The First Wave

A blueprint for commercial-scale zero-emission shipping pilots

A special report by the Energy Transitions Commission for the Getting to Zero Coalition

By the Energy Transitions Commission

Energy Transitions Commission

For the Getting to Zero Coalition

Global Maritime Forum
Friends of Ocean Action
World Economic Forum

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The Getting to Zero Coalition

The Getting to Zero Coalition, a partnership between the Global Maritime Forum, Friends of Ocean Action and World Economic Forum, is a community of ambitious stakeholders from across the maritime, energy, infrastructure and financial sectors, and supported by key governments, IGOs and other stakeholders, who are committed to the decarbonization of shipping.

The ambition of the Getting to Zero Coalition is to have commercially viable ZEVs operating along deep-sea trade routes by 2030, supported by the necessary infrastructure for scalable net zero-carbon energy sources including production, distribution, storage, and bunkering.

About the Global Maritime Forum

The Global Maritime Forum is an international not-for-profit organization dedicated to shaping the future of global seaborne trade to increase sustainable long-term economic development and human wellbeing.

About Friends of Ocean Action

Friends of Ocean Action is a unique group of over 55 global leaders from business, international organizations, civil society, science and academia who are fast-tracking scalable solutions to the most pressing challenges facing the ocean. It is hosted by the World Economic Forum in collaboration with the World Resources Institute.

About the World Economic Forum

The World Economic Forum is the International Organization for Public-Private Cooperation. The Forum engages the foremost political, business, cultural and other leaders of society to shape global, regional and industry agendas. It was established in 1971 as a not-for-profit foundation and is headquartered in Geneva, Switzerland. It is independent, impartial and not tied to any special interests.

About the Energy Transitions Commission

The Energy Transitions Commission (ETC) is a coalition of global leaders from across the energy landscape: energy producers, energy-intensive industries, equipment providers, finance players and environmental NGOs. Our mission is to work out how to build a global economy which can both enable developing countries to attain developed world standards of living and ensure that the world limits global warming to well below 2°C and as close as possible to 1.5°C. For this objective to be reached, the world needs to achieve net-zero GHG emissions by around mid-century.

Acknowledgements

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The Global Maritime Forum and the Energy Transitions Commission want to thank the Getting to Zero Coalition community for their inputs to this analysis, in particular those members from across the maritime and energy value chains who participated in interviews, review sessions and provided feedback on the draft report. Without this engagement and valuable input the report could not have been written.

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Foreword

The maritime industry has no time to waste if it is to meet the International Maritime Organization's ambition of at least halving emissions from international shipping by 2050. This is why the Getting to Zero Coalition – launched at the UN Climate Action Summit in September 2019 – is committed to the ambition of commercially viable zero-emission vessels operating along deep-sea trade routes by 2030.

A key step towards meeting this ambition is for first movers across the maritime and energy sectors to come together in commercial-scale demonstration projects. Such projects will be vital in improving and scaling technologies, reducing cost, as well as developing new business models and collaborations that can share risks and opportunities across the value chain.

As shown in this report, which has been developed by the Energy Transitions Commission for the Getting to Zero Coalition, there are many barriers to the early adoption of zero-emission technologies from a technical, regulatory, and economic perspective.

More importantly, the report shows that these barriers can be reduced and overcome through collaboration, the use of de-risking mechanisms, public-private partnerships, and the ability to pass on the cost of green shipping to the end consumer. While the immediate cost increase of using zero-emission fuels may seem insurmountable, the cost to the consumer is small. For example, for a pair of running shoes, the cost increase amounts to around 1% of the price of the shoes, which should not be prohibitive in light of the urgent need to reduce greenhouse gas emissions across all sectors.

As co-chairs of the Getting to Zero Coalition's Motivating First Movers workstream, we hope this report will help to inspire new collaborations that can catalyse commercial-scale zero-emission demonstration projects. We look forward to working together with stakeholders across the maritime and energy value chains, as well as with governments, to turn the recommendations in the report into tangible action that can put us on the path to commercially-viable zero-emission shipping.

