AN APPROACH TO

GREEN SHIPPING CORRIDOR **MODELING AND OPTIMIZATION**

ABS

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1 EXECUTIVE SUMMARY

Maritime decarbonization is a complex challenge with multiple pathways that are at various levels of technological and operational readiness. Because of the regional aspects and unique trading routes of the maritime industry, the shipping value chain has a unique opportunity to serve as a test bed for the implementation of infrastructure, development and application of novel technologies and adoption of alternative fuels. The establishment of green shipping corridors provides us the ability to test, calibrate and assess risk in a regionalized or specific industrial ecosystem which can be further scaled to other regions or sectors. To support the development and implementation of green shipping corridors, ABS has demonstrated the capability to help green shipping corridor value chain stakeholders make informed decisions as they transition into digitalized and more sustainable operations. Optimization and simulation tools are expected to play an expanding role in helping green shipping corridor value chain stakeholders in their decision-making process. Green shipping corridor represents a system-of-systems and each of these systems interact with each other in unique ways and modeling them using optimization methodology provides a framework for problem solving and collaboration. This insights publication provides a case study example of how this can be executed with approximations.

Green shipping corridors as a concept are likened to special economic zones at sea arenas where various value chain stakeholders can come together and deploy new technologies and business models that interact at full scale. The biggest advantage of such an initiative is to help diverse and disaggregated industry align and diversify their collective risks. Any green shipping corridor envisioned currently will require close collaboration between the different stakeholders such as shipowners, fuel providers and port operators. In addition, green shipping corridors will require an enabling environment where each of these value chain members can share risk at a smaller scale before scaling it up.

The purpose of this insights publication is to communicate the need of optimization models for resource planning and techno-economic analysis for a complex system-of-systems which is the “green shipping corridor.” This publication also provides a step-by-step logical methodology to achieve the same considering multiple variables and constraints. The input data in the developed models are approximations from publicly available sources. The scope of this insight is to look at the results from mostly two specific points of view which is the port and the shipowner who are at the center of this value chain and have the greatest impact on emissions.

Every green shipping corridor is expectedly unique as the geographical locations, behavior of the stakeholders, fuel availability, economy, trade patterns will be different. For example, a corridor may have commercially operating ships and port-operations that are utilizing alternative fuels derived from renewable energy with or without energy efficient technologies (EETs). Being able to simulate and optimize all those operational aspects is key to accelerating decarbonization across various stakeholders.

The development of a green shipping corridor begins by establishing a core group of stakeholders who will drive the development and implementation of the corridor, often with one organization or a third-party acting as a facilitator to guide the process. A working group develops a vision/charter and performs initial analysis (often called a pre-feasibility or feasibility study) to help set end state and intermediate goals. Based on this analysis, the working group develops phased plans to achieve reduction targets, then advocates for action by the stakeholders to implement those actions. Key decisions that focus on the critical building blocks of green shipping corridors are viable fuel pathways, policy and regulation, customer demand, and cross value chain collaboration.

The working group monitors implementation progress and attainment of goals, while continually reassessing options and strategies amid changing regulations/policies, technology availability, funding sources and operation incentives, etc. This is an iterative process informed by key analysis insights along the way.

Because of the number and variety of stakeholders involved in green shipping corridors, in some cases government agencies are expected to play a pivotal role in integrating individual stakeholder interests while testing and establishing policies. Figure 1 depicts how green shipping corridors can look when fully developed. Optimization and simulation models can help in resource planning and techno-economic analysis of the selected corridor while considering any permutation and combination of alternative fuels and technologies. In this way, such tools provide the ability to bring all stakeholders, industry, non-governmental organizations, and government together, to enable the exploration of the most optimal path forward for establishing and operating a green shipping corridor.

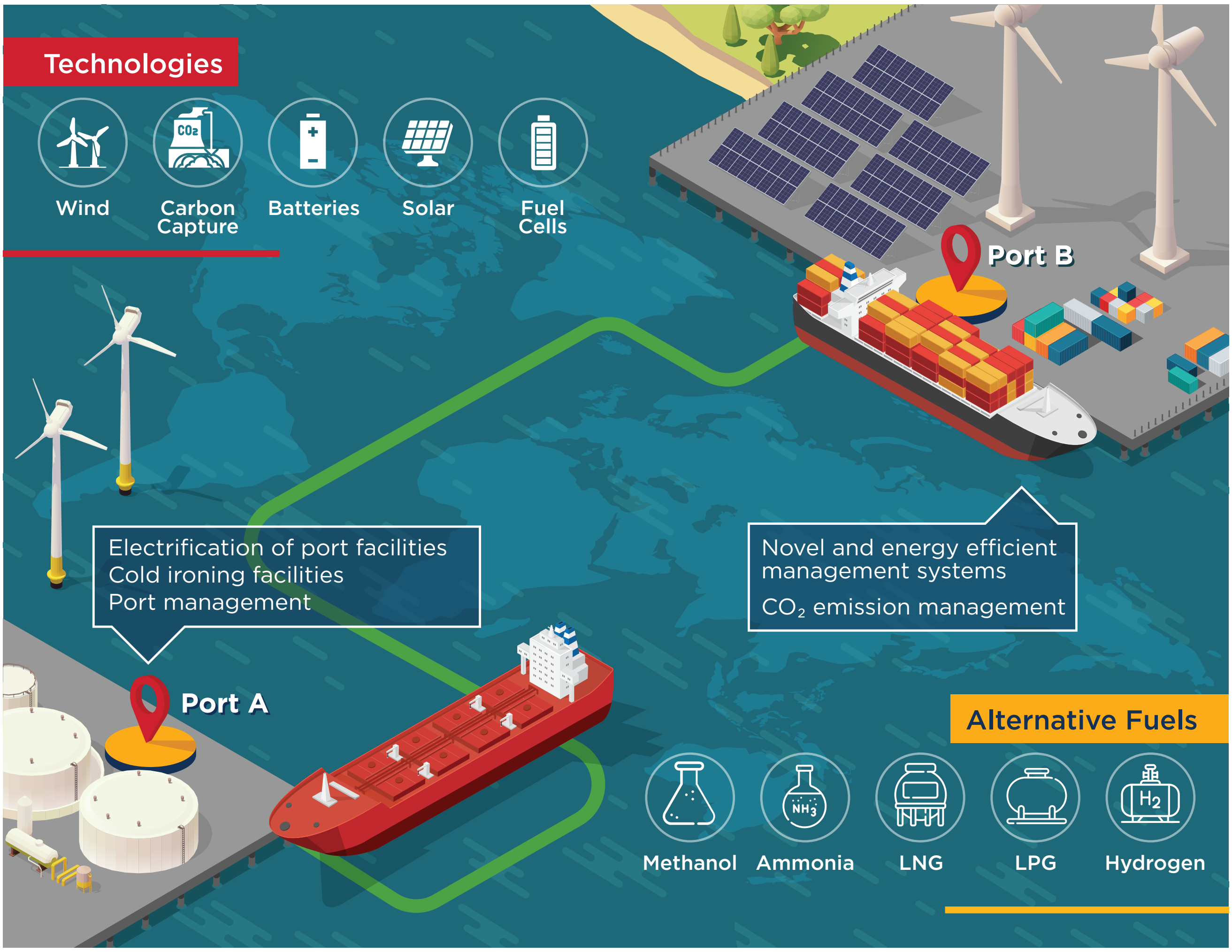


Figure 1: Green shipping corridor vision.

This publication includes two case studies, the Singapore-Rotterdam containership route and Australia-Japan iron ore bulk carrier route, to illustrate how the green shipping corridor initiative can be viewed as a resource planning and optimization problem that considers the diverse requirements of each of the stakeholders. For example, the shipowner's requirements and decision-making criteria will be fundamentally different from a port but each of these decisions are inextricably linked. Hence, the model acts as the canvas for a common ground among the consortium members and helps them in their pre-feasibility and feasibility assessment. It is likely that such analysis will become a foundational requirement for any green shipping corridor as the concept matures. As more green shipping corridors take off, the methodology will mature and as the data becomes easily available, there could be very creative use cases for these optimization and simulation tools.

RECOMMENDATIONS

- For any green shipping corridor initiative to be successful, a bedrock of data-based decision-making is imperative.
- Data sharing and transparency between value chain stakeholders is required, and agreements should be in place before making public announcements.
- To reduce the complexity of the problem, a core group should conduct the analysis before involving additional players. Typically, the core group will include ports, shipowners, fuel suppliers and as initiatives grow in viability, engine manufacturers and shipbuilders could also be added.
- As the level of complexity of any green corridor expands, additional modeling will be required, and these case studies provide the framework for future work.
- Based on the goals of the green corridor and the stakeholder, the level of emphasis on the outcomes will vary and should be considered before running a deeper analysis. The first step will always be to zero in on the stakeholder point of view, the variables of concern that can be controlled and then running analysis to optimize for those variables.

KEY FINDINGS

- Green Corridor Consortium members should at the earliest stages of the techno-economic analysis consider the emission trajectory as the controlling variable since, foundationally, a green corridor initiative is a decarbonization accelerator.
- The total cost of ownership (TCO) is heavily impacted by fuel costs, emission boundaries and the trajectory of decarbonization.
- The baseline scenario modeled in this study is the tank-to-wake (TtW) emission boundary and as the boundaries are expanded, and the decarbonization trajectories get steeper, the TCO will start increasing up to 1.6 times the baseline as inferred from Figure 2 and 3.
- The well-to-wake (WtW) scenario, in many cases, leads to a higher TCO in comparison to the tank-to-wake based on the assumptions for the fuel prices made in this study since well-to-wake emission factors are higher when compared to the base case of a tank-to-wake scenario.
- If the emission goals set are less ambitious during the techno-economic analysis phase, the outcomes could seem more optimistic than the reality, which will be very challenging to change at advanced stages of development. The best way forward would be to run multiple analyses looking at the least ambitious to the most ambitious trajectory with a well-to-wake emission boundary, to understand the worst-case scenario TCO.
- Irrespective of the corridor under consideration, over a 10-year horizon, the share of fossil fuels seems to drop at a gradual rate and is a function of the trajectory of emission reduction and the cost of fuel prices. The percentage of alternative fuels increases up to 30 percent by 2035 in both corridors as shown in Figures 4, 5, 6 and 7.
- Fuel prices and fuel availability are also important variables and, depending on the location and route specifics, should be looked at as additional controlling variables. The emission constraint set should be based on alternative fuel availability expected and should be in alignment with the reality of production forecasts.
- As alternative fuel availability increases and prices drop, the emission reduction trajectory should get more ambitious. The emission goals for the corridor. should be set ambitiously at the outset but need to be regularly revisited for fuel related sensitivities which will keep evolving.
- Consortia members should reconvene on a regular basis to re-confirm the emission targets set based on newly available data.

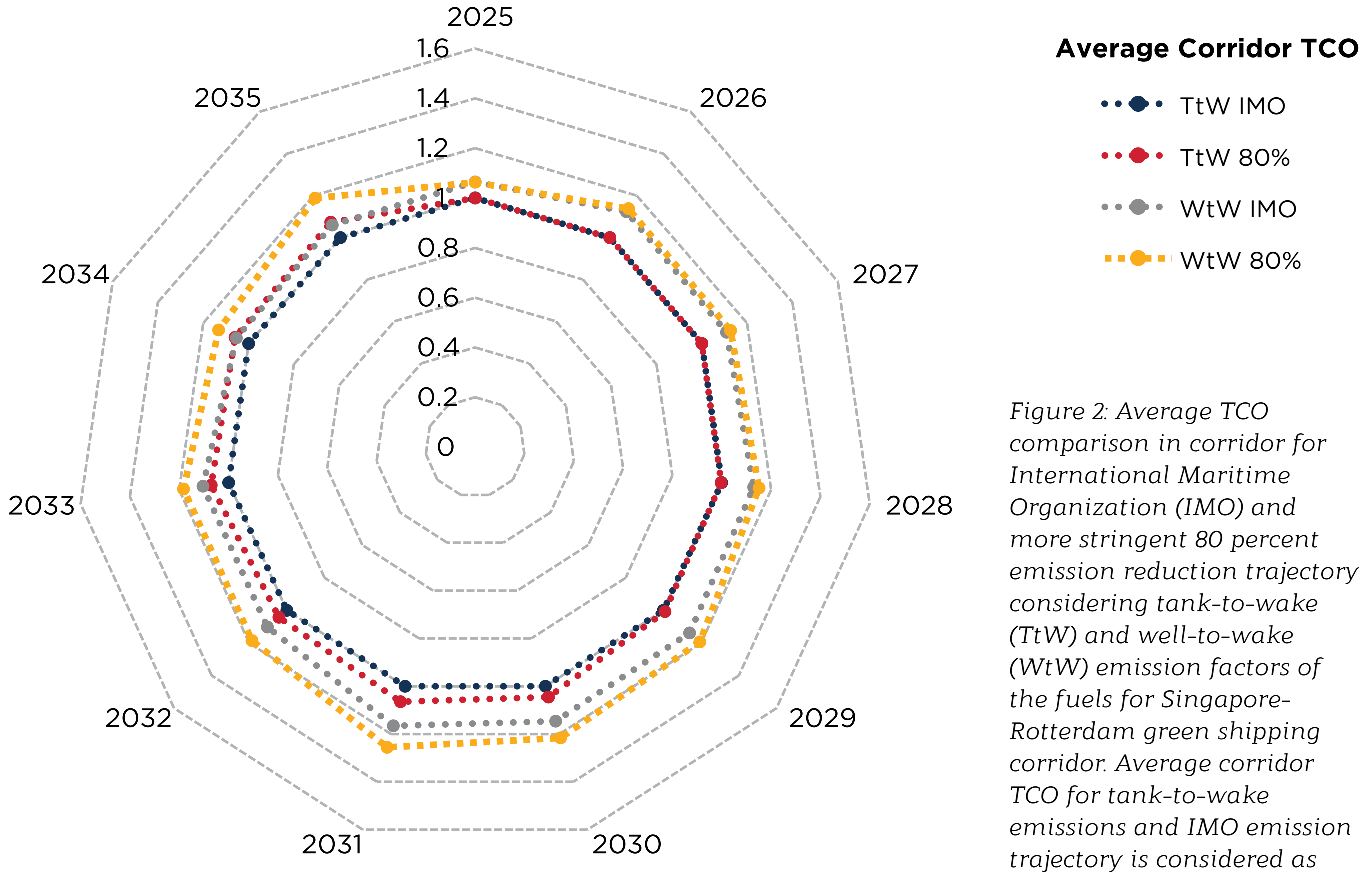


Figure 2: Average TCO comparison in corridor for International Maritime Organization (IMO) and more stringent 80 percent emission reduction trajectory considering tank-to-wake (TtW) and well-to-wake (WtW) emission factors of the fuels for Singapore-Rotterdam green shipping corridor. Average corridor TCO for tank-to-wake emissions and IMO emission trajectory is considered as baseline.

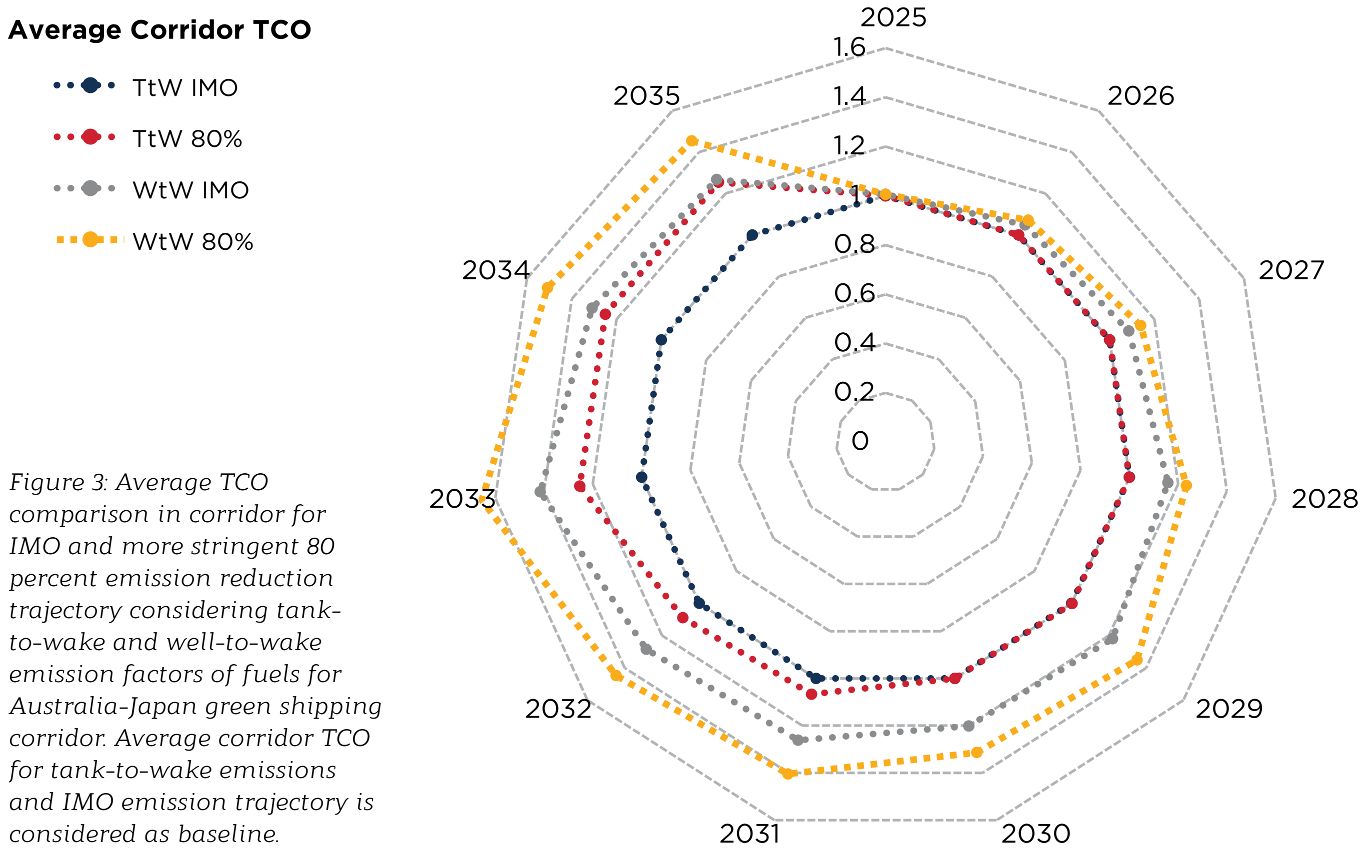


Figure 3: Average TCO comparison in corridor for IMO and more stringent 80 percent emission reduction trajectory considering tank-to-wake and well-to-wake emission factors of fuels for Australia-Japan green shipping corridor. Average corridor TCO for tank-to-wake emissions and IMO emission trajectory is considered as baseline.

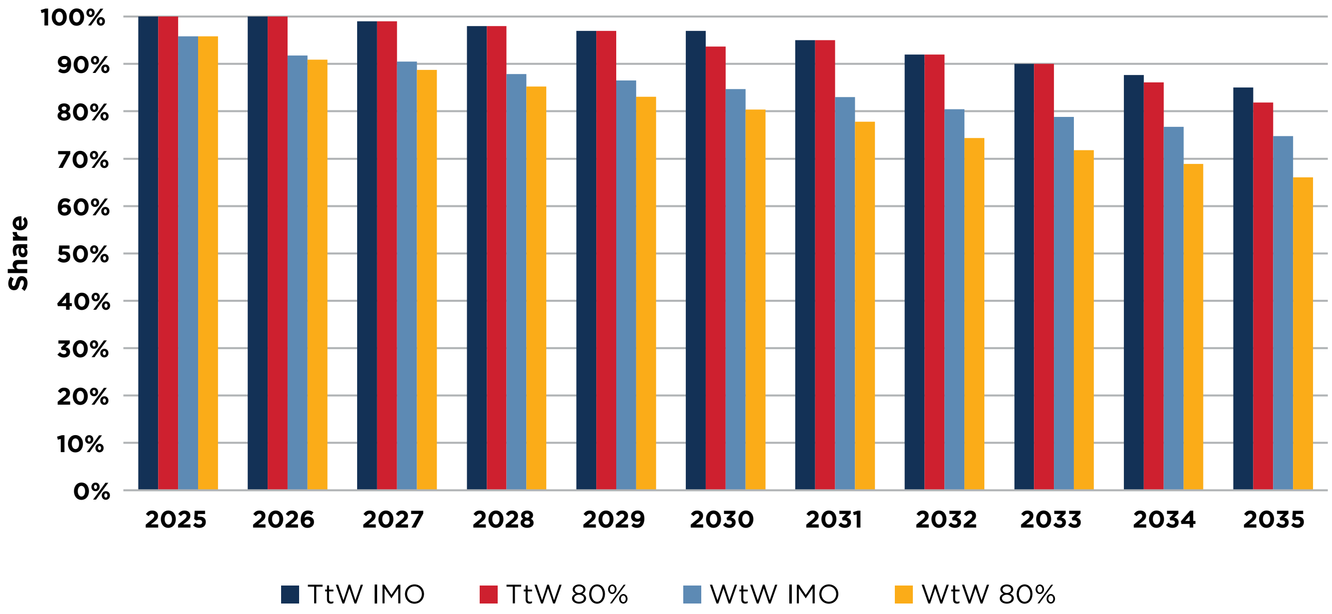


Figure 4: Share of fossil fuel usage from 2025 to 2035 in the Singapore-Rotterdam green corridor.

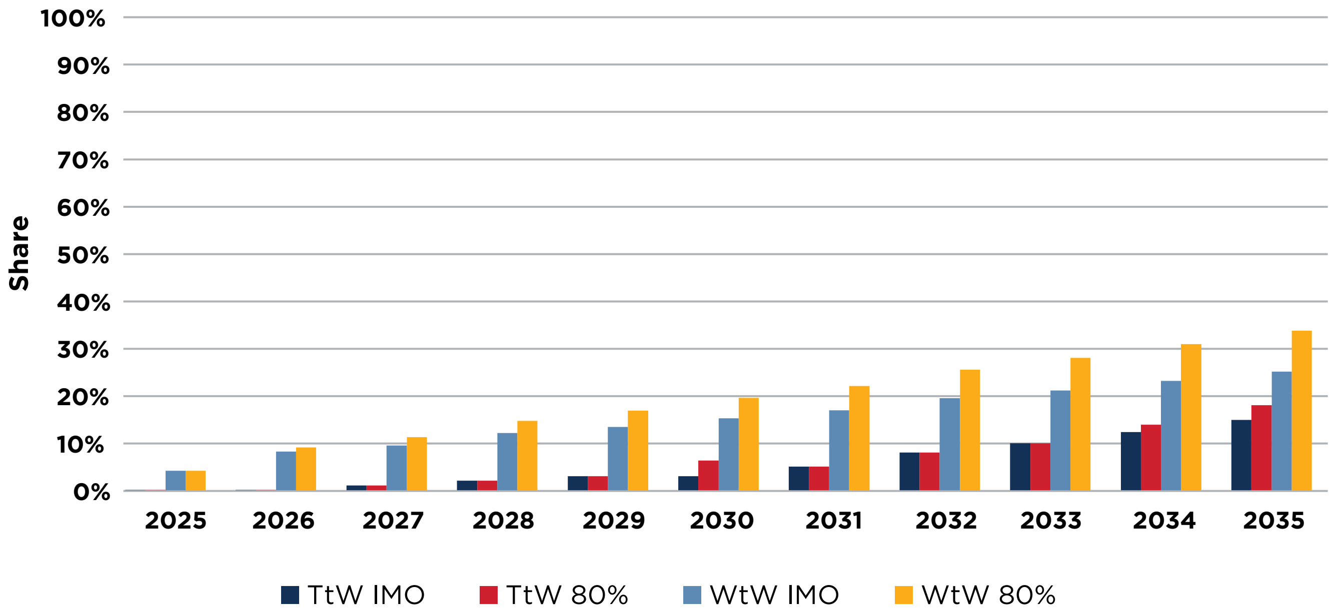


Figure 5: Share of alternative fuel usage from 2025 to 2035 in the Singapore-Rotterdam green corridor.

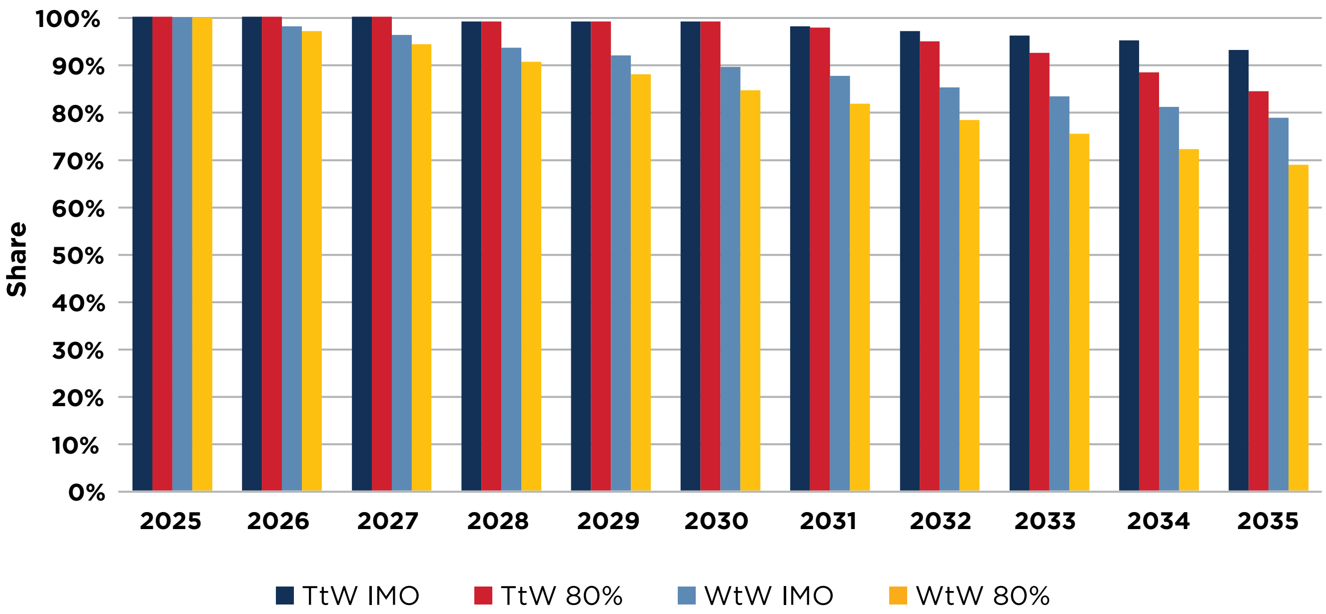


Figure 6: Share of fossil fuel usage from 2025 to 2035 in the Australia-Japan green corridor.

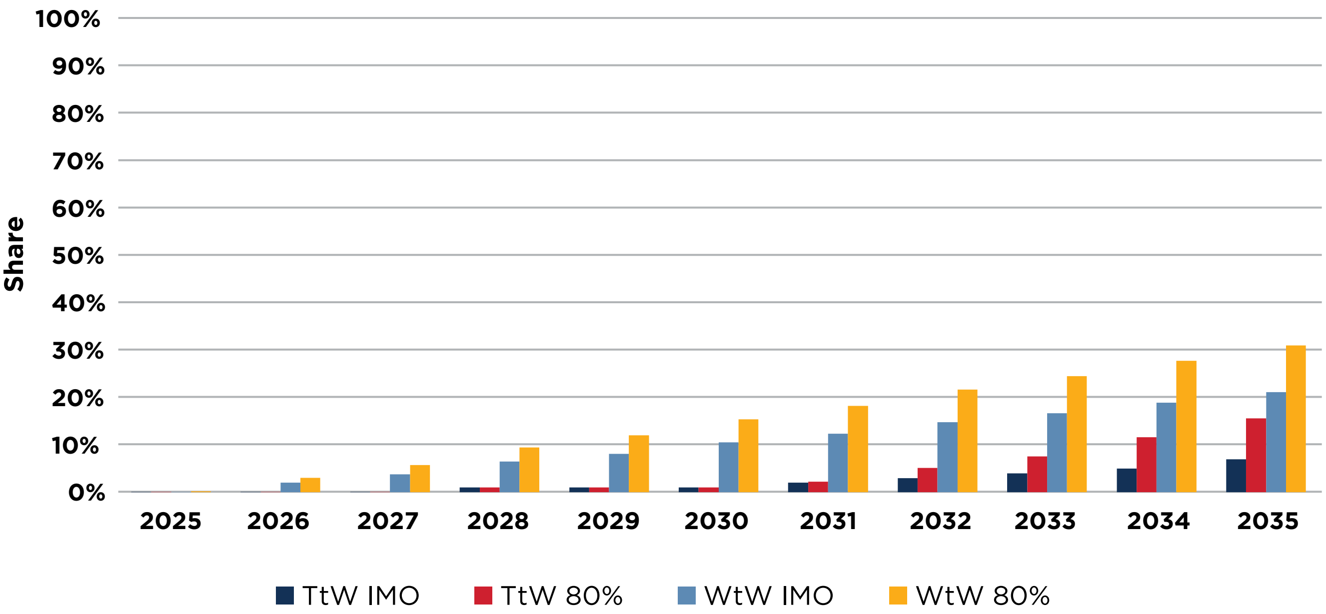


Figure 7: Share of alternative fuel usage from 2025 to 2035 in the Australia-Japan green corridor.

2 UPDATES SINCE GREEN SHIPPING CORRIDORS — LEVERAGING SYNERGIES PUBLICATION

As this publication is the second in the series on green shipping corridors[1], what is clear is that the concept has strengthened and is being quickly adopted by many players in the industry with new green shipping corridors being announced almost monthly. The first publication aimed at providing an overview of the concept of green shipping corridors and the identified foundation. This second publication intends to provide insights on details and decision-making criteria for the stakeholders utilizing an optimization and simulation framework. Table 1 indicates the number of new green shipping corridors that have been announced over the past six to 12 months. The corridors announced are geographically well spread and the type of routes are also very diversified, ranging from containership to bulk carrier-focused to even passenger-focused corridors.

