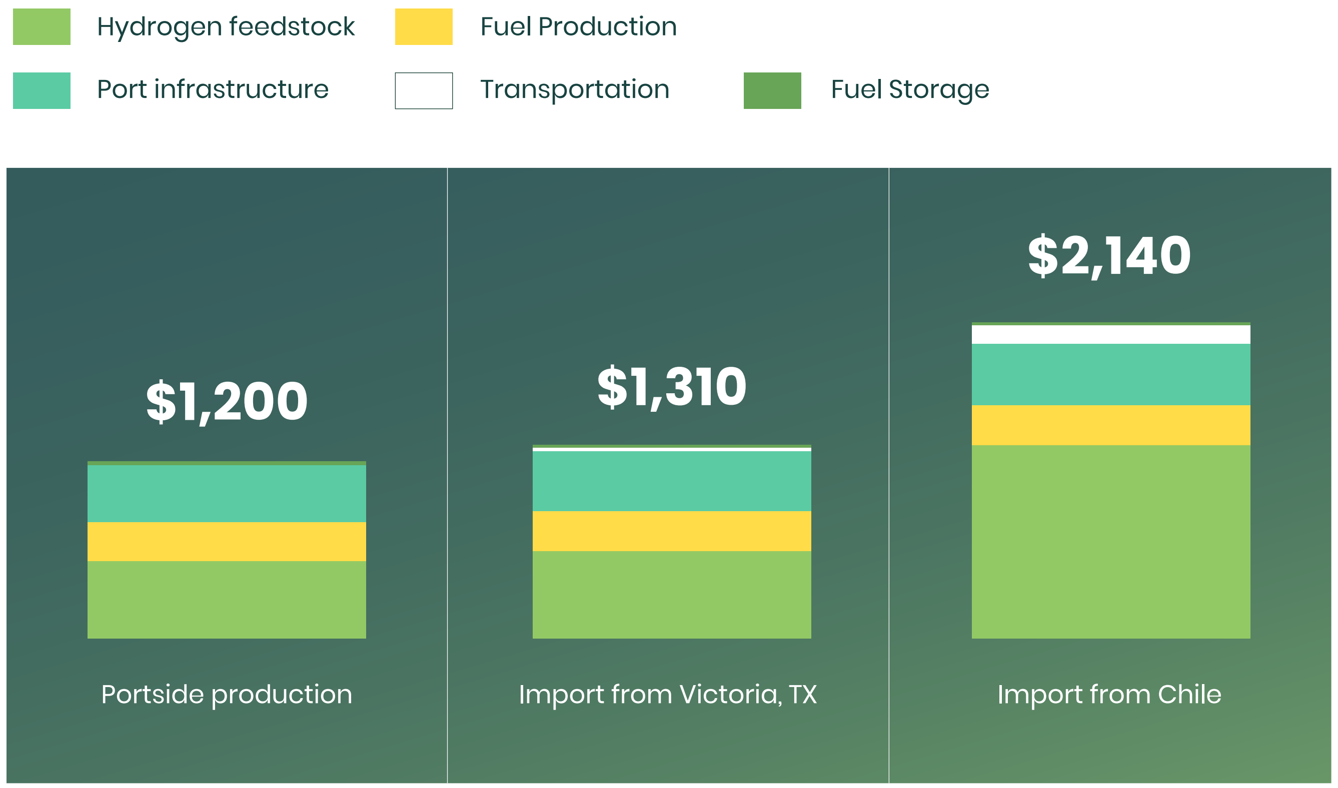
Aligning with the IMO's target of at least 5% uptake of zero-emission fuels in the sector by 2030 would mean the port replacing just under 40,000 tons per year of VLSFO with zero-emission fuels[28], or around 80,000 tons of ammonia. However, in practice, new traffic, such as ammonia carriers and potentially bulk carriers transporting green iron/steel products, is anticipated to drive early demand for green ammonia bunkers at the port.

Green ammonia supply pathways and costs

Exhibit 27

Corpus Christi could be able to provide highly competitive green ammonia

Potential ammonia supply scenarios for Corpus Christi in 2030
USD per metric ton VLSFO equivalent[29]



Source: RMI analysis.

28 Assumed that bunkering volumes will stay largely the same in 2030 compared to current levels, due to efficiency improvements offsetting increased traffic. Assumptions from the Maersk McKinney Moller Center for Zero-Carbon Shipping Industry Transition Strategy 2021 report
29 Imported green ammonia from Chile shown for purposes of comparison.

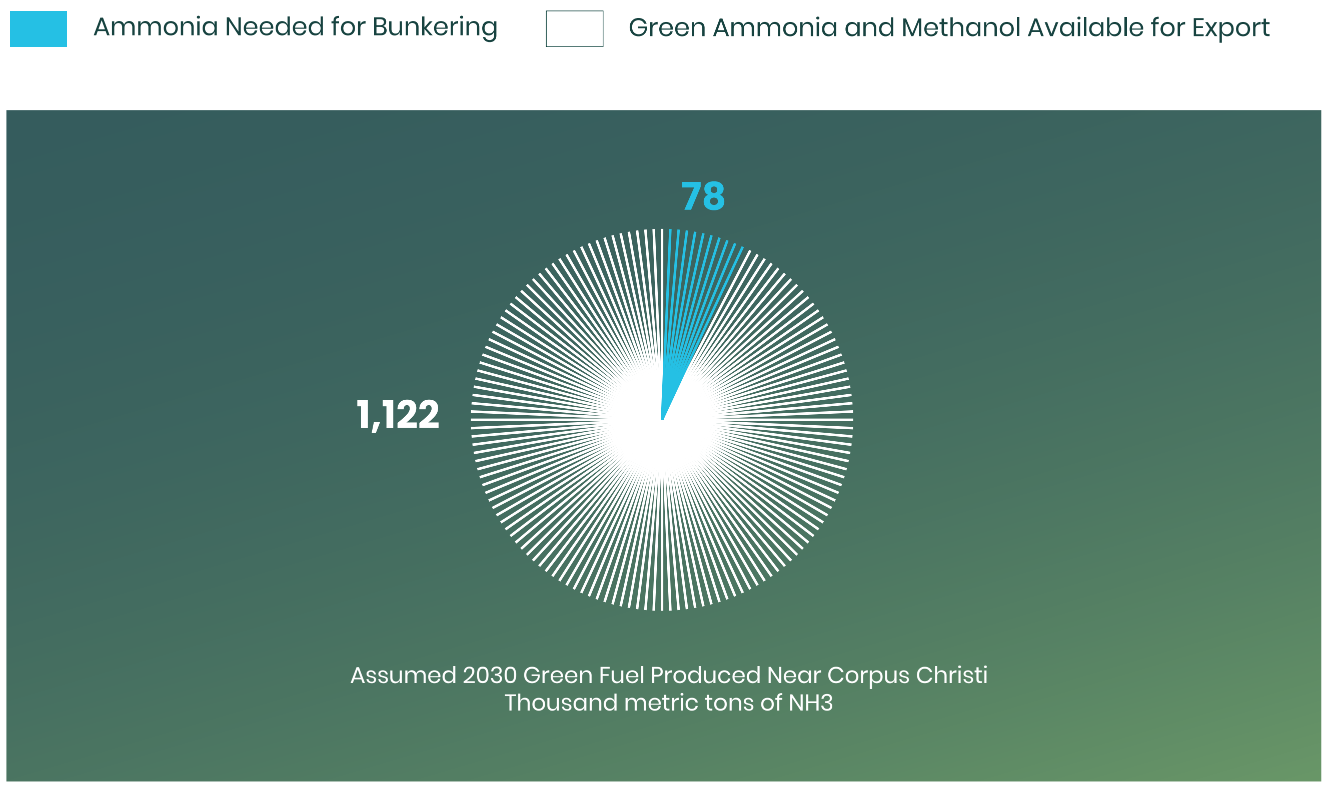
Portside production of green ammonia and volumes from a nearby project in Victoria, Texas provide the lowest cost supply at the port by a wide margin. Import options are significantly less economical, with, for instance, imports from Chile - itself a low-cost production region – estimated to be twice as expensive as local production. This gap is due to several, overlapping factors – the more favorable levelized cost of green hydrogen in Texas, the significantly lower transport and distribution costs, and the impact of IRA tax credits, which could reduce the levelized cost of hydrogen to just ~$1.1 per kilogram. This makes it highly likely that any green ammonia bunkers will be produced locally in or near Corpus Christi.

Announced green ammonia projects in the vicinity of the port suggest that there should comfortably be enough fuel available to meet required quantities for ammonia bunkering in 2030.

Exhibit 28

Significant production of green ammonia is planned near Corpus Christi

Corpus Christi's potential ammonia bunkering demand, considering the 5% IMO net-zero GHG emission goal, as a proportion of expected green ammonia production in the immediate area.



Source: RMI analysis.

Up to 1.2 million tons per year of green ammonia production by 2030 has been announced in the immediate area. Assuming these projects reach FID in a timely fashion, no more than 5% would be needed for the port to align with IMO targets for 2030. It should also be noted that significantly more clean ammonia is likely to be available locally, with the region also emerging as a hub for blue ammonia production.

The 5% requirement, which would translate to ~80,000 tons per year of green ammonia, would not be enough to fully offtake an export-scale green ammonia plant of the sort being developed near the port. However, it could provide support by being another offtaker, helping to reduce the developers' market risk by diversifying their customer base and allowing them to reach the minimum offtake volume for projects. Additionally, the scope for bunkering could grow with Corpus Christi potentially taking market share from larger proximate geographic bunker hubs such as Houston and Louisiana.

Ammonia bunkering readiness and progress

Exhibit 29

Corpus Christi is in the early stages of readiness for ammonia bunkering

Summary of Corpus Christi's progress towards bunkering ammonia.

	Port readiness	Infrastructure	Regulatory framework	Fuel sourcing	Generating bunker demand
Ammonia	• Corpus Christi has reached **Port Readiness Level two to three** for ammonia bunkering	• No existing ammonia storage infrastructure • Port authority reports that **space is available** for new infrastructure, and existing **LPG storage could be retrofitted** • Bunker vessel may be required • Ammonia infrastructure will be able to **facilitate in both ammonia exports and bunkering**, reducing last mile premiums (see Exhibit 30)	• Corpus Christi will **need to establish an ammonia bunkering ecosystem**, including ammonia bunkering guidelines, workforce competencies, and licensing regime • There will be overlap between framework and competencies for transfer of ammonia bunkering and ammonia as a cargo	• **Many sizable green ammonia projects expected in the vicinity of Corpus Christi** • Some risk for production potential due to: • **Requirements and longevity of IRA** • Scalable water supply • Timing of transmission upgrades to the grid	• As a member of the Transatlantic Clean Hydrogen Trade Coalition, the **port is well-positioned to secure export offtakers**

Port readiness

In the IAPH's Port Readiness Level framework, Corpus Christi's readiness for ammonia bunkering is estimated to be between PRL two and three on the nine-level scale - determining the interest of port stakeholders and gathering sufficient information.

Infrastructure

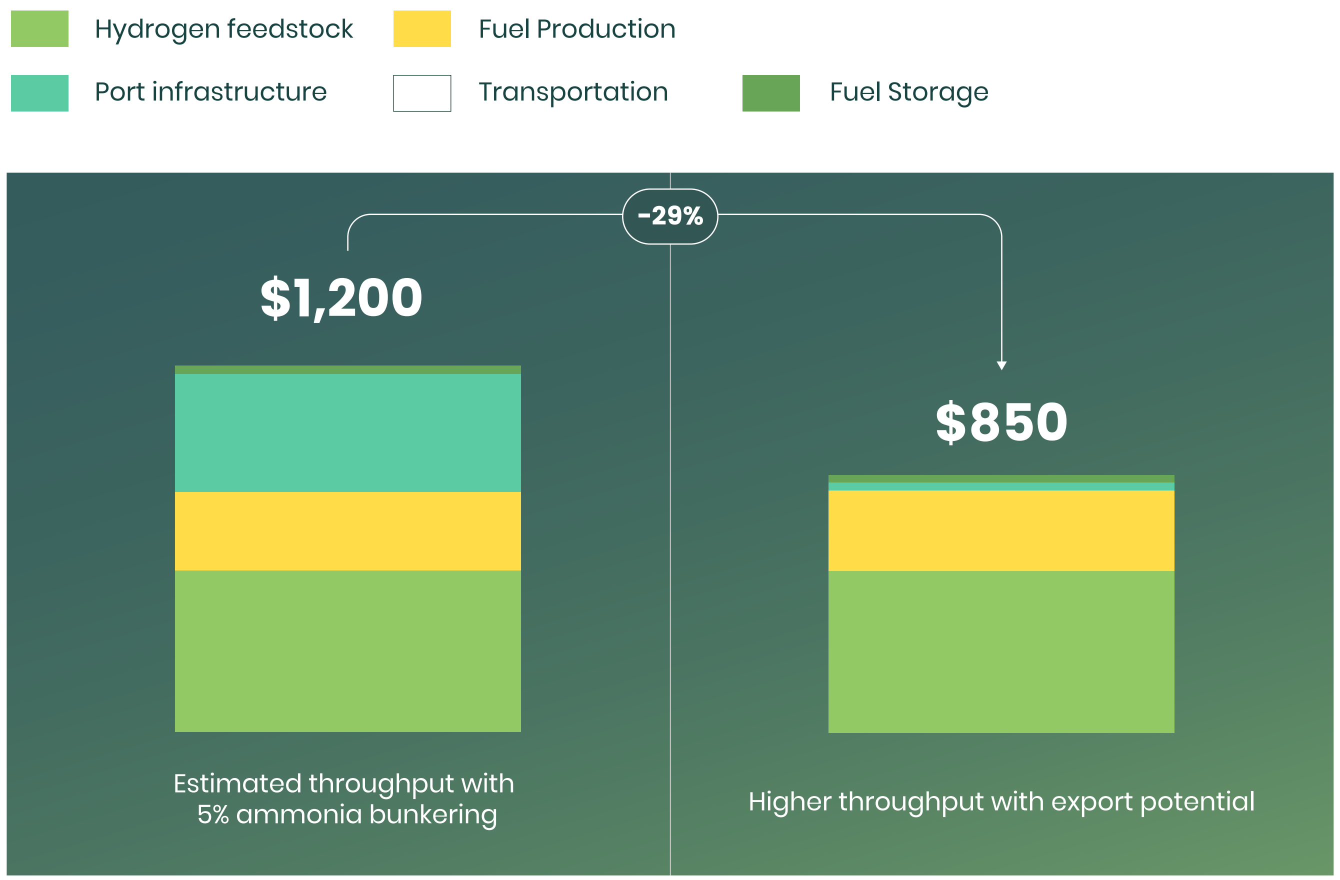
The port does not have existing ammonia storage infrastructure. As such, it would either need to build new infrastructure or retrofit existing infrastructure for other fuels/chemicals. Feedback from the port authority suggests that there is space for new infrastructure within its existing docks and opportunities to consider retrofitting the liquefied petroleum gas (LPG) storage present at the port. The requirement for a bunker vessel will depend on the ships bunkering at the port, with a lesser need if this is dominated by ammonia carriers.