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Executive Summary

The shipping sector is a key enabler of international trade, responsible for approximately 80% of the world's trade[1]. Demand for shipping is expected to continue to grow in line with global economic growth over the next three decades. Although less intensive than other freight transport modes in terms of CO2 emissions per tonne-kilometre, shipping represents about 3% of total global emissions from energy and industry today. Without concerted collective efforts, GHG emissions from the sector could rise by as much as 50% by 2050.

In April 2018, the International Maritime Organisation (IMO) set an objective to reduce absolute GHG emissions from shipping by at least 50% by 2050 compared with a 2008 baseline[2]. To achieve this target and ultimately progress towards carbon neutrality in the sector by mid-century, in line with IPCC scenarios to limit the rise in global temperature to 1.5°C, shipping will need to go beyond operational and energy efficiency and deploy zero-emission fuels and propulsion technologies. Given the 20-30 year lifetime of vessels and other industry assets, the maritime sector must ensure that zero-emission vessels are operating on a commercial scale on deep-sea trade routes by 2030, opening the way for a large-scale deployment in the 2030s and 2040s. The Energy Transitions Commission, the Global Maritime Forum and the Getting to Zero community are confident this is feasible with the appropriate policy support.

This report explains how 'first movers' from across the maritime value chain can come together to lower the economic, technical, and regulatory barriers facing the first wave of commercial-scale pilots. Pilots that are implemented in the next five to ten years to prove the technological and commercial viability of zero-emission shipping end-to-end from carbon free marine fuel production to cargo owners.

These 'full ecosystem' pilots will build on ongoing technology trials and represent the critical 'proof point' on the way to realising the 2030 ambition outlined by the Getting to Zero Coalition.

This report describes in turn:

1. The full value chain that needs to be mobilised for a zero-emission shipping pilot
2. The end-to-end economics of green ammonia and green methanol pilots
3. Cost reduction and risk mitigation strategies for each segment of the value chain
4. The potential impact of cost-lowering and de-risking mechanisms on pilots
5. Recommendations for private and public sector actors to realise the first wave of commercial-scale zero-emission shipping pilots

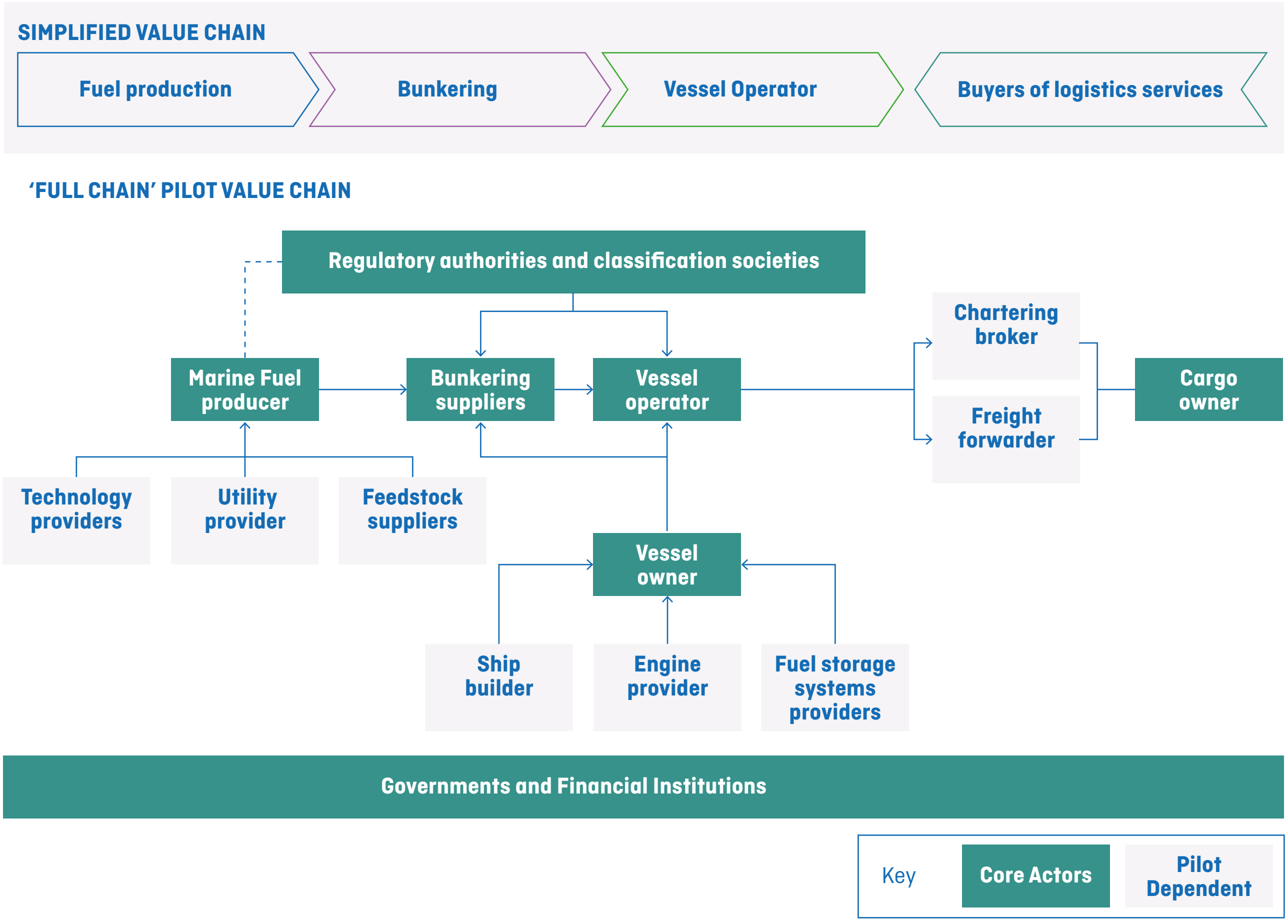
1 https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=109
2 https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