Below are the main conclusions from the initial publication and a commentary on the status:

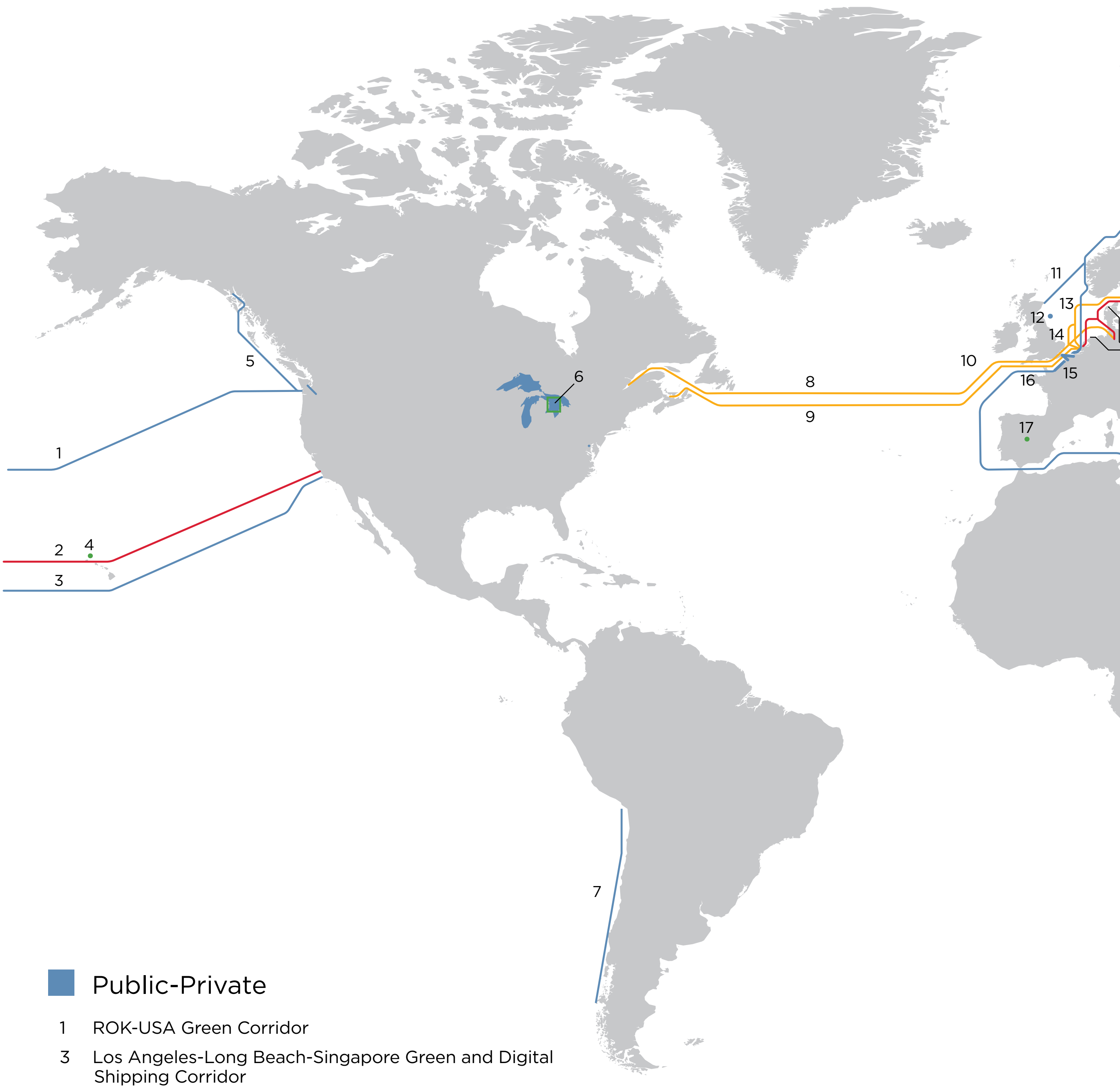
- Numerous green shipping corridors have been announced, particularly between Clydebank signatories, which indicates seriousness and follow up action post COP26.[2]
  - » The trend continues and green corridor initiatives are being consistently announced.
- Some green shipping corridors have made progress toward a feasibility assessment but none of them have come out with detailed plans or metrics on how these corridors will come to fruition, which indicates either slow movement or signals the magnitude of the task at hand.
  - » Pre-feasibility assessment for the Chilean[3] green corridor and Northern European and Baltic green shipping corridors[4] were completed, and some interesting insights have been published which will be useful for future analysis.
- Green shipping corridors, an all-encompassing concept which covers most aspects of the shipping value chain will require a detailed framework along with a tremendous amount of coordination among the stakeholders to get off the ground.
  - » This still holds true, and the challenge is still being addressed while the players are figuring out ways to understand this complex process. This publication aims to provide insights on utilizing a tool to unpack the problem further.

- The U.S. Department of State (DOS) has provided high-level guidance on green shipping corridors, and the current administration has promulgated several climate-related laws that have created a regulatory and policy framework which the shipping industry can take advantage off over the next decade. This is the decade of action, and the time is now to make rapid strides towards setting up of decarbonization initiatives in the shipping industry.
  - » Detailed guidance from the U.S. government is still pending. The current framework provides a problem-solving tool, but additional details are needed to fully understand the desired process.
  - » On November 7, 2022, Prime Minister Jonas Gahr Støre of Norway and Special Presidential Envoy for Climate John Kerry launched a Green Shipping Challenge during the World Leaders Summit of COP27. Countries, ports and companies made numerous major announcements on multiple issues which are expected to further progress the goal of green shipping.[5]
- Formation of a green shipping corridor is a techno-regulatory-commercial undertaking and will require broad expertise. Forming a consortium based on a pre-feasibility assessment followed by a top-down approach analyzing each part of the value chain and their individual criteria will help to make decisions based on solid quantitative backing.
  - » This publication aims to help conduct a high-level techno-economic assessment of two major announced green shipping corridors.
- From a fuel's perspective, low-carbon liquefied natural gas (LNG), ammonia, hydrogen and methanol seem to be the front runners from a decarbonization perspective and from a technology standpoint, battery-powered fuel cell vessels could also play a role at least for short-range applications. Onboard carbon capture can potentially be a useful technology to help bridge the gap between traditional fossil fuels and alternative fuels. Nuclear-powered vessels are a possibility, but the public perception may prevent usage despite being technologically sound and proven. According to ABS' future fuel mix forecast, alternative fuels will take off post 2030, which means construction of those vessels should start in the next two to three years, but even in 2050, there will still be vessels operating on traditional fuels. When vessels powered by alternative fuels are launched, they will operate within green shipping corridors, helping them operate viably despite the higher expected fuel costs.
  - » The future fuel mix is still very much evolving, and the above conclusions still hold true.
- Green shipping corridors are a nascent conceptual idea which will need to be tested in the physical world. The shipping industry, which does have a long history of cooperating with numerous stakeholders in a supply chain, is well situated to collaborate and develop green shipping corridors.
  - » This continues to hold true; the concept is being adopted but it is still in its infancy and until a green shipping corridor is operational with publicly available data points, some questions will remain.

TITLE/SCOPE	STATUS	KEY STAKEHOLDERS	FUEL FOCUS
Montreal – Antwerp green shipping corridor	Announcement Made	November 2021 – A memorandum of understanding (MOU) was signed with Green Field Biofuels being one of the known participants with the Port of Montreal and Port of Antwerp. Liquid bulk product is the focus.	TBD
Los Angeles/ Long Beach – Shanghai green shipping corridor	Developing Implementation Plan	January 2022 – Signed partnership with Mærsk, CMA, CGM, COSCO, Shanghai International Ports Group (SIPG), Cargo Owners for Zero Emission Vessels Initiative (coZEV), Maritime Tech Coop (Asia). C40 cities is the lead for this initiative.	TBD
Chile	Pre-feasibility Assessment Completed	April 2022 – Chile Ministry of Energy and Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping plan to establish a government funded Chilean Green Corridor Network consisting of Ministry of Energy of Chile, Ministry of Transport and Telecommunications of Chile, Ministry of Foreign Affairs of Chile, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping.	TBD
South Korea to USA green shipping corridors	Announcement Made – Feasibility Study by End of 2023, Decarbonization Goal by 2050	In 2022, Northwest Seaport Alliance, Busan Port Authority, Oak Ridge National Lab, National Renewable Energy Lab, Pacific Northwest National Lab, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping have joined hands to conduct a feasibility study by end of 2023 with a goal of decarbonization by 2050.	TBD
St. Lawrence Waterway	Conducting Route Specific Feasibility Assessment	April 2022 – Focused on bulk (ore, grain, cement, etc.) with members of the Canadian Chamber of Marine Commerce (CMC) evaluating the potential for a green shipping corridor with collaboration from government and research and development. CMC represents 100 clients including shippers, ports, etc., also including transport Desgagné's, CLS Algoma Central and Transport Canada.	Electric, advanced biofuels, hydrogen, ammonia, methanol
Australia-East Asia green corridor- Port Hedland (Australia to Japan)	Conducting Route Specific Feasibility Assessment	April 2022 – Focused on iron ore and includes BHP, Rio Tinto, Oldendorff Carriers and Star Bulk Carriers. The consortium Global Maritime Forum (incl. Rio Tinto et al.) signed a letter of intent (LOI) between miners (charterers) and owners to evaluate fuels and routes. November 2022, representatives from these organizations convened to accelerate the development of a green corridor for transportation of iron ore between Australia and East Asia (specific focus on green ammonia being the likely choice)[6]	Green ammonia bulk carrier
Ports Gdynia, Hamburg, Roenne, Tallinn and Rotterdam	Conducing Pre-Feasibility Assessment	March 2022 – Five European ports joined to form the European Green Corridor Network for Northern Europe and the Baltic region with the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping acting as a partner.	Methanol, advanced biofuels
Port Halifax and Port of Hamburg	Announcement Made	September 2022 – MOU was signed between the Halifax Port Authority and the Hamburg Port Authority to establish a green corridor with a focus on bunkering infrastructure and development of a green hydrogen pathway between the two ports and countries (Canada and Germany).	Hydrogen, green ammonia, methanol

TITLE/SCOPE	STATUS	KEY STAKEHOLDERS	FUEL FOCUS
Pacific Northwest – Alaska Green Corridor – Cruise Specific	Conducting Route Specific Feasibility Assessment	May 2022 – Ports of Seattle, Vancouver and Juneau with three major cruise corporations and cruise industry trade associations supported by three maritime forums have announced their effort to explore the feasibility of the world's first cruise-led green corridor. These parties consist of Port of Seattle, Port of Vancouver, City of Juneau, Carnival, Norwegian Cruise Line, Royal Caribbean, CLIA, GMF, Blue Sky Maritime, Washington Maritime Blue, Greater Victoria Harbor Authority, Haines Borough, City and Borough of Sitka and Municipality of Skagway.	Unknown
Singapore to Rotterdam	Conducting Route Specific Feasibility Assessment	August 2022 – The Port Authorities of Singapore and Rotterdam joined with others in the industry to expand on the concept of green shipping corridors. The port authorities will work with the Global Centre for Maritime Decarbonization and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. Other industry partners include bp, CMA CGM, Digital Container Shipping Association, Mærsk, MSC, Ocean Network Express, PSA International and Shell.	Methanol, green ammonia containerships
San Pedro Bay Ports and Singapore MPA	Announcement Made	November 2022 – The Maritime and Port Authority of Singapore (MPA) and California's San Pedro Bay, ports of Los Angeles and Long Beach have begun discussions to establish a green and digital shipping corridor between Singapore and the San Pedro Bay port complex. The corridor will focus on low- and zero-carbon fuels for bunkering, as well as digital tools to support deployment of low- and zero-carbon ships.	TBD
Turku and Stockholm	Has secured Financial Backing	September 2022 – Business Finland has granted EUR 1,596,000 in funding for a joint project between Rauma Marine Constructions, Viking Line, Åbo Akademi University and Kempower. The Decatrip project aims to develop a carbon-neutral green corridor between Turku and Stockholm through which cargo and passengers can travel.	TBD
Rotterdam – West Coast Norway green corridor	Announcement Made	In 2022, Rotterdam – West-coast Norway green corridor was announced which is a public-private partnership with methanol as a fuel. The participants are North Sea Container Line, Elkem ASA, Skretting AS with a Target Timeline: NCL aims to be the first carbon-neutral containership by 2030.	Methanol
U.S., U.K., Norway and the Netherlands green shipping corridors	Agreement Between Nations – COP27	November 2022 – the U.K. to join forces with the U.S., Norway and the Netherlands to roll out end-to-end decarbonized shipping routes.	TBD
Clean Tyne shipping corridor	Announcement Made	2022 – Port of Tyne Authority, Newcastle University, North of Tyne Combined Authority, EDF Energy R&D UK Centre, Ove Arup & Partners, Connected Places Catapult, Lloyd's Register EMEA.	TBD

Table 1: List of updated green shipping corridors announced as of February 2023.[7]



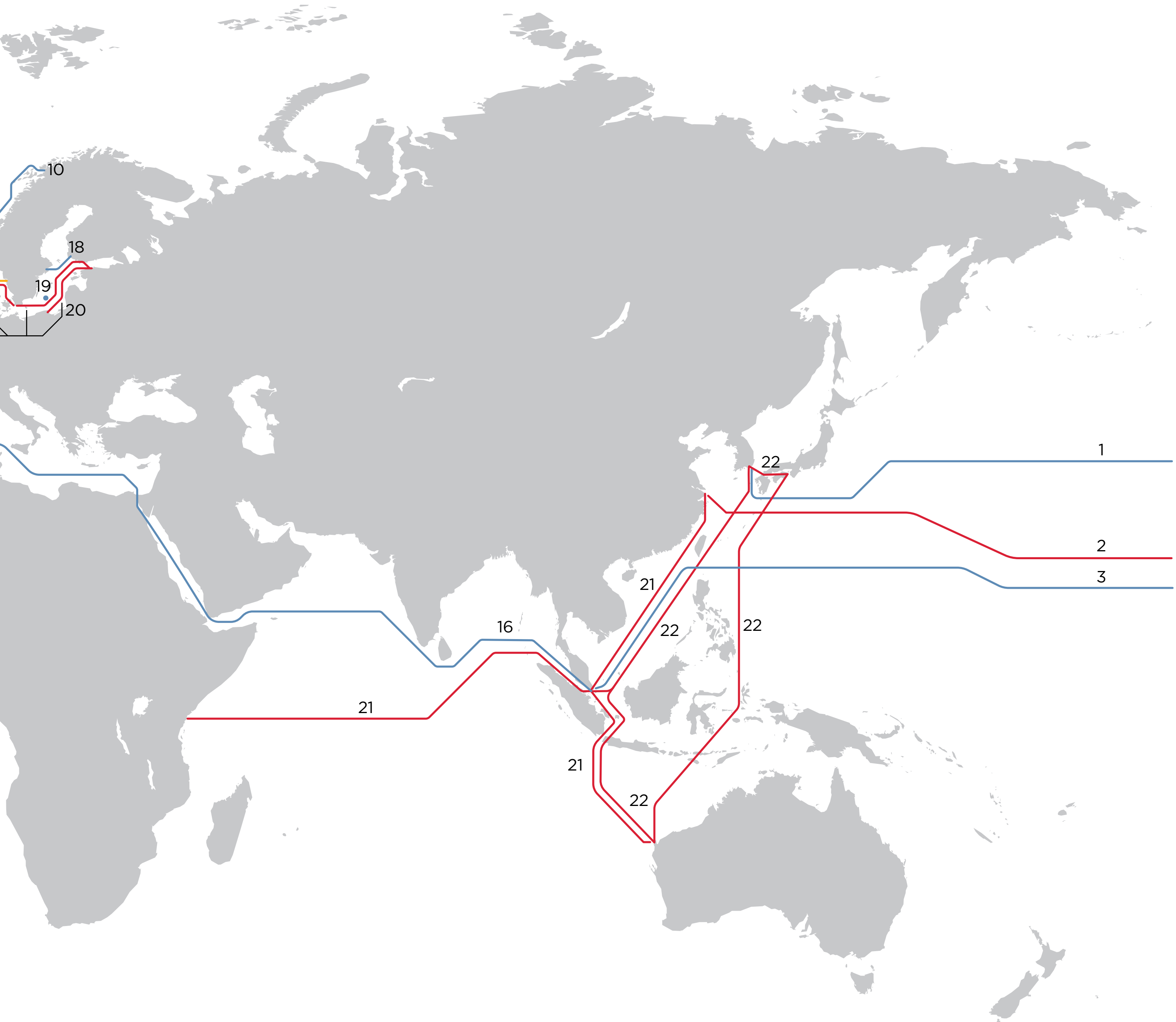
Public-Private

1 ROK-USA Green Corridor
3 Los Angeles-Long Beach-Singapore Green and Digital Shipping Corridor
5 Alaska, British Columbia, Washington Green Corridor
7 Chilean Green Corridors Network
10 Rotterdam-West Coast Norway Green Corridor
11 Feasibility Study of the World's First Hydrogen-Powered North Sea Crossing
15 Dover-Calais and Dover-Dunkirk Ferry Corridor
16 Rotterdam-Singapore Green and Digital Corridor
18 Decatrip
19 Nordic Regional Corridors

Government

4 QUAD Shipping Task Force/Green Shipping Network
6 Great Lakes-St. Lawrence *
12 Clean Tyne Shipping Corridor
17 Green Corridors Spain

Green corridor announcements are widespread and as seen in Figure 8, almost all regions have an announced green shipping corridor, and all have a different focus in terms of fuels, commodities and service type.



Industry or NGO

2 Shanghai-LA
20 European Green Corridors Network
21 SILK Alliance
22 Australia-Asia Iron Ore

Port

8 Antwerp-Montreal
9 Halifax-Hamburg
13 Gothenburg-North Sea Port
14 Gothenburg-Rotterdam

* Announced

Figure 8: Announced green shipping corridors – March 2023.[7]

3 TECHNO-ECONOMIC ASSESSMENTS OF A GREEN SHIPPING CORRIDOR

Among the varied pathways that are available for the maritime industry to decarbonize, almost nothing is more expansive, both geographically and stakeholder-wise, than the concept of green shipping corridor.[8,9] Resource planning and techno-economic assessments for green shipping corridor are extremely complex and require detailed analysis for each of the value chain members to be able to make prudent decisions. Any green shipping corridor will need to pass through such rigorous pre-feasibility and feasibility assessments to ensure the success of the initiative.

As an industry that is geographically and operationally so diverse, very few concepts can bring them under the same umbrella to align their goals toward end-to-end supply chain decarbonization. Some of the initial green shipping corridors will aim to start off small and grow over a period. There could also be other more ambitious green shipping corridors that make major moves that aim to re-wire certain routes. All approaches toward solving the problem are equally valid, but each of them will require rigorous resource planning which takes emission reduction into consideration. Every stakeholder, as a rational actor in a competitive business climate, needs strong decision-making tools to viably operate. The case studies presented in this publication will play a role in trying to understand the interconnections of the value chain.

Any green shipping corridor typically will include the following major stakeholders:

- Ports
- Fuel suppliers
- Shipowners, and
- Others who fall within the scope of the entire value chain.

Each of these value chain members will have a specific point of view and decision-making criteria that they will focus on to make the decision to go forward with any such initiative. Our focus for the case studies presented in this publication was to better understand the variables involved in making smarter decisions that provide a commercial advantage and lead to sustainable emission reductions.

The pre-feasibility assessment phase of the project typically involves the following steps:

- Project baselining
- Value chain mapping
- Screening criteria, and
- Screening of potential corridors and engagement with regulatory bodies and government.

At the end of the pre-feasibility assessment, it is expected that a letter of intent (LOI) will be announced confirming an initial list of core partners in the green corridor initiative.

Any pre-feasibility assessment will involve understanding the challenges faced by the individual stakeholders i.e., alternative fuels suppliers, port authorities, storage and bunkering infrastructure entities, shipowners/charterers profiles e.g. trade routes, types of vessels, cargo moved and policy/regulatory support in those jurisdictions. While looking at any corridor, one of the most important steps is to understand the future fuel mix. Each corridor will have access to different alternative fuels based on their geographic location. For example, any route located in a fossil fuel heavy production region may have a natural advantage in accessing liquefied natural gas (LNG), blue hydrogen and ammonia. On the other hand, if two ports are on the renewable energy supply chain, they may have easier access to green hydrogen, green ammonia and low carbon methanol production pathways. Additionally, there could be certain localized advantages for regional green shipping corridors where the access to certified biofuels (from biomass and bio-waste) could provide a viable alternative fuel option. In summary, each corridor needs to undergo a deep analysis of alternative fuel availability and make prudent choices.

The corridor consortia should get a fuel supplier on board to understand the supply currently available and understand the future forecasts, or help them create additional supply since the corridor will be a ready-made off taker of those fuels and will help the fuel supplier de-risk their investments. One of the initial steps to understand the future supply of alternative fuels will be to look at publicly available data of announced projects. This will need to be followed up with actual interviews to understand on-the-ground-level status of those projects, since a good percentage of these projects may not see the light of the day due to evolving business conditions and regulatory permitting delays. Additionally, not all projects will lead to supply availability for the maritime sector and hence, sectoral competition will need to be considered. The consortia should be created in such a way that a sizeable amount of future supply of the fuels are cornered by the corridor which will allow all the downstream operators such as the ports (storage, bunkering), shipowners (vessel building, engine costs) to ready themselves for these fuels.

Port development and bunkering infrastructure development will be a major part of any green shipping corridor initiative, since foundationally, a green corridor revolves around the ports. While looking at the value chain of the maritime sector, ports are at the center of all activity and will require a tremendous upgrade to handle newer fuels and help decarbonize the entire value chain. Once the ports are selected, the next step is to understand its current baseline capability to decarbonize and the incremental development that will be required to service the new normal, taking into consideration the evolution of the industry as it decarbonizes over the next two to three decades. Certain ports that are ahead of the curve in terms of decarbonization initiatives may have some organic advantages and be first movers, but even those will require re-investments for satisfying future demands.

Port specialization will be an important facet in deciding what type of green shipping corridor will be suitable for a specific location. For example, certain ports will be well-suited for a containership-focused green corridor and in other cases, they may be well suited for a specific commodity transport on bulk carriers. In addition, certain ports may not have high volume but handle value goods and hence, the economic incentive (can pass costs to the customer) to decarbonize may be higher but the emissions impact could be lower. On the other hand, high volume ports will have a tougher challenge with passing the costs to the customer, but each dollar spent will give greater returns in terms of emission reduction.

The ports will need to define the specific vessel types they would want to focus on, understand the alternative fuels that are best suited from an ability to scale standpoint, estimate the capital expenditure (capex) and operating expenditure (opex) required to develop new infrastructure and understand if the payback will occur over a reasonable amount of time.

Finally, as the role of alternative fuels expands, safety and training of personnel to handle the newer fuels will require a large amount of investment.

These initiatives are multi-decadal, multi-system, high-cost projects, and hence external funding from both the private and public sectors will play a critical role. A streamlined and speedy regulatory process will be a catalyst in helping accelerate maritime decarbonization using the green shipping corridor initiative as the framework. The feasibility of these initiatives is heavily dependent on regulatory and policy level support from governments or international authorities since these projects could have strategic implications for countries and cities that are deeply enmeshed with the activities of these ports. It is clear that financial and regulatory support could help qualify many of these green corridor initiatives to push it to an affirmative investment decision. There are numerous models for consortium setup, and it could be a bottom-up approach from a private sector, corporate level to a top-down approach led by governments.

The pre-feasibility assessment is the most important step for a top-down green shipping corridor initiative, since it will focus on a number of different possible pairs of ports. For a bottom-up initiative, the pre-feasibility assessment will play the role of understanding the challenges of the chosen port pairs. The outputs from the pre-feasibility assessment are utilized to complete the feasibility assessment which involves rigorous analysis of specific variables that impact each of the stakeholders. The outcome of a feasibility assessment will involve a technical, economic and regulatory evaluation, risk mitigation plan and a roadmap to achieve milestones.

The pre-feasibility assessment will need to address the following questions[9]:

- What are the ports of interest? If the assessment starts after the formation of a core group involving at least two ports, then the analysis will be confined to the realities of those ports.
  - If the assessment is top-down, with several different pairs of ports being considered, then this will lead to a list of corridors that could end up as feasible corridors.
- From an alternative fuel availability perspective, the assessment will provide a framework for answering the following key questions:
  - What is the expected production capacity in the region of interest?
  - What will impact the cost of fuel?
  - What will be the emission impacts for each of the fuel production pathways?
- Once the ports are decided, what is current storage and bunkering capacity and how will it evolve as the corridor matures over a period of time?
- What is the current port readiness level and what is the expected outlook?
  - Port readiness is one of the most important enabling factors for a green corridor, a less ready port from an alternative handling capacity will be a poor match for the corridor.
- What should be the vessel segments? What are the vessel types that are best suited for decarbonization on this specific route?
- What are the policies and regulations that can positively affect the green corridor?
- What are the existing funding opportunities?

The case studies that were conducted utilizing the optimization tool described in the following sections aim to provide deeper insights into the following critical decision-making points.

3.1 CORRIDOR-WIDE ANALYSIS

What are the sources of alternative fuel best suited to meet the future demand?

- In this case study, it was assumed that the current sources of fuel will remain the source of fuel over the next 10-year period and the fuel pricing methodology has been explained in detail in section 4.2.4.

What is the current and expected storage and bunkering infrastructure along the corridor?

- The case study only optimizes the future incremental capacity required and assumes at day zero of the analysis, the infrastructure is in place for current supply.

What are the characteristics of the vessel and emissions profile?

- The case study specifically studies two different green shipping corridors where the type of vessels is an indication of the trading that is currently occurring on the route. For example, the Singapore-Rotterdam green shipping corridor has a containership focus and the Australia-Japan (iron ore corridor) has a bulk carrier focus.
- Additionally, the number of vessels that are currently operating in the corridor were assumed based on current trade and growth forecast assumptions which is described in detail in the following sections.

3.2 ALTERNATIVE FUEL SUPPLY CHAIN

What will be the required volume of alternative fuel for this corridor?

- The case study focused on future demand and if the supply will match the demand and how it is expected to evolve over time.

What will be the production centers?

- The study assumes that current supply chain of fuels will have an advantage and continue to service these ports.

What are the capex requirements for the fuel suppliers?

- The study focuses more on the port side infrastructure and not the upstream costs.

3.3 PORT STORAGE AND BUNKERING INFRASTRUCTURE

What will be the expected demand at the port level and what infrastructure will be required?

- The demand for infrastructure is directly proportional to the fuel demand expected in the corridor which the port is a part of, and the study examines how the costs will evolve over time and the level of investment required.

3.4 VESSEL DECARBONIZATION PATHWAY

What will be the future vessel size requirements?

- An average vessel size was assumed and based on the trade growth; the number of vessels is expected to increase over the period of 10 years.
- Based on the decarbonization goal, the vessel decarbonization pathway is expected to evolve which is seen in the results described in sections 5.2 and 6.2.
- Capex requirements are also included in the case study to understand what the average total cost of ownership (TCO) will be over a period of 10 years.

4 RESOURCE PLANNING FOR A GREEN SHIPPING CORRIDOR: OPTIMIZATION MODEL

Optimization refers to the practice of finding the best or "optimum" allocation of available resources among competing activities while being subjected to a set of constraints. These constraints may be financial, organizational or technological in nature. Mathematical programming is the effort to construct these problems into a mathematical representation which aims to find the best solution. For this case study, a techno-economic optimization framework is proposed with a primary objective of long-term planning for the resources such as: fuels and location, bunkering size and mix for a corridor under consideration for the planning horizon of 10 years. Such techno-economic optimization framework considers financial parameters along with the technical limits of each of the stakeholders. This integrated analysis is imperative as they provide insights to multiple stakeholders such as:

- Regulatory authorities and government agencies can use this model to gain a deeper understanding of the decarbonization pathway of a green shipping corridor. By testing various policies and incentives, they can also evaluate the impact on the year-over-year fuel mix and technological preferences, investment requirements and the total cost ownership (TCO).
- Port owners and operators can use this model to identify the required fuel mix to meet the targets of the corridor, evaluate the year-over-year investment timelines for alternative fuel storage and develop fuel contract strategies.
- Shipowners can use the analysis to better plan their decarbonization strategies by understanding the timelines of retrofits, decommissioning, and newbuilds, and forecast the TCO.

The output will be the identification of resources needed which will be dependent on the various stakeholders and interactions with one another. Once the resources needed for the green corridor are determined, further targeted and customized investigations for each of the stakeholders can be carried out.

The model considers various stakeholders which are considered as sub-units of the green shipping corridor. The sub-units of the corridor include the ports and bunkers, fuel suppliers, shipowners and corridor features. Note that the case study assumes that the fuel demand will be supplied and does not take into consideration the upstream constraints towards production and availability of the fuels. The aim of the study is to understand how the optimization model could be utilized for a complex system and the focus is on two major stakeholders in the maritime sector: ports and shipowners. Figure 9 below indicates the various stakeholders that are part of the corridor and their constraints and inputs. Not all inputs will apply to each of the case studies and appropriate assumptions are made wherever required.

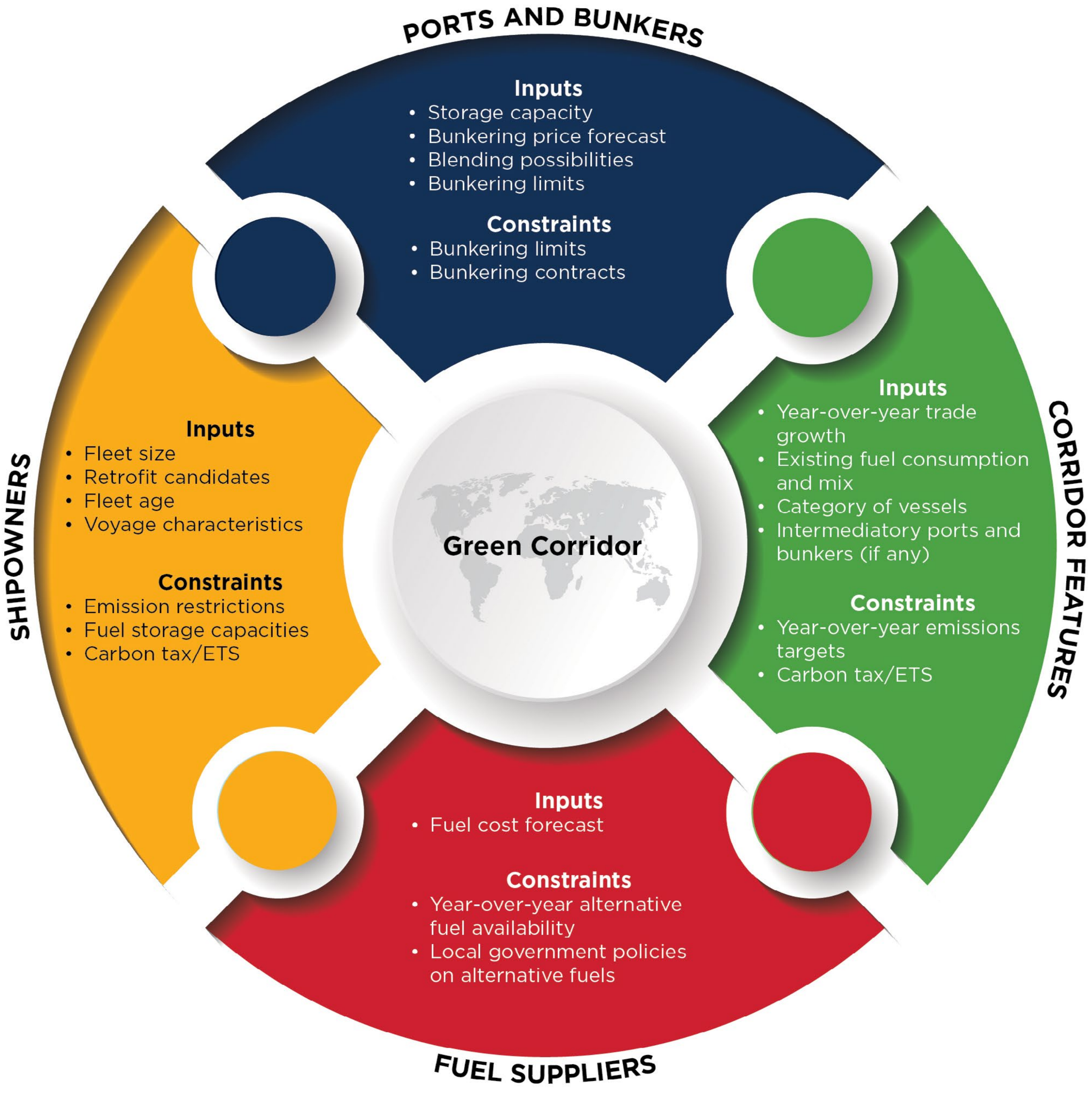


Figure 9: Various stakeholders i.e., sub-models of the green corridor.