This is an area in which the port is likely to benefit from synergies. Any ammonia storage and jetties will be able to "double up", facilitating both ammonia exports and bunkering. Not only will this make investments in this infrastructure more feasible, but it also has the potential to significantly reduce the last-mile bunkering premium. If the full pipeline of ammonia export projects around the port is realized, this would reduce the delivered cost of ammonia bunkers by ~30% compared to if the infrastructure were developed solely for bunkering.

Exhibit 30

Corpus Christi can significantly reduce last mile costs by utilizing port infrastructure for bunkering and exports

Impact of total delivered cost from varying throughput on port infrastructure, in USD per metric ton VLSFO equivalent. A volume of ~80,000 metric tons of ammonia per year is assumed for 5% ammonia bunkering and a volume of 1.2 million metric tons of ammonia per year is assumed for 2030 exports.
USD per metric ton VLSFO equivalent



Source: RMI analysis.

Regulatory Framework

As well as infrastructure, the port will need to establish an ammonia bunkering ecosystem – including guidelines, workforce competencies, and licensing regime. There will be some overlap between the framework and competencies required for the transfer of ammonia as a cargo and bunkering, but the process for bunkering specifically has not yet been initiated.

Fuel Sourcing

With the port's zero-emission bunkering opportunity being intertwined with its potential as a low-cost green ammonia producer, risks affecting green ammonia production are expected to have significant knock-on effects for the port's bunkering potential. The port authority acknowledges uncertainty about the requirements and longevity of the IRA, as well as the compatibility of US and EU policies, as particular risks in this regard. Other production-related challenges, including identifying a scalable water supply solution and the timing of transmission upgrades to the grid, were also highlighted as potential constraints in realizing its green ammonia production/bunkering potential.

Demand

The port has taken steps to activate demand, both from shipping and exports. As a member of the Transatlantic Clean Hydrogen Trade Coalition– a partnership connecting fuel producers in the US Gulf with European customers – the port is well-positioned to secure export offtakers, kickstarting production.

Recommended next steps

Corpus Christi has significant potential to become a green ammonia bunkering hub, maximizing local value from planned ammonia production. Synchronizing the development of infrastructure with export projects and establishing green corridors on emerging ammonia export routes, the port can move quickly and provide some of the lowest-cost green ammonia globally. It can prioritize the following next steps:

Catalyzing supply

- Initiate the **development of a regulatory framework** for ammonia bunkering, leveraging best practices and knowledge from the IAPH Clean Fuels Working Group, Society for Gas as a Marine Fuel, and first-mover ports working on ammonia bunkering trails, such as Savannah, Singapore, Antwerp, Algeciras, and Rotterdam. An ammonia bunkering trial could provide a steppingstone within this process, helping to build stakeholder confidence.
- **Explore subsidies and/or low-cost financing for infrastructure** build out, including through the Bipartisan Infrastructure Law.

Activating demand

- Implement **incentives for zero-emission ships** to attract first movers to bunker at the port. This could include reductions in port fees and/or preferential berthing for zero-emission vessels. Alignment with Rotterdam - at the other end of potential green ammonia trade routes - could strengthen the business case for investment by shipowners and operators.
- Consider opportunities to **participate in green shipping corridors** as a means of activating demand for green ammonia bunkering. This could include green ammonia carrier corridors.
- Initiate discussions with potential **first-mover ship operators that bunker within the wider Gulf region**, to increase the potential bunker market beyond ammonia carriers.

Bespoke Player: Ports of Seattle and Tacoma

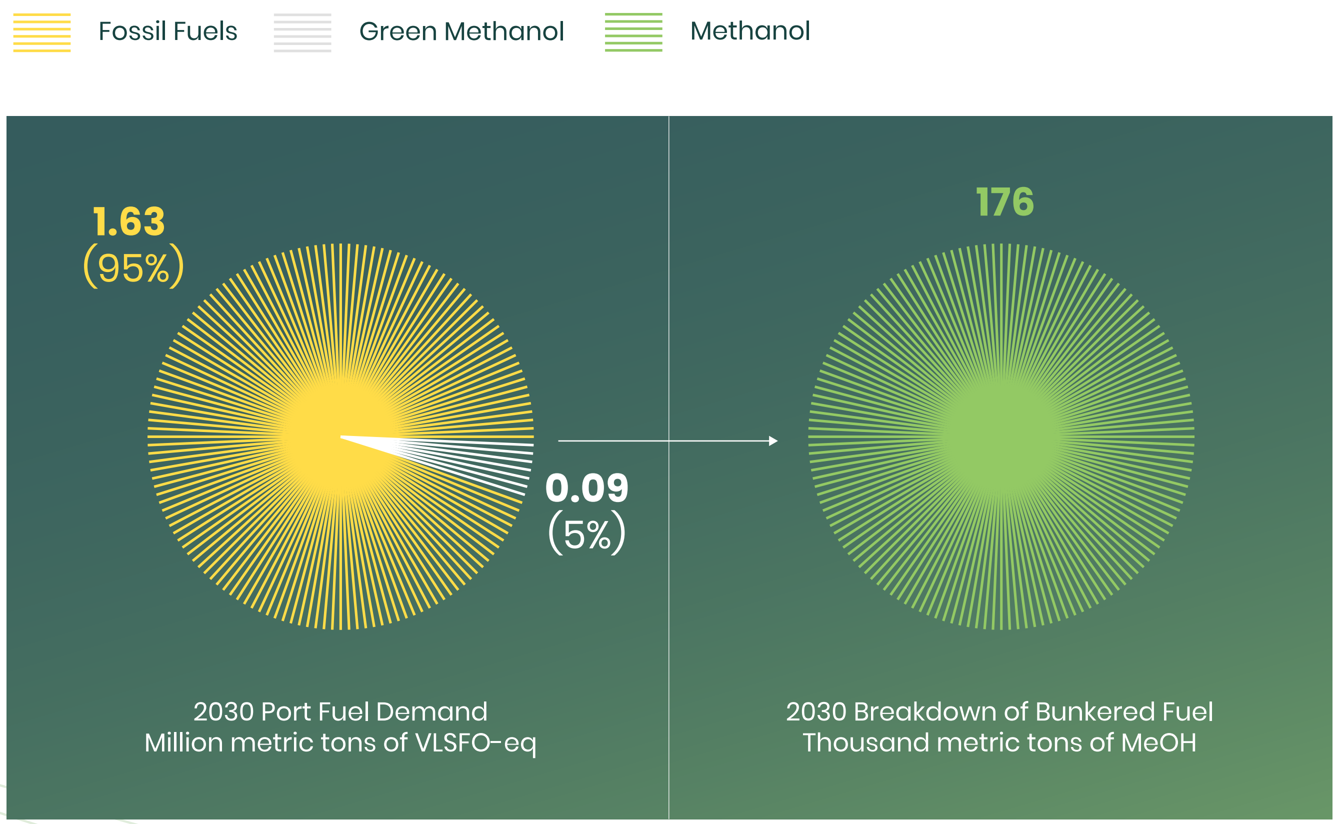
Seattle and Tacoma are major ports in Washington State, USA. Most cargo terminals in Seattle and Tacoma are managed by the Northwest Seaport Alliance, a marine cargo operating partnership between the two ports.

The Alliance is a significant container gateway, handling ~3.4 million twenty-foot equivalent units (TEUs) in 2022, as well as a breakbulk and agribulk hub. Seattle is also a significant cruise port, with 295 cruise calls in 2022.

Exhibit 31

Seattle and Tacoma are medium-sized bunkering ports and could have opportunities for green methanol bunkering

Assumed overall 2030 bunker demand (left) and assumed 2030 methanol demand (right) in Seattle and Tacoma.



Source: Port of Seattle & Tacoma; RMI analysis.

A total of around 1.7 million tons of conventional bunker fuel per year is sold at the ports. Aligning with the IMO's target of at least 5% uptake of zero-emission fuels in the sector by 2030 would, therefore, require about 90,000 tons of conventional bunkers to be replaced with clean fuels[30].

Green methanol is expected to be the most viable zero-emission fuel at the ports in the near term, given container liners' early adoption of the fuel, the reduced scope for ammonia use on onboard cruise ships, and the ports' urban locations. Accounting for differences in energy density, hitting the 5% target solely with methanol would require ~170,000 tons of the fuel to be bunkered by 2030. This would be roughly the amount of methanol needed to power seven Panamax container ships operating all year on the fuel[31].

Green methanol supply pathways and costs

The Pacific Northwest has significant hydropower generation capacity, supplying around half of the US total. In theory, this capacity could be leveraged to provide low-cost green electricity for producing e-methanol. However, this may not be a practical option. First, it would put methanol production in competition with the grid for scarce green electrons, as the region's surplus renewable generation declines with increasing demand. Using hydropower directly for the electricity grid would reduce carbon emissions more efficiently than e-methanol production. Second, the initial guidance associated with the IRA requires that green hydrogen be produced from new renewables to qualify for tax credit support[32]. This makes new solar and wind the most viable feedstocks for e-methanol production in the area[33].

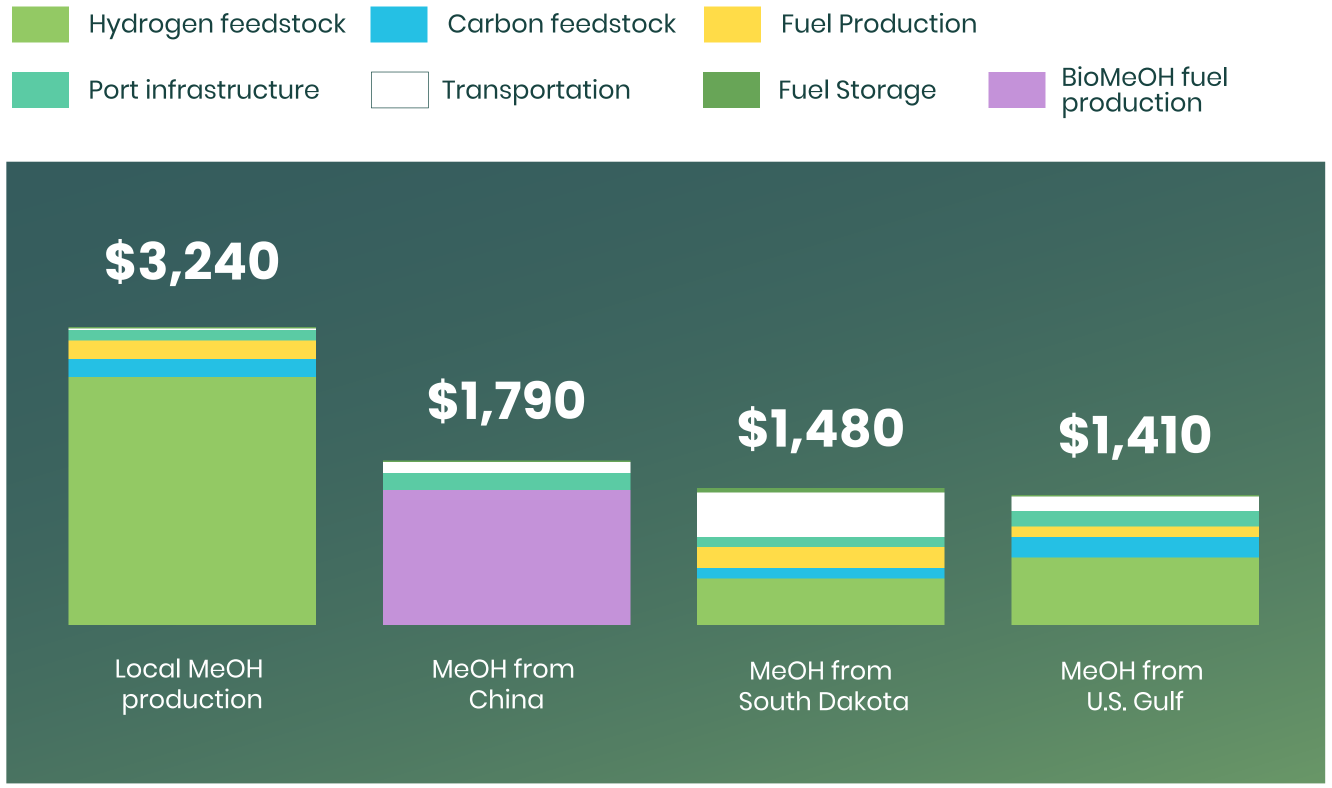
With low wind and solar capacity factors, local production would, however, be expensive. The delivered cost of locally produced e-methanol is estimated to be around $3,240 per metric ton VLSFO equivalent. As such, the ports will be more competitive when importing fuel. Importing methanol from planned production in the US Gulf is found to be the lowest-cost pathway at $1,410 per metric ton VLSFO equivalent, reducing the cost of fuel by more than half relative to local supply. It is closely followed by production in South Dakota. South Dakota has lower production costs than the US Gulf, but fuel sourced from the state would likely have to be transported via rail, which is costlier than seaborne transport from the US Gulf[34].

30 Assumed that bunkering volumes will stay largely the same in 2030 compared to current levels, due to efficiency improvements offsetting increased traffic. Assumptions from the Maersk McKinney Moller Center for Zero-Carbon Shipping Industry Transition Strategy 2021 report.
31 Based on IMO Fourth Greenhouse Gas Study data.
32 With the potential for a small carve-out that could allow for 5% of existing hydropower to be used.
33 The 2021 Washington State Energy Strategy envisioned the use of excess renewable generation to produce hydrogen. Recent studies on hydrogen and renewable fuels indicate scale up for widespread use including aviation and maritime fuels will require a significant increase in renewable generation and transmission (36.8 GW by 2050).
34 This includes the added costs imposed by the Jones Act. See Annex 3 for more information on the impact of the Jones Act on intra-US transport of green methanol and ammonia.

Exhibit 32

Imports from elsewhere in the US would offer the lowest cost pathway for Seattle and Tacoma to source green methanol

Assessed green methanol supply pathways for Seattle & Tacoma in 2030
in USD/metric ton VLSFO equivalent



Source: RMI analysis.