1. The full value chain that needs to be mobilised for a zero-emission shipping pilot

The deployment of zero-emission vessels globally will require significant modification of the existing shipping value chain, with new entrants joining existing stakeholders. It will involve new forms of collaborative and contractual relationships and, in the early stage of the journey toward shipping decarbonisation, this new value chain will need to exist in parallel with the conventional marine fuels value chain. **The specific set of partners involved in an end-to-end zero-emission pilot will vary by fuel pathway and vessel type, but a set of 'core actors' will need to be at the centre of any project**. These are:

- **Fuel producers** to build a first wave of zero-emission maritime fuel production facilities;
- **Bunkering suppliers** to build and operate an appropriate bunkering infrastructure for new fuels and handle the fuelling process at ports;
- **Classification societies and regulatory authorities** to develop necessary safety and fuel handling standards;
- **Engine, fuel storage equipment providers and ship builders** to develop, integrate and build zero-emission propulsion systems;
- **Vessel operators and owners** to make the investments in and operate the new or retrofitted vessels;
- **Cargo owners** to absorb and pass on the additional cost of green shipping to customers;
- **Financial institutions** to provide the necessary capital across the value chain; and,
- **Governments** to create or augment support mechanisms that can de-risk the first wave of commercial-scale projects through both direct funding and de-risking of private sector investment.

Exhibit 1. The set of core actors needed for an end-to-end zero-emission pilot



Industry leaders willing to engage in the first commercial-scale end-to-end projects will benefit from **technology leadership, operational understanding, and early-mover partnerships, which will represent significant competitive advantages** as the global maritime industry undertakes the transition. At the same time, a new set of cost drivers and risks will need to be navigated to get the first wave of projects off the ground.