4.1 OBJECTIVE FUNCTION

The objective of the green shipping corridor optimization is to understand the resources needed while adhering to the corridor-wide emission trajectories as prescribed by the International Maritime Organization (IMO) and a more aggressive goal trajectory outside the envelope of IMO goals. The output of the optimization will aim to reduce the cost over a 10-year planning horizon. As described earlier, the optimization model will comprise of the stakeholders participating in the corridor such as shipowners, ports, and bunkering infrastructure which are modelled as different sub-models. The interactions among the stakeholders are crucial to determine the optimum investment decisions such as retirements or retrofits for shipowners and bunkering facilities and to project the future fuel mix. For this long-term plan, the objective function is to minimize the capital expenditure (capex) and operating expenditure (opex) while strictly adhering to the emission trajectory. To achieve optimal results, the analysis was carried out in linear programming mode using PLEXOS® [10] simulation engine.

4.2 OPTIMIZATION SUB-MODELS: INPUTS, CONSTRAINTS AND OUTPUTS

Every green shipping corridor involves multiple stakeholders and each of these players has unique inputs, constraints and outputs that reflect their individual perspectives. The boundaries of these inputs, constraints and outputs are a function of the specific operations of the stakeholder (e.g., a port operator will need to focus on port infrastructure and investment required to meet the increasing demand, the shipowner will be focused on TCO).[8,9]

The section below identifies the capabilities of the model, indicating the level of detail which it is capable of and some of these capabilities were utilized in the case study depending on its applicability to the modeled corridor.

4.2.1 SHIPOWNERS SUB-MODEL

Vessel-level modeling on a macro-level is needed to emulate its characteristics, with the following inputs that can be included in the model:

- **Existing fleet size:** This is needed to understand the current or existing type of vessels and fuel mix.
- **Vessel opex:** Opex is needed to understand the current cost of operation of vessels in the corridor.
  - » Only fuel cost is used to compute the opex and if required, the variable operation and maintenance cost portion of the opex can be considered.
- **Fleet age:** Fleet age is required to formulate constraints on retirement and commissioning logics and needed retrofits.
  - » In this study, it is assumed that on Year 1 of the model run, new vessels are put into service with 25 years of economic and 30 years of technical life.
- **Retrofit candidates:** Capex, opex, weighted average cost of capital (WACC), technical life, economic life of the retrofit candidates such as alternative fuel generators are needed to understand the investment decision timelines. As technology matures, capex and opex will possibly decrease over time and will impact the timelines of the investment decisions.
- **Voyage characteristics:** Depending on the data availability, voyage characteristics of individual vessels could be included to model the vessel operations more realistically.
  - » Predefined voyage characteristics with known voyage duration and port stays are used for each of the case studies.

The constraints of this shipowners sub-model are:

- Carbon tax and emission constraints on the fleet level with penalty prices varying over the quantum of emissions and yearly variations. If required, emission constraints can be given on monthly/yearly levels for more granular simulation consideration.
  - » EU ETS price of $100/tonne of CO_2e was applied in the Singapore-Rotterdam green shipping corridor. Carbon price is not applied to the Australia-Japan iron ore green shipping corridor.
- Maximum fuel storage limits on each of the vessels and maximum blending limits of pilot fuels with alternative fuels.
  - » Maximum fuel storage limits on each of the vessels is considered in this study.
  - » Varying blending ratio of pilot fuels for engines based on alternative fuels have been considered in this study. This is described in subsequent sections.
- Commissioning and retirement logic of the vessels which could be based on technical life, opex, capex, retirement costs, etc.

The main outputs of the shipowners model will be:

- The type of fleet operating in future categorized by fuel mix
- Cost of operating the individual vessel
- Fuel mix and consumption levels of individual vessels
- Timelines on retrofits, retirements (or early retirements) and commissioning

The inputs, constraints and outputs of the shipowners sub-model are shown in Figure 10.

INPUTS	CONSTRAINTS	OUTPUTS
• Existing fleet size, vessel segments, vessel opex • Fleet age (year built, technical life, economical life) • Possible retrofit candidates with capex, opex, WACC, technical life, economical life • Voyage characteristics	• Emission constraints over years. Monthly emissions for more granular analysis • Max fuel storage in each vessel • Fleet commissioning and retirement criteria	• Type of fleet operating in future • Cost of operating the vessel • Fuel consumption and emission projections • Possible re-fueling locations (ports)

Figure 10: Shipowners sub-model description.

4.2.2 PORT INFRASTRUCTURE AND BUNKERING SUB-MODEL

The aim of the bunkering sub-model is to understand the storage requirements and investments in storage infrastructure based on the capex and opex at each port site.

The main inputs to the bunkering sub-model are:

- Available bunkering capacity and fuel mix
- Maximum bunkering capacity in the source, destination and intermediary ports (if any)
- Projected bunkering cost for the existing fuels
- Alternative fuel sourcing locations for each of the bunkering sites
- Capex, opex, WACC, technical life, economic life for the new bunkering investments

The main constraints for the bunkering sub-model will be:

- Max bunkering capacity for the corridor
- Maximum bunkering in an hour/day/month/year depending on the data availability
- Nature of existing contracts and projected future contracts with fuel suppliers

The outputs of this bunkering sub-model will be:

- Bunkering fuel mix projection
- Bunkering usage projection on daily/monthly/yearly basis
- Projected timeline of investments in bunkering facilities

The inputs, constraints and outputs of the bunkering sub-model are shown in Figure 11.

INPUTS

- Available bunkering capacity with fuel mix blending possibilities
- Maximum bunkering capacity in the source, destination and intermediate ports
- Projected bunkering price based on the existing fuels
- Fuel sources and vendors
- Capex, opex, technical life, WACC of various fuel bunkering technologies

CONSTRAINTS

- Max bunkering capacity for a corridor
- Max bunkering in an hour/ day/month/year
- Sensitivity on bunkering price with changing economic conditions
- Contracts of fuel vendors

OUTPUTS

- Bunkering mix projection in a port
- Projected bunkering costs
- Bunkering usage projection (daily/monthly/yearly)
- P&L analysis of bunkering business
- Projected bunkering quantity (preferably on daily basis)

Figure 11: Bunkering sub-model description.

4.2.3 FUEL SUPPLIERS SUB-MODEL CAPABILITIES

In this study, it is assumed that all alternative fuels are available at a given price forecasted on a daily interval. However, if required the upstream fuel suppliers can be included in the model. This can be done by considering:

- Existing fuel supply locations, cost and mix
- Potential alternative fuels and sourcing countries for each of the intermediary ports along with renewable energy price projections
- Price projections on alternative fuel production technologies
- Capex, opex, WACC, technical life, economic life of the renewable energy and alternative fuel production technologies along with transportation cost to each of the bunkering locations
- Nature of fuel contracts such as take-or-pay contracts, spot markets, etc.

The following constraints are considered in the fuel suppliers' sub-model:

- Maximum renewable energy capacity built or allocated each year to produce alternative fuels
- Yearly supply chain and manufacturing constraints on the alternative fuel producing technologies such as electrolyzers, etc.
- Government policies (of each of the sourcing countries) related to producing alternative fuels vary with the economic growth

The following outputs are expected from the fuel suppliers' sub-model:

- Alternative fuel demand projection for each of the suppliers
- Fuel mix for the corridor and the ports
- Fuel cost and usage projections for each port
- Off takers: which bunkering facility to sell and how much quantity along with the timeline
- Fuel contract evaluation

The inputs, constraints and outputs of fuel suppliers' sub-model are shown in Figure 12.

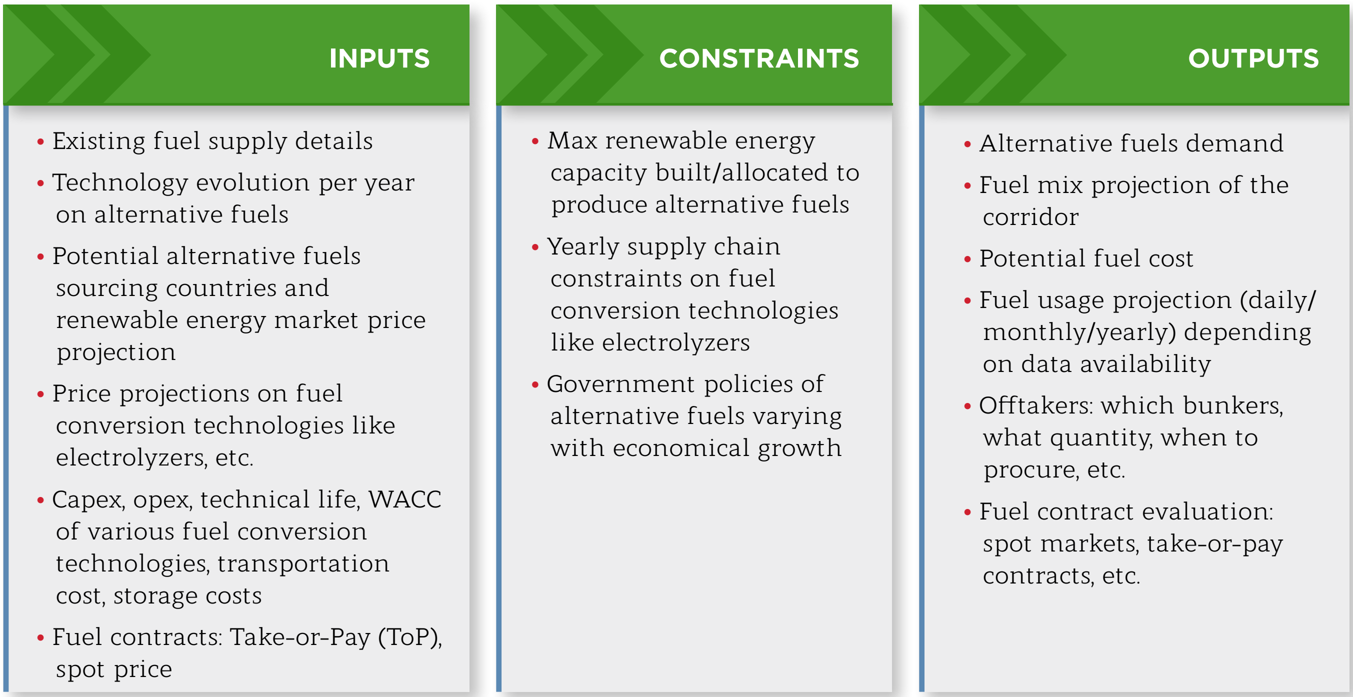


Figure 12: Fuel suppliers' sub-model.

4.2.4 CORRIDOR SUB-MODEL CAPABILITIES

Shipowners and operators and port operators will be key defining stakeholders for a corridor. Some of the additional inputs to represent a corridor are:

- Existing category of vessels and projected category of vessels operating on the route
- Year-on-year increase or decrease in the trade growth
- Choosing the locations on intermediary stopovers for bunkering
  - » Intermediary stopovers are not considered in the case study

The following constraints will be considered in the corridor sub-model:

- Year-over-year emission constraints based on Carbon Intensity Indicator (CII) and fixed carbon taxes have been considered.
- If needed, carbon taxes varying every month or year can be added for more granular and stringent analysis

The major outputs expected from this sub-model are:

- Year-over-year fuel mix and consumption in the corridor
- Bunkering usage and fuel-mix projection

The inputs, constraints and outputs of the corridor sub-model are shown in Figure 13.

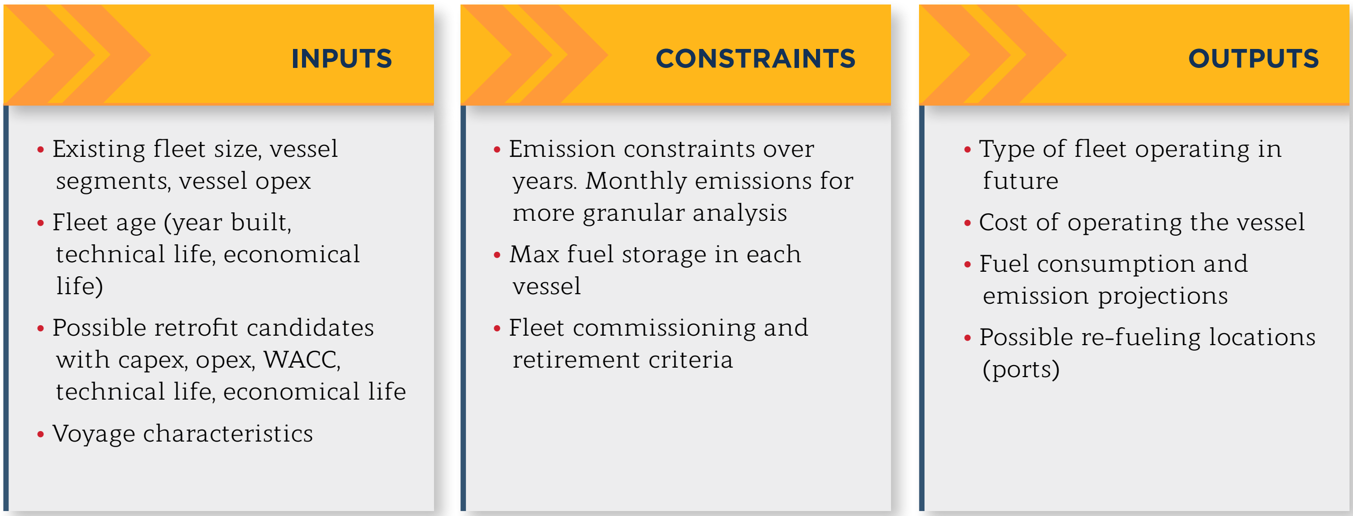


Figure 13: Corridor sub-model description.

4.3 METHODOLOGY FOR DAILY FUEL PRICING

The different fuel prices based on the various sourcing locations play a crucial role for the simulation and planning of the alternative fuel infrastructure across the examined green shipping corridors. The methodology for establishing the current fuel cost landscape and forecasting the future prices typically involves analyzing historical data on fuel prices, production costs and market trends. Once it was completed, we emphasized feature engineering based on the relationships of the different fuels and used statistical methods that have been found able to identify and re-produce price patterns over an extended period.

Since there are many uncertain and unforeseen factors that affect the fuel costs, we worked on an approach that considers well established differences between the range of available and alternative fuels and allows the simulation to optimize the emissions reduction trajectory that different green shipping corridors have to offer.

Our selected methodology can be broken down into four distinct steps:

Learning: Initially, our model learns from historical daily crude oil and other fuel price data that extends 25 years from 1987 to 2022. The data was obtained from the U.S. Energy Information Administration (EIA).[11] From this process, the price patterns and daily price variance emerges.

Sourcing location price differentiation: For the selected sourcing locations, we examined the price trajectories and scored future price competitiveness based on the production cost developments.

Type of fuel price differentiation: Based on the categorization of fuels to conventional, gray and green, the current price differences and the future projected prices for alternative fuels to be attractive, we provide a direction for each fuel.

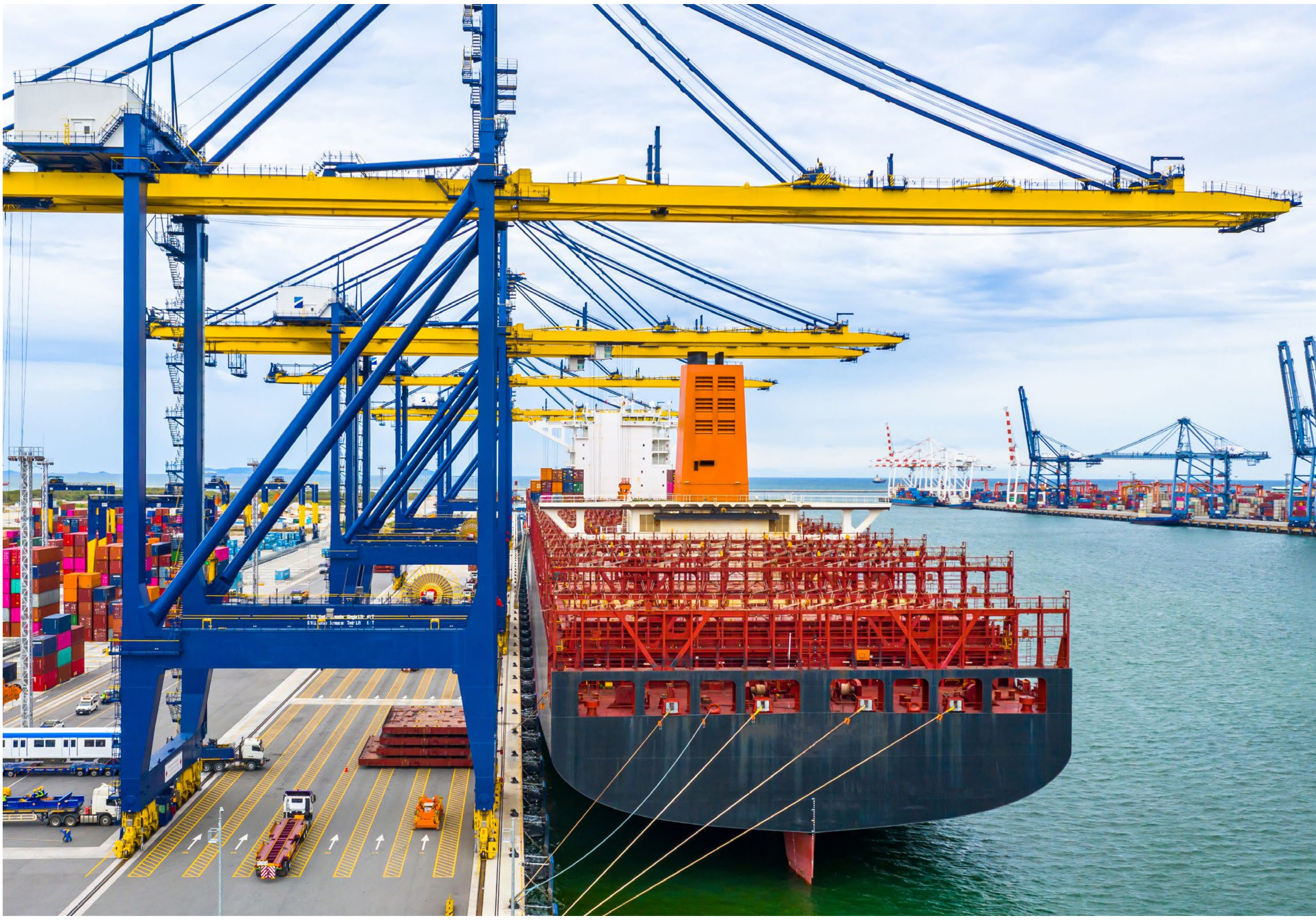
Forecasting: To predict the values based on the historical data and after the feature engineering we used the AAA version of the Exponential Smoothing Algorithm. Finally, we validate the projections against recent prices.

By utilizing the above-mentioned stepwise methodology, we predict the daily fuel cost prices. It is essential to highlight that this projection aims at providing a realistic foundation for the simulation to conduct its automated decision-making process by considering information that is consistent with the current and past fuel price landscape. Finally, note that the methodology used for price prediction is continually evolving as new data and techniques become available, and therefore, the accuracy of predictions can improve over time.

Very low sulfur fuel oil (VLSFO), liquefied natural gas (LNG), green ammonia, bio-methanol and marine gas oil (MGO) are considered in the corridor with as pilot fuel. The fuel characteristics such as lower calorific value (LCV) with well-to-wake and tank-to-wake emission factors are listed in Table 2.

FUEL CHARACTERISTICS	VLSFO	LNG	GREEN AMMONIA	MGO	BIO-METHANOL
LCV (MJ/g)	0.04	0.048	0.019	0.043	0.02
WtW (t-CO_2-eq/t-Fuel)	3.73	3.667	0.007	3.891	0.075
WtW (kg-CO_2-eq/GJ)	93.25	76.40	0.37	90.49	3.75
TtW (t-CO_2-eq/t-Fuel)	3.163	2.779	0.007	3.255	1.375
TtW (kg-CO_2-eq/GJ)	79.075	57.90	0.37	75.70	68.75

Table 2: Fuel characteristics and emission factors.[12]



5 SINGAPORE TO ROTTERDAM GREEN SHIPPING CORRIDOR

The Singapore to Rotterdam green shipping corridor is an initiative aimed at promoting sustainable and eco-friendly shipping between Singapore and Rotterdam, two major global ports. In August 2022, the port authorities of Singapore and Rotterdam joined with others in the industry to expand on the concept of green shipping corridors. The port authorities will work with the Global Centre for Maritime Decarbonization and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. Other industry partners include bp, CMA CGM, Digital Container Shipping Association, Mærsk, MSC, Ocean Network Express, PSA International and Shell.[13]

In our previous green corridor-focused publication,[1] Singapore and Rotterdam were identified as one of the most promising green shipping corridor ports when considering port of calls, port facility readiness level and shipping impacts. With the help of the ABS green shipping corridor simulation capability, the optimization case study with four well defined scenarios is presented to showcase the optimal fleet decarbonization strategy.

5.1 ASSUMPTIONS

In general, the objective of this study is to minimize the stakeholder investment while meeting the carbon reduction targets as required by the International Maritime Organization (IMO) and additionally, identify scenarios which push the envelope on the goals well beyond the envelope of regulatory requirements. The International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI are in force starting November 1, 2022, and have come into effect starting January 1, 2023.[14] These measures are part of IMO's initial strategy of reducing greenhouse gas (GHG) emissions by reducing carbon intensity by 40 percent by 2030 compared to 2008 and pursuing efforts towards 70 percent by 2050 compared to 2008.[15]

The following emission targets were considered for the case study:

1. IMO goals – containership following the IMO CII (g/t-nm). The trajectory projected from the base year of 2025 indicates a reduction of over two percent per year, resulting in an overall reduction of more than 50 percent over a 25-year period.
2. 80 percent reduction – containership following a more aggressive reduction trajectory that represents an overall 80 percent reduction in CII by 2050 with 2025 as the base year.

Figure 14 below shows the two trajectories under consideration:

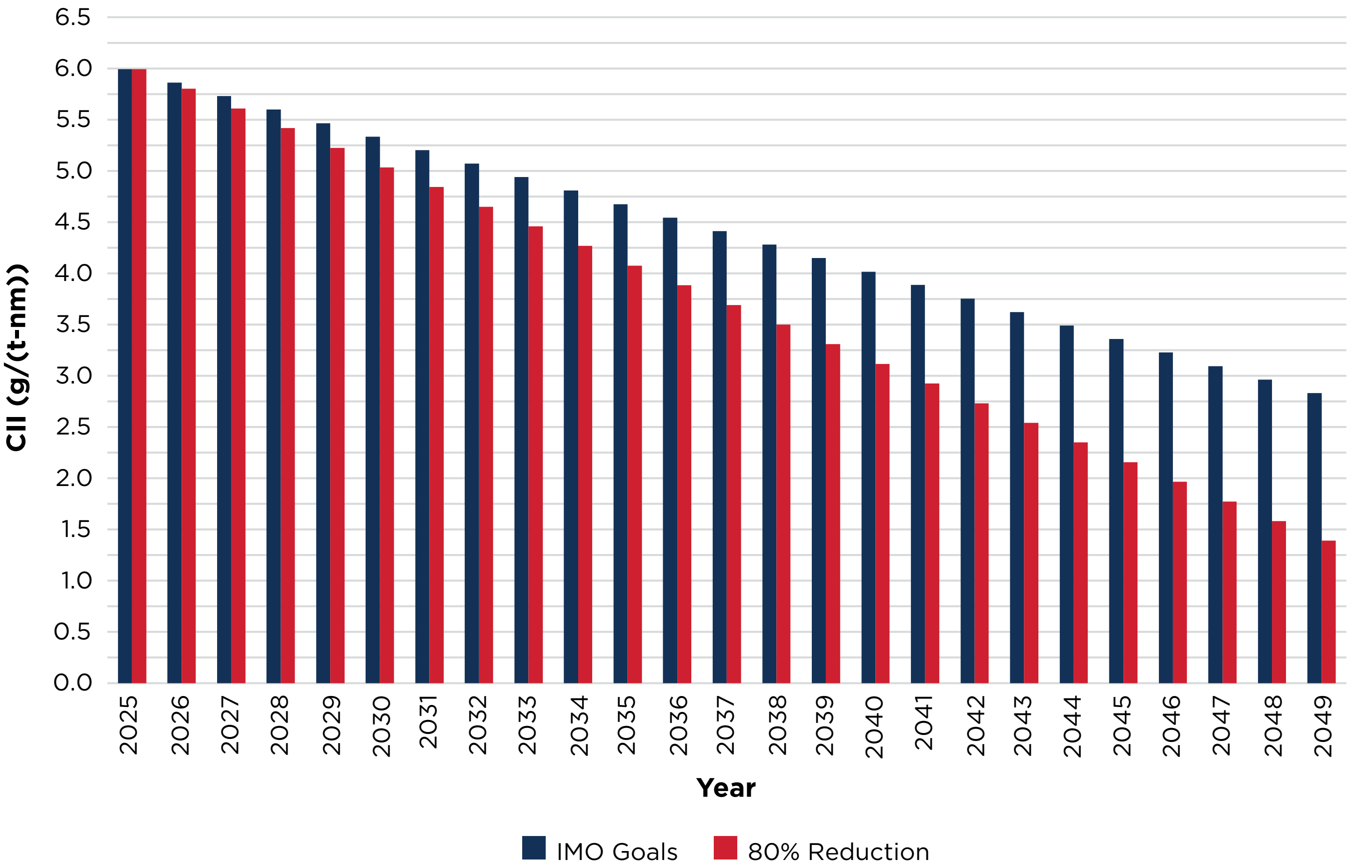


Figure 14: CII goal trajectories containerships Rotterdam to Singapore.

5.1.1 FLEET ASSUMPTIONS

According to data from the respective port authorities, the annual container throughput of Singapore and Rotterdam is approximately 36.9 million twenty-foot equivalent units (TEUs) and 14.5 million TEUs, respectively.[16,17]

This work assumes that around 10 percent of the container volume is transported directly between the two ports, leading to around 5.15 million TEUs of direct container traffic annually. Assuming that the average vessel size is around 10,000 TEUs, this requires around 515 vessel calls annually to transport the estimated 5.15 million TEUs of direct container traffic. In addition, each vessel is assumed to operate on a bi-weekly schedule (i.e., a vessel departs from one port to the other once every two weeks). This requires approximately 26 vessels operating directly between the two ports at any given time. With the assumption of seven percent trade growth year-over-year,[18,19] the number of vessels in the Singapore-Rotterdam green shipping corridor fleet is increasing from 26 in 2025 to 51 in 2035 as shown in Figure 15. Table 3 lists the details on the fleet and voyage information.

FLEET INFORMATION		
Size	8,000	TEUs
dwt	117,315	Tonnes
One Way Distance	9,325	nm
Total Voyage	14	--
Total distance	126,060.2	nm
CII Target in 2025	5.993	g/t-nm
CII Target in 2049 (IMO Goal Trajectory)	2.832	g/t-nm
CII Target in 2049 (80% Reduction Trajectory)	1.3904	g/t-nm
Fuel Tank Size	5,500	m^3
VOYAGE DETAILS		
Voyage Time	25	Days
Port Stay Time in Singapore	2	Days
Port Stay Time in Rotterdam	2	Days
ME Max Capacity	40	MW
AE Max Capacity	10	MW
Service Speed	18	knots
Approx Trips per Year	13.5	--

Table 3: Fleet and voyage information for Singapore-Rotterdam green shipping corridor.[20]

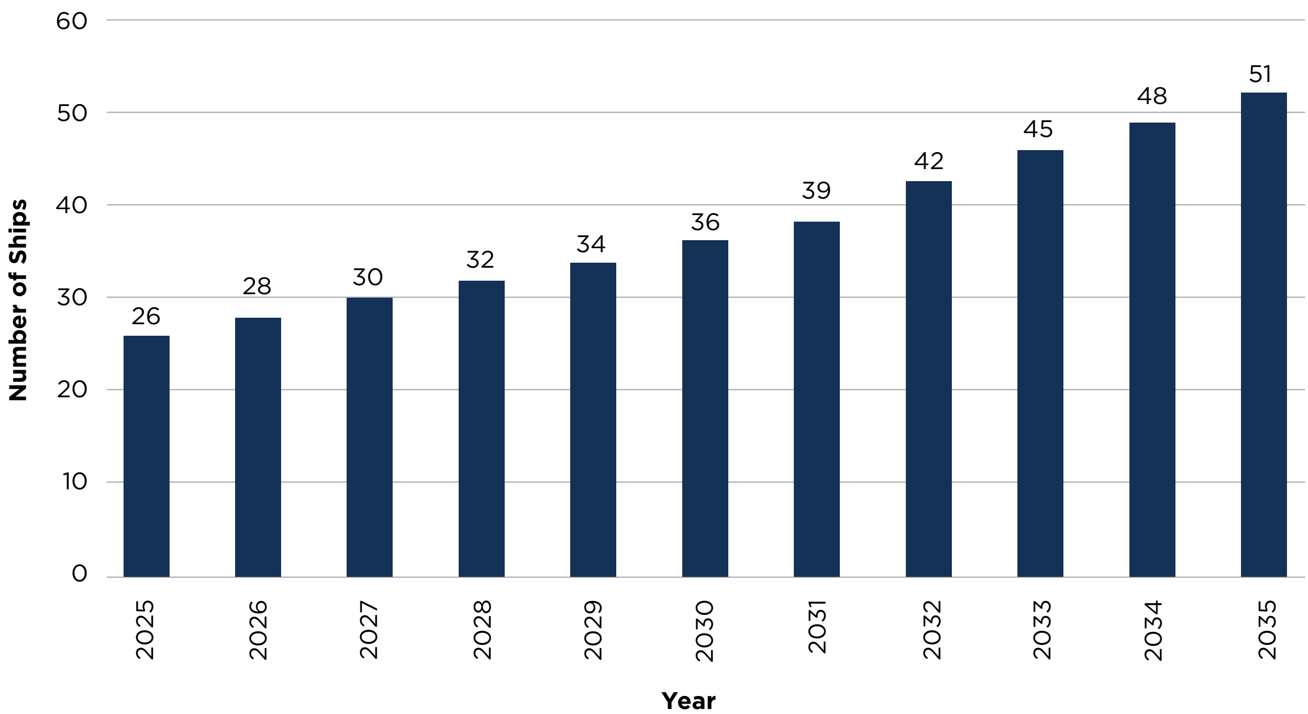


Figure 15: Year-over-year fleet size between Rotterdam and Singapore.

5.1.2 FUEL ASSUMPTIONS

Five marine fuels, Very low sulfur fuel oil (VLSFO), liquefied natural gas (LNG), green ammonia, marine gas oil (MGO) and bio-methanol, are pre-selected as the available marine fuels for the Singapore-Rotterdam green shipping corridor. The emissions profile accounts for both tank-to-wake and well-to-wake life cycles of marine fuels.

One-way distance between the Port of Singapore Authority (PSA) and Port of Rotterdam (PoR) is 9,325 nautical miles and we assume 25 voyages are completed per year with a service speed of 18 knots. Both tank-to-wake and well-to-wake emission factors of the fuels (see Table 2) have been considered for the optimization case studies, and each case has two carbon emission scenarios (IMO aligned goals and 80 percent reduction scenario). Therefore, this work developed four scenarios to showcase the different cost and emission performance of five marine fuels (VLSFO, LNG, green ammonia, MGO and bio-methanol).