Both domestic pathways would be more economical than foreign imports, represented in Exhibit 32 by bio-methanol from China. This would be some 27% more expensive than e-methanol from the US Gulf and around 21% more expensive than e-methanol from South Dakota.

This suggests that Seattle and Tacoma should focus on the domestic supply opportunity. This should have the added benefit of making the fuel sourcing process simpler. Overall, the analysis shows that methanol bunkering at Seattle and Tacoma can be competitive with other first-mover ports, should they succeed in securing low-cost imports.

Methanol bunkering readiness and progress

Exhibit 33

Seattle & Tacoma are in the early stages of becoming ready for methanol bunkering

Summary of Seattle & Tacoma's progress towards bunkering methanol.

	Port readiness	Infrastructure	Regulatory framework	Fuel sourcing	Generating bunker demand

Methanol	• Seattle & Tacoma have reached **Port Readiness Level one to two** for methanol bunkering	• No methanol storage currently, but Tacoma has previously discussed methanol facilities
		• Port authorities are working on a **risk assessment study exploring portside storage of hydrogen and hydrogen carriers** incl. methanol
		• Infrastructure requirements are being considered as part of the **ports' ongoing corridor initiatives**
		• Bunker vessels will be required for container and cruise demand
			• Methanol bunkering provisions will need to be added to existing regulatory framework
			• Establishing a framework for methanol bunkering will **require coordination and time from stakeholders**
				• Stakeholders haven't established partnerships to explore zero-emission fuel sourcing options	• **Three green shipping corridors** under exploration
					  • Container corridor with Busan
					  • Car carrier corridor with South Korean ports
					  • Regional cruise corridor with Alaska

Port Readiness

In the IAPH framework, the ports are estimated to have reached PRL one to two for methanol bunkering – assessing the relevance of methanol and determining the interest of port stakeholders.

Infrastructure

Neither port currently has methanol storage capacity. To enable methanol bunkering, new storage facilities would need to be built. While there are no known plans at present, the port authorities are working with the Pacific Northwest National Laboratory on a risk assessment study exploring hydrogen storage at the ports. This will consider both hydrogen and hydrogen carriers, including methanol.

Infrastructure requirements are also being considered as part of the ports' ongoing green corridor initiatives (see below). These efforts should provide an initial fact base to support the development of the required infrastructure.

In addition to storage, methanol bunker vessels would be required to service container and cruise demand, either in the form of dedicated bunker vessels or chartered methanol carriers.

Regulatory Framework

While there is an existing regulatory framework for conventional and LNG bunkering at the ports, new provisions will be needed to enable methanol bunkering. The Ports of Seattle, Tacoma, and the Northwest Seaport

Alliance do not have regulatory authority over bunkering; bunkering changes require coordination among several different actors, including the US Coast Guard, Washington State Department of Ecology and local fire departments. These authorities have had limited engagement with methanol as a marine fuel to-date and the ports may face long lead times for the required regulation to be established.

The port terminals in Seattle and Tacoma are also located adjacent to urban centers. There has been debate in Washington State about methanol in recent years, with two proposed grey methanol production and export facilities shelved following opposition from community groups and NGOs. A proposal to establish methanol bunkering is likely to raise public scrutiny. Although green methanol bunkering would have a substantially different environmental profile than grey methanol production, public attitudes may nonetheless impact permitting and approvals timelines.

Fuel Sourcing

The ports (and the stakeholders operating in them) have not yet established partnerships to explore green methanol sourcing options, though these efforts are beginning as part of the ongoing green corridor projects. As time goes by, the ports are likely to face increasingly stiff competition to secure low-cost volumes, particularly from large shipowners and bunker ports with higher purchasing power. Given the limited project pipeline, this competition may be especially acute for green methanol.

Demand

Clear demand signals can play a role in accelerating the development of bunkering infrastructure at the ports. This is an area in which the ports have been leaders, with three green shipping corridors currently under exploration – a container corridor with the South Korean port of Busan, a car carrier corridor with South Korean ports such as Masan, Ulsan and Pyeongtaek, and a regional cruise corridor between Seattle and Alaska.

If successfully operationalized, the corridors could create substantial zero-emission fuel demand. The initiatives have not yet announced targets for the introduction of zero-emission vessels, which will depend on the outcomes of forthcoming feasibility studies. However, setting ambitious 2030 targets could provide an opportunity for the ports' bunkering ambitions. For example, introducing just five methanol cruise ships would generate demand for ~150,000 tons of green methanol per year, while the same number of large methanol containerships could require up to ~275,000 tons per year[35]. If Seattle and Tacoma were to capture half of these volumes, this would unlock over ~210,000 tons per year of methanol bunker demand. This would be sufficient to offtake a large-scale green methanol plant, like those being developed in South Dakota and the Gulf of Mexico.

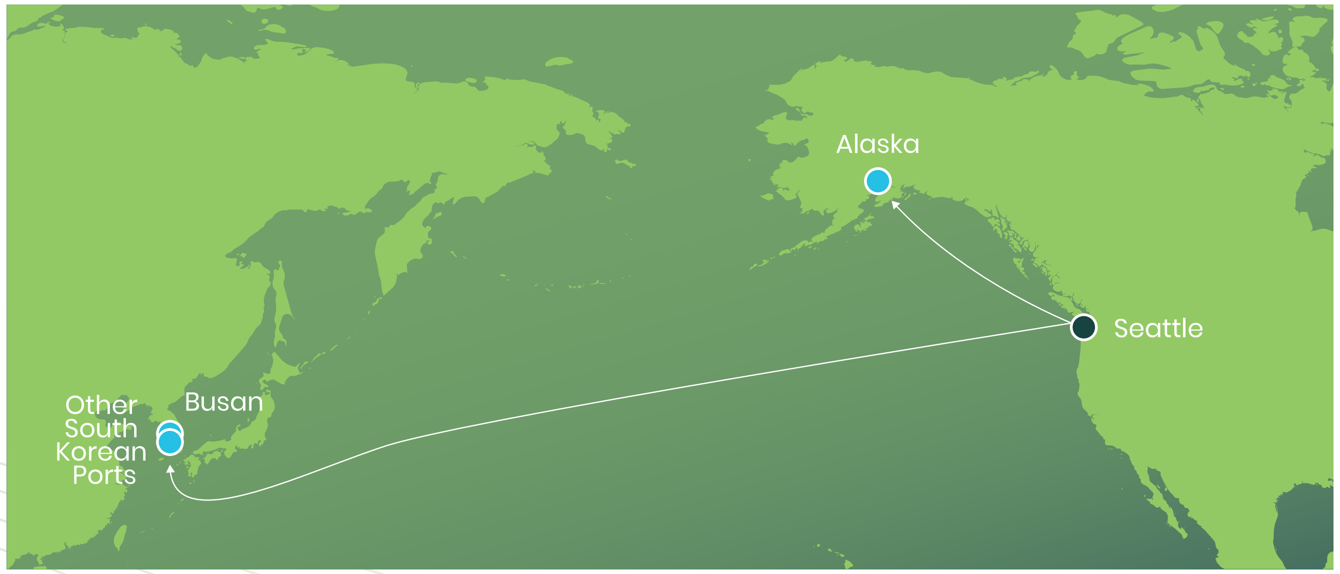
One challenge may be the seasonality of cruise traffic, since fuel suppliers will primarily seek buyers with steady demand to avoid their production plant standing idle. This issue should, however, be surmountable, with opportunities for the ports to leverage other sources of demand to meet developers' requirements; there is a clear opportunity to coordinate the three corridor initiatives by aligning them around the same fuel pathway and synchronizing their timelines.

As well as supporting fuel offtake, aggregating fuel demand would also help minimize the last-mile bunkering premium. If, for example, the ports achieved ~350,000 tons per year of methanol throughput – equivalent to switching 10% of their bunker volumes to methanol, in line with the IMO's 2030 "striving" target - the last-mile premium would be halved, limiting it to just $50 per metric ton VLSFO equivalent.

35 Calculation for cruise ships based on fuel oil consumption for cruise ships operating in the region. Calculation for container based on fuel oil consumption for archetypical 15,000 TEU containership using IMO 4th Greenhouse Gas Study data.

Exhibit 34

Seattle and Tacoma are currently involved in three green corridor initiatives



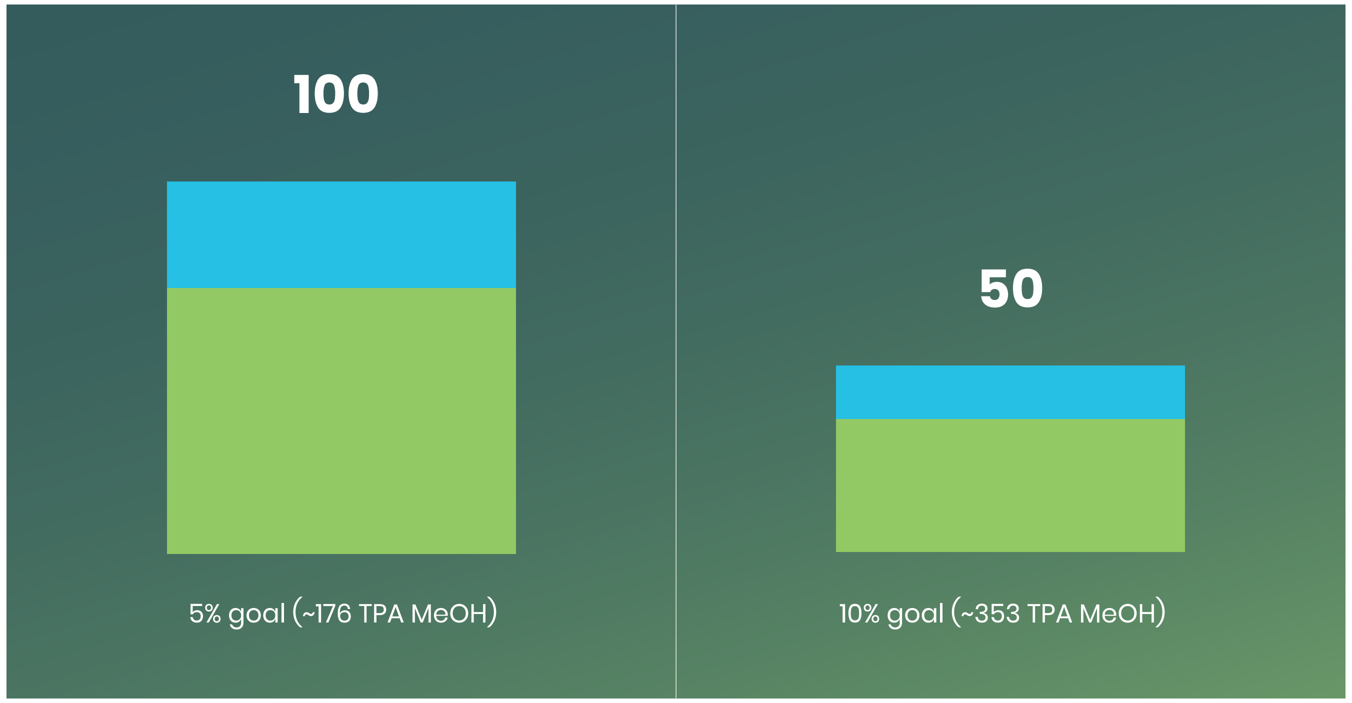
Source: Global Maritime Forum, "Annual Progress Report on Green Shipping Corridors" 2023.

Exhibit 35

Seattle & Tacoma's last-mile costs could be reduced by aligning with the IMO's 10% zero-emission fuel uptake goal

Levelized cost of bunkering infrastructure associated with hitting the 5% versus 10% IMO zero-emission fuel uptake goal for Seattle & Tacoma
USD per metric ton VLSFO equivalent

Portside storage   Bunker vessel



Source: RMI analysis.

Recommended next steps

Seattle and Tacoma are on a path to becoming first-mover ports and realizing the opportunities associated with zero-emission shipping. To overcome the challenges identified and make the most of the ports' advantages, the following next steps are recommended:

Catalyzing supply

- **Accelerate efforts to source green methanol**. The analysis suggests that production within the US is likely to be the lowest-cost sourcing pathway for the ports and a logical starting point for these efforts.
- Leverage the low-carbon marine fuel provisions under the **Washington Clean Fuel Standard**[xxxvii] **to reduce the cost of zero-emission fuel** and enhance the competitiveness of bunkering at the port.
- Initiate the **development of a regulatory framework** for methanol, leveraging best practices and knowledge from the IAPH Clean Fuels Working Group, and first-mover ports with methanol bunkering experience, such as Houston, Gothenburg, Rotterdam, or Singapore. A methanol bunkering trial could provide a steppingstone within this process, by helping to build stakeholder confidence. This could be integrated into the green corridor action plans, in line with the approach being taken by the Singapore-Rotterdam Green and Digital Corridor and the Silk Alliance[xxxviii,xxxix].
- Begin **close engagement with community organizations, civil society, and policymakers** about the ports' zero-emission bunkering options, trade-offs and planning needs, to ensure community input from the start of work to develop methanol bunkering. The ports have established several mechanisms for near-port community engagement – including a web portal, regular community newsletter, and the Duwamish Valley Community Hub and Port Community Action Team – that provide a good basis for these efforts. Best practices from establishing LNG bunkering, the Environmental Protection Agency's Community-Port Collaboration Toolkit[xl], and local NGOs can also be leveraged.
- Explore **creative siting and/or storage solutions**, which could help mitigate permitting delays. This could include performing bunkering operations directly from methanol carriers or considering permanent storage outside of the ports' current estates.

Activating demand

- Set **ambitious 2030 targets** for zero-emission fuel/vessel uptake within the ports' **green corridor initiatives** and accelerate their operationalization.
- Explore **collaborative offtake opportunities**, including the port authorities' potential to align their corridor initiatives around a given fuel. In addition, the ports could take a similar role to Port of Rotterdam, proactively leading efforts to secure zero-emission fuel supply for different end users related to the ports. This could also be done through the Sustainable Maritime Fuels Collaborative[xli], under development by Port of Seattle, the Northwest Seaport Alliance, Washington Maritime Blue and Washington State University's Consortium for Hydrogen and Renewable E-fuels (CHARGE) – an entity that would serve as a third-party convener and potential aggregator between supply and demand parties.
- Implement **incentives for zero-emission ships**. Since the Northwest Seaport Alliance does not charge harbor dues[36], the ports could look for funding to reduce the cost of installing bunkering infrastructure, lowering last-mile costs.