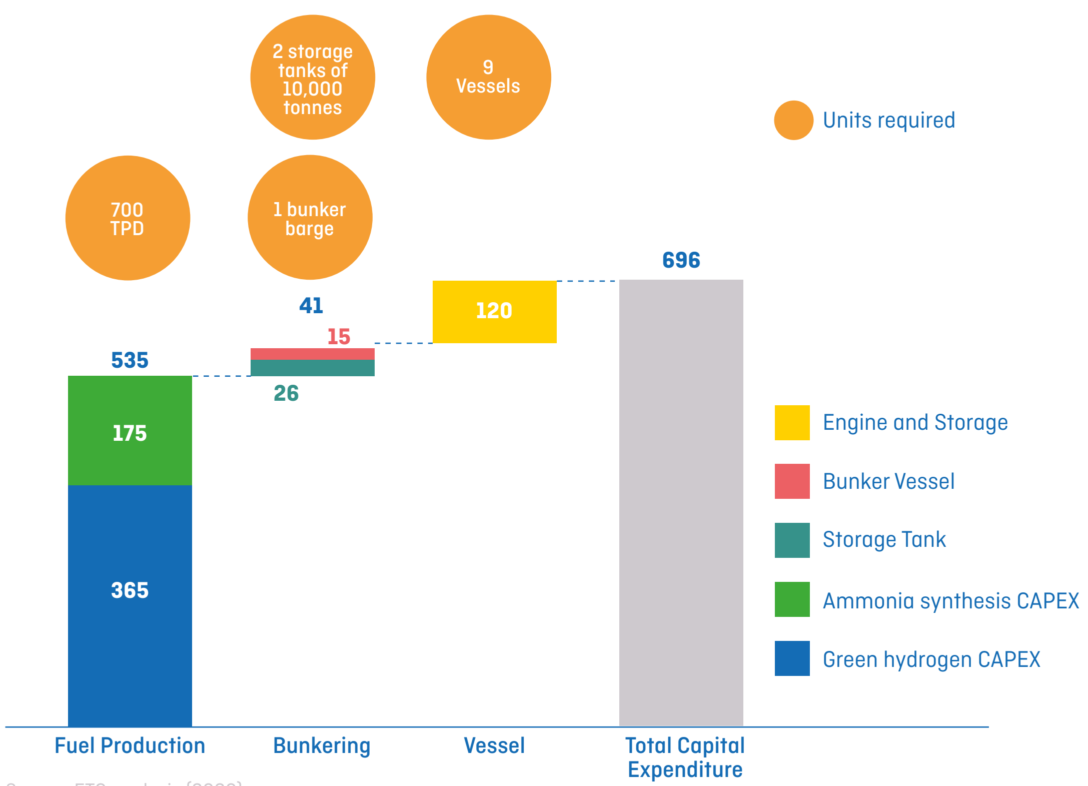
2. The economics of zero-emission fuels

The development of end-to-end zero-emission pilot projects will present a completely new set of opportunities, investments and operating considerations for the maritime industry. For the first movers at all stages of the value chain, the shift to zero-emission fuels will represent a significant cost differential. To understand the economics of a zero-emission vessel pilot, the report sets out industry-validated worked examples that illustrate the relative importance of different cost components. This analysis focuses on green ammonia and green methanol use in pilots involving containerships, but insights will be relevant for other potential zero-emission fuel options.

The capital outlay will not be split proportionally across the chain: **the majority of CAPEX (75-90%) for an end-to-end pilot will be related to land-based fuel production** – in particular to electrolysers for green hydrogen production, which is a key input to both the ammonia and methanol synthesis. The remainder of the capital outlay relates to the fuel bunkering infrastructure and to vessel fuel storage and engine systems.

Exhibit 2. End-to-end capital spend for a 700 tonne per day green ammonia pilot

'REFERENCE CASE FULL CHAIN' 700 TPD GREEN AMMONIA PILOT
Capital expenditure needed across value chain, $m