The fuel blending is also considered for fuel combustion process. Table 4 represents the fuel and pilot fuel ratio for LNG, green ammonia and bio-methanol marine engines. Please note, while the fuel blending options are provided until 2050, the model results are provided up to 2035.

FUEL OPTION	FUEL/PILOT FUEL RATIO
LNG Blending from 2025 to 2050	
LNG	98.5%
VLSFO	1.5%
Green Ammonia Blending from 2025 to 2034	
Green Ammonia	85%
MGO	15%
Green Ammonia Blending from 2035 to 2044	
Green Ammonia	90%
MGO	10%
Green Ammonia Blending from 2045 to 2050	
Green Ammonia	92%
MGO	8%
Bio-methanol Blending from 2025 to 2050	
Bio-methanol	95%
VLSFO	5%

Table 4: Fuel/Pilot Fuel Blending Assumptions

Table 5 presents the fuel sourcing locations for the Singapore-Rotterdam green shipping corridor.

FUEL	SINGAPORE	ROTTERDAM
VLSFO	Malaysia	North Sea
	Saudi Arabia	Saudi Arabia
MGO	Malaysia	North Sea
	Saudi Arabia	Saudi Arabia
LNG	Qatar	Qatar
	China	Russia
Green ammonia	Malaysia	Spain
	Australia	Germany

Table 5: Fuel sources for the Singapore-Rotterdam green shipping corridor.

5.1.3 COST ASSUMPTIONS

The simulation inputs in the model are summarized in Table 6 below.

PROPERTY	HFO ENGINE VESSEL	LNG ENGINE VESSEL	GREEN AMMONIA ENGINE VESSEL	BIO-METHANOL ENGINE VESSEL
Base capex (Including Cost of AE and ME)	116,842,500	137,720,000	133,030,000	129,770,000
Cost of Capital (USD)	133,815,384	157,725,610	152,3543,27	148,620,770
Total Cost (USD)	250,657,884	295,445,610	285,384,327	278,390,770
WACC (%)	7	7	7	7
Economic Life (Years)	25	25	25	25
Technical Life (Years)	30	30	30	30

Table 6: Simulation inputs for container vessel capex.[20]

5.2 RESULTS AND DISCUSSION

The ABS green shipping corridor simulation can deliver the following visualized outputs: fleet fuel shares, newbuilding vessel shares, annualized port investments, fuel demand prediction in specific ports, fuel storage requirements at specific ports, and year-over-year fuel procurement for port bunkering stations, etc. Among them, the major key performance indicators (KPIs) for a maritime fleet decarbonization strategy are identified as fleet fuel options and their shares, and the corresponding return on investment (ROI). Therefore, this case study will focus on the prediction of the shares of pre-selected fuel options, and averaged total cost of ownership (TCO) per vessel, and TCO contributor shares. To determine the average TCO, the cost indicators cover annualized building cost, ship opex and carbon tax.

5.2.1 TANK-TO-WAKE EMISSION AND COST

Figures 16 and 17 illustrate the future fuel mix from 2025 to 2035 (IMO trajectory scenario and 80 percent reduction) considering tank-to-wake emission factors of fuels.

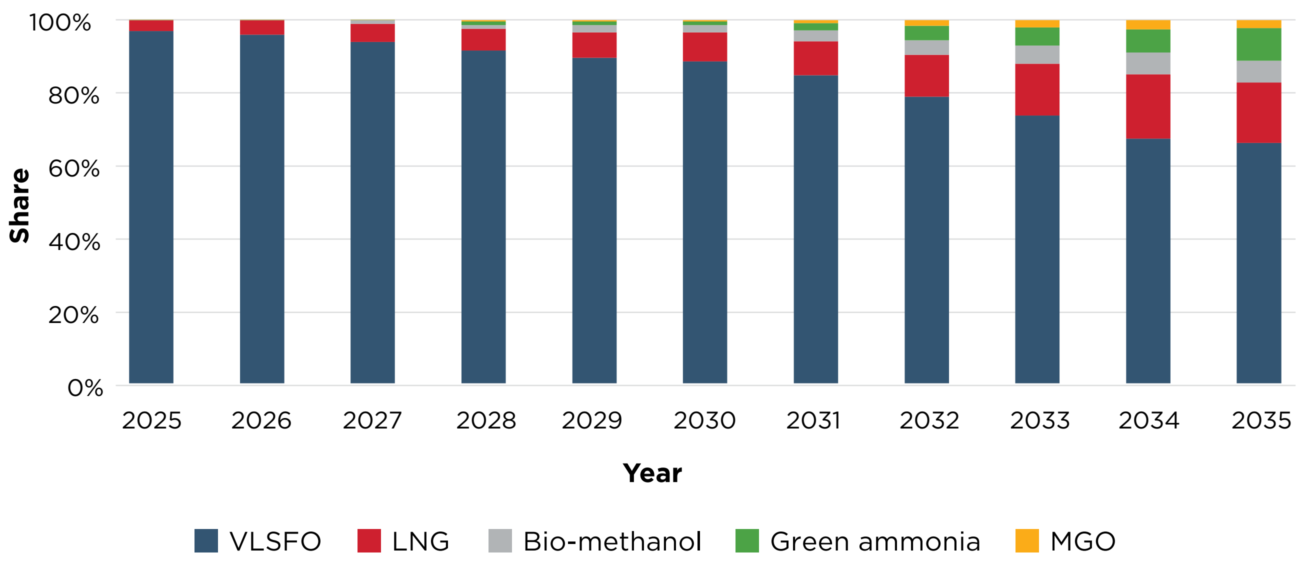


Figure 16: Annual fuel option shares for tank-to-wake emissions and IMO CII trajectory.

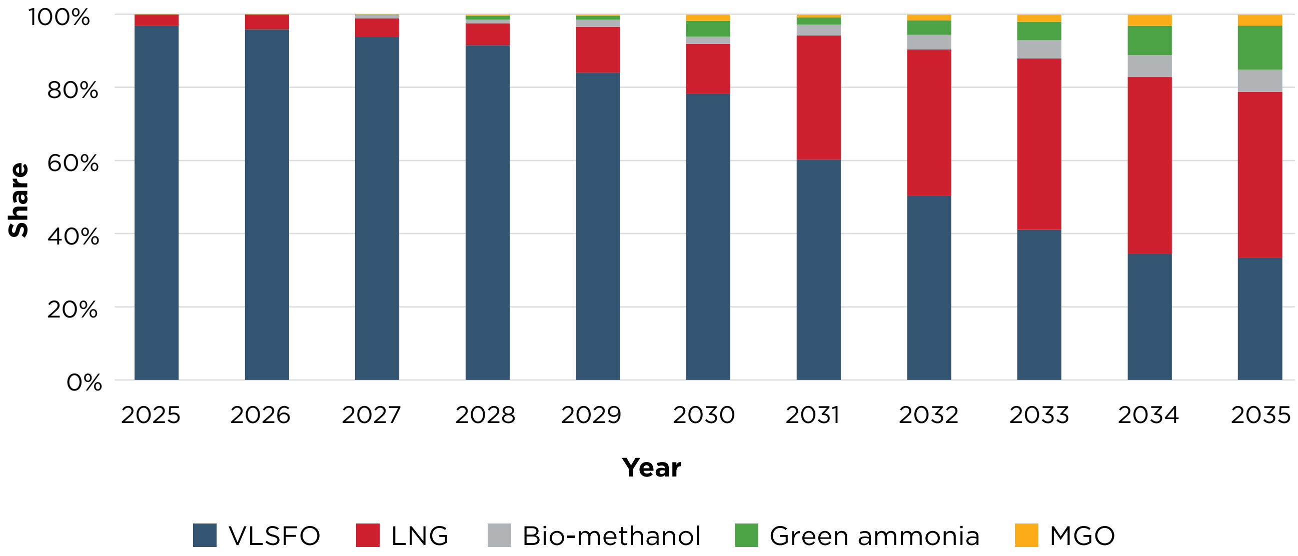


Figure 17: Annual fuel option shares for tank-to-wake emissions and 80 percent emission reduction trajectory.

One can conclude that a more ambitious decarbonization strategy will accelerate the phasing out of VLSFO. Both scenarios have clearly shown that the share of alternative fuels (LNG, green ammonia, bio-methanol) is increasing. Initially, LNG displaces VLSFO and then eventually, a good mix of LNG, bio-methanol, green ammonia is seen in the future fuel mix. While following the IMO CII trajectory, in the tank-to-wake case, by 2035, the predicted share includes VLSFO (65 percent), LNG (19 percent), green ammonia (nine percent), bio-methanol (six percent) and MGO (two percent). While for 80 percent reduction in the tank-to-wake scenario, by 2035, LNG (48 percent) becomes the most dominant fuel replacing VLSFO (31 percent) and the amount of green ammonia (11 percent) increases substantially while bio-methanol (six percent) and MGO (three percent) stay almost level. This means that, as the goals get more ambitious, VLSFO share drops precipitously and will get replaced by the next easily available cheaper alternative fuel which could vary from port-to-port (depending on the price and availability) and in this case, it happens to be LNG for the tank-to-wake scenarios with green ammonia and bio-methanol slowly absorbing a lot of the demand for low-emission alternative fuels.

FUEL PRICE SENSITIVITY ANALYSIS

Two additional scenarios were completed to understand the impact of alternative fuel prices on the future fuel mix. The following additional scenarios were completed but please note, this was done only for the IMO CII trajectory model runs as a sample data point for the model's sensitivity to fuel prices.

- Case A – Fossil fuel prices stay the course as expected (base case) but the difference in price between alternative fuel price and fossil fuels was increased by 25 percent. This assumes that the alternative fuels get dearer over the 10-year period.
- Case B – Fossil fuel prices stay the course as expected (base case) but the difference in price between alternative fuel price and fossil fuels was decreased by 25 percent. This assumes that the alternative fuel prices reduce over the 10-year period.

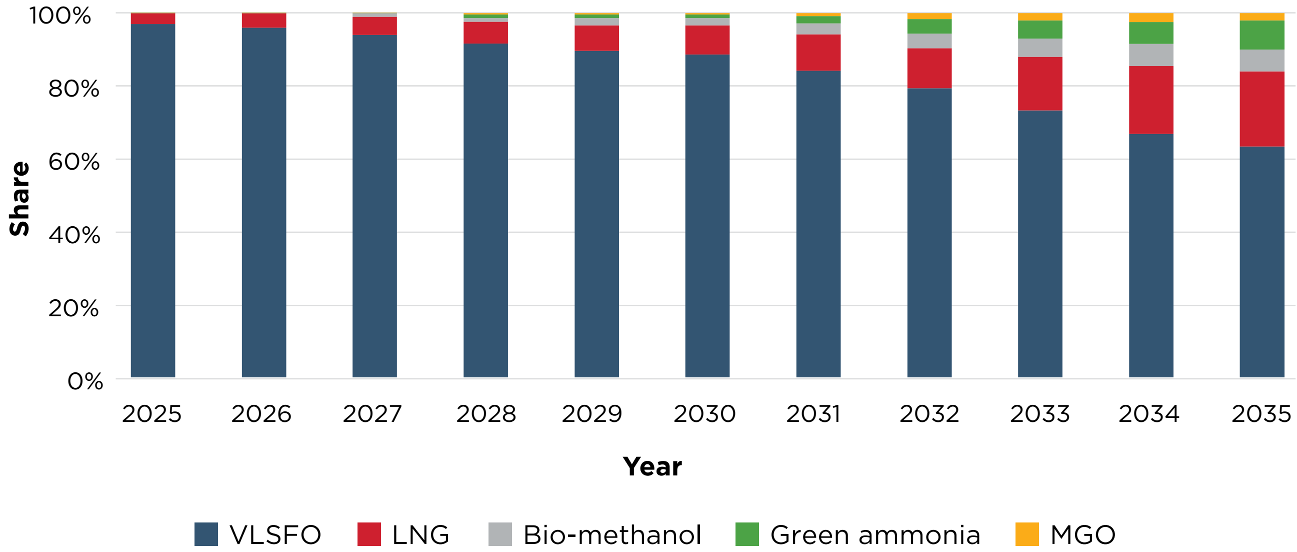


Figure 18: Case A – Annual fuel option shares when the fuel price difference is increased by 25 percent for tank-to-wake emissions and IMO CII trajectory.

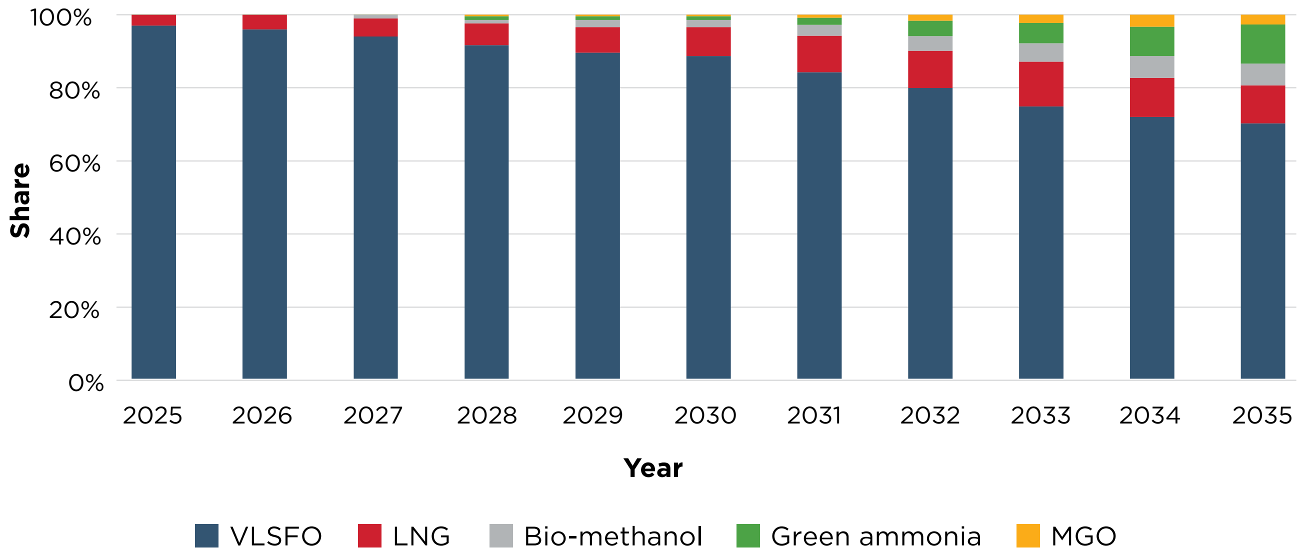


Figure 19: Case B – Annual fuel option shares when the fuel price difference is decreased by 25 percent for tank-to-wake emissions and IMO CII trajectory.

For Case A, a broader price spread between renewable and fossil fuels will restrict the growth of methanol and green ammonia as shown in Figure 18, while extending the share of LNG as a transitional and viable option to achieve mid-term decarbonization. In the inverse scenario as depicted in Case B, a lower price spread on green ammonia and bio-methanol will develop robust supply volumes earlier driving industry decarbonization at an acceptable level. This is shown in Figure 19. Other factors that may affect the growth rates of the alternative fuels include green financing and carbon taxation.

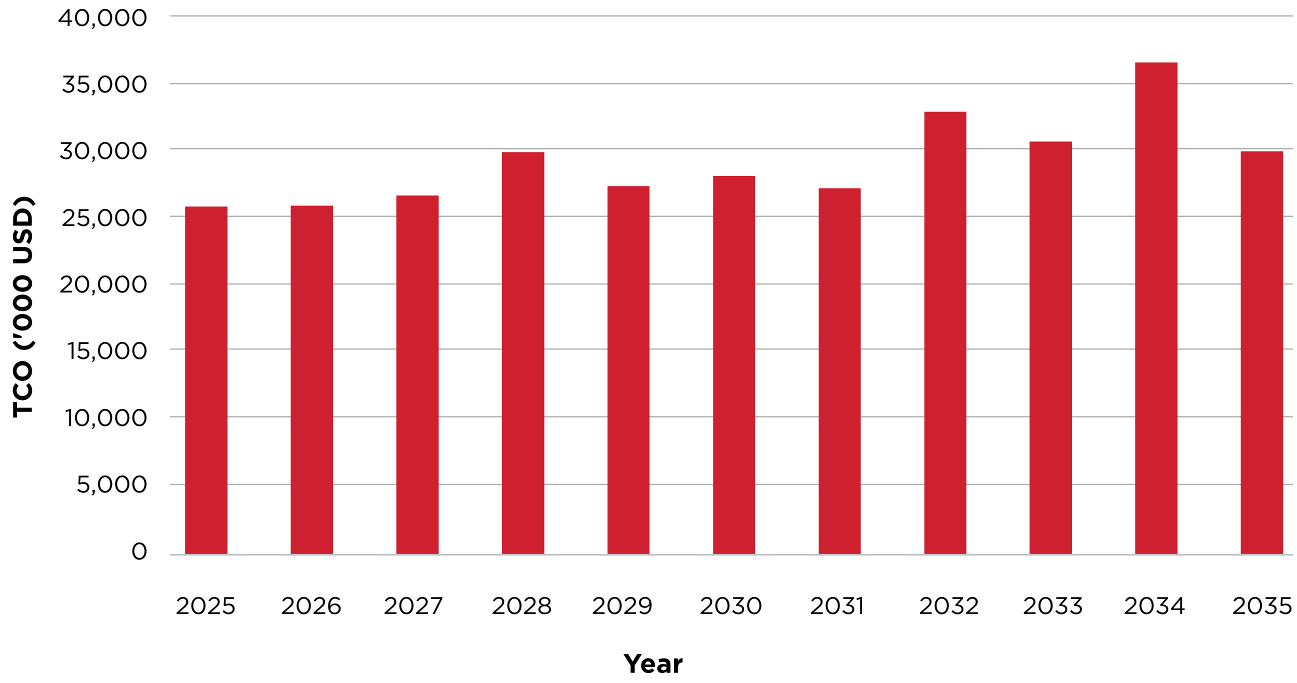


Figure 20: Average TCO in corridor for tank-to-wake emissions and IMO CII trajectory.

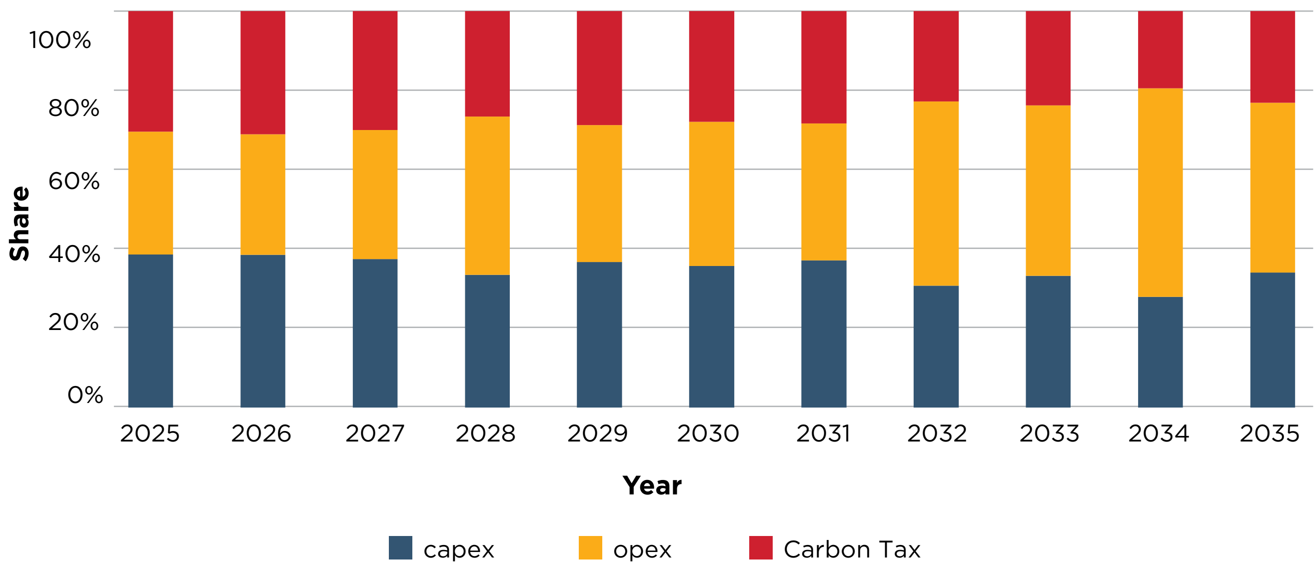


Figure 21: TCO contribution share by capex, opex and carbon tax considering tank-to-wake emissions and IMO CII trajectory.

Figures 20 and 21 illustrate the average TCO of the corridor (total cost of all vessels divided by the number of vessels in the route), and its contributor share for tank-to-wake emissions and CII following IMO trajectory. Irrespective of the trajectory of emission reductions, the trend line of the total TCO generally fluctuates due to consideration of fuel price variations (10-year horizon) and number of new vessels needed to absorb the additional demand caused by trade growth and its peak value occurs in 2034.

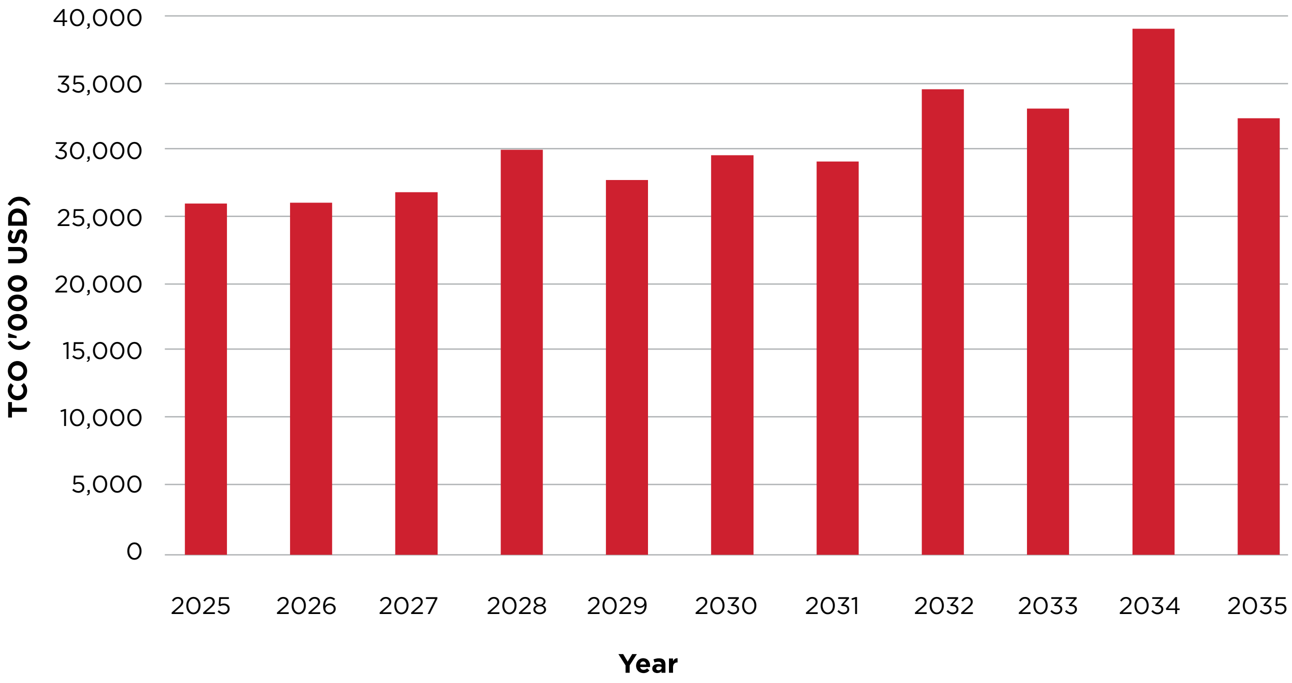


Figure 22: Average TCO in corridor for tank-to-wake emissions and 80 percent emission reduction trajectory.

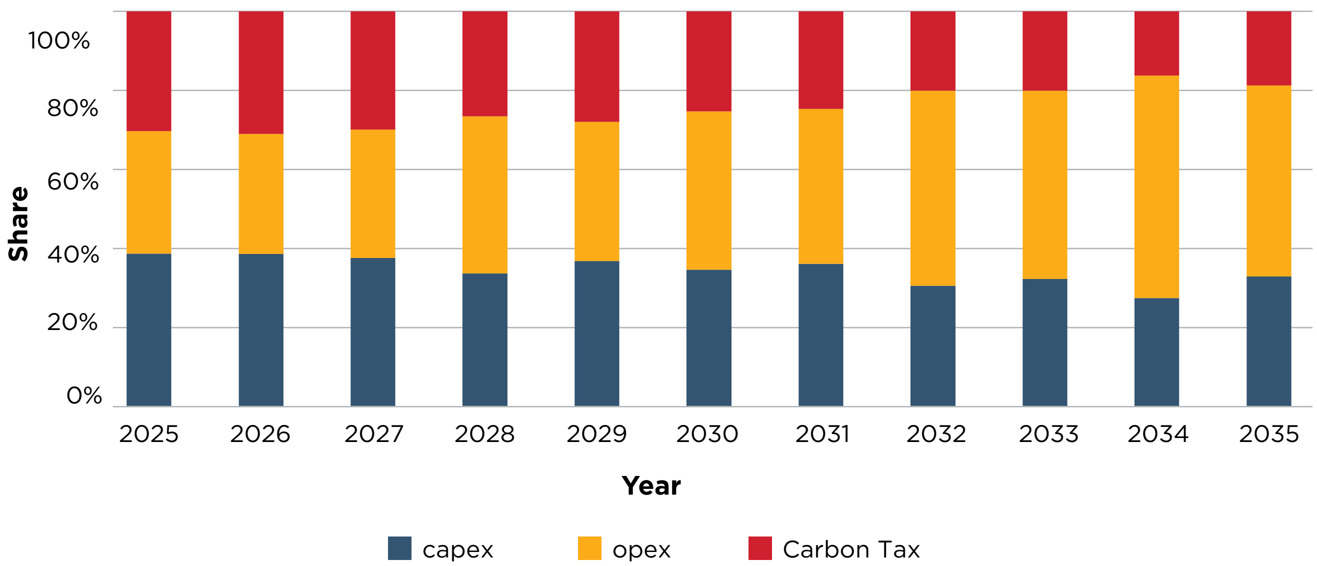


Figure 23: Average TCO contributions for tank-to-wake emissions and 80 percent emission reduction trajectory.

Figures 22 and 23 illustrate the average TCO of the corridor (total cost of all vessels divided by the number of vessels in the route), and its contributor share for tank-to-wake emissions and CII following a deeper decarbonization trajectory (80 percent reduction). The trend line of the total TCO generally fluctuates due to consideration of fuel price variations and number of new vessels needed to absorb the additional demand caused by trade growth and its peak value occurs in 2034.

It can be concluded that as the emission goals get more ambitious, the constraints on the resources increase leading to a need for sharper emission reductions and pushing a larger quantity of alternative fuels into the fuel mix, which in turn increases the average TCO.

5.2.2 WELL-TO-WAKE EMISSION AND COST

Figure 24 illustrates the fuel option shares from 2025 to 2035 considering well-to-wake emissions adhering to IMO CII trajectory whereas Figure 25 represents fuel option shares for well-to-wake emissions adhering to 80 percent reduction in emission.

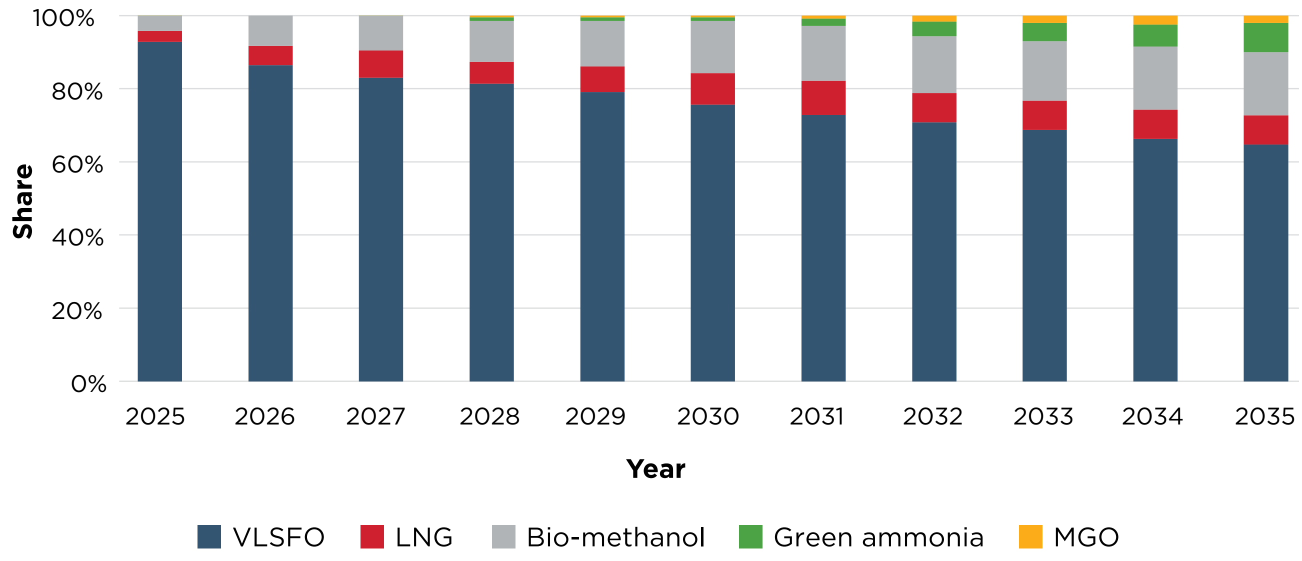


Figure 24: Annual fuel option mix considering well-to-wake emissions and IMO CII trajectory.

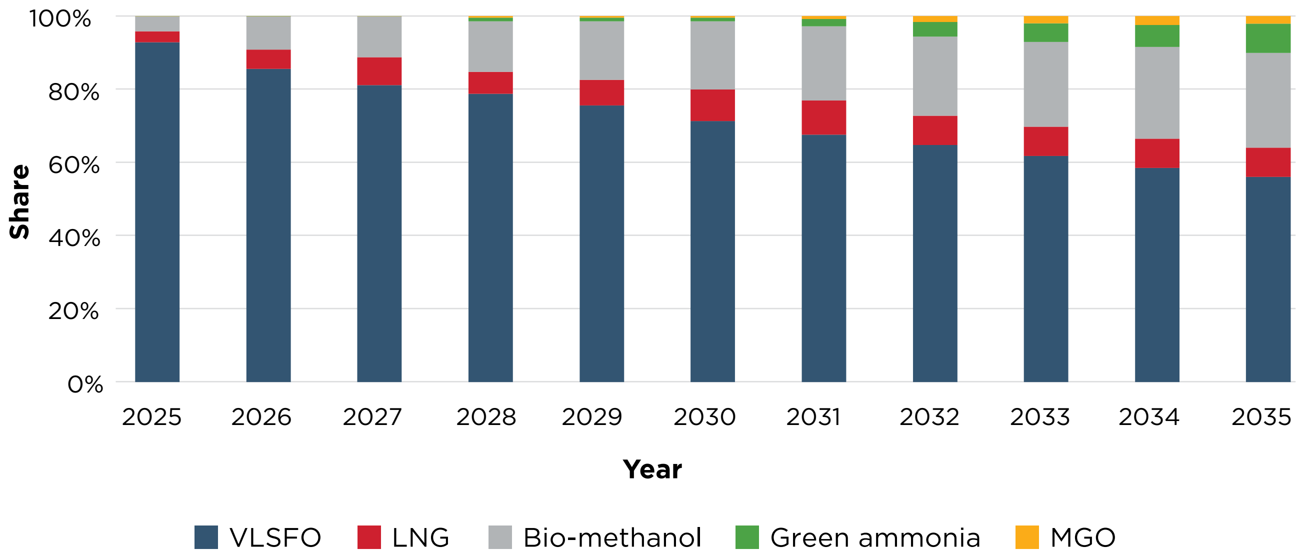


Figure 25: Annual fuel option shares for well-to-wake emissions and 80 percent emission reduction scenario.