36 Preferential use is granted to terminal operators via leases.

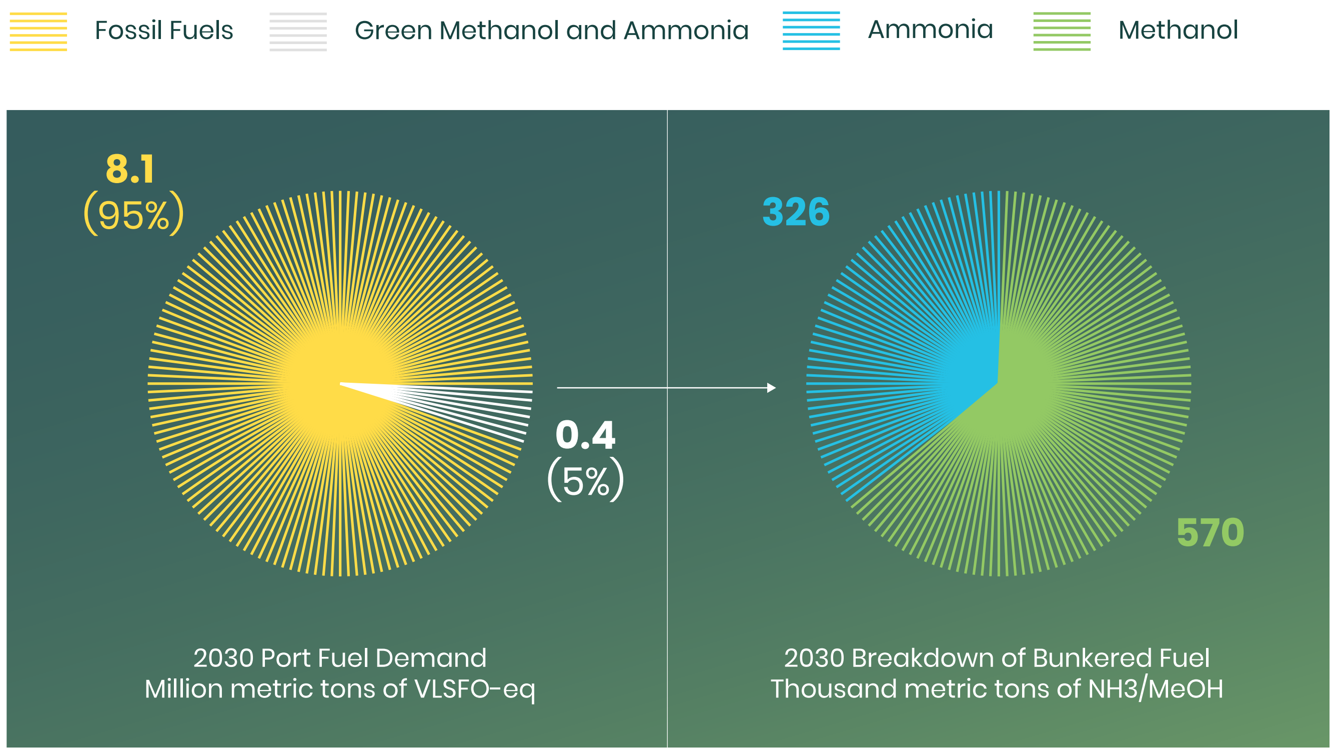
Hybrid case: Port of Rotterdam

Rotterdam is the largest port in Europe and the second largest bunker hub in the world. In recent years it has supplied between 8.5 and 10 million tons of fuel oil annually[xlii]. As such, aligning with the IMO's target of at least 5% uptake of zero-emission fuels by 2030 would require Rotterdam to replace between ~400,000 and ~500,000 tons of conventional bunkers with zero-emission fuels.

Exhibit 36

Rotterdam is a top global bunkering port, with large potential zero-emission fuel demand

Assumed overall 2030 bunker demand (left) and assumed 2030 methanol and ammonia demand (right) in Rotterdam[37].



Source: Ship & Bunker; Xinde Marine News; RMI analysis.

37 It is assumed that current bunkering volumes will stay largely the same by 2030 compared to current levels based on the assumption that efficiency improvements will be largely offset by increased volumes of traffic. Assumptions are derived from the Maersk McKinney Moller Center for Zero-Carbon Shipping Industry Transition Strategy 2021 report.

The port has set both 2030 and 2050 carbon emissions reduction targets and stated its intention to continue as a multi-fuel port, providing methanol, ammonia, and various biofuels. The contribution of methanol and ammonia to meeting the 5% target will depend on several factors.

This case study uses a scenario in which methanol and ammonia meet all 5% of the zero-emission bunker demand. A split between methanol and ammonia is assumed, with two thirds of the 5% target being met with methanol and one third with ammonia, based on an extrapolation from existing methanol and ammonia vessel orders[38]. In Rotterdam, this would translate into ~570,000 tons of green methanol and ~326,000 tons of green ammonia per year.

Green methanol and ammonia supply pathways and costs

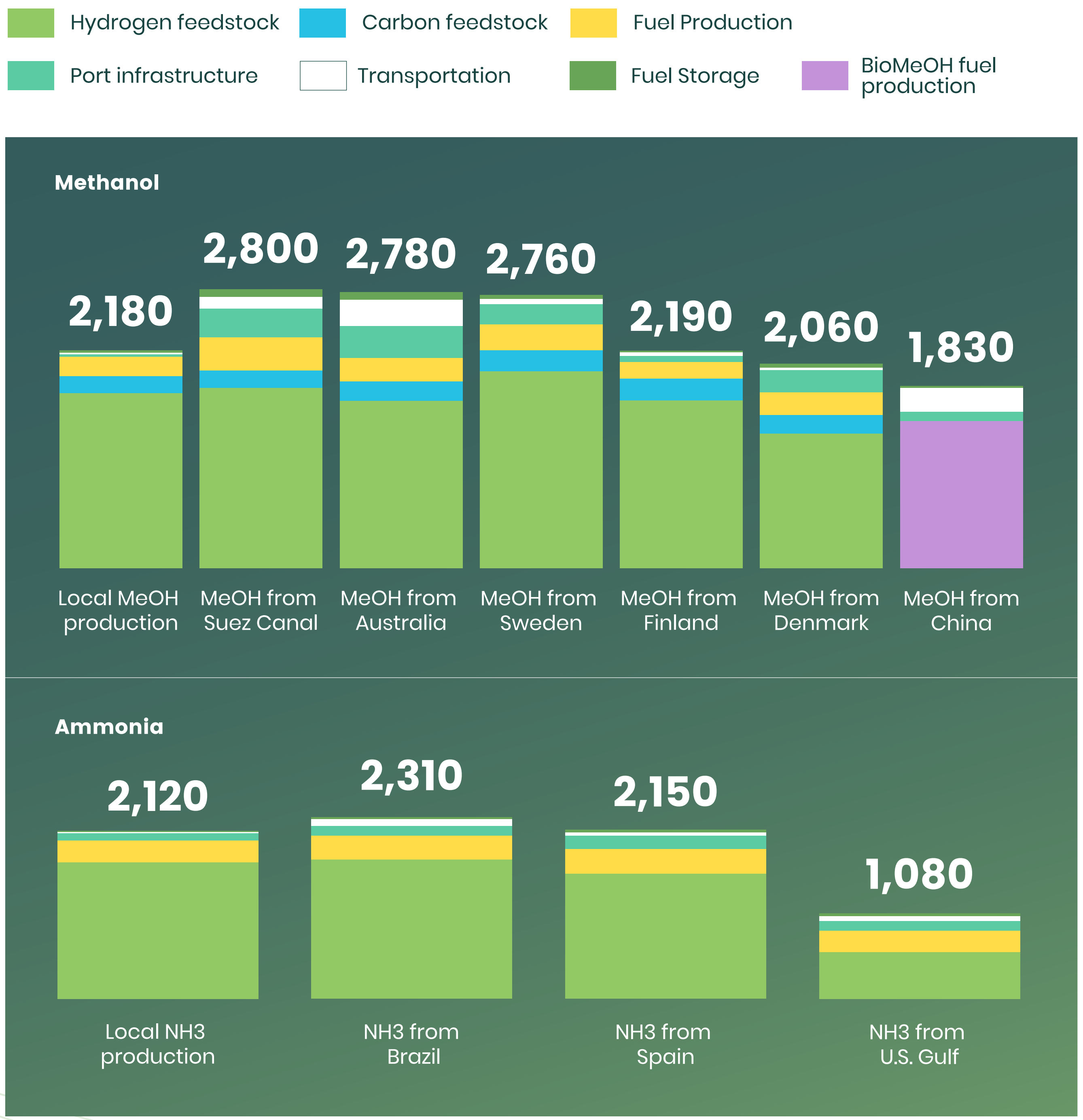
Thanks to Rotterdam's location on the North Sea, the port has good renewable energy potential. When distribution costs are accounted for, producing green hydrogen-based fuels locally in Rotterdam would be quite economical. E-methanol produced in the vicinity of the port would be competitive with methanol sourced from planned production in Finland and Denmark. Similarly, local ammonia supply would be competitive with planned volumes from low-cost regions like Spain and Brazil. This creates opportunities for local green hydrogen-based production at or around the port.

38 RMI analysis. Existing vessel order data is from DNV Alternative Fuels Insights (AFI) platform.

Exhibit 37

Rotterdam would likely source green methanol and ammonia from multiple production locations

Assessed green methanol and ammonia supply pathways for Rotterdam in 2030[39,40].
USD per metric ton VLSFO equivalent



Source: RMI analysis.

39 Existing infrastructure was not considered in port infrastructure costs for these scenarios.
40 The Egyptian and Australian methanol projects are relatively small. Their port infrastructure costs could be ~$200 per ton VLSFO equivalent lower if the exporting port reaches the suggested demand threshold of 200,000 tons per year. This threshold is likely to be met if a port participates in other methanol exporting and bunkering activity. For more information on the how bunkering benefits from economies of scale, see Exhibit A2.

However, Rotterdam is also a significant industrial cluster and several of the industries in the port's hinterland are seeking to use hydrogen for decarbonization[xliii,xliv]. Given the level of existing development in the port's estate, its location in a densely populated area, and the pressure it would place on scarce green electrons, stakeholders suggest it would be challenging to accommodate the production required to meet the port's wider hydrogen demand through local production. As such, the port is expected to import most of its green hydrogen-based fuel supply.

There are a variety of locations that Rotterdam could explore for green methanol and ammonia imports.

The trade modeling suggests that green ammonia imports could come from a combination of the US Gulf Coast, Spain, and Brazil, specifically the production planned at the Port of Pecem, which is co-owned by Port of Rotterdam. While Spanish and Brazilian volumes would be roughly the same cost as local production - in the low to mid-$2,000s per metric ton VLSFO equivalent - US ammonia would be nearly half this cost.

Though US-produced green fuels are likely to be in high demand, Rotterdam can benefit from EU incentives for hydrogen imports, lower-emission fuel demand created by the EU ETS and FuelEU Maritime, and the size of its likely hydrogen market. It is therefore likely to be in a strong position to secure a share of US exports. But it should be noted that the EU's draft Renewable Energy Directive could limit the potential for European ports like Rotterdam to import US green fuels. The draft additionality requirements in the Directive disallow fuel from some projects that benefit from renewable electricity incentives, like the renewable energy production tax credit provided by the IRA, after 2028. If these draft requirements are accepted in the final regulation, they could limit the window of opportunity for hydrogen imports from the US to Rotterdam to the period before 2028.

In a scenario in which a high proportion of projects reach FID, the modeling suggests that the cheapest available green methanol imports to the port would come from within Europe, namely planned e-methanol production in Denmark and Finland. Imports from countries like Denmark or Finland would be roughly on par with local production in terms of cost and able to meet the scale of demand assumed for Rotterdam. If fewer projects reach FID, the modeling suggests that the port would require a broader, more global portfolio of green methanol imports to satisfy the level of demand assumed here, including not only e-methanol production in the EU, but e-methanol from Australia and Egypt and bio-methanol from China.

Overall, the model suggests European production would form the backbone of Rotterdam's green methanol and ammonia supply this decade, supplemented by global import to minimize costs and/or bolster fuel volumes.

Rotterdam is an interesting border case within the archetype framework. While imports are likely to be the most feasible pathway for the port to source the large volumes of low-cost green methanol and ammonia it could require, there are also clear opportunities to produce green methanol and ammonia in the vicinity of the port from a cost perspective. Though the port falls within the Importing Incumbent archetype, it also, therefore, has features of the Producing Incumbent archetype. Decisive factors and influencers determining the best supply strategy for Rotterdam– including cross-sectoral demand, system efficiency considerations, and spatial constraints - are not included in the study's techno-economic model. This highlights the importance of stakeholders building on the study's framework, using supplementary data sources to fine-tune their strategies.

Methanol and ammonia bunkering readiness and progress

Exhibit 38

Rotterdam has developed methanol bunkering capability and is working on ammonia bunkering

Summary of Rotterdam's progress towards ethanol and ammonia bunkering.

	Port readiness	Infrastructure	Regulatory framework	Fuel sourcing	Generating bunker demand
Methanol	• Rotterdam has reached **Port Readiness Level eight** for methanol bunkering	• Rotterdam is the **largest methanol hub in Northwestern Europe** • Rotterdam **currently offers methanol bunkering on an ongoing basis** • Additional storage capacity will be needed • A dedicated methanol bunker barge expected to be deployed by end of this year	• Currently bunkering methanol successfully	• GIDARA is developing a green methanol facility, **expected to come online in 2026** • X-Press Feeders have **offtake agreement** with OCI HyFuels to **supply green methanol to Rotterdam**	• The port has put in place incentives like ZEMBA to attract first-mover shipowners • Under ZEMBA, Rotterdam will offer a **port fee reduction for bunkering sustainable fuels** • Involved in **green shipping corridor** initiatives with: • Singapore • Multiple EU ports
Ammonia	• Rotterdam has reached **Port Readiness Level five** for ammonia bunkering	• **First ammonia bunkering operation scheduled to take place second half of this year** • Multiple terminals are operationalizing **new ammonia storage terminals by 2026/7** • **Bunkering** infrastructure can **capture synergies** with energy **import** infrastructure	• **Will obtain basis for a licensing framework for ammonia bunker suppliers** via Rotterdam's first ammonia bunkering operation • Acceptance of ammonia bunkering by stakeholders may be a challenge	• Rotterdam has **80+ collaborations for supply of hydrogen from low-cost production locations** • First imports are **likely to be in the form of ammonia** • Rotterdam will be supported **in sourcing US ammonia imports** as a member of the H2TC	

Port Readiness

Rotterdam has been a global first mover in preparing for methanol and ammonia bunkering. The port is estimated to have reached PRL eight for methanol - system for bunkering of fuel complete and qualified – and PRL five for ammonia - framework for bunkering designed - in the IAPH's Port Readiness Level framework.