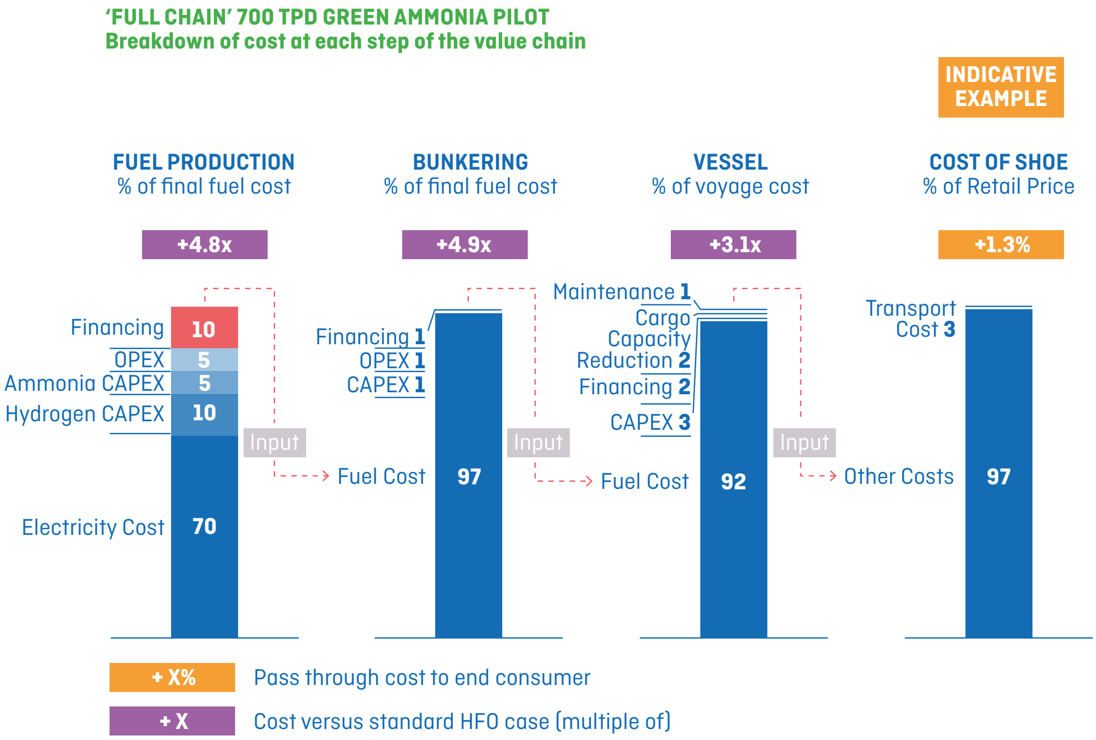


Source: ETC analysis (2020)
Key assumptions listed in Appendix

While sizeable land-based investment is required, capital outlay is, in fact, a relatively small contributor to the total cost of the pilot. Today, on a per tonne basis, the cost of green ammonia is approximately two and a half times the cost of conventional HFO fuel. Correcting for energy density means that 'first movers' would face green ammonia costs around five times the cost of HFO. The cost increase would be similar for green methanol. **High fuel cost subsequently cascades across the value chain and would represent more than 90% of total voyage cost for 'first mover' pilots**.

In turn, the energy intensity of green hydrogen production makes electricity the dominant cost driver for green ammonia and methanol production. For green ammonia, approximately 70% of the final fuel cost relates to electricity. Methanol production is less energy-intensive than green ammonia (electricity representing only 60% of fuel cost), but the need for carbon as an input in the methanol synthesis process means it is likely to present a higher total cost for the first wave of projects.

Exhibit 3. End-to-end costs breakdown for 700 tonne per day green ammonia pilot



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Despite the cost difference relative to HFO, **the potential cost to the end consumer of a shift to zero-emission shipping is relatively low**, given that freight costs are generally a minute portion of consumer good prices. For instance, the cost increase to a $100 high-end consumer product, such as a pair of shoes, would be less than +1.5% for both fuels. **This price impact suggests that the cost of decarbonisation for the maritime sector – even for the first wave of 'full ecosystem' pilot projects – can be managed through relatively modest price increases for end-use markets and consumers.** Finding ways to pass through this cost to consumers despite the global and competitive nature of the maritime sector will be key to bring zero-emission shipping closer to market; and lowering the cost premium associated with the first wave of commercial-scale pilots should make it easier for 'first movers' to develop a viable business model.