Interestingly, if well-to-wake emission factors are considered and a more aggressive constraint is placed in terms of emissions, a greater amount of bio-methanol, green ammonia and to a lesser extent LNG will flow into the fuel mix since a faster decarbonization trajectory will accelerate the need for low- to zero-carbon fuels.

Similarly, the more ambitious decarbonization strategy will accelerate the process of VLSFO phasing out. Both scenarios have clearly shown that the share of bio-methanol is continuously increasing. It is to be noted that the fuel pricing methodology can be further refined, and availability limits can be enforced which may lead to different fuel shares. Another finding is that bio-methanol will limit the application of LNG and green ammonia since bio-methanol has a better cost-effective performance and it can meet the long-term decarbonization goal from the perspective of well-to-wake. For the IMO CII goals scenario, the predicted share of bio-methanol and VLSFO are all around 17 percent and 65 percent in 2035, respectively and the MGO share only accounts for about two percent. While for the 80 percent emissions reduction scenario, a lot more bio-methanol enters the fuel mix accounting for 26 percent of the total share in 2035 and if the same trend continues, bio-methanol could possibly be the most dominant fuel by 2050 in this corridor. Irrespective of the decarbonization scenarios, based on the assumptions made in this study, VLSFO remains a very significant part of the fuel mix.

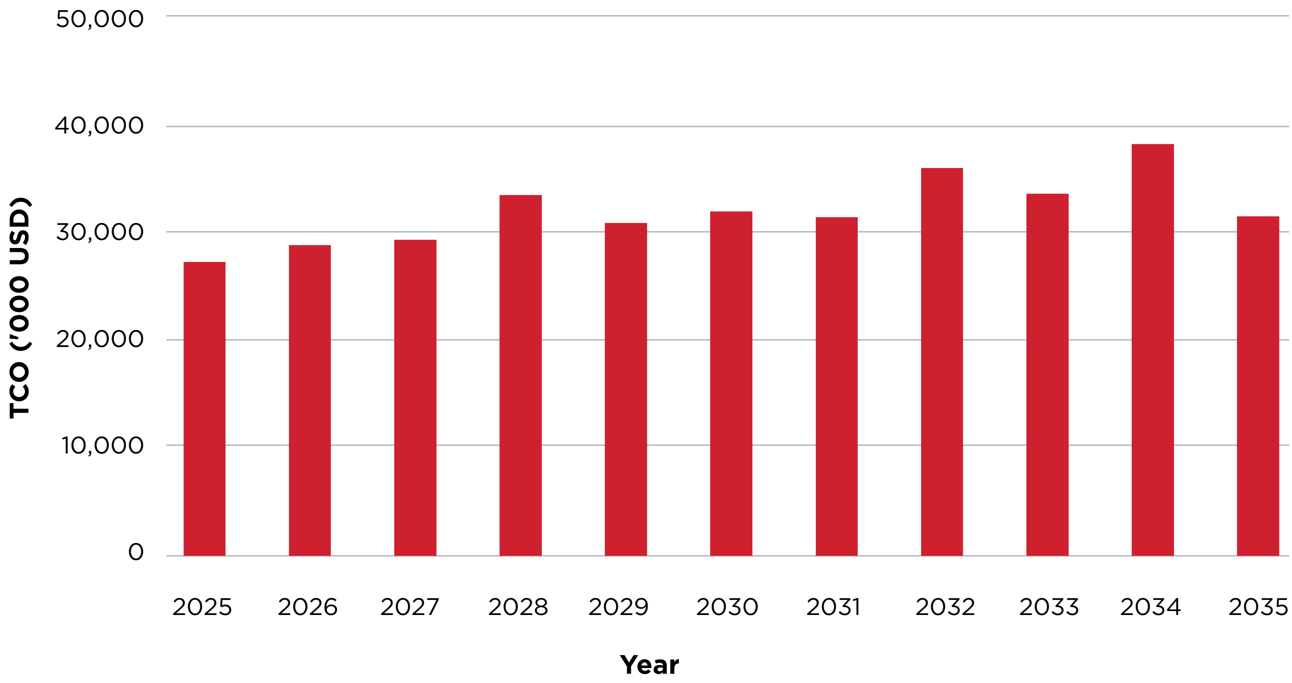


Figure 26: Average TCO in corridor considering well-to-wake emissions and IMO CII trajectory.

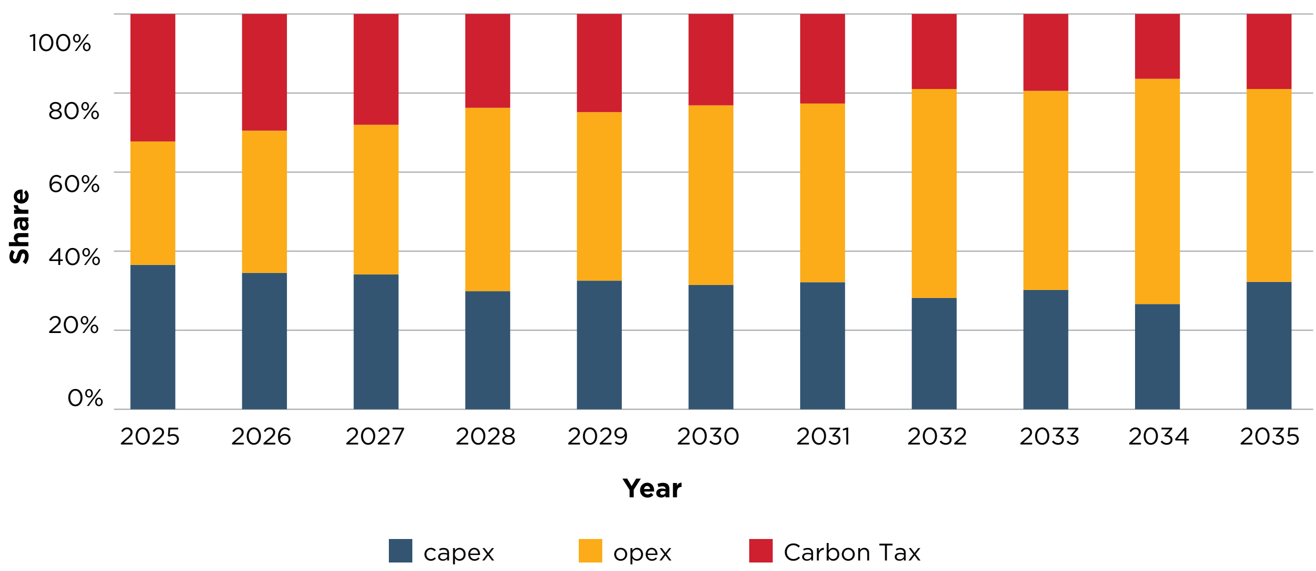


Figure 27: Average TCO contributions for well-to-wake emissions and IMO CII trajectory.

Figure 26 represents the comparison of average TCO of an IMO aligned well-to-wake decarbonization strategy. Figure 27 provides the share of TCO among capex, opex and carbon tax. In general, they both illustrate similar trend lines with the peak value of TCO occurring in 2034.

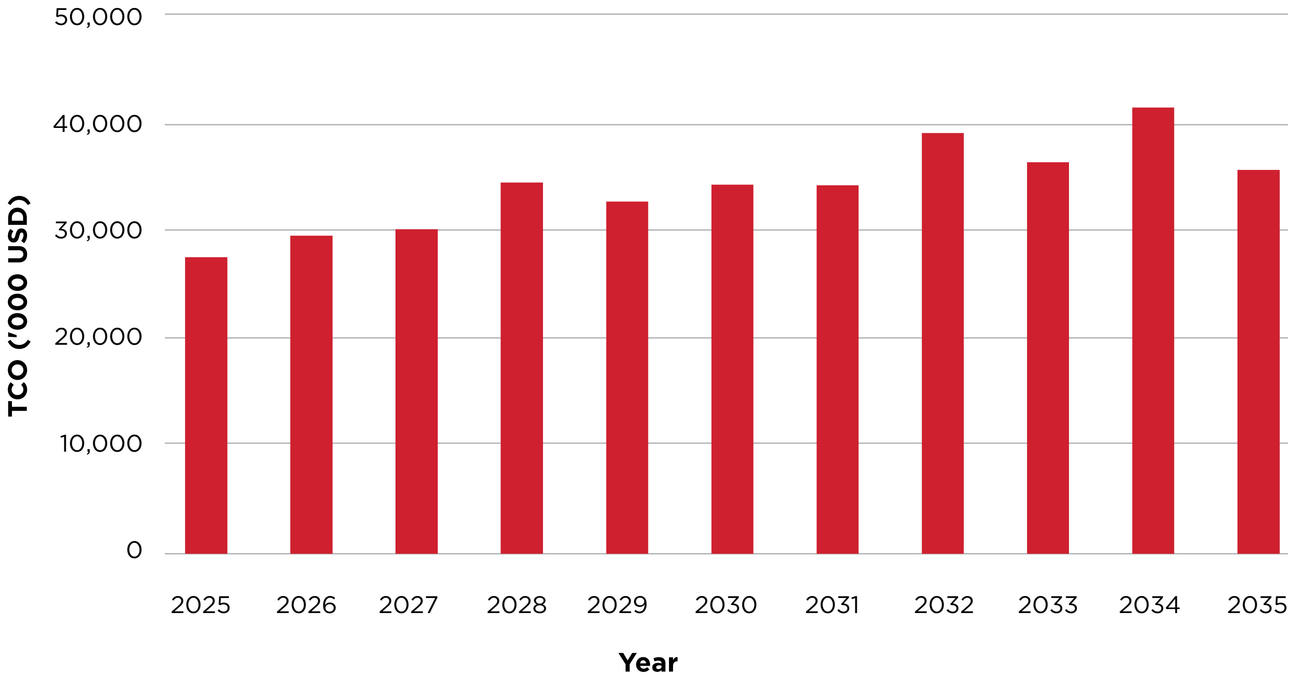


Figure 28: Average TCO in corridor considering well-to-wake emissions and 80 percent emission reduction trajectory.

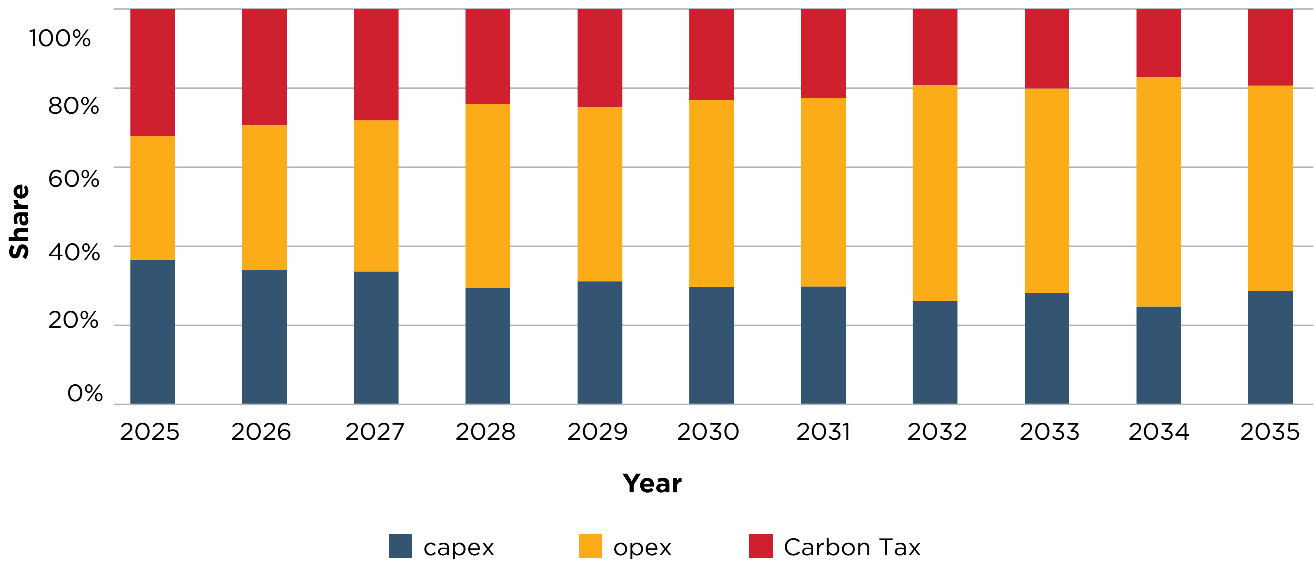


Figure 29: Average TCO contributions for well-to-wake emissions and 80 percent emissions reduction trajectory.

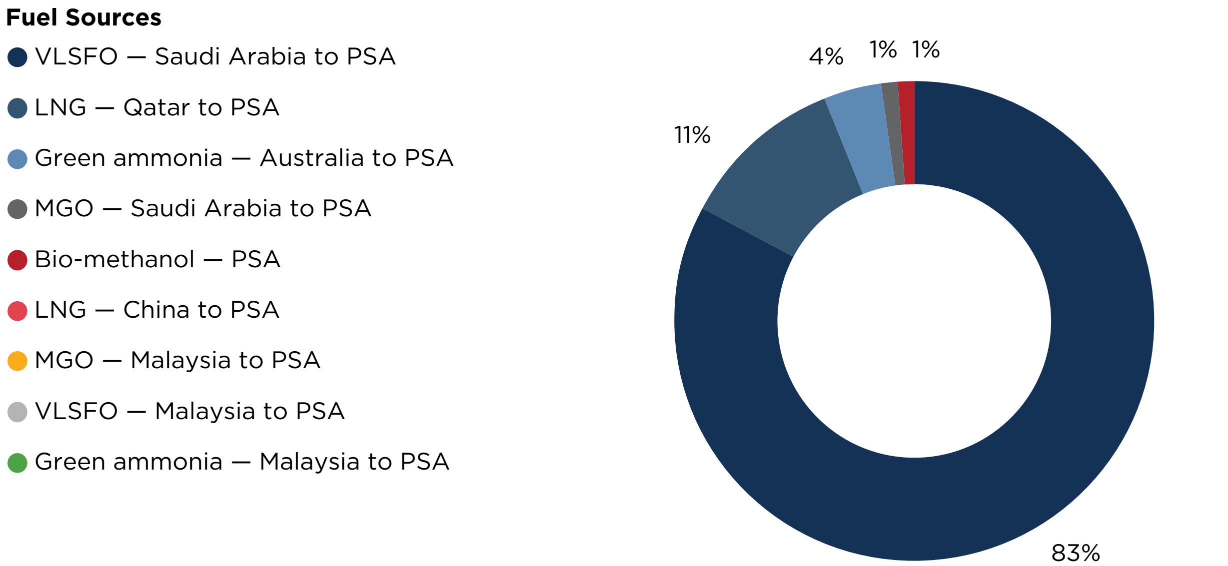
Figure 28 represents the average TCO for 80 percent reduction in well-to-wake emissions by 2035. Figure 29 provides the share of TCO among capex, opex and carbon tax. In general, they both illustrate similar trend lines, with the peak value of TCO occurring in 2034.

An interesting aspect of this result is that when bio-methanol's well-to-wake emission factors are considered, overall emissions are less since the well-to-tank (WtT) portion of the methanol emission factors are negative. The well-to-wake emission factor for bio-methanol is higher than green ammonia, due to the pricing assumptions made in the study, the model optimizes for lower TCO and lower emissions and hence, more bio-methanol is found in the final mix. As the supply of any of these fuels increases, the cost is expected to go down and eventually will lead to one of the alternative fuels moving ahead. This is a multi-variate problem, with numerous unknowns (fuel availability, engine technology development, port infrastructure deployment, emission reduction trajectory) and depending on the rate of deployment of these various fuels, the final fuel mix could substantially vary.

5.3 PORT FUEL PROCUREMENT

In addition, from the perspective of port authorities, Figures 30 to 33 illustrate the share of fuel procurement for the PSA and PoR over a 10-year horizon. These fuel procurement percentages are a function of the fuel prices that were input into the model and emission constraints that are placed on a yearly basis.

Share of Fuel Procurement in PSA



Share of Fuel Procurement in PoR

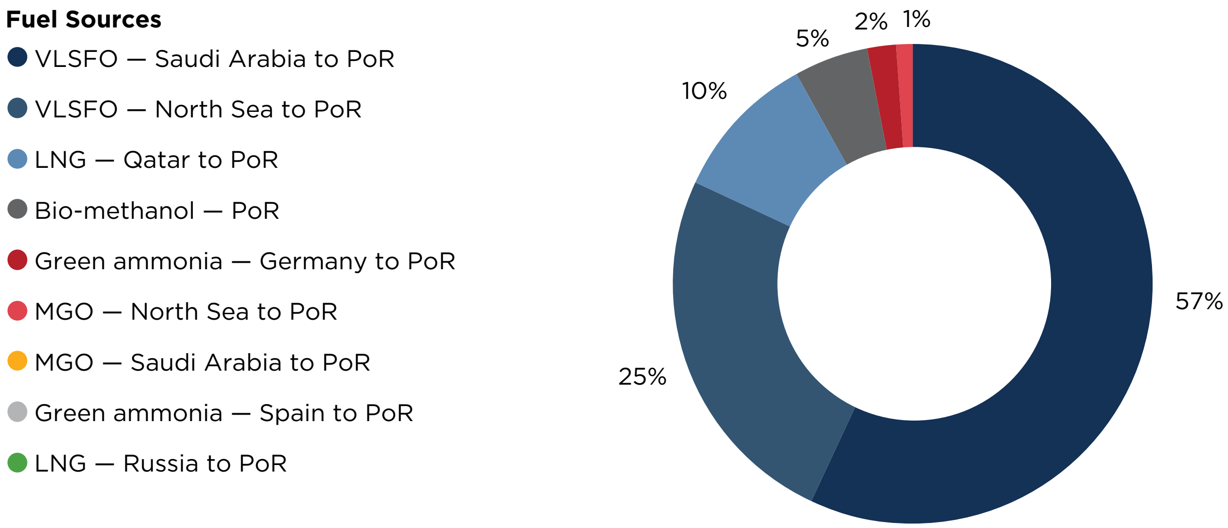
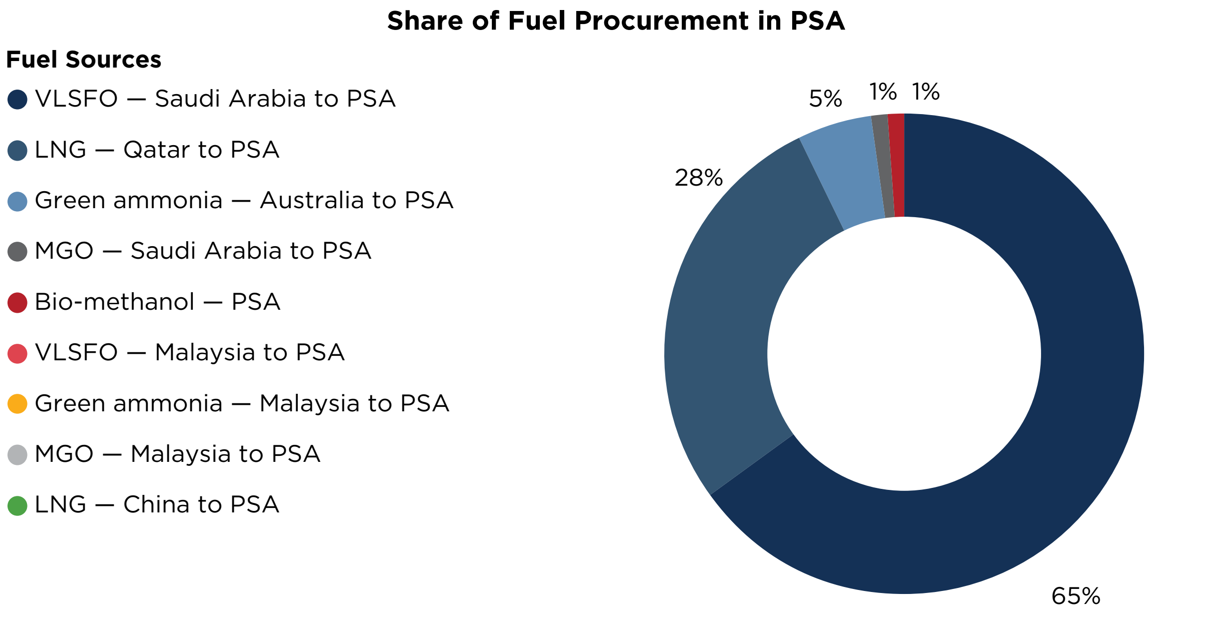


Figure 30: Share of fuel procurement from 2025 to 2035 for PSA and PoR considering tank-to-wake emissions and IMO trajectory scenario.



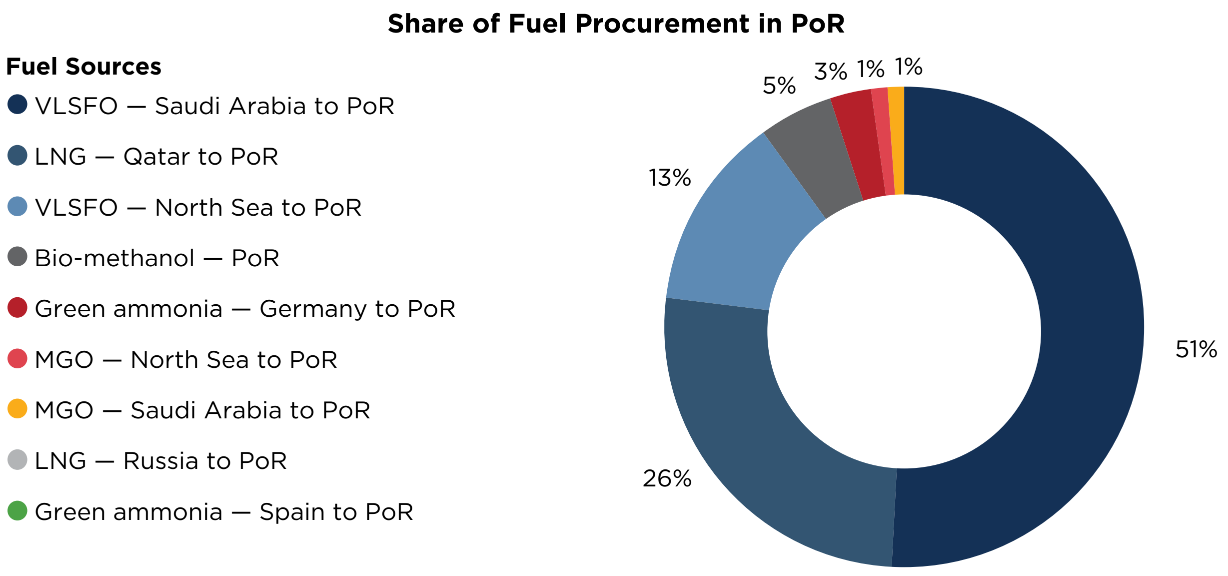
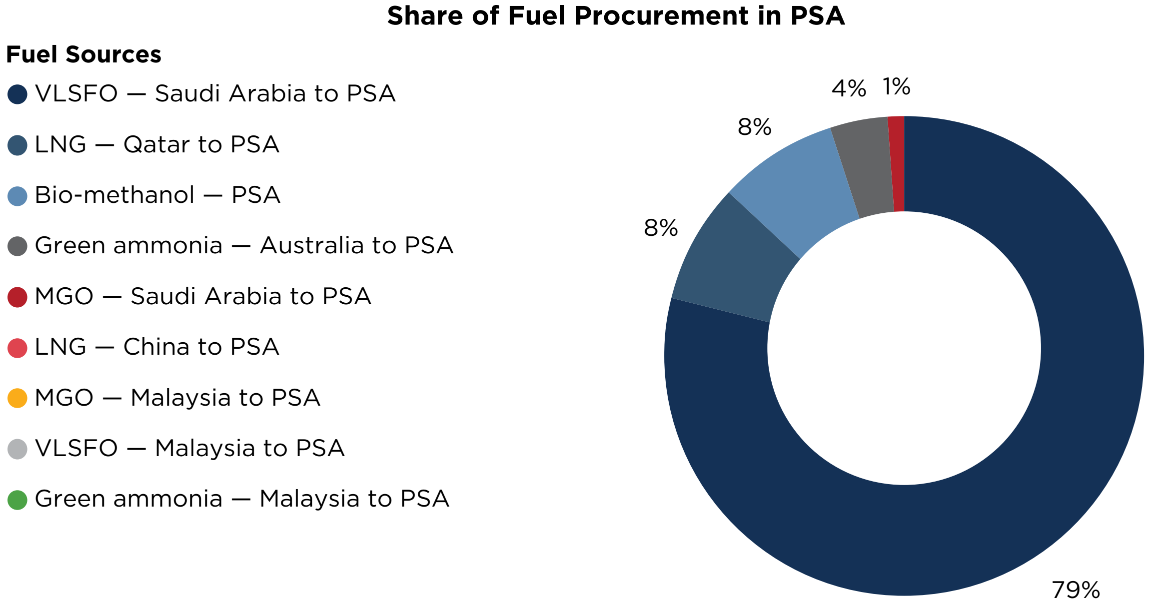


Figure 31: Share of fuel procurement from 2025 to 2035 for PSA and PoR considering tank-to-wake emissions and 80 percent emission reduction scenario.



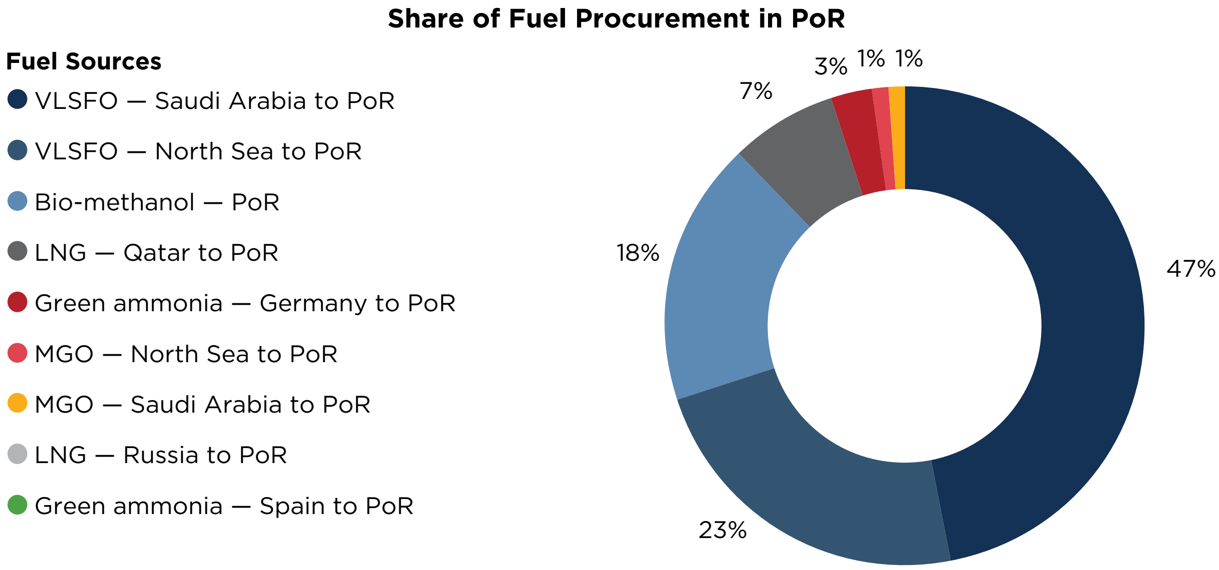
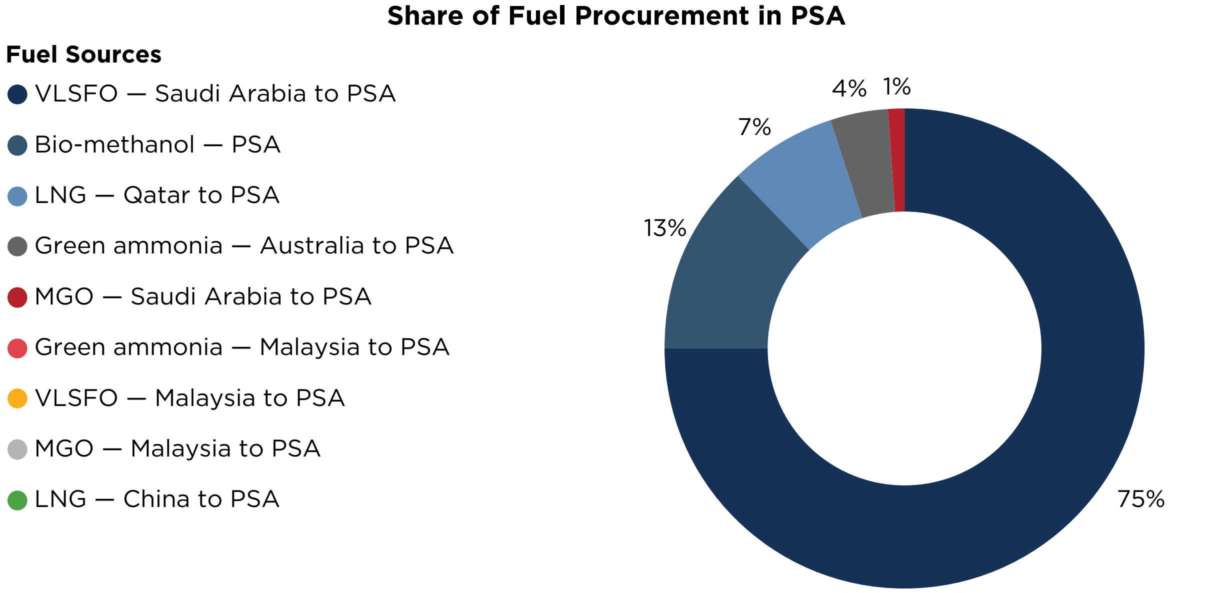


Figure 32: Share of fuel procurement from 2025 to 2035 for PSA and PoR considering well-to-wake emission and IMO trajectory scenario.