Infrastructure

The port is the largest methanol hub in Northwestern Europe and there are several terminals within the port capable of handling methanol, including EVOS, Vopak, ETT, and Koole's terminals. However, investment in additional jetty capacity is likely to be required for large-scale methanol bunkering, to mitigate congestion, cater to the fast bunkering expected by container liners, and potentially to segregate volumes of methanol with different lifecycle emissions profiles to comply with current Dutch chain of custody requirements. A dedicated methanol bunker barge will be deployed in the port from the second half of 2024, operated by OCI N.V. and Unibarge.

Infrastructure for the import and storage of ammonia is being built out and by the middle of the decade, the port will have several terminals able to handle ammonia at scale. OCI recently tripled the capacity of its existing ammonia terminal to 1.2 million tons per year and has the option for further expansion. Meanwhile, Air Products and Gunvor, ACE Terminal, and Koole Terminals are operationalizing new ammonia terminals by 2026/7. While primarily being developed with energy imports in mind, this infrastructure could also be leveraged for bunkering.

Regulatory Framework

Ship-to-ship methanol bunkering has successfully taken place several times, including the Laura Maersk during her maiden voyage to Copenhagen in summer 2023. As such, the Port of Rotterdam now offers methanol bunkering to sea-going vessels on an ongoing basis.

The port's first ammonia bunkering operation is scheduled to take place in the second half of 2024, making it among the first ports in the world to trial ammonia bunkering. The trial is intended to provide the basis for a licensing framework for ammonia bunker suppliers, enabling the scale-up of ammonia bunkering at the port from a regulatory point of view.

The port authority notes that the safety of zero-emission bunkering, particularly ammonia bunkering, will require ongoing attention. Acceptance of ammonia bunkering by stakeholders, local residents, and regulators may be a challenge, with the regional environmental protection agency DCMR having voiced concerns about the safety of large-scale transportation and handling of ammonia at the port[xlv].

Fuel Sourcing

The port has been proactive in securing hydrogen supply. It has over 80 collaborations and a global portfolio of feasibility studies and MOUs for supply of hydrogen, including with low-cost producers like Australia, South Africa, Saudi Arabia, Brazil, and Morocco[xlvi]. The first imports of hydrogen are likely to take the form of ammonia. The import of hydrogen in the form of ammonia is likely to increase ammonia bunker supply at the port.

There is also momentum for green methanol supply within the port, albeit at a smaller scale. Work is underway by GIDARA to develop a bio-methanol facility at the port, which could produce ~90,000 tons of the fuel per year starting 2026. Meanwhile, X-Press Feeders has entered an offtake agreement with OCI HyFuels supplying green methanol at the Port starting this year - one of the first deals of its kind in the industry.

Finally, the port is a member of the Transatlantic Clean Hydrogen Trade Coalition, a partnership connecting fuel producers in the US Gulf with European customers, which is expected to facilitate Rotterdam sourcing US ammonia imports.

Demand

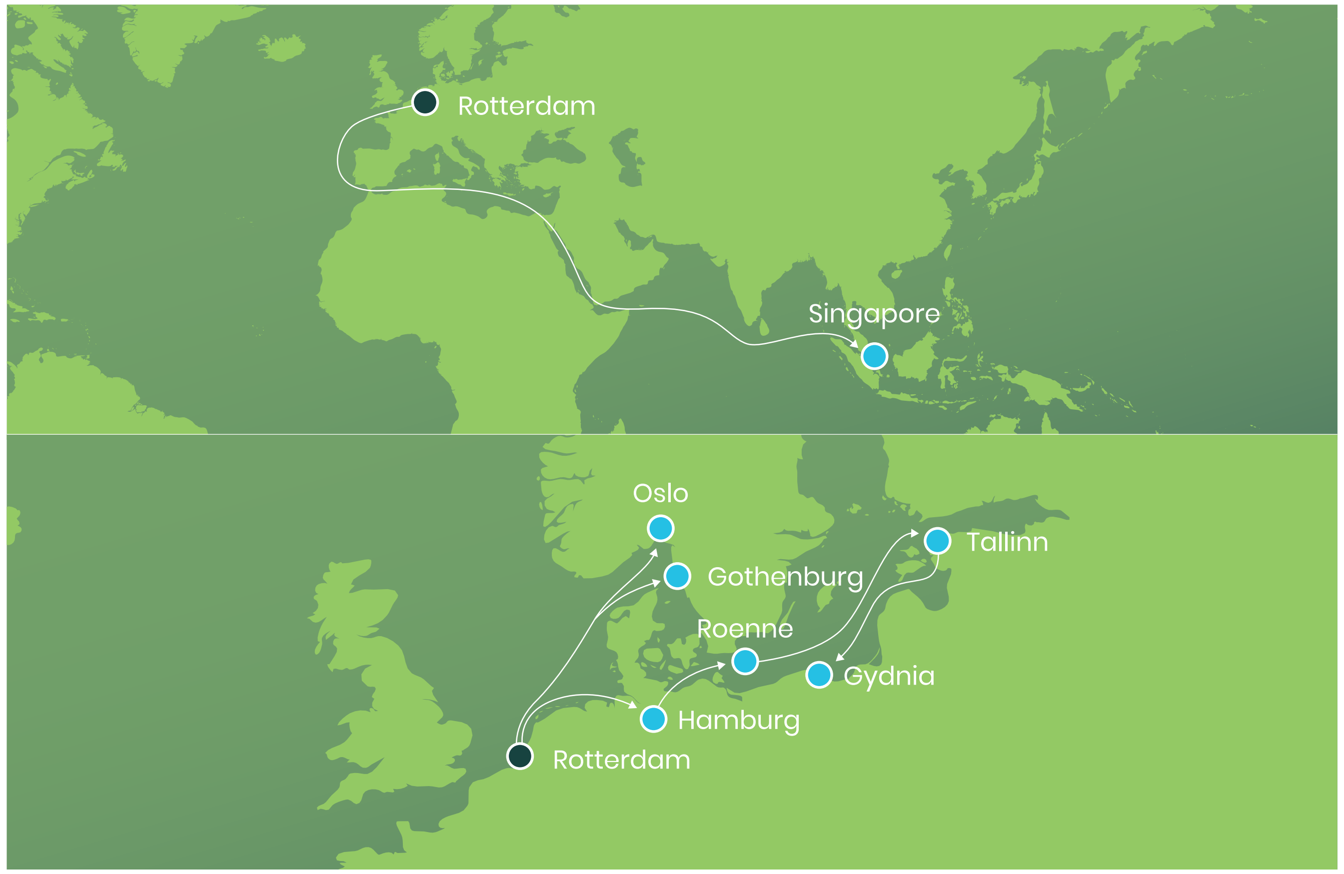
The port considers the "chicken-and-egg" problem – where ports cannot invest in zero-emission bunkering infrastructure in the absence of clear levels of demand for new fuels and shipowners cannot deploy new vessels without assurance about ports' ability to supply the fuels– a continuing challenge in developing methanol and ammonia bunkering. It is therefore taking several actions to help stimulate demand for zero-emission bunkers.

The port has put in place incentives to attract first-mover shipowners, including a scheme in support of the Zero-Emission Maritime Buyers Alliance (ZEMBA), under which a substantial port fee reduction will be offered to ships that bunker zero-emission fuels[xlvii].

Rotterdam's involvement in green shipping corridor initiatives has the potential to catalyze first-mover demand. It is working on a portfolio of green corridor initiatives, including short-sea corridors with Oslo, Gothenburg, and Hamburg-Roenne-Tallinn-Gydnia, and a deep-sea corridor with Singapore.

Exhibit 39

Rotterdam has several green shipping corridor initiatives



Source: Global Maritime Forum, "Annual Progress Report on Green Shipping Corridors" 2030.

If successfully operationalized, these corridors could create significant demand for zero-emission fuel by 2030, particularly the Singapore-Rotterdam Green and Digital Shipping Corridor (which covers one of the busiest shipping routes in the world), the European Green Corridor Network (which can leverage EU policies to accelerate its development)[xlviii], and routes to the UK, which are the subject of bilateral collaboration between the British and Dutch governments[xlix].

Recommended next steps

The Port of Rotterdam has reached a high level of regulatory, infrastructural and supply readiness, putting it on track to offer zero-emission bunkering at scale by 2030. At the same time, risks around stakeholder and community acceptance of a large increase in ammonia volumes, as well as challenges in activating first-mover demand, will need to be managed. The following next steps are recommended:

Catalyzing supply

- Consider setting a **target for up to 5% of fuel sold at the port to be zero-emission by 2030**, supporting the delivery of the IMO's targets and increasing shipowners and operators' confidence in the availability of zero-emission fuel.
- **Progress from MOUs to firm agreements** for green hydrogen, methanol, and/or ammonia supply as soon as feasible, to ensure access to the lowest-cost volumes. The analysis suggests that green ammonia imports from the US, Spain, and Brazil, and green methanol imports from the Nordics could be cost-effective options.
- As one of the biggest ports in Europe, **signal the relevance of the maritime sector** to fuel suppliers and governments to help ensure the sector benefits from green fuel imports and incentives. This could include using the port's influence to advocate for further supportive policy to close the fuel cost gap through earmarked funding under the EU Innovation Fund, H2Global/the EU Hydrogen Bank, and/or building on the Dutch Maritime Masterplan with an OPEX subsidy scheme.
- **Continue to participate in import/export coalitions**, which can provide a platform for engagement with foreign fuel suppliers and demand aggregation to secure lowest-cost fuel volumes, especially from the US.
- Mitigate the risks of permitting and approvals delays through **close engagement** with stakeholders, the community, local officials, and regulators.

Activating demand

- Set **ambitious 2030 targets** for zero-emission fuel/vessel uptake within its portfolio of **green shipping corridors** and accelerate the initiatives' operationalization.
- **Continue coordinating standards** for green methanol and ammonia bunkering with other ports to facilitate first-mover investments by shipowners and accelerate regulatory developments. This could include harmonizing port guidelines and chain of custody approaches with ports of call for anticipated first-mover ship operators and other global bunkering hubs.

Key recommendations moving forward

Given the urgency of the maritime industry to decarbonize and reach its interim 2030 targets, there is no time to delay the establishment of zero-emission bunkering at ports, particularly if the industry is to maximize the opportunities brought about by shipping's fuel transition.

While the bunkering ecosystem traditionally responds to customer demand, delivering on the IMO's targets is likely to require a new way of working. Proactive collaboration between first movers on both the supply and demand sides of the zero-emission fuel equation should be at the center of this new way of working. Different actors will be crucial and several priority actions can be identified for each:

Overarching action recommendations

Fuel producers and suppliers

Fuel producers and suppliers have an opportunity to **close the existing supply gap for green methanol**. Considering the maritime industry's projected demand for methanol, producers and suppliers could look into developing additional green methanol projects, especially in locations with favorable conditions for low-cost green hydrogen production, streamlined permitting timelines, and good availability of sustainable carbon.

Increasing engagement with the maritime industry can help fuel producers and suppliers better understand the sector's needs, while realizing the significant offtake opportunity created by shipping's transition.

Port authorities and bunkering ecosystems

Port authorities and bunkering ecosystems should take a number of actions moving forward.

As a key first step, they should **develop a strategy for zero-emission bunkering as soon as feasible**. This should reflect likely future fuel supply dynamics, such as those outlined in this report. Ports can start by assessing which archetype they fit within and their readiness to supply green methanol and ammonia by using, for instance, the IAPH's Port Readiness Level Tool.

Ports and actors in the bunkering ecosystem should **remain up to date with fast moving developments in shipping regulation and hydrogen policy**. This will allow them to keep their zero-emission bunkering strategies up-to-date and take advantage of opportunities to accelerate action.

Ports and actors in the bunkering ecosystem should work with shipping companies in **developing green shipping corridors**. They can play a role communicating with first-mover shipowners about the timelines for green methanol and/or ammonia bunkering readiness at the port and coordinating the scale up of bunkering capacity with the delivery of zero-emission vessel orders.

Shipowners and operators

Shipowners and operators can accelerate the deployment of zero-emission vessels by placing vessel orders and send clear fuel demand signals. This will in turn **build confidence in zero-emission bunkering infrastructure investments**.

They should **carefully consider fuel availability when deciding on zero-emission vessel technologies**. In the short to medium term, some ports and routes are likely to have better fundamentals for green methanol supply, while others may take better advantage of local conditions for green ammonia supply. Shipowners and operators need to ensure they **tailor their investments to the opportunities** in question.

Meanwhile, to support the growth of trade in green methanol and ammonia, shipowners and operators should also consider opportunities to **increase ammonia and methanol tanker capacity**. Given the multi-year lead times for vessel construction, investments in methanol and ammonia tankers need to be made in the next couple of years if they are to be available by 2030. Making these vessels methanol or ammonia-capable can help future-proof the investments and enhance the shipowner and operator's value proposition, by minimizing the lifecycle emissions of the transported fuel.

Finally, shipowners and operators should take advantage of emerging hydrogen incentives and shipping decarbonization regulations in closing the cost gap for zero-emission fuels, by, for example, **optimizing the bunkering strategies of their zero-emission vessels**.

Policymakers and regulators

Policymakers and regulators can support international trade in green methanol and ammonia, and unlock different supply geographies, by **harmonizing and/or enhancing mutual recognition of hydrogen and carbon certification schemes**.

To de-risk production, coordinate infrastructure development, and reduce costs, policymakers can **support green methanol and ammonia demand aggregation**. In particular, governments can help mitigate potential anti-trust challenges associated with collaboration between shipping companies in this space and connect shipping with land-based offtakers.

Building out the distribution and bunkering infrastructure for methanol and ammonia will be capital-intensive and may be perceived as high risk by private investors at this stage of the transition. Governments should step in to **incentivize the build out of methanol and ammonia bunkering infrastructure**, for instance through grants or **national subsidies and regulations**.

Governments should advocate for **IMO mid-term measures** that help create a level playing field that drives rapid adoption of, and investment in, zero-emission fuels in the 2030s. In parallel, they should **intensify multilateral collaboration on green corridors** and explore joint packages of support to help close the cost gap facing these first-mover initiatives. This could include better **coordination between national hydrogen and shipping decarbonization strategies** especially providing demand-side incentives for the use of green hydrogen-based fuels in shipping.

Port archetype recommendations

Ports can use the archetype framework as a starting point to structure their approach to green methanol and ammonia bunkering.

The case studies can be used to identify packages of priority actions that each of the archetypes should consider. Recommended actions for each archetype follow.