3. Cost reduction and risk mitigation strategies for each segment of the value chain

With targeted cost reduction measures, it will be possible to lower costs – both CAPEX and OPEX – at each segment of the value chain, yielding significant cost reduction for the pilots overall. The potential measures comprise both proven and novel interventions that each represent a different level of potential impact and implementation difficulty. The report categorises the measures into three types:

- **Game Changers:** mechanisms that have the potential to yield significant cost reduction and are relatively easy to implement in the next 5 years.
- **Quick Wins:** mechanisms that are easy to implement, but will likely have a more limited impact on pilot cost.
- **High-Hanging Fruits:** mechanisms that have the potential to yield significant cost reduction, but are likely to be more difficult to implement and will require the mobilisation of the whole value chain. Their implementation might therefore not be fast enough to benefit first-of-a-kind commercial-scale pilots, but could be critical to early deployment of zero-emission shipping in the late 2020s and early 2030s.

Fuel production costs

Reducing zero-emission fuel costs constitutes the most critical priority to support 'first mover' pilots. For both green ammonia and green methanol, fuel production costs are overwhelmingly related to electricity, which comprises around 60-70% of total cost, while about 25% is attributable to direct capex and related cost of capital.

Game Changers:

- Fuel providers have several levers at their disposal to significantly reduce capex related to zero-emission marine fuel production, including **repurposing existing fuel production facilities** and **sourcing least-cost equipment (in particular electrolysers)** from international vendors.
- What would make the biggest difference to total cost of 'first mover' pilots, though, are mechanisms that would enable marine fuel providers to **access low-cost renewable electricity**. Access to power at $35/MWh instead of $60/MWh would reduce the cost of zero-emission fuels by 30-35%. This could be achieved **through location-based cost optimisation, long-term power purchase agreements, as well as exemptions and waivers on power network and grid charges**

Quick Wins:

- A range of public investment support tools – including **direct capex subsidy** as well as de-risking mechanisms such as **loan guarantees** – could also contribute to reducing the cost related to investment in electrolysers and synthesis equipment.
- For the purpose of testing the reliability of new fuels throughout the shipping value chain, there might be a case for a **transitional use of ammonia and methanol produced from "blue hydrogen" or even from "grey hydrogen"**, which would currently be respectively 25% and 40% cheaper[3] than "green hydrogen" from renewable power electrolysis. However, such a use of fossil-fuel derived grey hydrogen should be clearly time-bound (e.g. 1-2 years) and only serve as an initial step before a transition to "green" fuels.

High-Hanging Fruits:

- The shipping sector should also **actively participate in the development of new fuel clusters, in particular hydrogen clusters**, which will serve several sectors of the economy. These clusters would enable to scale-up the production of green hydrogen and hydrogen-based fuels, while sharing energy infrastructure costs across a broader pool of stakeholders and **reducing offtake risks for fuel providers**, potentially reducing fuel costs by up to 20%.

3 Hydrogen - The Economics of Production From Renewables, BloombergNEF (2019)

Bunkering costs

Beyond fuel, the dominant cost for bunkering suppliers involved in zero-emission pilots is the storage tank and bunker vessel CAPEX, and the related cost of capital – which jointly represent up to 50% of their non-fuel costs. Accordingly, **Game Changers** at bunkering level all relate to investment:

Game Changers:

- The single most effective measure to reduce capital expenditure at bunkering level lies in the hands of the industry: **repurposing and retrofitting existing storage facilities and bunker vessels** could reduce capital outlay by up to 50%. Alternatively, **truck-to-shore bunkering** offers an approach to delaying capital outlay until sufficient scale of offtake is reached.
- Given the importance of capital expenditure, **bunkering suppliers, zero-emission fuel providers, as well as port authorities could also decide to co-invest in zero-emission fuel bunkering facilities to share costs and risks** while building their know-how and competitive advantage ahead of the scale-up of new marine fuel value chains.
- **Grants and public investment support mechanisms** targeted to investment in zero-emission bunkering barges, as well as onshore and offshore fuel tanks, can lower capex and cost of capital for bunkering suppliers. These forms of public support should also be accessible for the retrofitting of existing assets.