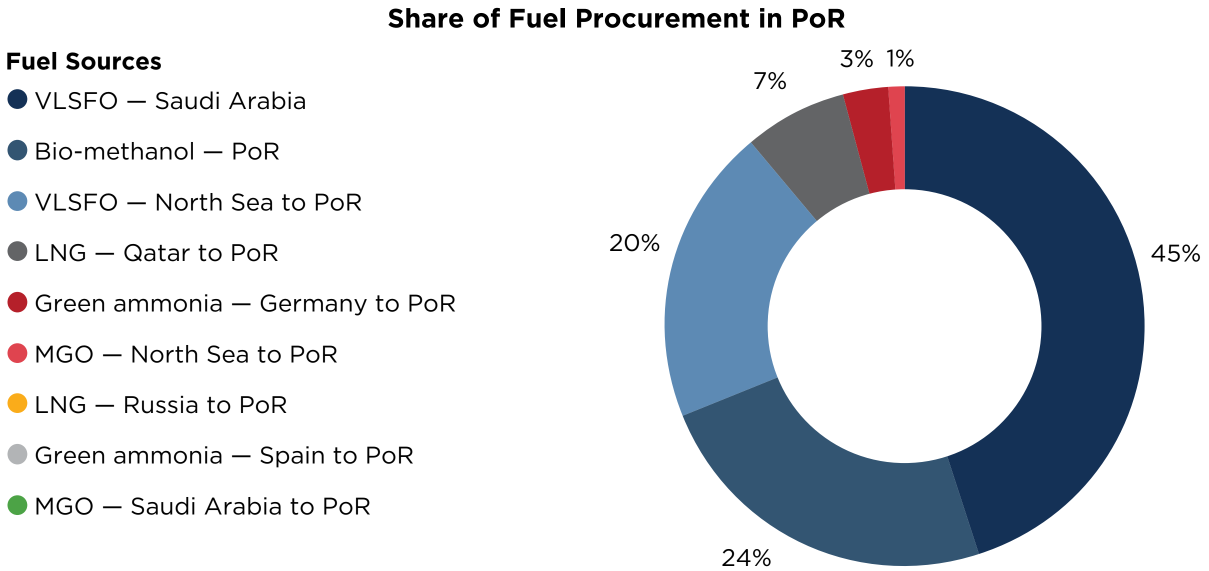


Figure 33: Share of fuel procurement from 2025 to 2035 for PSA and PoR considering well-to-wake emissions and 80 percent emission reduction scenario.

Below are some of the salient insights from the fuel procurement outputs for the years 2025 to 2035 from the optimization model.

- For tank-to-wake IMO aligned scenario, the top three fuel procurement sources in PSA are VLSFO from Saudi Arabia (83 percent), LNG from Qatar (11 percent) and green ammonia from Australia (four percent). This is shown in Figure 30.
- For the tank-to-wake IMO aligned scenarios, the top three fuel procurement sources for PoR are VLSFO from Saudi Arabia (57 percent), VLSFO from North Sea (25 percent) and LNG from Qatar (10 percent). This is shown in Figure 30.
- For tank-to-wake 80 percent reduction scenario, the top three fuel procurement sources in PSA are VLSFO from Saudi Arabia (65 percent), LNG from Qatar (28 percent) and green ammonia from Australia (five percent). This is shown in Figure 31.
- For the tank-to-wake 80 percent reduction scenario, the top three fuel procurement sources for PoR are VLSFO from Saudi Arabia (51 percent), LNG from Qatar (26 percent) and VLSFO from North Sea (13 percent). This is shown in Figure 31.
- While for well-to-wake IMO aligned goals, the top three PSA fuel procurement sources, VLSFO from Saudi Arabia (79 percent), LNG from Qatar (eight percent) and regionally sourced bio-methanol (eight percent). This is shown in Figure 32.
- While for well-to-wake IMO aligned goals, the top three PoR fuel procurement sources are VLSFO from Saudi Arabia (47 percent), VLSFO from the North Sea (23 percent) and regionally sourced bio-methanol (18 percent). This is shown in Figure 32.
- For well-to-wake 80 percent reduction scenario, the major fuel procurement sources for PSA are VLSFO from Saudi Arabia (75 percent), regionally sourced bio-methanol (13 percent) and LNG from Qatar (seven percent). This is shown in Figure 33.
- For well-to-wake 80 percent reduction scenario, the major fuel procurement sources for PoR are VLSFO from Saudi Arabia (45 percent), regionally sourced bio-methanol (24 percent), and VLSFO from the North Sea (20 percent). This is shown in Figure 33.

5.4 CONCLUSION — SINGAPORE–ROTTERDAM CONTAINER LINER GREEN CORRIDOR

LNG being widely available as fossil sourced and adopted as lower carbon fuel option today, can drive decarbonization on a tank to wake emissions approach, complementing VLSFO in the long term, following the decarbonization drive rates. On a well-to-wake basis and the life-cycle assessment of fuel emissions, biogenic produced as well as synthetic methane will be a sustainable option to achieve the decarbonization goals. Although bio-methanol is rising to a noticeable portion of the fuel mix in both cases, it is the well-to-wake approach that benefits from its significantly lower emissions and increases its share among the alternative fuel options. A steeper decarbonization trajectory will only accelerate the uptake of bio-methanol. Green ammonia having significantly low emissions potential being a carbon free option is growing strongly on the tank-to-wake approach, while on the well to wake emissions scenario it's complementing bio-methanol in decarbonizing the fuel mix towards lowering emissions.

The current dominant fuel, VLSFO, is expected to give way to the alternative lower carbon fuel options in all scenarios, following the decarbonization drive. The focus on tank-to-wake emissions approach will accelerate phasing out in favor of LNG, while in a well to wake approach it will give way to non-fossil originated options. Singapore as one of the two major hubs in this route will have to facilitate the projected energy demand, by adapting its storage infrastructure and capacity, also following the trade and market growth. In that aspect, in most scenarios where VLSFO has a smooth phasing out, the capacity shall remain largely unchanged, while the requirement for investment in capacity for the alternative fuel options will be imminent. The current LNG fuel capacity may suffice for the well to wake approach, however the future demand for biogenic and synthetic methane will require expansion to facilitate the demand. The requirement for green ammonia and bio-methanol storage capacity will be substantial after 2030 and projected to overtake the oil tanks capacity in the long term. Rotterdam, being the other pillar of this route, will also have a declining but stable demand for VLSFO, despite its decline on the fuel mix, thanks to the increase in trade and market size. LNG demand is more significant on the tank-to-wake scenarios, gaining significant volume after 2030. For the lower carbon options, Rotterdam will require to supply more bio-methanol than green ammonia for this route, with a substantial demand from the mid-2020s.

6 AUSTRALIA TO JAPAN (IRON ORE) GREEN SHIPPING CORRIDOR

In April 2022,[21] there was an announcement made that focused on iron ore and includes BHP, Rio Tinto, Oldendorff Carriers and Star Bulk Carriers. The consortium, Global Maritime Forum (incl. Rio Tinto et al.) inked a letter of intent (LOI) between miners (charterers) and owners to evaluate fuels and routes (ABS, 2022). In November 2022,[7] representatives from major maritime and energy organizations convened with the aim of working towards accelerating the formation of a green corridor with a specific focus on iron ore between Australia and East Asia and identify key actions and match supply to demand for green ammonia with the specific green corridor acting as a possible off taker. Therefore, this study focused on green ammonia, however, methanol or other alternative fuels may become part of the fuel mix as this corridor materializes which will impact the results of the case study presented. While the corridor is called as the Australia-East Asia green corridor, this specific case study focuses on the Australia-Japan iron ore transport sector of the larger geographical spread of the green corridor.

According to the latest available data from the World Steel Association, in 2020, Japan imported approximately 73.5 million tonnes[22] of iron ore from Australia. However, it's worth noting that this figure includes all types of iron ore, not just the iron ore transported by bulk carriers. Additionally, the amount of iron ore transported between Australia and Japan can vary from year-to-year based on factors such as demand, supply and price fluctuations.

6.1 ASSUMPTIONS

In general, the objective of this study is to minimize the stakeholder investment while meeting the carbon reduction targets as required by the International Maritime Organization (IMO) and additionally, identify scenarios which push the envelope on the goals well beyond the envelope of regulatory requirements. The International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI are in force starting November 1, 2022, and have come into effect starting January 1, 2023.[14] These measures are part of IMO's initial strategy of reducing greenhouse gas (GHG) emissions by reducing carbon intensity by 40 percent by 2030 compared to 2008 and pursuing efforts towards 70 percent by 2050 compared to 2008.[15]

The following emission targets were considered for the case study:

1. IMO goals – bulk carriers following the IMO CII (g/t-nm) trajectory projected from 2025 representing approximately over two percent reduction on a yearly basis leading to an overall reduction of 55 percent over the time (25 years) with 2025 as the base year.
2. 80 percent reduction – bulk carriers following a more aggressive reduction trajectory that represents an overall 80 percent reduction in CII from 2025 as the base year for 25 years.

Figure 34 below shows the two CII trajectories under consideration.

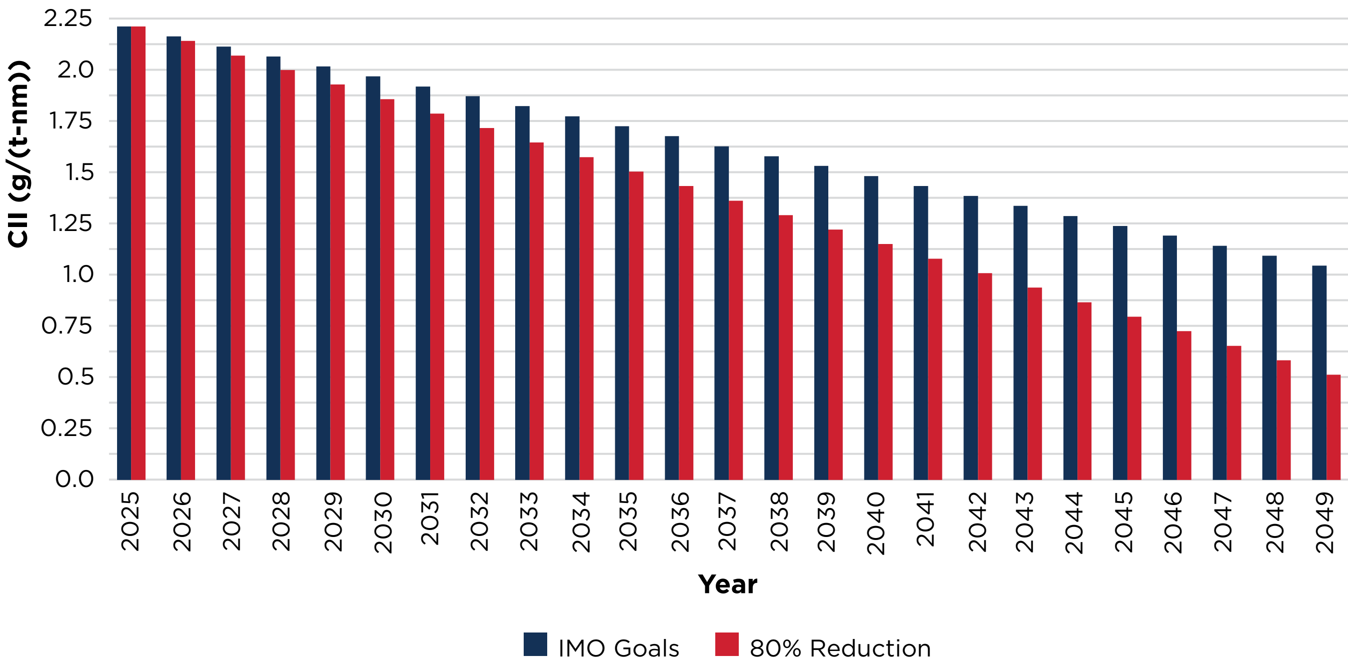


Figure 34: CII goal trajectories bulk carriers Australia to Japan.

6.1.1 FLEET ASSUMPTIONS

Based on the actual demand for iron ore export from Australia to Japan, the following assumptions are made to serve as the inputs for the fleet and voyage information. Please note, the fleet assumptions are deliberately conservative to cover all scenarios, but the operational assumptions are more in alignment with typical operations between Australia and Japan.

- Assumption 1: The average capacity of a bulk carrier operating between Australia and Japan is around 170,000 tonnes of iron ore.
- Assumption 2: The average travel time for a bulk carrier to travel between Australia and Japan is approximately 20 days.
- Assumption 3: Bulk carriers operating between Australia and Japan make round trips once every 40 days.

Total iron ore traffic between Australia and Japan per year = approximately 73.5 million tonnes per year. Average number of bulk carriers needed to transport this amount of iron ore = 73.5 million tonnes / (170,000 tonnes x 365 days/year) = 4.7 ships per day. Average number of bulk carriers making round trips per day = 4.7 ships per day / 2 = 2.4 ships per day. Average number of days required for a round trip = 20 travel days + 20 days to load and unload the cargo = 40 days. Average number of bulk carriers operating between Australia and Japan = 2.4 ships per day x 40 days/round trip = 96 ships.

Then the following assumptions are employed to calculate the estimated bulk carriers transporting in one specific pair of ports of the Australia-Japan green shipping corridor.

- Assumption 1: All iron ore imports from Australia are evenly distributed among the iron ore handling ports in Japan.
- Assumption 2: The top iron ore handling ports in Japan are Kashima, Yokohama, Shimizu, Kawasaki and Chiba.

Based on these assumptions, we can estimate the distribution of iron ore handling ports for the 96 bulk carriers operating between Australia and Japan as follows:

- Assuming equal distribution of iron ore imports, each iron ore handling port in Japan would receive approximately 19.2 bulk carriers per year.
- The actual number of bulk carriers per port may vary depending on factors such as the proximity of the port to the importing companies, the availability of infrastructure and other operational considerations.

Therefore, the estimated number of vessels for one specific pair of ports is 19 to 20 bulk carriers in 2025. With the assumption of seven percent trade growth year-over-year,[29] the number of vessels in the Australia-Japan green shipping corridor fleet is increasing from 20 in 2025 to 39 in 2035 as shown in Figure 35. Table 7 depicts the fleet and voyage information.

FLEET INFORMATION		
Size	200,000	dwt
One Way Distance	4,230	nm
Total Voyage	22	--
Total distance	93,060	nm
CII Target in 2025	2.178	g/t-nm
CII Target in 2050 (IMO Trajectory)	0.981	g/t-nm
CII Target in 2050 (80% Reduction)	0.4356	g/t-nm
Fuel Tank Size	3,000	m^3
VOYAGE DETAILS		
Voyage Time	14	Days
Port Stay Time in Australia	3	Days
Port Stay Time in Japan	3	Days
ME Max Capacity	15.5	MW
AE Max Capacity	3.875	MW
Service Speed	13	knots
Approx Trips per Year	21.5	--

Table 7: Fleet and voyage information for Australia-Japan green shipping corridor.[20]

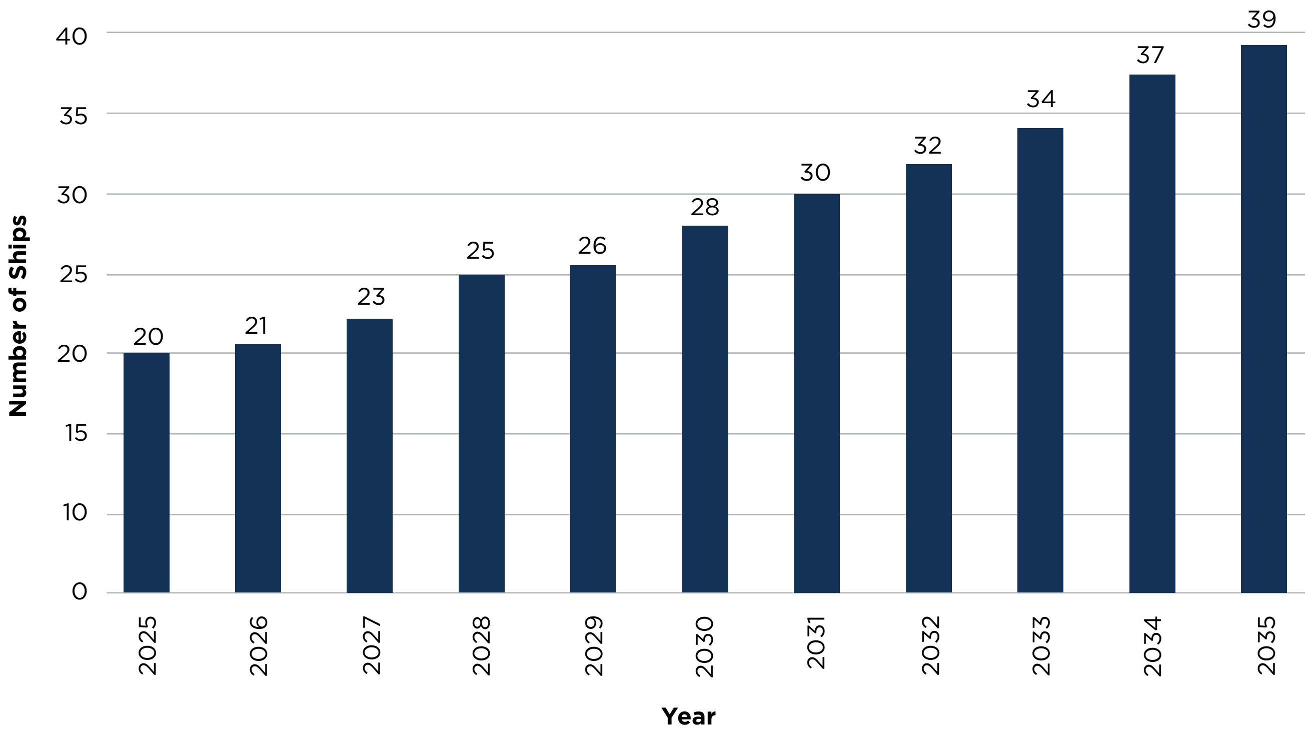


Figure 35: Year-over-year fleet size Australia to Japan.

6.1.2 COST ASSUMPTION

Table 8 summarizes our assumptions that were input into the model.

PROPERTY	HFO ENGINE VESSEL	LNG ENGINE VESSEL	GREEN AMMONIA ENGINE VESSEL
Base capex (Including Cost of AE and ME)	52,290,625	61,542,500	59,760,000
Cost of Capital (USD)	59,88,6514	70,482,343	68,440,912
Total Cost (USD)	112,177,139	132,024,843	128,200,912
WACC (%)	7	7	7
Economic Life (Years)	25	25	25
Technical Life (Years)	30	30	30

Table 8: Simulation inputs for bulk carrier vessel capex.[20]

6.1.3 FUEL ASSUMPTIONS

Table 9 presents the fuel sources for the Australia-Japan green shipping corridor. Four marine fuels, very low sulfur fuel oil (VLSFO), liquefied natural gas (LNG), green ammonia and marine gas oil (MGO), are pre-selected as the available marine fuels for the Australia-Japan green shipping corridor. Please note, some of the ports sourcing selections were a function of data points available and hence, there were some situations where certain fuels were not considered. Please note, while the fuel blending options are provided until 2050, the model results are provided up to 2035.

FUEL	JAPAN	AUSTRALIA
VLSFO	USA	--
	Saudi Arabia	--
MGO	--	Malaysia
	--	Singapore
LNG	Qatar	Australia
	Australia	
Green ammonia	Malaysia	Australia
	Australia	

Table 9: Fuel sources for the Australia-Japan green shipping corridor.

The emissions consideration will focus on both tank-to-wake and well-to-wake life cycles of marine fuels. Since the one-way distance between port of Hedland (Australia) and port of Kashima (Japan) is 4,230 nautical miles, this work assumes around 22 voyages are completed per year. Both tank-to-wake and well-to-wake have been considered for the optimization case studies, and each case has two carbon emission scenarios (IMO aligned goals and 80 percent emissions reduction scenario). Therefore, this work developed four scenarios to showcase the different cost and emission performance of four marine fuels (VLSFO, LNG, green ammonia, MGO and bio-methanol). See Figure 34 for the annual target emissions for the IMO aligned scenario and 80 percent reduction scenario.

FUEL OPTION	FUEL/PILOT FUEL RATIO
LNG Blending from 2025 to 2050	
LNG	98.5%
VLSFO	1.5%
Green Ammonia Blending from 2025 to 2034	
Green Ammonia	85%
MGO	15%
Green Ammonia Blending from 2035 to 2044	
Green Ammonia	90%
MGO	10%
Green Ammonia Blending from 2045 to 2050	
Green Ammonia	92%
MGO	8%

Table 10: Fuel/pilot fuel blending assumptions.

The fuel blending has been well considered for the fuel combustion process, and this work applies the same fuel blending assumptions as discussed in Section 5. Table 10 describes the fuel and pilot fuel ratio and pilot fuel ratio for LNG, green ammonia and bio-methanol marine engines.

6.2 RESULTS AND DISCUSSION

The ABS green shipping corridor simulation can deliver the following visualized outputs: fleet fuel shares, newbuilding vessel shares, annualized port investments, fuel demand prediction in specific ports, fuel storage requirements at specific ports, and year-over-year fuel procurement for port bunkering stations, etc. To help the shipowners better compare different corridors, this work identified the same key performance indicators (KPIs) as Case Study 1 described in Section 5, and the fleet fuel options and their shares, and the corresponding return on investment (ROI) will be discussed among the four developed scenarios. In this section, the Australia-Japan green shipping corridor is considered with an analysis is focused on the prediction of the shares of pre-selected fuel options, and the average total cost of ownership (TCO) over vessel and TCO contributor shares. To determine the average TCO, the cost indicators cover annualized building cost and ship opex.

6.2.1 TANK-TO-WAKE EMISSION AND COST

Figures 36 and 37 illustrate the future fuel mix from 2025 to 2035 for tank-to-wake emissions and considering IMO CII trajectory and 80 percent reduction in emissions.

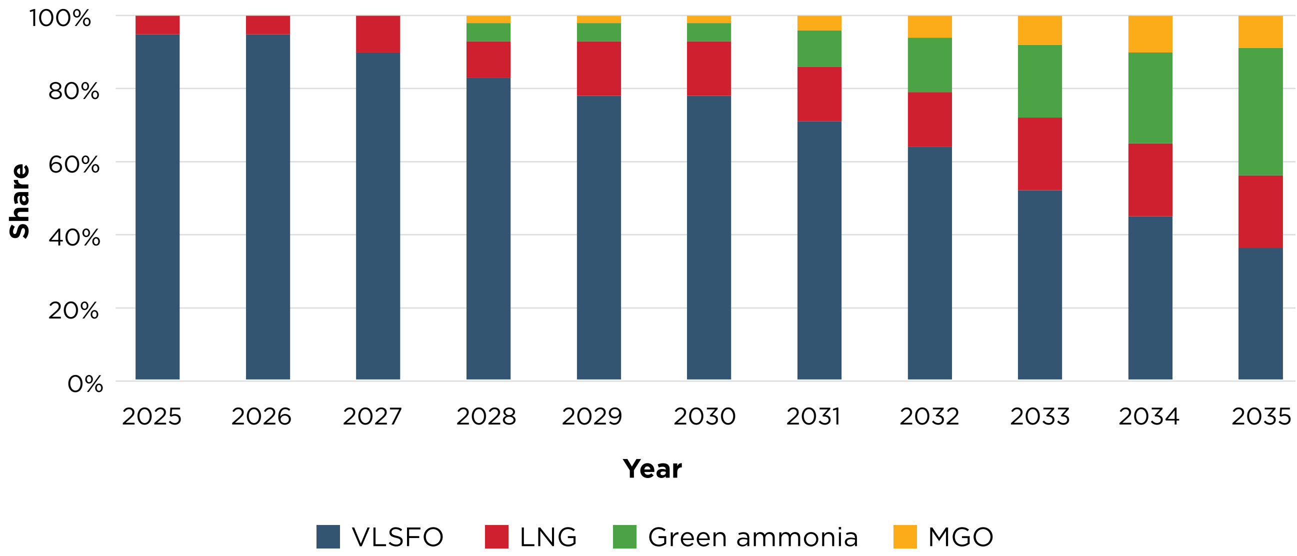


Figure 36: Annual fuel option shares for tank-to-wake emissions and IMO CII trajectory.

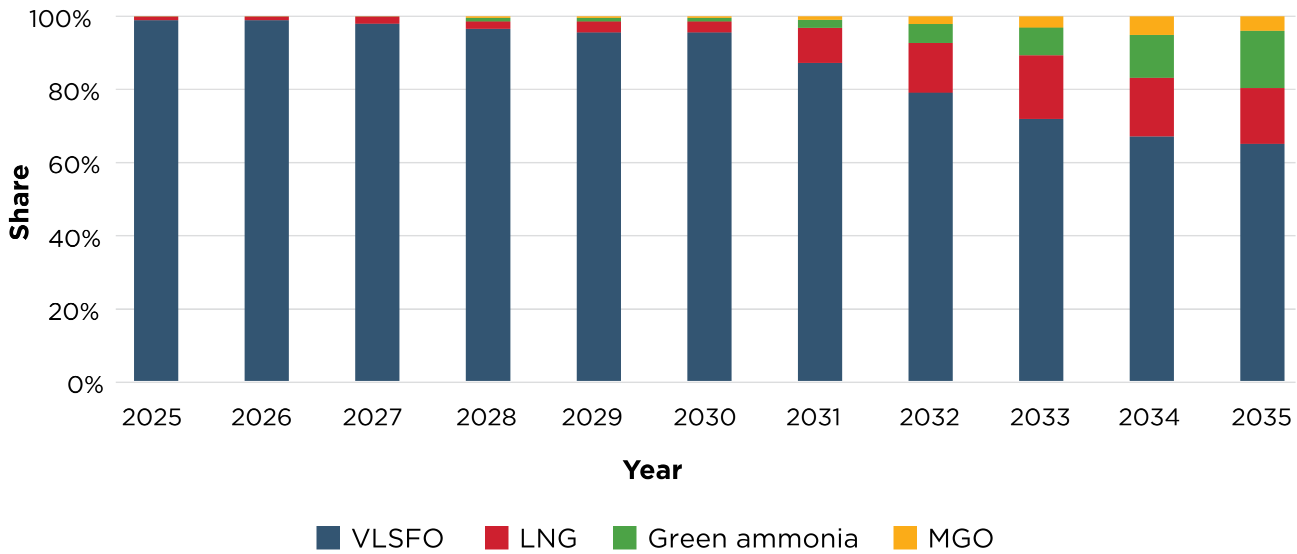


Figure 37: Annual fuel option shares for tank-to-wake emissions and 80 percent emissions reduction scenario.

One can easily conclude that a more ambitious decarbonization strategy will accelerate the process of VLSFO. Both scenarios have clearly shown that the share of green ammonia is increasing. By the year 2035, the predicted share of LNG (seven percent), green ammonia (six percent), VLSFO (85 percent) and MGO share accounts only for two percent while following the current IMO projected CII trajectory goals. While for 80 percent reduction scenario, the dominant fuel option is green ammonia, accounting for nearly 16 percent of the total share, and the share of VLSFO nearly 66 percent. This means that, as the goals get more ambitious, VLSFO share drops precipitously and will get replaced by the next easily available cheaper fuel which could vary from port to port (price and availability) and in this case, it happens to be green ammonia.

FUEL PRICE SENSITIVITY ANALYSIS

Two additional scenarios were completed to understand the impact of alternative fuel prices on the future fuel mix. The following additional scenarios were completed, please note, this was done only for the IMO CII trajectory model runs as a sample data point for the model's sensitivity to fuel prices.

- Case A – Fossil fuel prices stay the course as expected (base case) but the difference in price between alternative fuel price and fossil fuels was increased by 25 percent. This assumes that the alternative fuels get dearer over the 10-year period. This is shown in Figure 38.
- Case B – Fossil fuel prices stay the course as expected (base case) but the difference in price between alternative fuel price and fossil fuels was decreased by 25 percent. This assumes that the alternative fuel prices reduce over the 10-year period. This is shown in Figure 39.

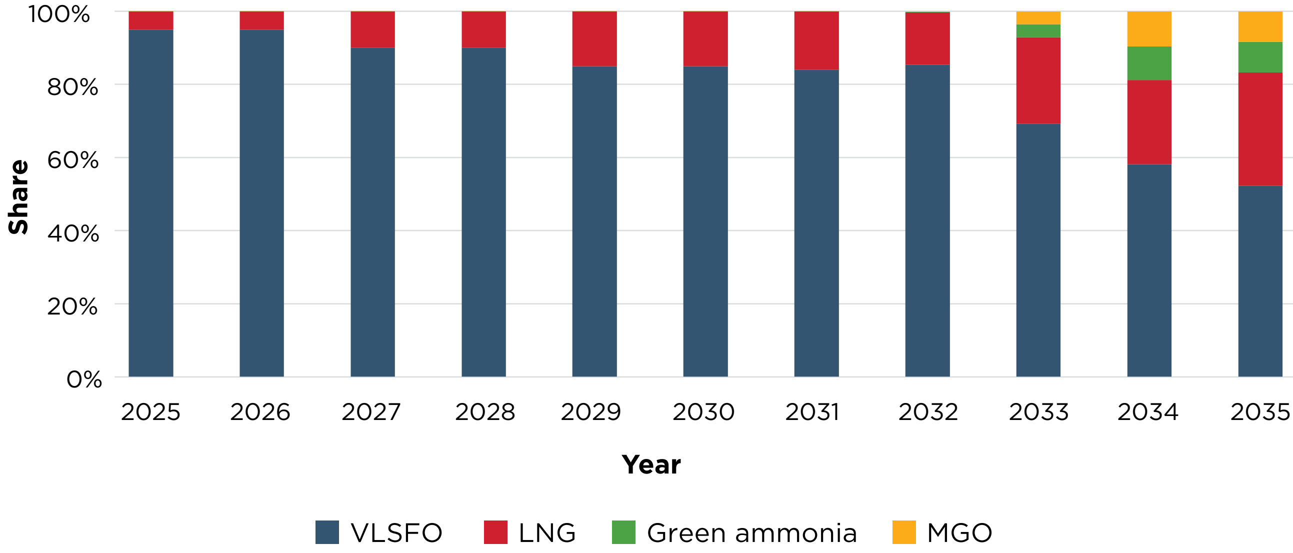


Figure 38: Case A- Annual fuel option shares when fuel price difference increased by 25 percent for tank-to-wake emissions and IMO CII trajectory.

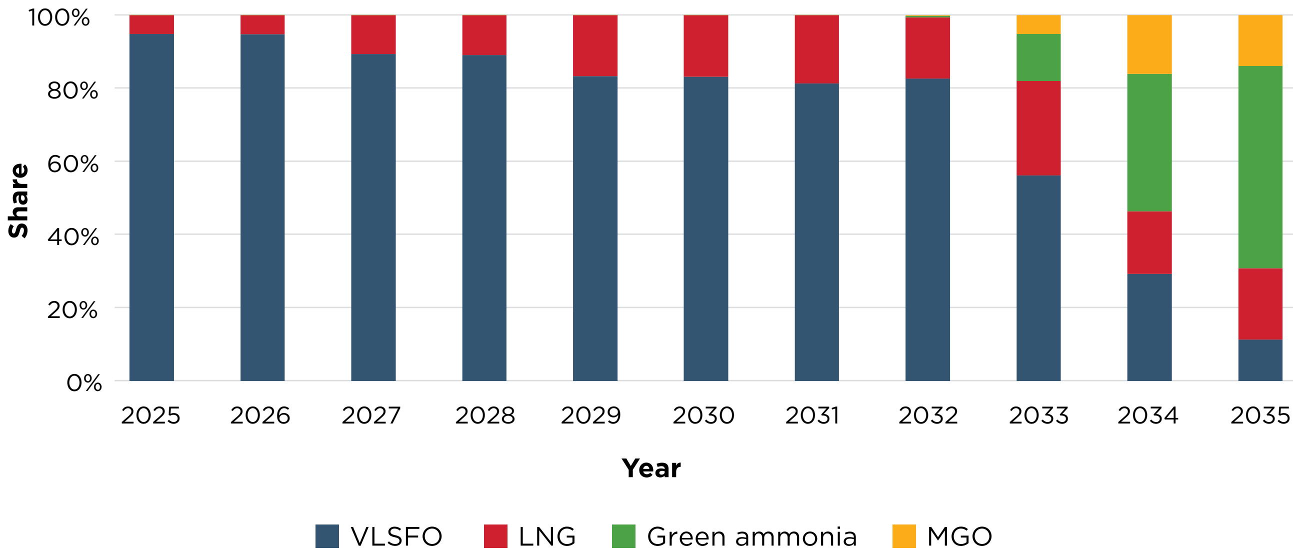


Figure 39: Case B- Annual fuel option shares when fuel price difference decreased by 25 percent for tank-to-wake emissions and IMO CII trajectory

While in this case we may have lesser fuel options (green ammonia-focused), it is always interesting to investigate how different parameters could affect the development of the green corridor in the long term. Green ammonia is the main alternative low carbon fuel examined and it is in competition with both VLSFO and LNG for enabling decarbonization. With the current price levels of green ammonia, it may be quite challenging to achieve wide adoption in the green corridor. Other industry enablers for decarbonization like green financing tools and focused market-based measures could affect the economic dynamics of zero carbon fuel options and boost the adoption of green ammonia.