Importing Incumbents

These ports should focus on engaging with first-mover segments, locking in fuel supply and harmonizing bunkering guidelines with other ports. Importing incumbents can:

- Establish **MOU and/or undertake feasibility studies with partners in low-cost regions**. Doing so early will help earmark the lowest-cost volumes of green methanol and ammonia.
- Initiate or **participate in hydrogen import/export coalitions** to provide a platform for engagement between fuel suppliers and offtakers and help aggregate demand.
- **Coordinate standards** for green methanol and ammonia bunkering with other ports in order facilitate investments by shipowners and accelerate regulatory developments (for instance by harmonizing port guidelines and chain of custody approaches).
- **Engage likely first movers** to activate demand for green methanol and ammonia bunkering. Promising first-mover segments include dry bulk for ammonia and container and ferry for methanol. Developing **green corridors** on impactful and feasible routes could additionally be an effective framework for doing so.

Producing Incumbents

Producing Incumbents' strategy should focus on the following priorities:

- **Engage likely first-mover segments** to activate demand for green methanol and ammonia bunkering, including car carriers and dry bulk for ammonia and container and ferry for methanol. Similarly to the importing incumbents, impactful **green corridors** could be an effective framework for doing so.
- Set up **green export routes** to supply low-cost green fuel to other ports for use in shipping and industry. These export corridors could even be made into **green shipping corridors** if the vessels transporting clean ammonia/methanol on the route are also powered with ammonia/methanol. This would allow stakeholders to take advantage of the low barriers to the implementation of ammonia/methanol as a fuel onboard product carriers while enabling fuel producers to provide a lowest-GHG value proposition.
- **Coordinate standards** for green methanol and ammonia bunkering with other ports. Harmonized standards, port guidelines, and chain of custody approaches facilitate first-mover investments by shipowners and accelerate regulatory developments.

Future Exporters

The Future Exporters' priority actions combine some of the recommendations for the two previous groups while placing a focus on fuel targets and financing mechanisms.

- Similar to previous archetypes, Future Exporters should **engage likely first-mover segments** (dry bulk and automotive carriers for ammonia, container and ferry for methanol) and consider **green corridors** on impactful and feasible routes. Additionally, they can partner with ports that fall within the Importing Incumbent archetype.
- To attract these first-mover segments, ports can implement **incentives for zero-emission ships**, which could include reductions in port fees and/or preferential berthing for zero-emission vessels.
- For future exporters it may be more viable to **consider focusing on one zero-emission fuel pathway** and, in conjunction, they could also aim to set up **green export routes** to supply low-cost green fuel to other ports for use in shipping and industry.
- Ports could further explore making these export corridors into **green shipping corridors** by powering the vessels transporting clean ammonia/methanol on the route with ammonia/methanol. This would allow stakeholders to take advantage of the low barriers to the implementation of ammonia/methanol as a fuel onboard product carriers while enabling fuel producers to provide a lowest-GHG value proposition.

Future exporters can also take a number of viable actions to reduce the costs of establishing zero-emission bunkering and to bring down the fuel cost gap:

- To minimize the last-mile premium, future exporters could consider a **target of 10% zero-emission fuel sales by 2030** (aligning with the IMO's upper ambition level), or another supply target keyed to 200-300,000 tons of demand threshold. To further help offset the last-mile premium, they may also explore opportunities to access **capital grants** or preferential loans, and **customize infrastructure** build-out based on potential demand ramp-up.
- Ports can also consider **collaborative offtake opportunities**, including between different shipping segments, green corridors, and other sectors to scale quicker while lowering costs and increasing fuel availability.

Bespoke Players

Bespoke Players can develop their bunkering strategies by including a combination of recommendations across all archetypes:

- To manage the cost and complexity of zero-emission bunkering and infrastructure investment costs, these ports can consider focusing on **one zero-emission fuel pathway** in the near term.
- To earmark the lowest cost volumes of green methanol/ammonia, these ports should seek to establish **MOU's and/or undertake feasibility studies with partners in low-cost regions.**
- In parallel, they should **engage likely first movers** (dry bulk for ammonia, container and ferry for methanol), through a number of actions:
  - **Green corridors** to create a framework for aligning first movers.
  - **Partnerships with ports** that fall within the Producing Incumbent or Importing Incumbent archetypes.
  - **Incentives for zero-emission ships** to attract first movers to bunker at the port, such as reductions in port fees and/or preferential berthing for zero-emission vessels.
- To minimize the last mile premium, Bespoke Player ports can:
  - Consider a **target of 10% zero-emission fuel sales by 2030** (aligning with the IMO's upper ambition level), or another supply target keyed to 200-300,000 tons per year demand threshold.
  - Explore opportunities to access **capital grants** or preferential loans, and **right-size infrastructure** based on potential demand ramp-up.
- Finally, exploring **collaborative offtake opportunities** between different shipping segments, green corridors, and other sectors, can help scale bunkering quicker by lowering costs and increasing fuel availability.

This report has shown a path forward and a set of shared priorities for actors in the bunkering ecosystem for scaling green methanol and ammonia bunkering this decade. It has reinforced the opportunities associated with shipping's fuel transition, including for the growth of new bunkering hubs and for new countries to participate as producers in the marine fuel market. While there remain challenges and uncertainties, there is no time to delay if the industry is to meet its 2030 targets and seize these opportunities.

Annex

1. Port characteristics sensitivity analysis

Key factors influencing ports' green methanol and ammonia sourcing strategies

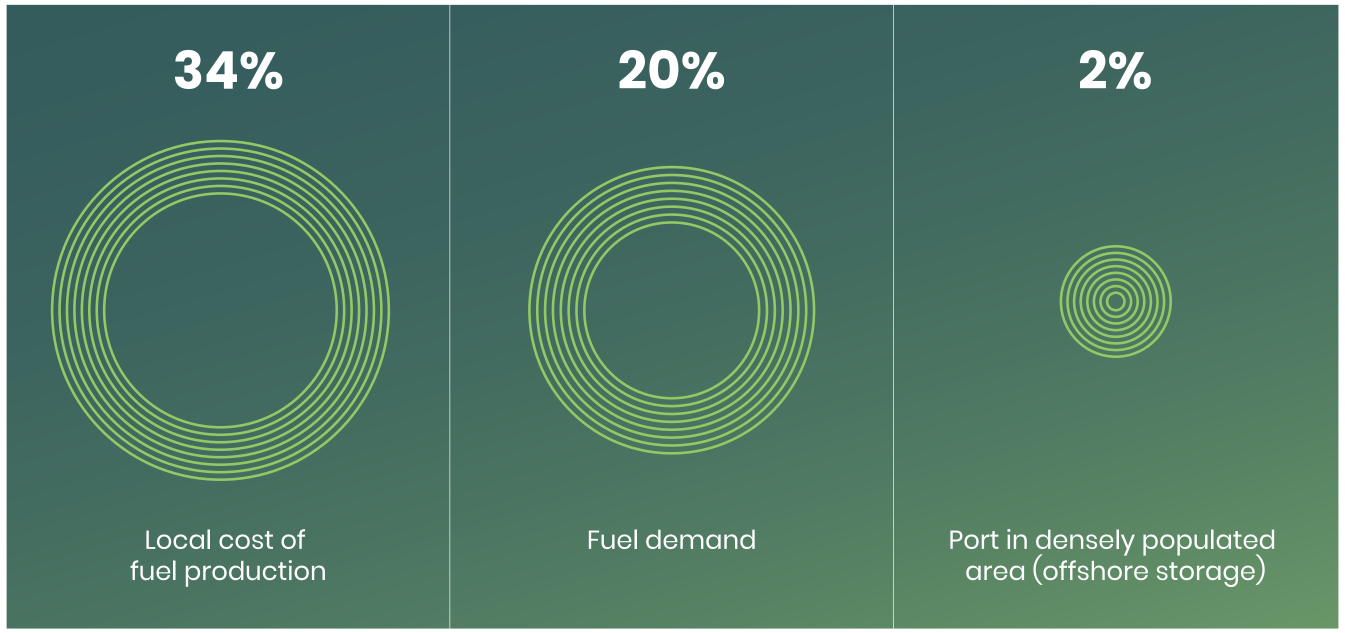
The importance of several different factors on ports' green methanol and ammonia sourcing strategies was examined for the report.

A prioritization exercise with the industry sounding board identified three factors with the greatest expected influence on ports' fuel sourcing - i) the size of fuel demand at the port, ii) local cost of green hydrogen-based fuel production, and iii) proximity to populated areas. The relative impact of these factors on the delivered cost of fuel was then analyzed. The results showed that fuel demand and the cost of local green-hydrogen-based fuel production have the most significant impact.

Exhibit A1

Local cost of fuel production and fuel demand volume have the highest impact on the delivered cost of fuel

Impact of characteristics on delivered cost of fuel in % difference between lowest and highest impact of scenarios tested. Percentages/ impact varies based on the scenarios tested.



Source: RMI analysis.

Local cost of fuel production: Determining impact from solar and wind resources

The local cost of green methanol and ammonia production was determined by assessing the renewable production capacity factors for wind and solar in the vicinity of the port, the financial landscape of the country, and the impact of the Inflation Reduction Act (IRA) on US-produced fuel. As shown in Exhibits 8 & 9, the lowest fuel is subsidized via the IRA, has low cost of capital, and good renewables. The impact from the IRA, cost of capital, and renewable resources can be observed in the Production costs subsection of chapter 1a of this report.

Fuel demand: Determining last mile impacts

As shown in Exhibit A2, there is a clear relationship between levelized bunkering cost and bunkering volume, with costs dramatically higher at lower levels of bunkering volume. This is driven by the storage infrastructure, which due to high capital expenditure and low operating costs, benefits massively from increased throughput.

The report references discrete thresholds – ~200,000 tons per year and ~300,000 tons per year of methanol and ammonia respectively - as the point where last mile infrastructure becomes less relevant. These thresholds were determined by evaluating where the levelized port infrastructure starts to become less significant and less sensitive to the bunker volume. These values act as general goals and shouldn't be taken as absolutes. Ports can continuously reduce last mile cost impacts beyond these thresholds by bunkering higher quantities of methanol or ammonia.

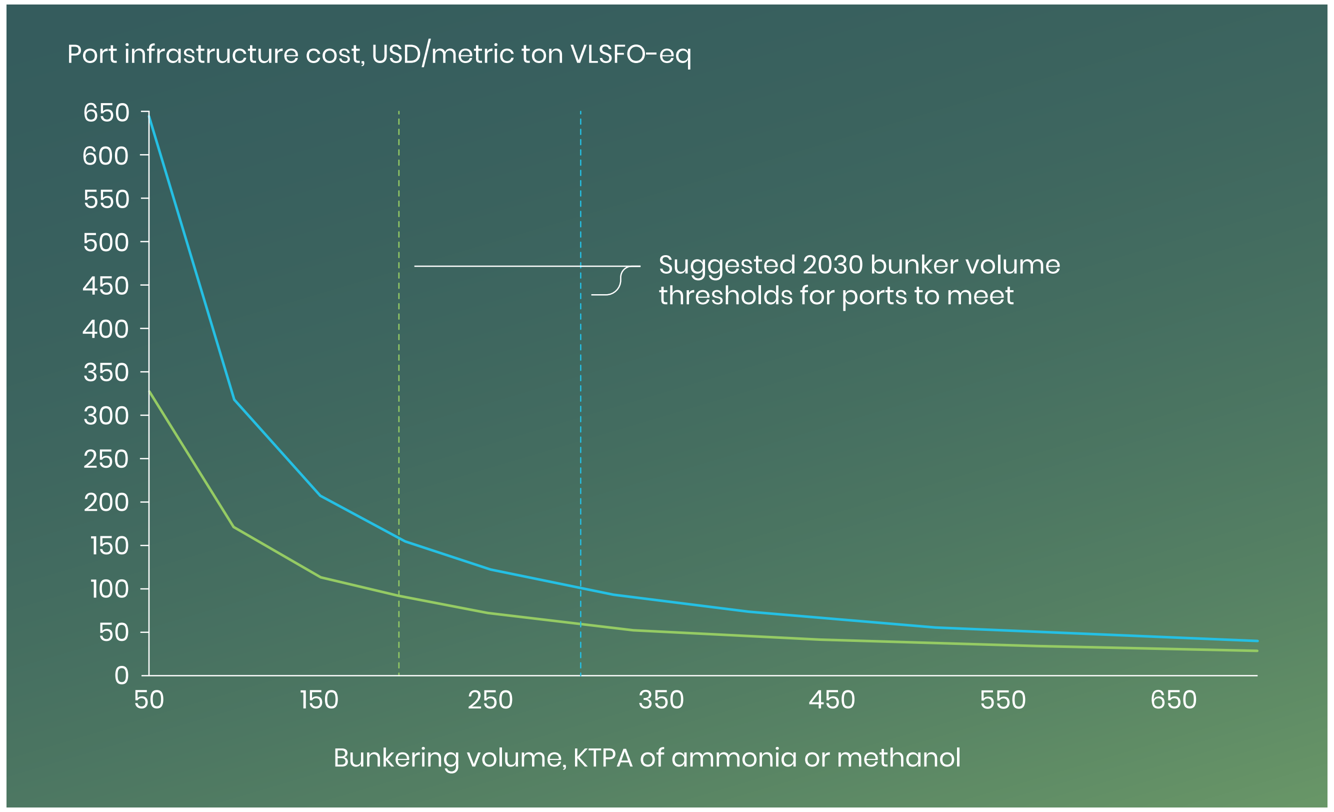
It is important to note that ammonia benefits more from economies of scale than methanol, due to the higher capital expenditures associated with ammonia storage.

Exhibit A2

Levelized port infrastructure cost is significant, but it becomes less significant as bunker demand increases

Impact on levelized bunkering costs from a port's bunker volume of ammonia or methanol
USD per metric ton of VLSFO equivalent

Methanol   Ammonia



Source: RMI analysis.

Densely populated areas: Determining offshore storage cost impact (only tested for ammonia)

On the assumption that offshore storage of methanol or ammonia could improve safety, public opinion, and space considerations for ammonia, the cost of offshore vs onshore storage of the fuels was compared to understand the cost impact of proximity to population-dense areas[1].