In and of itself, this will not make a profound difference on the overall pilot economics, representing a potential reduction of 1-5% of total end-to-end cost. **But avoiding, delaying, and defraying investments will be key to unlock the participation of bunkering suppliers in the first wave of commercial-scale pilot projects.**

Vessel retrofitting and operation costs

Reducing zero-emission fuel costs constitutes the most critical priority to support 'first mover' pilots. For both green ammonia and green methanol, fuel production costs are overwhelmingly related to electricity, which comprises around 60-70% of total cost, while about 25% is attributable to direct capex and related cost of capital.

Game Changers:

- For the first wave of commercial-scale pilots, which aim to prove the operational reliability of new engines and fuel tanks when operating on commercial deep-sea routes, **equipment providers, ship manufacturers and zero-emission marine fuel providers could have an interest in co-investing in on-ship equipment**, therefore sharing cost and risks while jointly benefitting from the operational understanding that the pilot will bring.
- Here again, different forms of **targeted public support to investment** – with a particular focus on the retrofitting of zero-emission engines and fuel tanks on existing deep-sea vessels – can be a very effective way for governments to facilitate the necessary capital expenditure. Although significant for individual ship owners, total amounts to cover 50% of the cost of new equipment for 10 pilots would not be higher than $30-70 million in total.

Quick Wins:

- **Governments could also financially support some one-off extra operating costs, in particular the re-training of the workforce** participating in the pilots with regards to safety and handling of zero-emission fuels.

High-Hanging Fruits:

- Although direct fuel subsidies for zero-emission marine fuels are unlikely to be implemented in national jurisdictions, given the international and fragmented nature of the shipping industry, proposals for **a global carbon levy and feebate system to subsidise zero-emission fuels** appear to gain traction. If such a system was implemented, **initially on a voluntary basis and eventually under the auspices of the IMO**, zero-emission fuel costs could be brought down for ship operators regardless of their flag.

Mitigating risks across the value chain

First-of-a-kind projects come, by nature, with a set of risks – real and perceived – which often increase the cost of capital for stakeholders involved (by up to 5-7%[4 5]) and may even deter their implementation. For 'first mover' pilots in shipping, three major risks need to be addressed jointly by industry leaders across the value chain:

Technology risks

New maritime engines need to be validated over a defined number of operating hours and complete tests spanning a range of conditions (e.g. running at high rates for extended periods) to rule out potential failure of key components. **Enhanced collaboration between fuel providers**, engine providers and shippers is an obvious Quick Win to help accelerate that process for zero-emission fuels.

Regulatory risks

Safety in both ports and at sea is paramount for the industry as marine fuels cannot be transacted at ports or handled on ships without approval the relevant regulatory authority. It is possible to **expedite domestic regulatory approvals by partnering with classification societies and interested regulators** from the inception of the pilot projects. This is especially relevant for ammonia, as IMO regulations for methanol are expected to be approved shortly.

Offtake risks

The cost differential between zero-emission fuels and HFO creates a chain of market uncertainty throughout the maritime industry. Fuel providers face uncertain offtake from the shipping sector. This risk is even higher for bunkering suppliers as they cannot diversify their offtakers beyond shipping. The same market uncertainty also applies to vessel operators who are unlikely to invest in new technologies and buy fuel at a significant premium without assurance that there is a market that will be willing to pay for the additional cost that zero-emission shipping entails. In the short term, solutions to this offtake risks are twofold:

- The critical Game Changer to underpin the development of the first wave of commercial-scale pilots is therefore the creation of **a chain of voluntary long-term offtake agreements cascading through the maritime value chain**. This chain should start with cargo owners agreeing to pay premium for "green shipping" and passing through that extra cost to end consumers. **Protocols that enable robust traceability and verification of "green shipping"** are likely to be a prerequisite for these initial agreements, which would then underpin a series of fuel offtake agreements higher up the value chain.

- Policymakers can facilitate those voluntary agreements by contributing to bridging the cost gap between zero-emission fuels and HFO through **contracts-for-difference** – adapted from renewable power auctions. Such a High-Hanging Fruit would enable the shipping industry to access lower-cost zero-emission fuels and offer a cheaper "green shipping" service to cargo owners, while providing investors in fuel provision with price certainty.