Figure 40 represents the average TCO of an IMO aligned decarbonization strategy considering tank-to-wake emissions and Figure 41 provides the share of TCO between opex and capex. In general, they both illustrate similar trend lines with the peak value of TCO occurring in 2034.

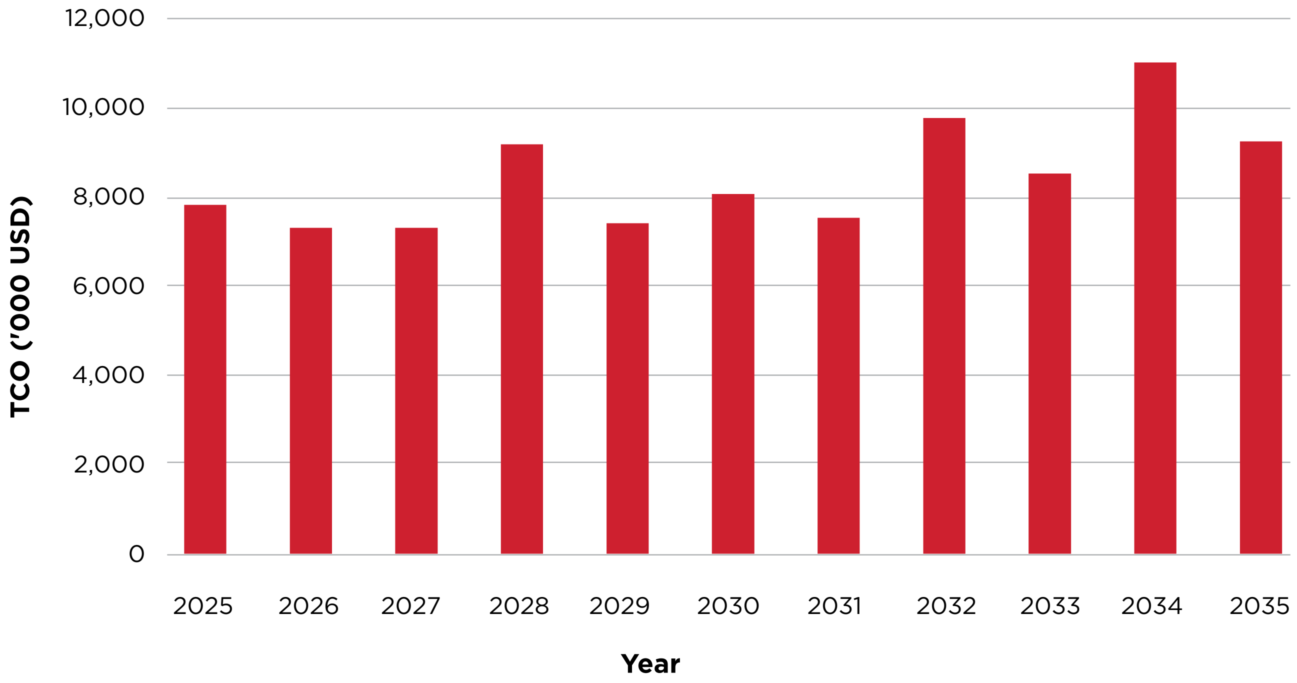


Figure 40: Average TCO in corridor for tank-to-wake emissions and IMO CII trajectory.

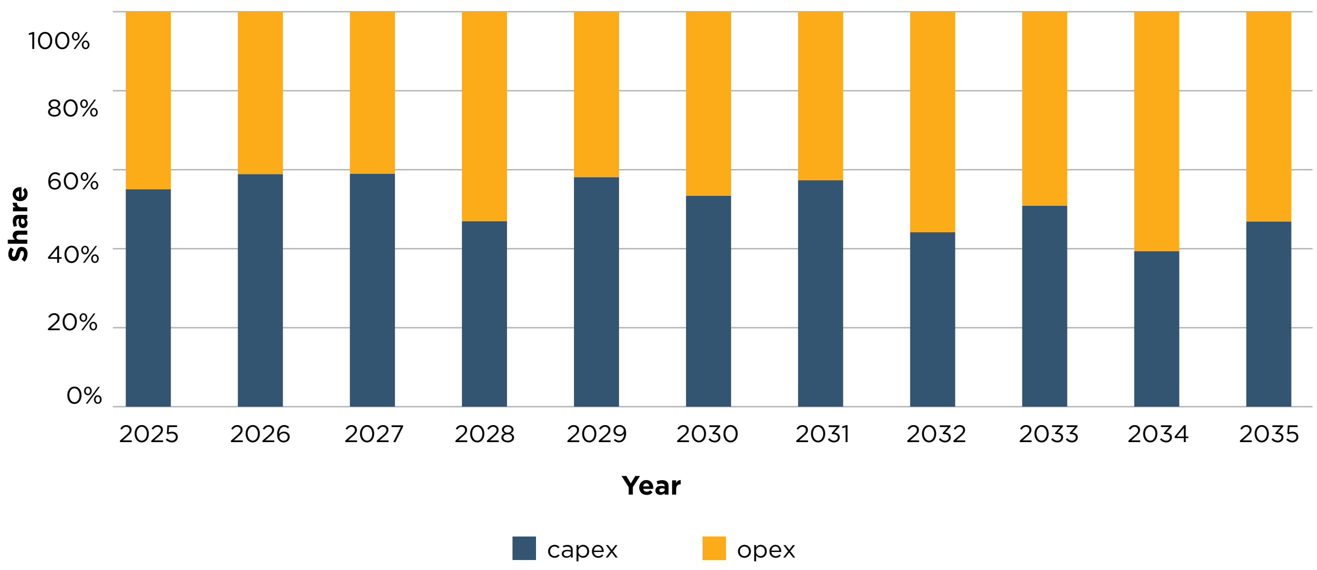


Figure 41: TCO contributions for tank-to-wake emissions and IMO CII trajectory.

Figures 42 and 43 illustrate the average TCO, and its contributor share for tank-to-wake 80 percent reduction scenario. The trend line of the total TCO generally fluctuates due to consideration of fuel price variations and its peak value occurs in 2034. Specifically, the major TCO contributors have always been the annualized build cost and opex. The largest opex year is 2034, while in 2031 capex reaches its largest value.

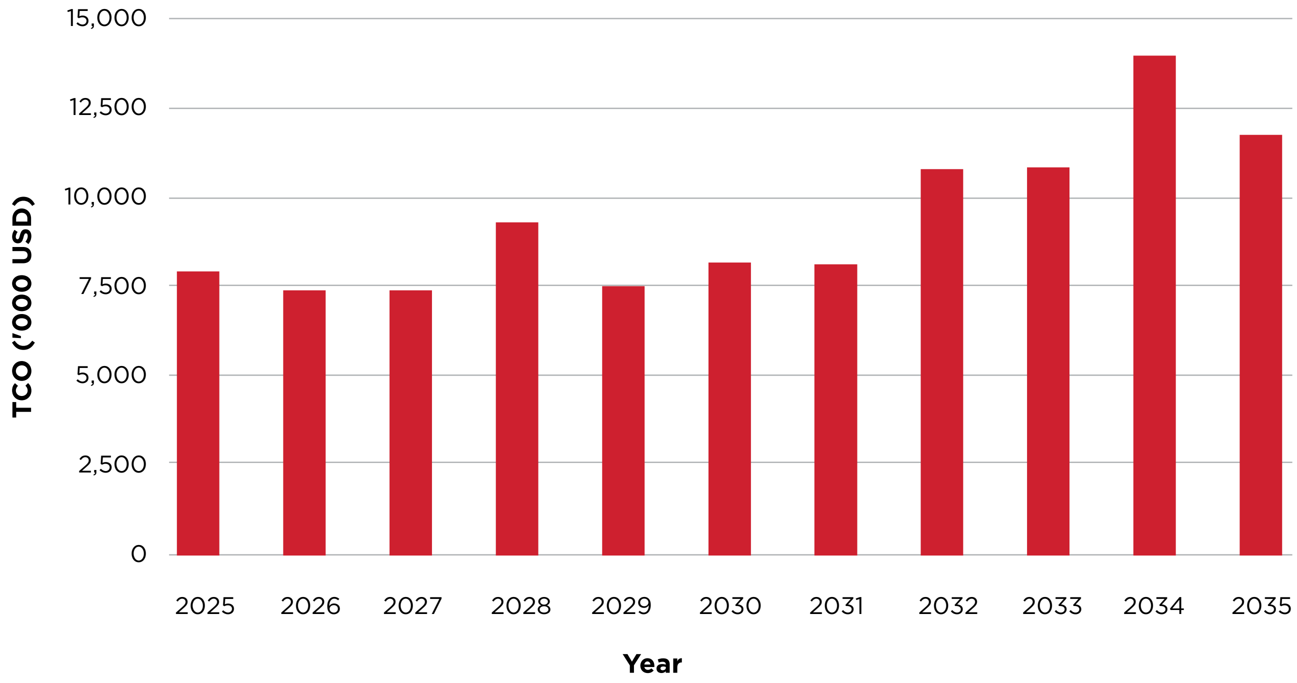


Figure 42: Average TCO in corridor for tank-to-wake emissions and 80 percent emissions reduction scenario.

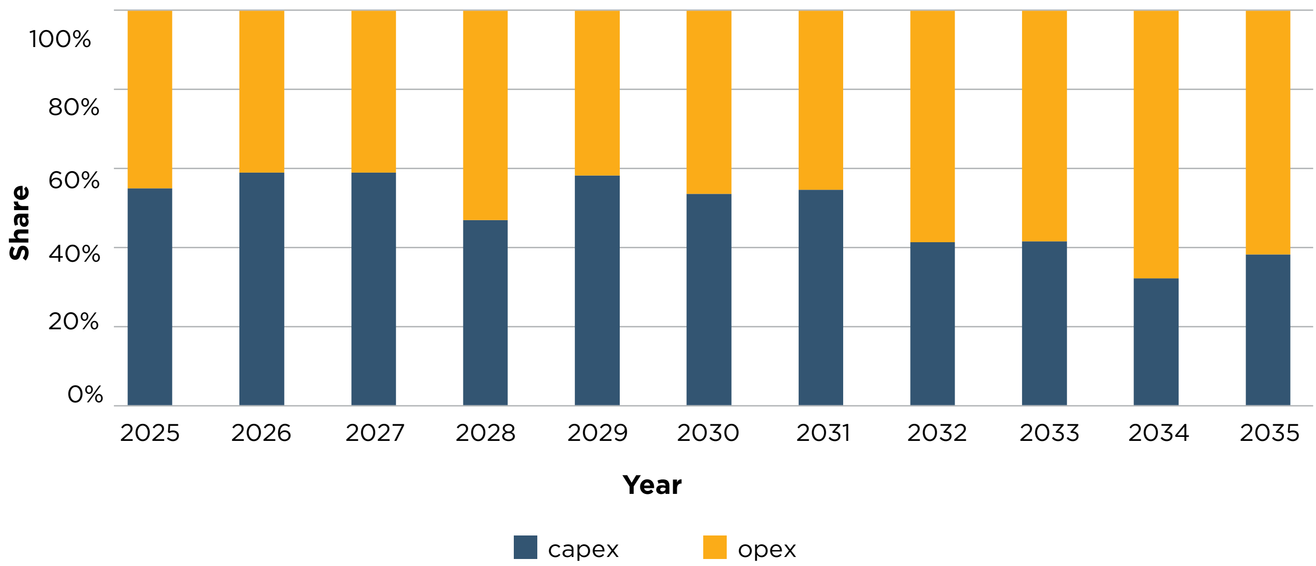


Figure 43: Average TCO contribution for tank-to-wake emissions and 80 percent emissions reduction scenario.

6.2.2 WELL-TO-WAKE EMISSION AND COST

Figures 44 and 45 show the fuel mix from 2025 to 2035 considering well-to-wake emissions considering IMO CII trajectory and 80 percent reduction in emissions. Both scenarios have clearly shown that the share of green ammonia is increasing. By the year 2035, the predicted share of green ammonia (21 percent), VLSFO (63 percent) and MGO share accounts for about 5 percent while following the current IMO projected CII trajectory goals. The 80 percent emissions reduction decarbonization strategy will increase the share of green ammonia to 31 percent by 2035, the share of VLSFO is 57 percent, followed by MGO (8 percent), and LNG (4 percent).

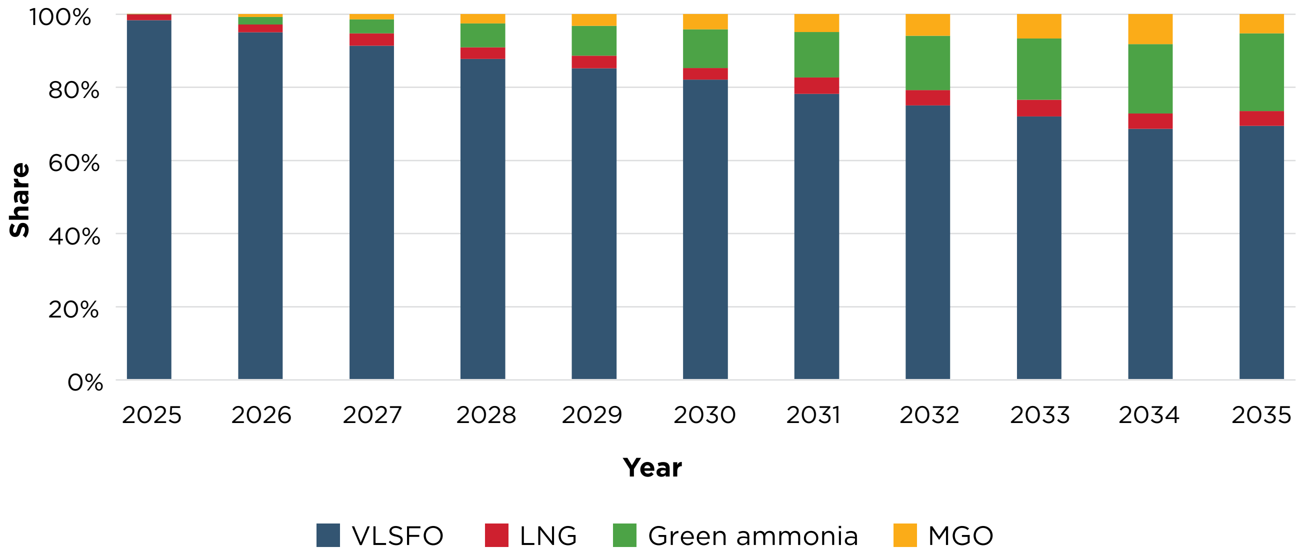


Figure 44: Annual fuel option shares for well-to-wake emissions and IMO CII trajectory.

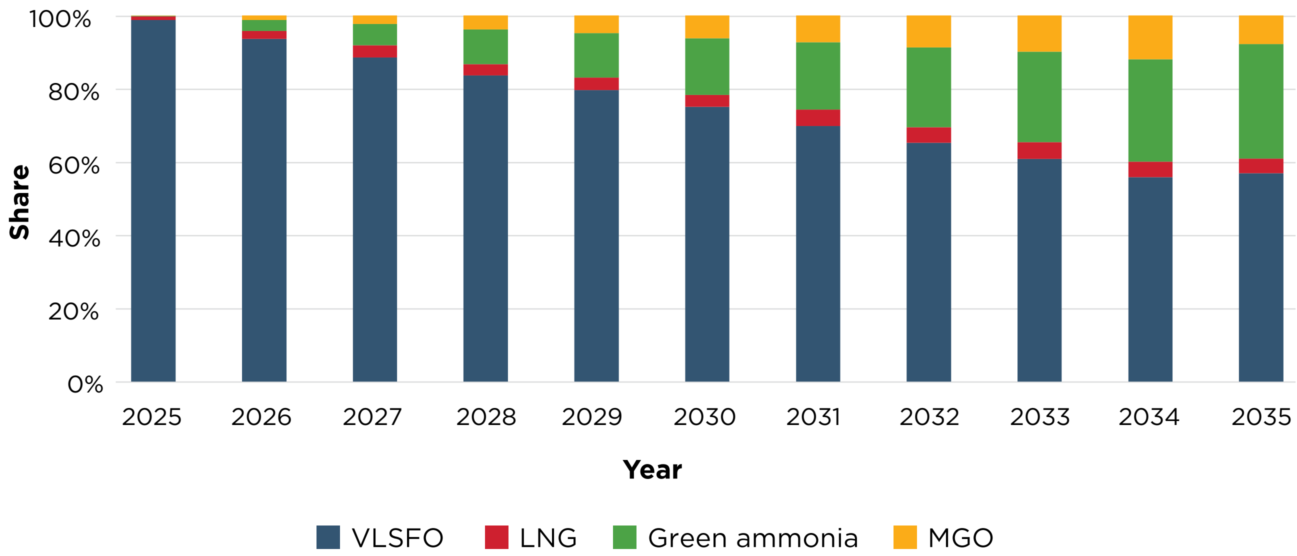


Figure 45: Annual fuel option shares for well-to-wake emissions and 80 percent emission reduction trajectory.

Figure 46 represents the comparison of average TCO of an IMO aligned well-to-wake decarbonization strategy. Figure 47 provides the share of TCO between opex and capex. In general, they both illustrate similar trend lines with the peak value of TCO occurring in 2034.

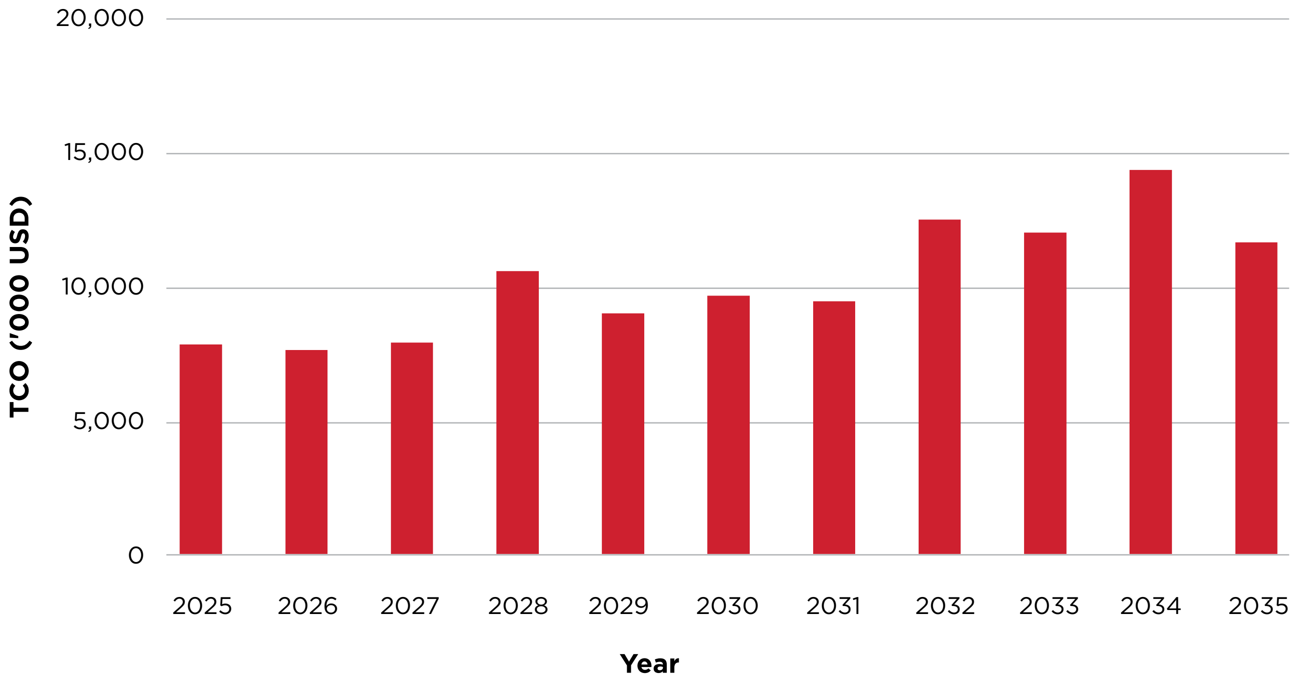


Figure 46: Average TCO in corridor for well-to-wake emissions and IMO CII trajectory.

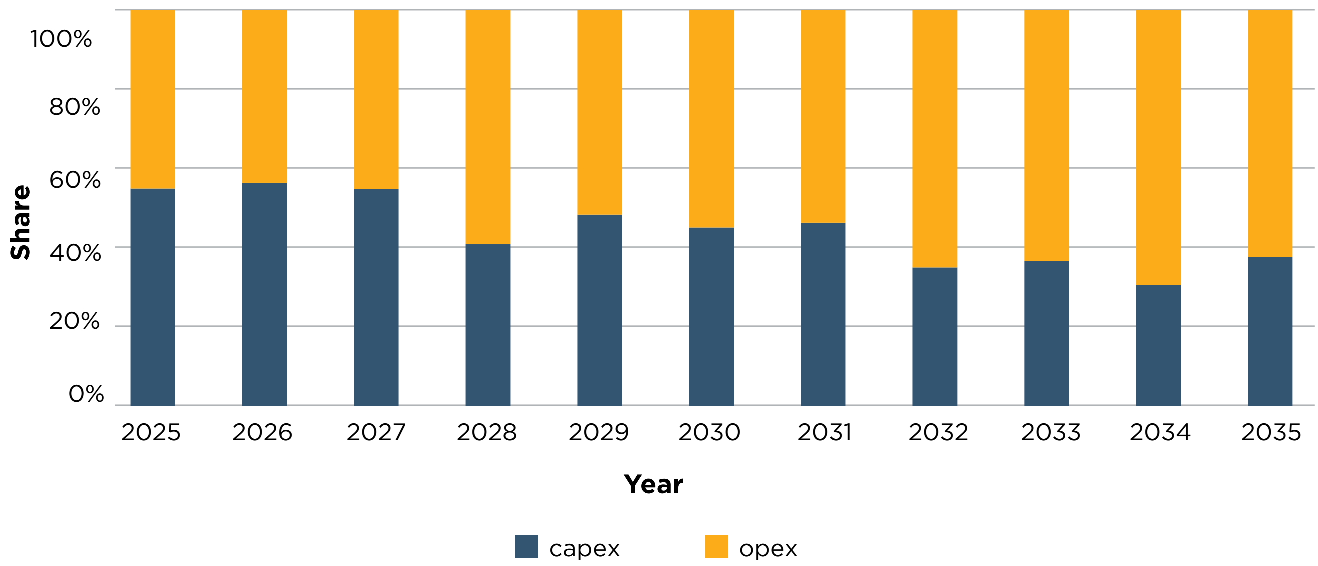


Figure 47: TCO contributions for well-to-wake emissions and IMO CII trajectory.

Figures 48 and 49 illustrate the average TCO, and its contributor share for well-to-wake 80 percent reduction scenario. The trend line of the total TCO generally fluctuates due to consideration of fuel price variations and its peak value occurs in 2034. Specifically, the major TCO contributors have always been the annualized build cost and opex. The largest opex year is 2034, while in 2035 capex reaches its largest value.

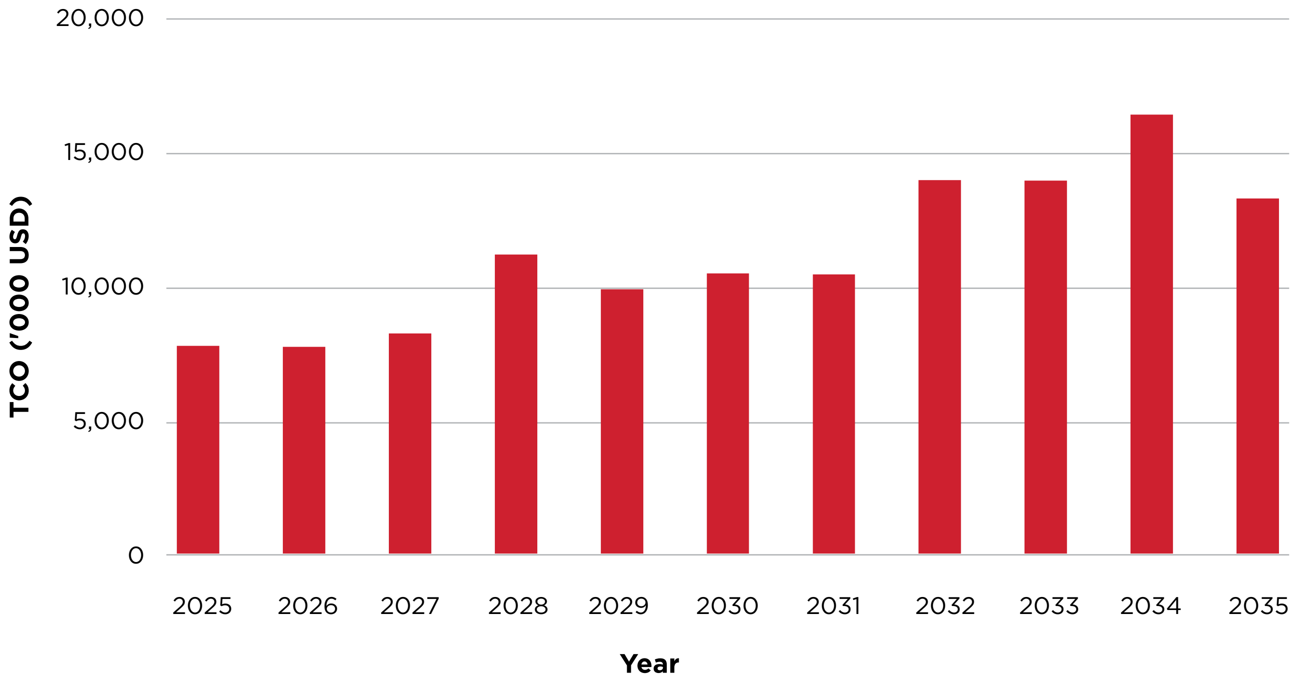


Figure 48: Average TCO in corridor for well-to-wake emissions and 80 percent emission reduction scenario.

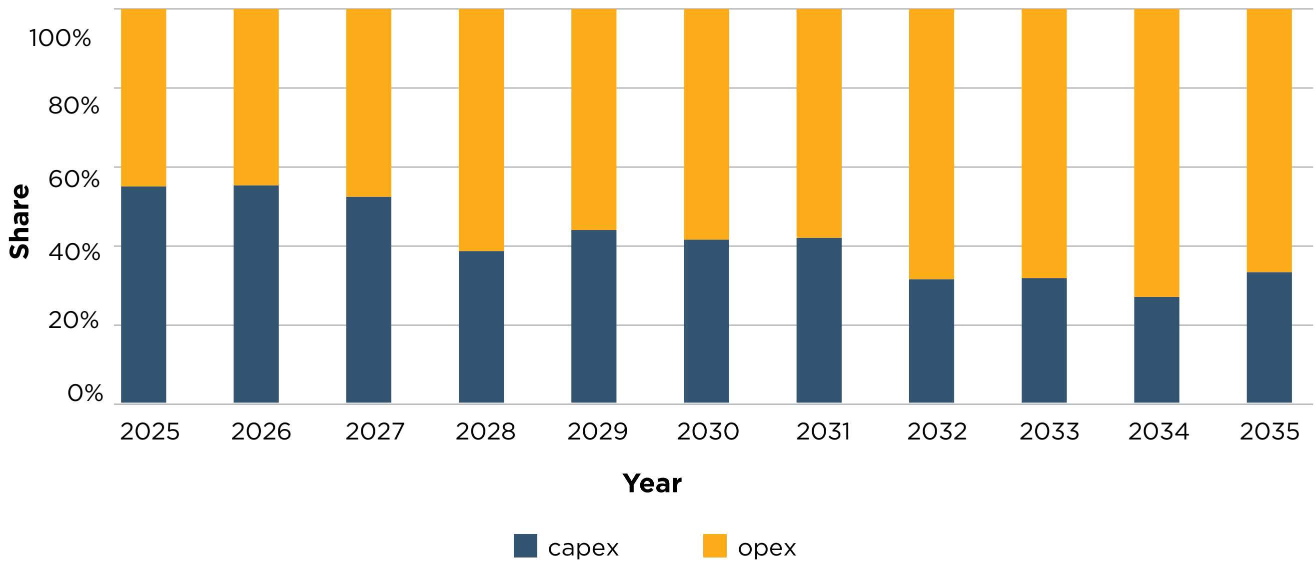
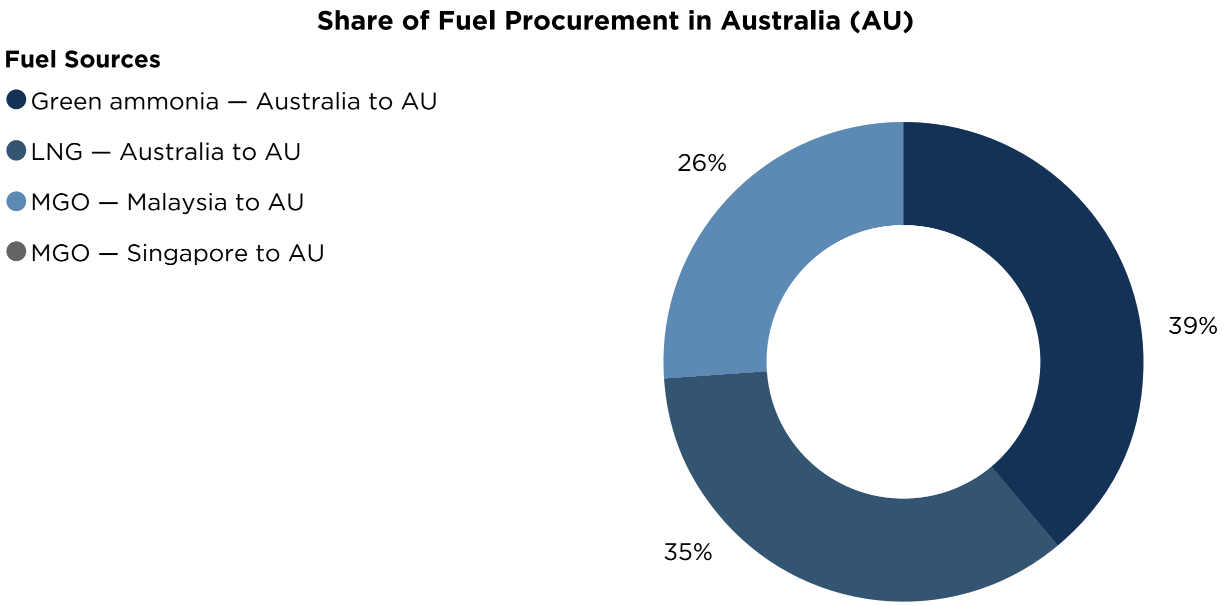


Figure 49: Average TCO contributions for well-to-wake emissions and 80 percent emission reduction scenario.