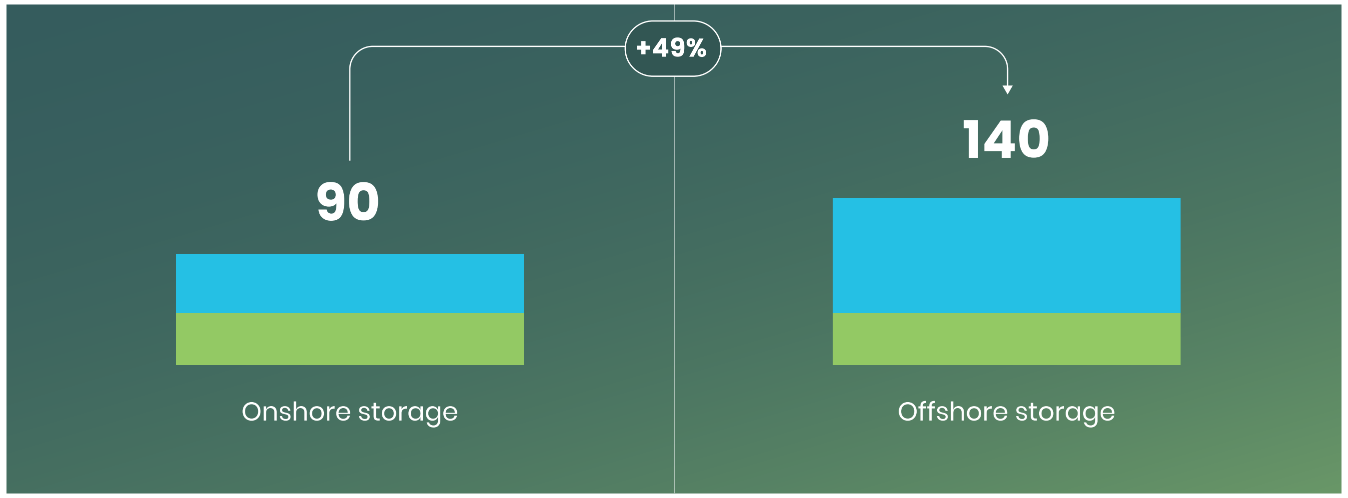
Though offshore subsea storage solution has cost efficiencies from lower electricity consumption, it is more expensive on a cost-per-ton basis, due to having a much shorter lifetime of ~10 years. As seen in Exhibit A3, offshore ammonia storage can increase last-mile infrastructure costs by ~49%, which translates into a ~2% increase in the delivered cost of green ammonia.

Exhibit A3

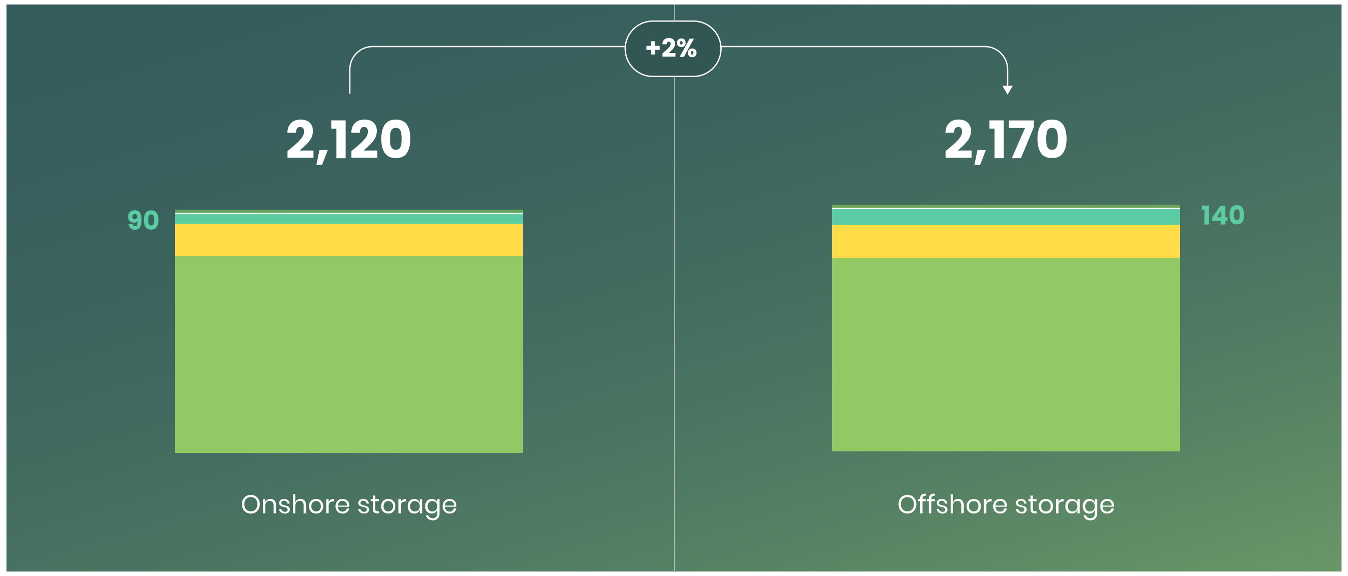
Offshore ammonia storage is more expensive than conventional onshore storage, but this cost difference doesn't significantly impact total delivered cost

Cost difference to port infrastructure and the total cost of ammonia when offshore portside storage is used instead of onshore portside storage at the port of Rotterdam
USD per metric ton of VLSFO equivalent

Portside storage   Bunker vessel



Hydrogen feedstock   Fuel Production
Port infrastructure   Transportation   Fuel Storage



Source: CAPEX and lifetime assumptions based on expert feedback; RMI analysis.

2. Carbon costs

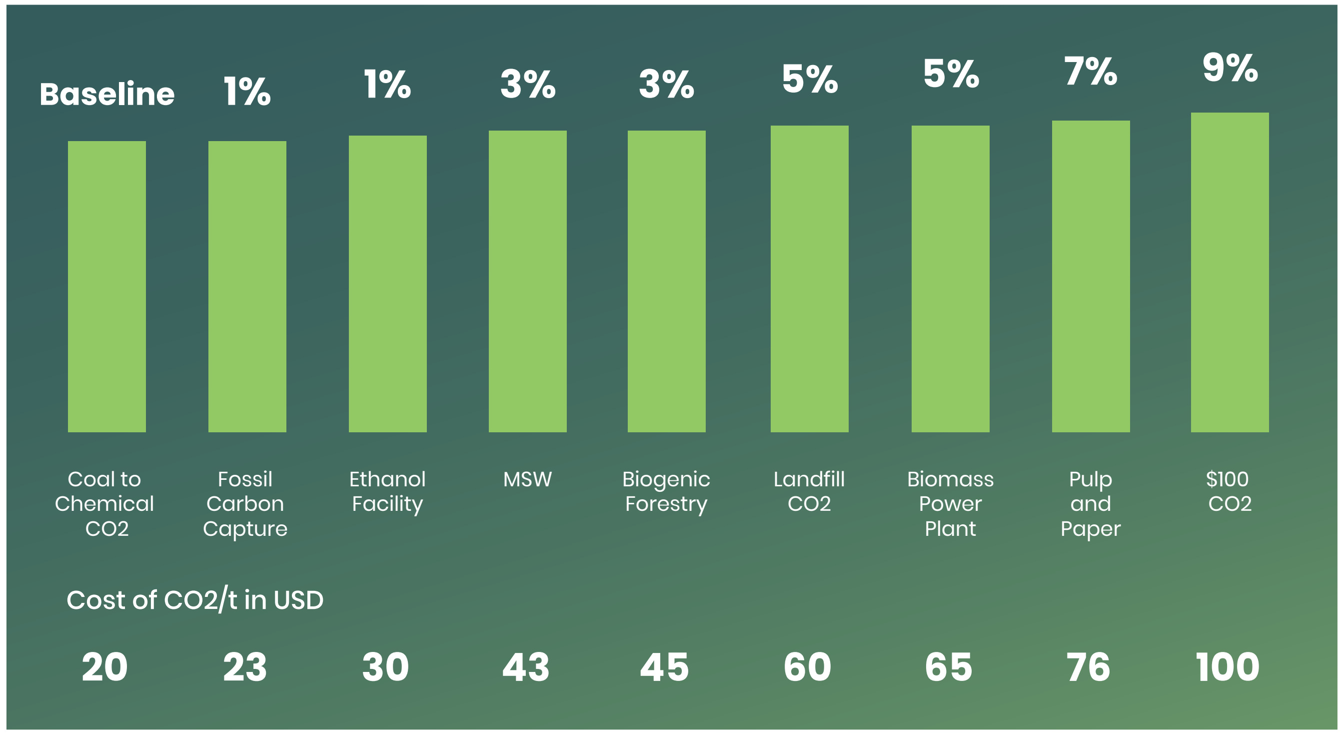
The production of e-methanol requires a carbon feedstock. The emissions intensity, expected availability, and cost vary across different carbon sources. Variations in the cost of carbon have relatively little impact on the cost of delivered e-methanol compared to hydrogen cost (i.e. renewable electricity cost and electrolyzer cost)[41].

The following exhibit evaluates potential costs for various potential carbon sources based on estimates from academic and other secondary sources. It should be noted that specific carbon sources may have different commercial pricing depending on the nature of a specific source location.

Exhibit A4

The cost of carbon doesn't have a significant impact on the delivered cost of methanol

Impact of carbon cost on delivered cost of methanol[42].



Source: RMI analysis.

A $100 per metric ton of carbon would increase the delivered cost less than 10% compared to the lowest cost of carbon options.

41 This statement concerns biogenic carbon cost, the cost of carbon associated with direct air capture (DAC) could impact the cost of delivered methanol more significantly on a 2030 timescale.

42 Assumes 1.4 tons of carbon needed per ton of methanol. Coal to chemical captured carbon assumed to be a proxy for an activated charcoal industrial process. Assumed e-methanol production in Lafayette Louisiana, and a ~200 km pipeline. CO2 costs across various sources are derived from literature review; market research and industry feedback indicate that CO2 prices are significantly higher due to scarcity and competition among fuel producers.

3. The Jones Act and how it impacts green ammonia and methanol trade dynamics

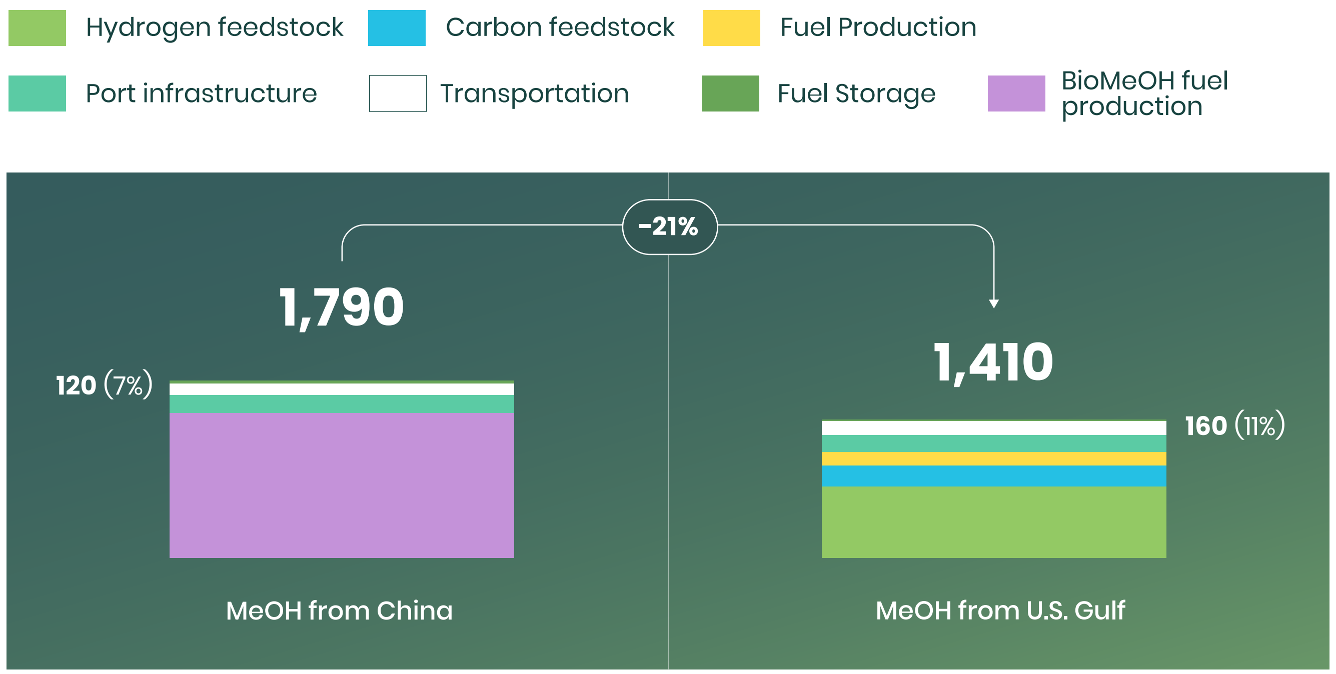
The Jones Act is a United States federal law that requires vessels transporting goods between US ports to be built, at least 75% owned, and operated by US citizens or permanent residents. The Jones Act increases the costs of maritime transportation between US ports due to the higher capital expenditure associated with building vessels at US shipyards, higher tax liability, and increased labor and charter costs. As a result, transporting e-ammonia or methanol between two US ports can be up to two times more expensive than equivalent international shipping.

For US ports like Seattle & Tacoma, the Act makes transporting fuels from Houston ~35% more expensive than from China, despite the voyage from Houston-Seattle only being 8% longer. However, due to the impact of the IRA, e-ammonia or methanol from Houston would still be lower cost option, with over 300 USD per metric ton difference in the delivered cost of ammonia compared to China.

Exhibit A5

The US Jones Act impacts the transport cost between two US locations, but likely won't significantly alter trade dynamics

Cost impact of the Jones Act on green methanol imports from the US Gulf vs China to Port of Seattle & Tacoma.



Source: RMI analysis.

4. Fuel project inclusion criteria for green methanol and ammonia cost curves

Exhibit 8 and 9 from section 1 of this report show the 2030 announced volumes of green ammonia and methanol available for the shipping sector by 2030 and modelled fuel costs. This section explains the methodology and assumptions behind these announced volumes. It is important to note that projects' production capacities and commercial viabilities are rapidly changing and difficult to predict. This report aims to capture the magnitude and cost of green shipping fuel currently expected to be available in 2030.

The 2023 International Energy Agency (IEA) hydrogen production project database was used as the starting point to compile a list of relevant projects. Projects were included if they 1) signaled interest in producing green hydrogen-based ammonia or methanol in the IEA database, 2) were noted to come online by 2030, and 3) had an estimated production volume (not capacity) of at least ~100,000 metric tons per year of hydrogen (for ammonia projects) or ~15,000 metric tons per year of hydrogen (for methanol projects)[43].

Other filters were applied to the IEA database, primarily to exclude projects that showed interest in non-shipping end-uses. Additionally, projects were excluded if their main energy source for hydrogen production was nuclear, offshore wind, or hydropower since that is prohibitive on a cost basis for 2030 and/or is not considered additional renewable capacity. Methanol projects were excluded if their carbon feedstock was non-biogenic.