6.3 PORT FUEL PROCUREMENT

In addition, from the perspective of port authorities, Figures 50 to 53 illustrate the share of fuel procurement for Japan and Australia over a 10-year horizon. These fuel procurement percentages are a function of the fuel prices that were input into the model and emission constraints that are placed on a yearly basis.



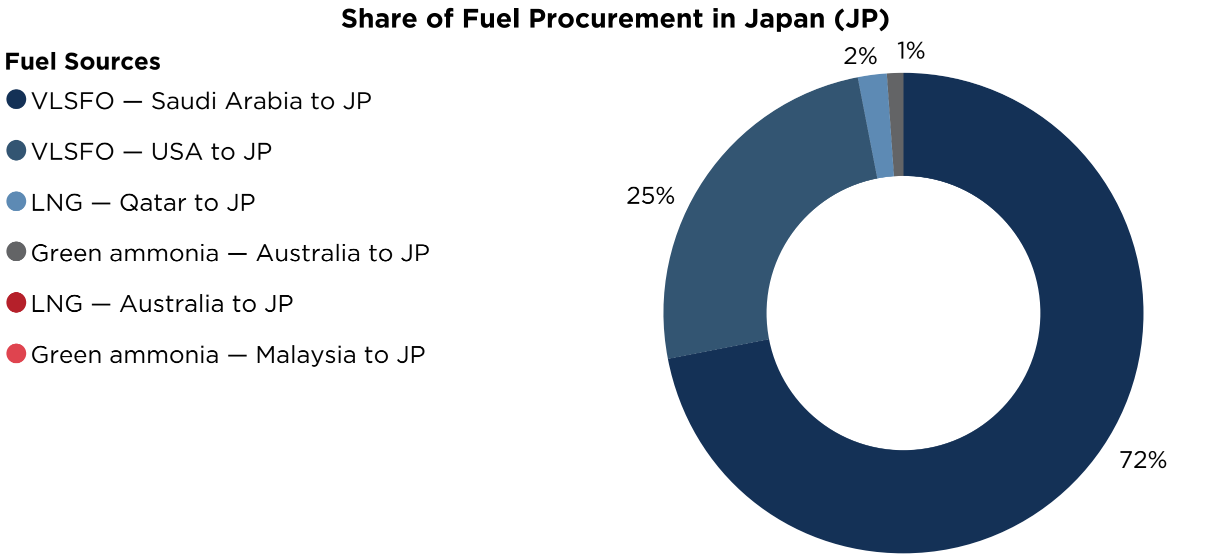
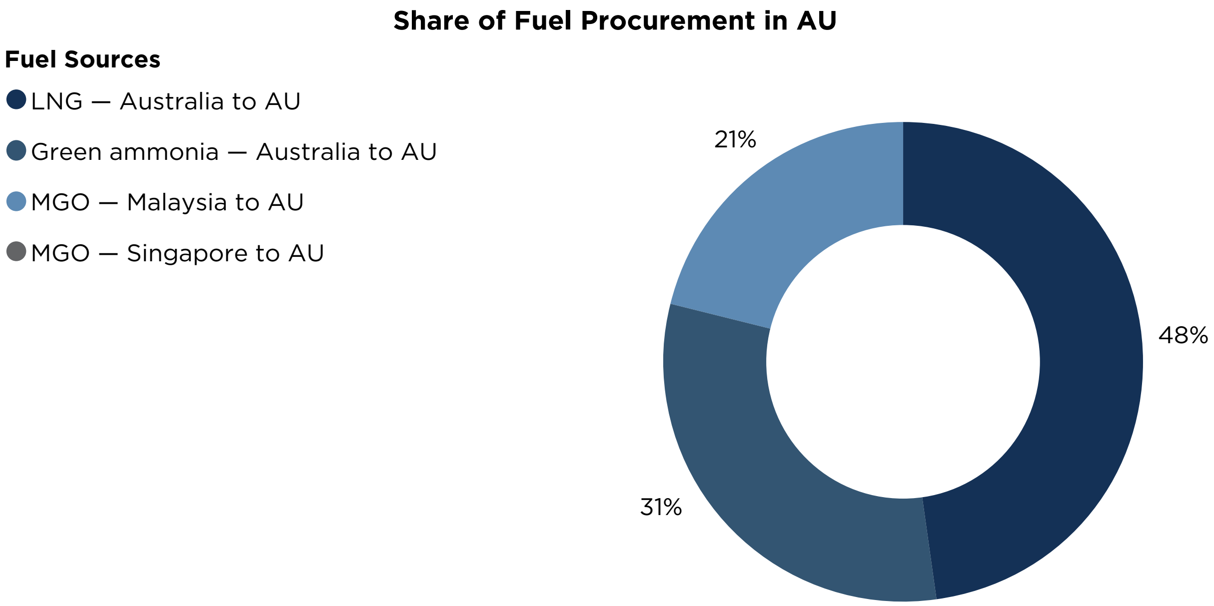


Figure 50: Share of fuel procurement from 2025 to 2035 for Australia and Japan considering tank-to-wake emissions and IMO CII trajectory.



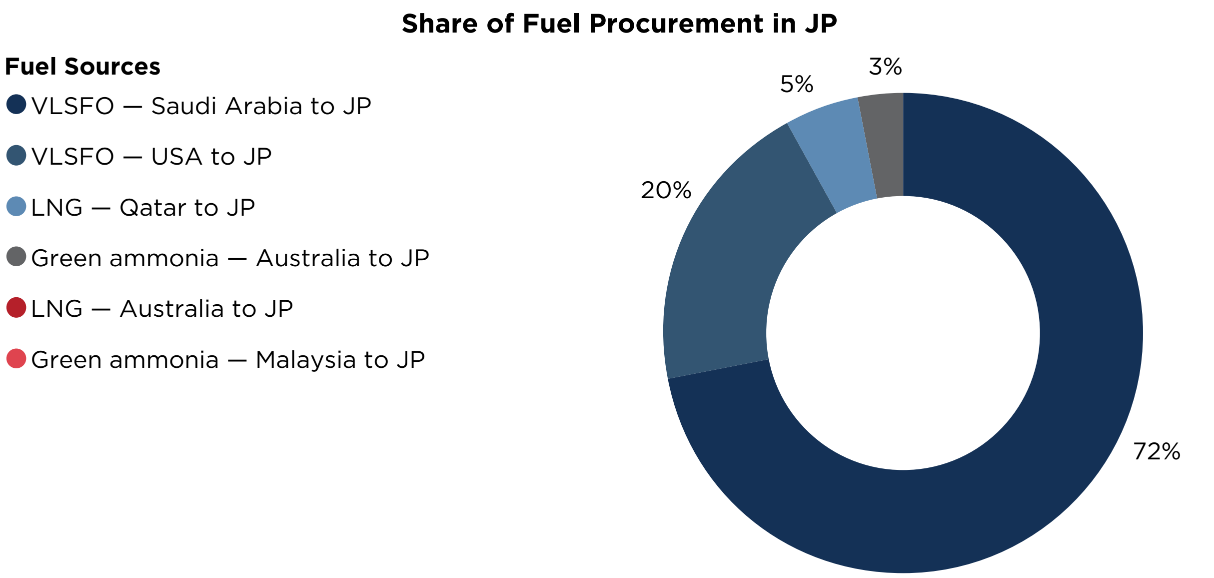
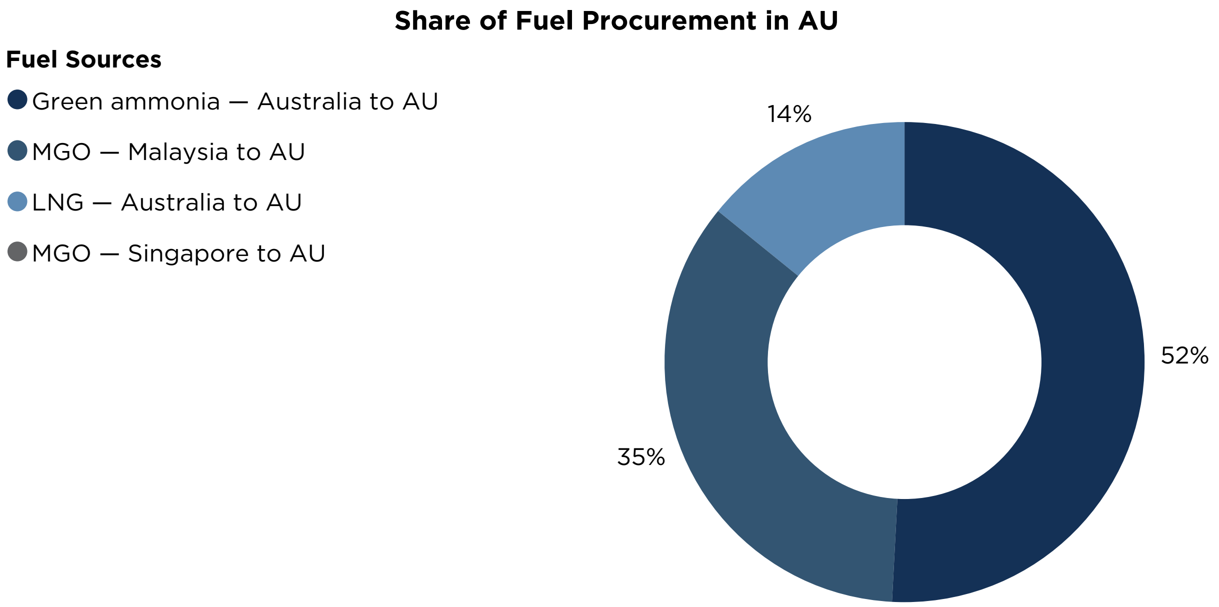


Figure 51: Share of fuel procurement from 2025 to 2035 for Australia and Japan considering tank-to-wake emissions and 80 percent emission reduction scenario.



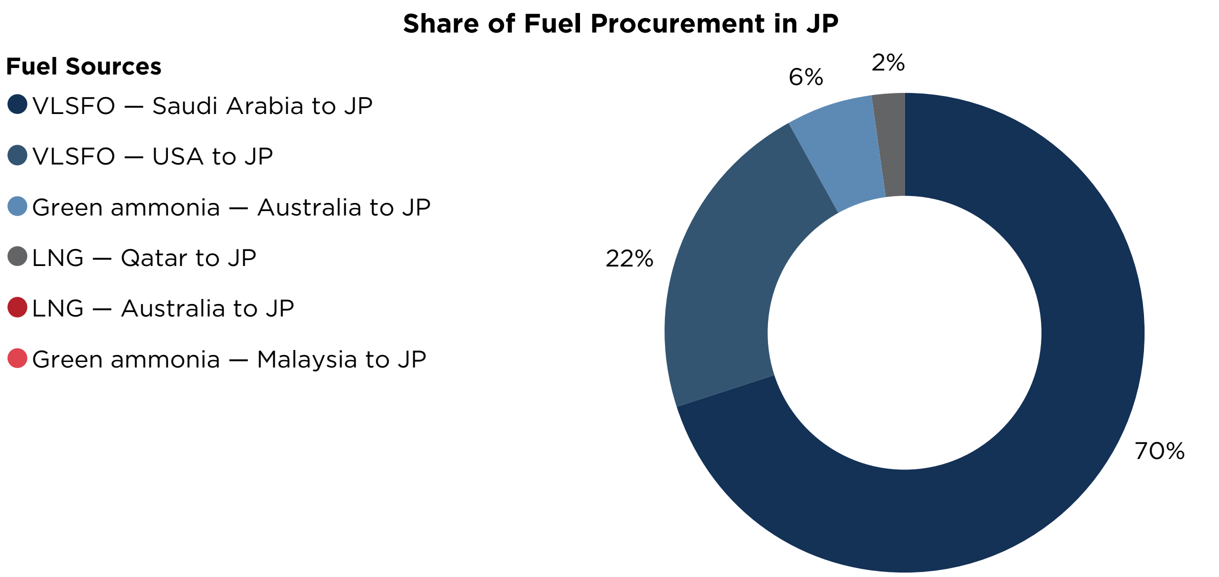
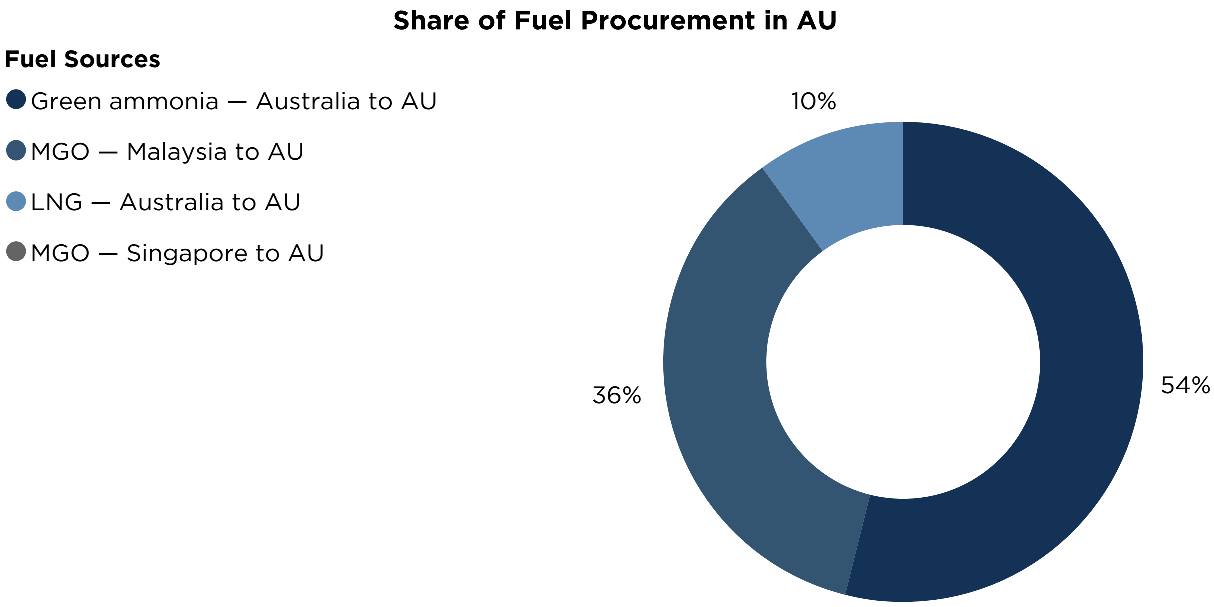


Figure 52: Share of fuel procurement from 2025 to 2035 for Australia and Japan considering well-to-wake emissions and IMO CII trajectory.



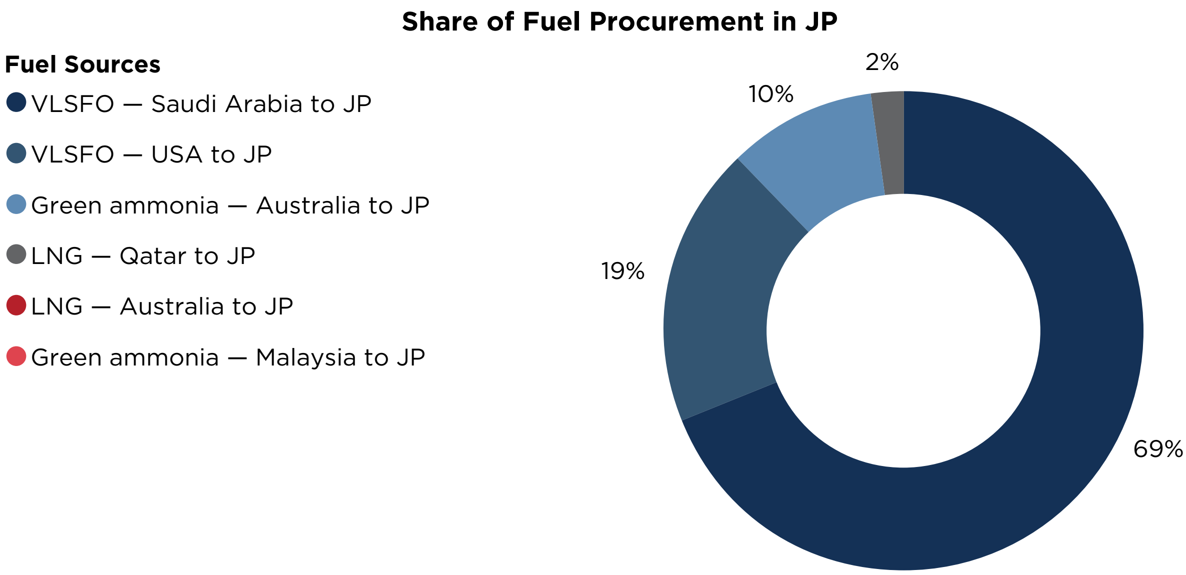


Figure 53: Share of fuel procurement from 2025 to 2035 for Australia and Japan considering well-to-wake emissions and 80 percent reduction scenario.

6.4 CONCLUSION — AUSTRALIA-JAPAN IRON ORE BULK CARRIER GREEN CORRIDOR

The fuels mix shares have clear trends in all the four case studies. The low-carbon fuel options will gradually substitute the current and dominate marine fuel, VLSFO, and a more ambitious strategy will tremendously accelerate the speed of VLSFO phasing out, with green ammonia gradually increasing for tank-to-wake cases and well-to-wake cases. As noted earlier, fossil fuels are projected to decline in favor of the low carbon fuel options in both emissions approaches, in which case, green ammonia, as the main zero carbon option, will rise to fill the gap. LNG can be a catalyst for lower emissions on a tank to wake approach scenario, especially when steeper decarbonization targets are set. However, on a well-to-wake emissions approach, biogenic and synthetic methane options shall be considered. While green ammonia is becoming a strong fuel option in the long term, the well to wake approach is a catalyst for its earlier adoption in larger quantities. Furthermore, fuel procurement strategies of the two port authorities will benefit from the ship fleet decarbonization strategies, and the identified alternative fuel sources are key to prioritizing port investments. Japan will need to provide the VLSFO required in this route, which although declining in the fuel mix, remains largely in stable demand, thanks to market and trade growth. At the same time, Japan is expected to become a hub for green ammonia fuel, thus facilitating to supply green ammonia starting from one third and rising to half of the quantity required for this route. Australia on the other hand, well positioned as green ammonia production hub, will satisfy the larger part of the demand for green ammonia in this route with significant storage capacities required as early as 2030.

7 CONCLUSION

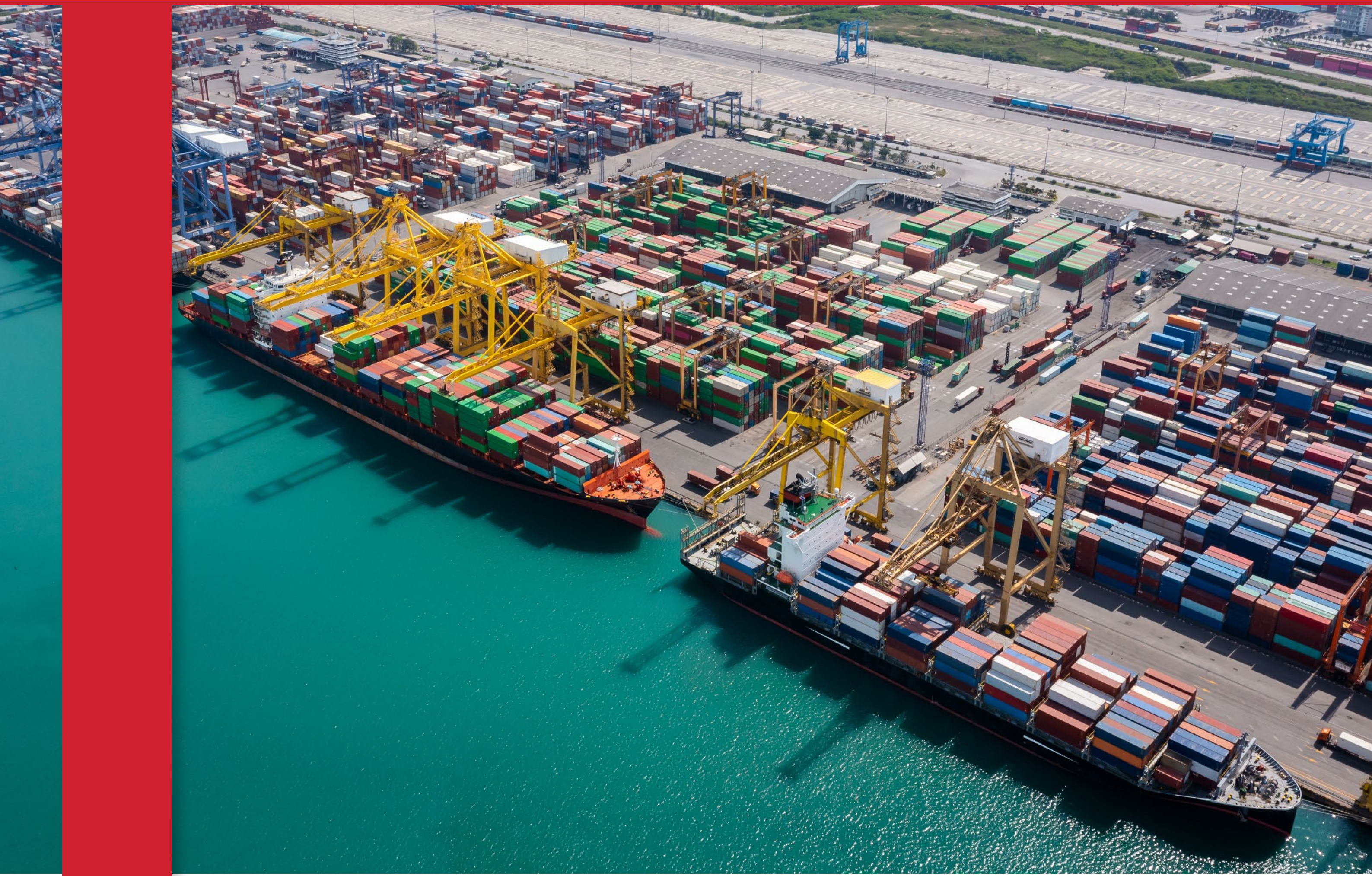
The ABS green shipping corridor optimization and simulation capabilities can be used by the shipowners and port authorities to optimize their decarbonization strategy with quantitative evidence and trackable projections. The outputs of the simulation cover fleet fuel shares, newbuilding vessel shares, annualized port investments, fuel demand prediction in specific ports, fuel storage requirements at specific ports, and year-over-year fuel procurement for port bunkering stations, etc.

To help green shipping corridor decision-makers develop a decarbonization strategy, the major key performance indicators (KPIs) of fleet fuel options and their shares, and the corresponding costs are investigated in the case studies covered in this publication. Both tank-to-wake and well-to-wake life cycles of marine fuels have been considered in the optimization case studies, and two decarbonization goals are set to create a total of four scenarios per corridor.

The fuel mix shares have shown clear trends in all the developed scenarios: the low-carbon fuel options will gradually substitute the current dominate marine fuel, very low sulfur fuel oil (VLSFO), and a more ambitious strategy will tremendously accelerate the speed of VLSFO phasing out. Green ammonia has been projected to be the dominant fuel option for tank-to-wake cases, and bio-methanol would be the most cost-effective fuel option for well-to-wake emissions in 2050.

Furthermore, this publication discusses the average total cost of ownership (TCO) for the fleet of the selected green shipping corridors, considering operating expenditure (opex), annualized building cost, fuel tank cost and carbon pricing. The opex and annualized building cost are identified as the major indicators to determine the average. Lastly, the optimization outputs presented insights on fuel procurement shares for decision-makers within port authorities. The fuel sources and associated infrastructure readiness levels are key to reach the maximum return on investment (ROI) as well as meet the long-term maritime decarbonization goals.

Optimization and simulation are very powerful capabilities that can help various stakeholders understand the variables in their systems with as much detail as possible to make the most prudent decisions from their point of view. One of the biggest advantages of this optimization tool is that it can help each of the stakeholders understand their maximum risk profile and understand the impact of their decisions on the entire corridor. The results of the optimization model when shared among the consortia members will provide a common ground for de-risking and sharing the costs which will be one of the most important outcomes of a collaborative initiative of this size.



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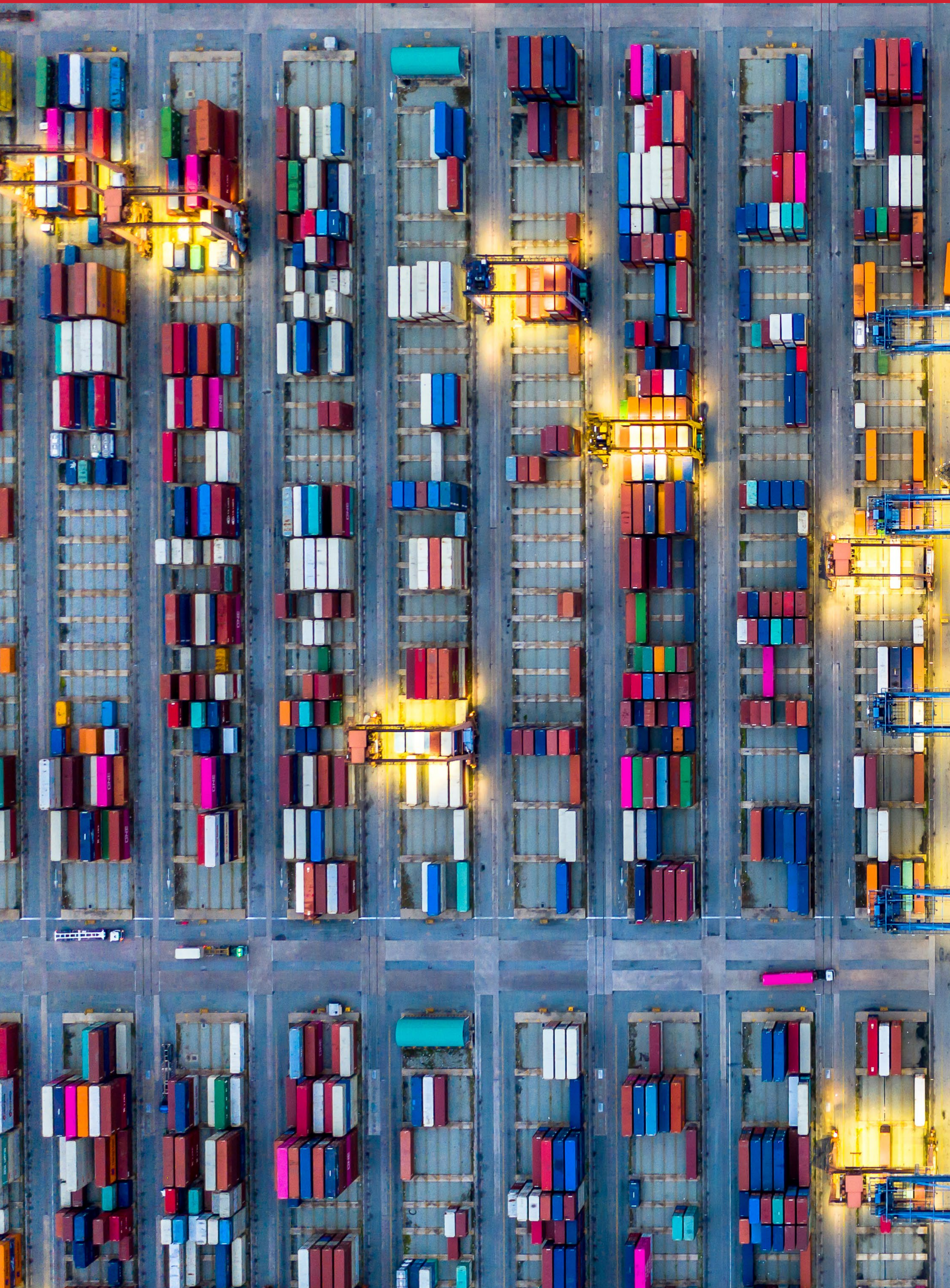

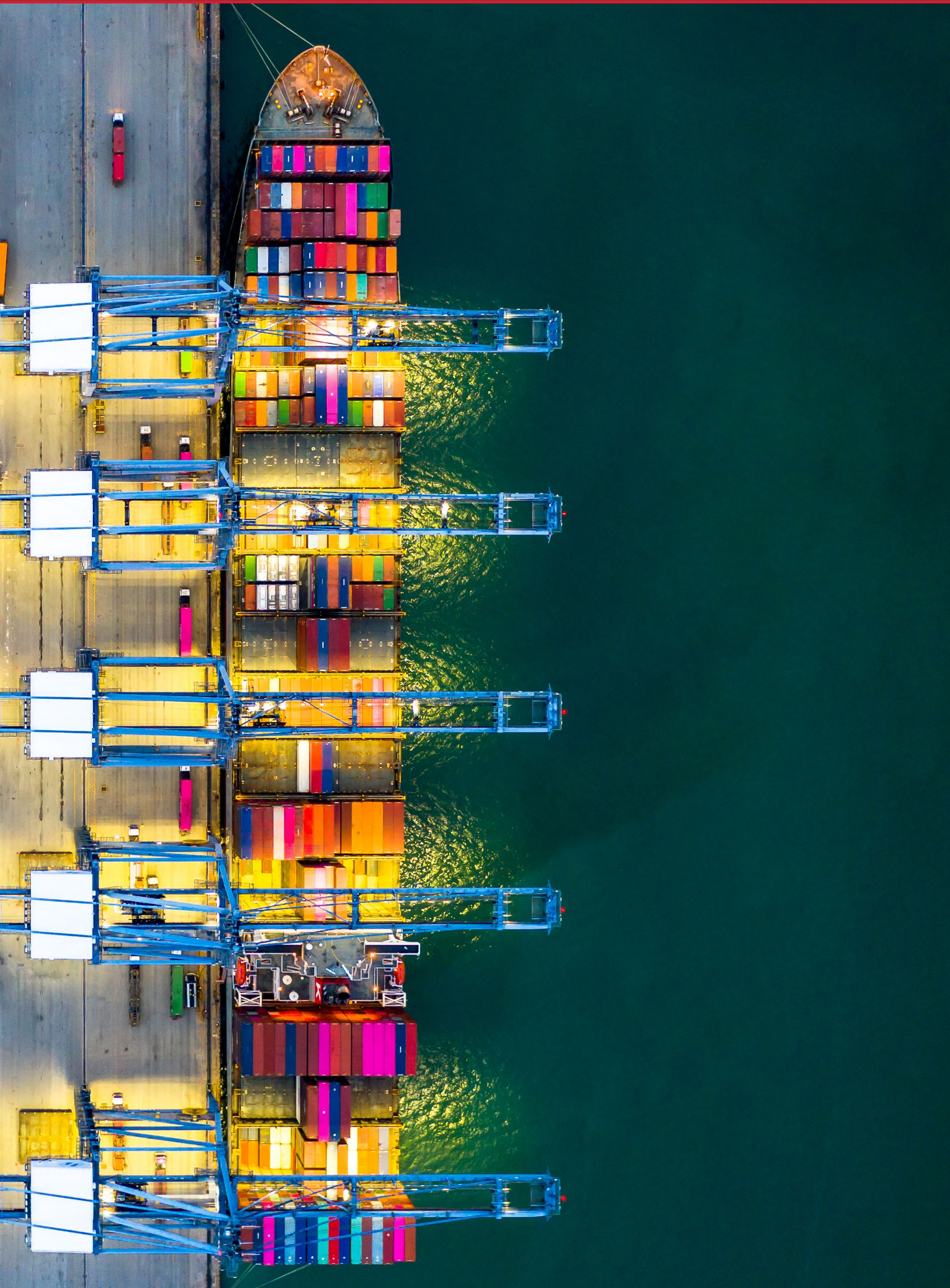

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