Relevant projects were cross-checked with Rystad's database to validate projected 2030 production volumes, with the more conservative figure being used in the case of discrepancies. Our analysis also included additional methanol production projects that have entered into contracts with Maersk, per Maersk's public announcements. These announcements include several bio-methanol production projects, which are not represented in the IEA hydrogen project database.

After the resulting list of production projects was compiled, additional research and stakeholder input was used to further refine this list. The most notable exception was for the US Gulf Coast HyVelocity[li] hub. Part of their production volume was assumed to be for export-purposes based on expert input.

While the analysis generally relies on the IEA and Rystad, there are several organizations that publish green hydrogen, ammonia, and methanol project databases, such as Bloomberg New Energy Finance (BNEF) and the Methanol Institute[44] (for methanol only). The quality of project-level information in the public domain varies widely; input from expert stakeholders can help produce a more accurate representation of the project landscape.

43 The ammonia production project volume minimum was larger than methanol's because the announced methanol project volumes were generally smaller on average than announced ammonia project volumes.
44 There has been a recent update of the Methanol Institute's methanol project database that projects ~7.4 million metric tons of e-methanol with biogenic CO2 feedstock. It has not been possible to analyze the update in depth and adjust our analysis due to timing of the release. The discrepancy between the volumes can at least be partially explained by the fact that the Methanol Institute volume includes all methanol supply, including end-uses which are not shipping related.

5. Trade flow scenario allocation logic

The 2030 green methanol and ammonia fuel flow modeling, seen in Exhibits 10 through 13, modeled a scenario in which ports seek to provide 5% of their total bunker fuel supply as green methanol and/or ammonia by 2030, in accordance with the IMO target.

Almost thirty ports were included, including eighteen of the world's current larger bunkering hubs and ten smaller bunker ports representing the Future Exporter and Bespoke Player archetypes. Available fuel was based on the announced volumes of green methanol and ammonia assessed in section 1 of the report.

The model followed a series of allocation rules relating to the demand side (ports' ammonia or methanol demand) and supply side (fuel projects being assigned to ports):

Demand side: Assumptions on ports' 2030 alternative fuel bunker demand

Ports' overall bunker demand in 2030 is based on their existing level of bunker demand with an applied 0.8% reduction, reflecting projected demand by 2030 and improvements in energy efficiency in the sector[lii]. Ammonia or methanol demand is determined by taking five percent by energy of the ports' total 2030 overall bunker demand.

- Because the Pilbara Ports and Boegoebaai do not offer bunkering today, they are instead assumed to have a 2030 bunker demand of 100 thousand metric tons per year of ammonia.
- Ports that currently bunker more than a total of 3 million metric tons of conventional fuel are assumed to offer both ammonia and methanol bunkering in 2030, in the absence of announcements to the contrary. An assumed split of 65% methanol and 35% ammonia by energy is then assumed, based on an extrapolation from existing methanol and ammonia vessel orders[45]. Ports with bunker volumes totaling less than 3 million metric tons of conventional fuel are assumed to bunker either ammonia or methanol, based on the ports' stated plans and expert input.
- If a port needs more than 250 thousand tons per year of methanol or ammonia, the port is assumed to diversify their fuel supply by sourcing volumes from more than one production project.

Supply side: Assumptions on how fuels from production projects are assigned to ports

Project volumes are assigned to ports in the order of lowest to highest levelized production cost per metric ton of fuel. Ports generally get priority based on their bunkering demand, with larger ports getting assigned fuel first. This is due to the assumed higher bargaining power larger bunkering ports have. There are a few additional factors that determines how ports are assigned fuel:

1. Ports are allocated domestically produced fuel if this fuel is available. If a port has publicly announced plans to import fuel from a specific project, it is allocated this fuel.
2. EU ports that have shown public interest in bunkering green fuels receive preferential priority and are allocated fuel before other ports. This is due to EU ETS and FuelEU Maritime, which incentivize EU ports to

45 RMI analysis. Existing vessel order data is from DNV Alternative Fuels Insights (AFI) platform.

be first movers in providing green fuels. Relevant EU ports receive fuel in order of largest ammonia or methanol bunkering demand to smallest.

3. After the two steps above are done, the remaining ports get assigned the remaining ammonia or methanol until either all the ports receive fuel (in the case of ammonia allocation)or the fuel supply runs out (in the case of methanol allocation). Once again, larger ammonia or methanol bunkering demand ports receive fuel before smaller ammonia or methanol bunkering demand ports, and projects are allocated from lowest levelized cost to highest levelized cost.

6. Overarching cost modeling assumptions[46]

Levelized hydrogen cost model assumptions for 2030 production		
45V and 45Y subsidies considered if the fuel is produced in the US (45Z not considered). Ratio of wind and solar is optimized based on renewable capacity factors from Renewables Ninja.		
Electrolyzer total installed CAPEX (including Stack, Balance of Plant, and Engineering, Procurement, & Construction)	882 USD per kW / 952 USD per kW for US subsidized[47]	RMI assumption. Based on stakeholder interviews and DOE, "Pathways to Commercial Liftoff: Clean Hydrogen" (2023)
Electrolyzer energy requirement	50 kWh per kg / 53 kWh per kg for US subsidized	RMI assumption
Wind CAPEX	700 USD per kW / 1000 USD per kW for US subsidized	NREL Annual Technology Baseline (2022)
Solar CAPEX	620 USD per kW / 750 USD per kW for US subsidized	NREL Annual Technology Baseline (2022)
Hydrogen storage CAPEX	0.20-0.90 USD per kg for pipeline / 0.30 USD per kg for salt cavern	RMI assumption. Adapted from DOE, "System Level Analysis of Hydrogen Storage Options" (2019) and BNEF, "Hydrogen: The Economics of Storage" (2019)
Levelized green ammonia cost model assumptions for 2030 production		
Overall CAPEX	611 USD per metric ton ammonia[48]	RMI assumption based on Fasihi et al., "Global potential of green ammonia based on hybrid PV-wind power plants" (2021) and Nayak-Luke et al., "Techno-Economic Aspects of Production, Storage and Distribution of Ammonia" (2021)
Electricity consumption	719 kWh per year	Cesaro et al., "Ammonia to power: forecasting the levelized cost of electricity from green ammonia in large-scale power plants" (2020)
OPEX	4% of CAPEX	Lloyd's Register & UMAS "Fuel production cost estimates and assumptions" (2019)

46 This annex provides insights into modeling assumptions on a high-level. There are additional smaller-impact cost assumptions that are not included in this report for simplicity.
47 US subsidized scenarios are assumed to have slightly more conservative assumptions because producers will have to meet stricter manufacturing and labor provisions.
48 Ammonia CAPEX was not scaled in included scenarios in this report since projects were of similar magnitude.

Levelized green e-methanol cost model assumptions for 2030 production			
Default biogenic carbon cost assumption	55 USD per metric ton carbon		RMI assumption
Carbon capture from ethanol facility (only used if project specified this source)	30 USD per metric ton carbon		IEA, "Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019"
CAPEX	263- 562 USD per metric ton MeOH, depending on size of plant		Nyári, "Techno-economic feasibility study of a methanol plant using carbon dioxide and hydrogen" (2018)
Fixed OPEX	4% of CAPEX		Lloyd's Register & UMAS "Fuel production cost estimates and assumptions" (2019)
Electricity requirement	216 kWh per metric ton MeOH		Lloyd's Register & UMAS "Fuel production cost estimates and assumptions" (2019)
Levelized bio-methanol cost assumptions for 2030 production			
Fuel production cost	714-764 USD per metric ton MeOH		IRENA, "Innovation Outlook: Renewable Methanol" (2021)
Storage (at the production site) cost assumptions			
	Ammonia	*Methanol*	*Source(s)*
CAPEX	843-1,418 USD per metric ton NH3	417-614 USD per metric ton MeOH	RMI assumption based on HyDelta, "Technical analysis of hydrogen supply chains" (2022) and Nayak-Luke et al., "Techno-Economic Aspects of Production, Storage and Distribution of Ammonia" (2021)
OPEX	3% of CAPEX	0.60% CAPEX	HyDelta, "Technical analysis of hydrogen supply chains" (2022); Lloyd's Register & UMAS "Fuel production cost estimates and assumptions" (2019)
Electricity requirement	37.8 kWh per metric ton MeOH	None	Lloyd's Register & UMAS "Fuel production cost estimates and assumptions" (2019)
Tank utilization	80%		Industry experts
Maximum frequency of tank usage	20 times/year		Industry experts

Transport cost assumptions		
Via rail	0.095 USD per metric NH3 or MeOH per km	Industry experts
New pipeline		
CAPEX	857,000 USD per km	Nayak-Luke et al., "Techno-Economic Aspects of Production, Storage and Distribution of Ammonia" (2021)
OPEX	500 USD per km per year	
Booster station capital expenditures	2,220,000 USD	
Booster station electricity requirement	800 KW	
Assumptions behind oceangoing vessel costs		
Laden energy consumption	363 kWh per day	Industry experts
Ballast energy consumption	323 kWh per day	Industry experts
Ship speed	15 knots	RMI assumption
Loading + unloading time	4 days	RMI assumption
Charter cost	23,000 USD per day / 80,000 USD per day if Jones Act applies	RMI assumption based on Salmon et al., "Green ammonia as a spatial energy vector: a review" (2021) and Argus Media, "Argus LNG daily" (2023)
Insurance cost	12,600 USD/day	RMI assumption

Port Infrastructure			
Portside storage			
	Ammonia	*Methanol*	*Source(s)*
CAPEX	1,156-1,418, USD per metric ton NH3	501-614 USD per metric ton MeOH	RMI assumption based on HyDelta, "Technical analysis of hydrogen supply chains" (2022) and Nayak-Luke et al., "Techno-Economic Aspects of Production, Storage and Distribution of Ammonia" (2021)
OPEX	3% of capital expenditures	0.60% of capital expenditures	HyDelta, "Technical analysis of hydrogen supply chains" (2022); Lloyd's Register & UMAS "Fuel production cost estimates and assumptions" (2019)
Electricity requirement	37.8 kWh per metric ton MeOH	None	Lloyd's Register & UMAS "Fuel production cost estimates and assumptions" (2019)
Bunker vessel (based on a chemical carrier powered by VLSFO)			
CAPEX	25 Million USD per bunker vessel	Industry experts	
Bunkering crew & other operational costs	8,000 USD per day	Industry experts	
Size	12,000 metric ton NH3/ MeOH	Assumption	
Bunker vessel utilization	60%	Industry experts	
Conversions			
Energy equivalency of ammonia to VLSFO	2.18 kg ammonia per kg VLSFO		
Energy equivalency of methanol to VLSFO	2.06 kg methanol per kg VLSFO		
Financial assumptions for countries			
Debt	70%		
Equity	30%		
Inflation Rate	2%		
Weighted average cost of capital and tax rate varied depending on country and according to Damodaran from NYU Stern.			
Bunker volumes of ports			
Current bunker volumes of the selected ports in the report were determined with Ship & Bunker (2022), industry stakeholders, Xinde Marine News (2021), and Bunker Spot (2019).			

7. Port Readiness Level Framework

Ports' estimated "readiness level" for methanol and/or ammonia bunkering are provided in each of the five port case studies.

The Port Readiness Level (PRL) for Marine Fuels Framework was developed by the World Ports Climate Action Program (WPCAP) and the International Association of Ports and Harbors (IAPH) Clean Marine Fuels Working Group. The framework provides a standard means of baselining a port's readiness for the bunkering of marine fuels, such as ammonia and methanol, using a nine-point scale similar to that used for evaluating technology readiness levels or TRLs.

Exhibit A6

The Port Readiness Level framework for Marine Fuels from WPCAP and IAPH can be used to quickly assess a port's current progress towards bunkering ammonia and methanol

Port Readiness Level (PRL) for Alternative Fuels on Ships (AFS)

Research	**PRL 1**	Fuel relevance assessed
	PRL 2	Interest of port stakeholders determinded
	PRL 3	Sufficient information gathered
Development	**PRL 4**	Vessel call or bunkering approach decided
	PRL 5	Vessel call or bunkering framework designed
	PRL 6	Vessel call or bunkering framework demonstrated in a closed environment
Deployment	**PRL 7**	Vessel call or bunkering system established on a project basis in an operating environment
	PRL 8	Vessel call or bunkering system completed and qualified
	PRL 9	Vessel call or bunkering service readily available

Source: WPCAP & IAPH.

8. Emerging learnings on ammonia bunkering safety

Below is an overview of resources with emerging learnings on ammonia bunkering safety.

Color Line Green Shipping Programme pilot study[liii]

- Conducted a Quantitative Risk Assessment for tank-to-ship and ship-to-ship bunkering of an ammonia-powered ship at the Port of Oslo, focused on third-party risk.
- The ship-to-ship concept was found to have acceptable third-party risk. Several specific risk reduction measures were proposed, in line with the ALARP principle. Second-party risk to crew and passengers onboard the ship was not assessed.

Global Centre for Maritime Decarbonisation ammonia bunkering safety study[liv]

- Undertook Quantitative Risk Assessment to three identified sites for potential cross-dock breakbulk, shore-to-ship bunkering, and ship-to-ship bunkering ammonia pilots in Singapore.
- A HAZID process identified and assessed 400 operational and locational risks associated with the pilots, but found them to all be low or mitigable.

Pilbara Ports Authority and Yara Clean Ammonia[lv]

- Assessed the potential risks and regulatory requirements for ammonia bunkering at the Pilbara ports in Western Australia.
- Found that ship-to-ship bunkering operations could be performed within acceptable risk levels at anchorages at Dampier and Port Hedland, the two main ports in the region.

Singapore Ammonia Bunkering Feasibility Study (SABRE)

- Performed an end-to-end technical (and commercial) feasibility study for ammonia bunkering in Singapore. Completed in March 2023 and initial findings shared during a webinar in September 2023[lvi].
- Progressed to a second phase, focused on establishing ammonia bunkering standards in Singapore and obtaining a provisional bunkering permit. To conclude in Q1 2024.

World's First Use of Ammonia as a Marine Fuel[lvii]

- Loaded liquid ammonia on The Fortescue Green Pioneer from the existing ammonia facility at Vopak Banyan Terminal on Jurong Island. The ship received flag approval from the Singapore Registry of Ships (SRS) and the "Gas Fueled Ammonia" notation by classification society DNV to use ammonia, in combination with diesel, as a marine fuel.
- Conducted crew training and safety drills in preparation of the operation and an ammonia plume model was developed to support the safety and incident response planning.

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