4 Angelopoulos, Dimitrios, et al. "Risks and Cost of Capital for Onshore Wind Energy Investments in EU Countries." Energy & Environment, vol. 27, no. 1, 2016, pp. 82–104.
5 https://www.globalccsinstitute.com/resources/global-status-report/

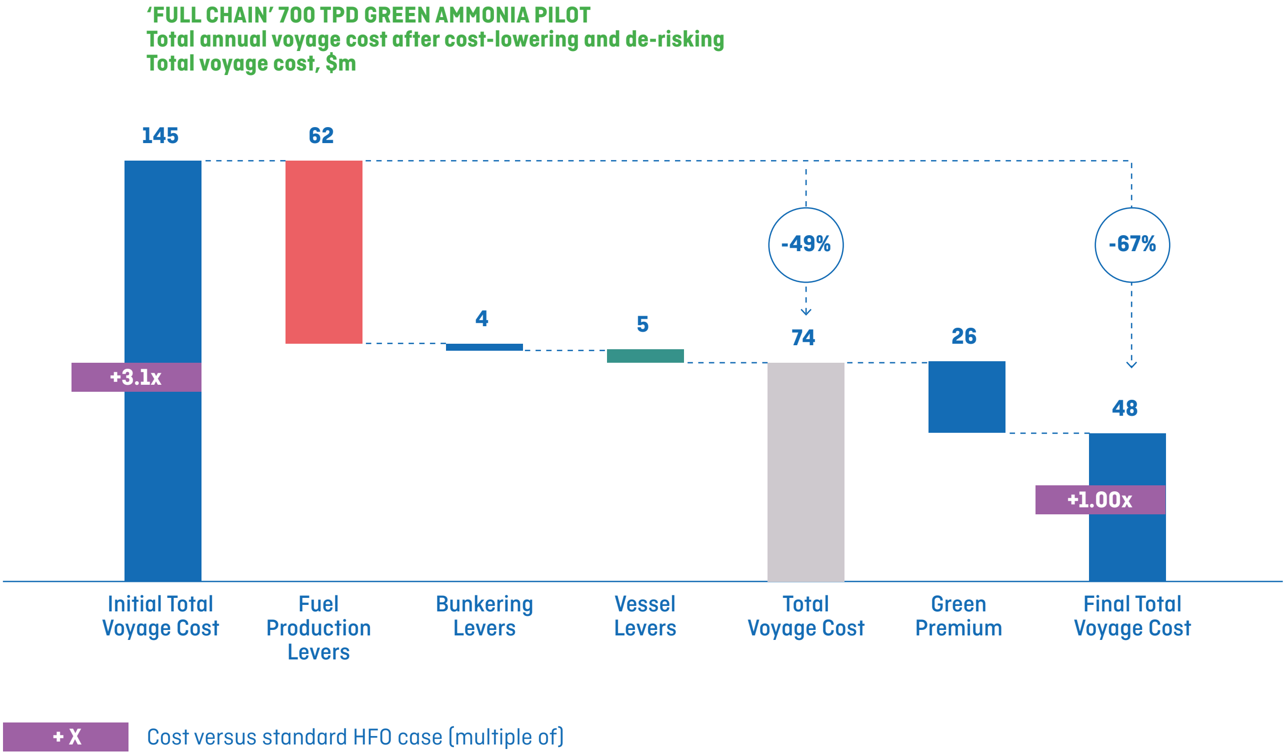
4. The impact of cost-lowering and de-risking mechanisms on pilots

The cumulative effects of the cost-lowering mechanisms described as Quick Wins and Game Changers in this report could lower total costs of a commercial-scale zero-emission shipping pilot by as much as 30-50%.

The largest cost reductions could be achieved through strategies aimed at lowering electricity prices and reducing capital expenditure at the fuel production stage. At the same time, approaches to reduce specific costs facing bunkering suppliers and vessel owners and operators will be necessary to unlock the participation of those stakeholders in the first wave of 'first mover' projects.

To effectively unlock commercial-scale projects, those cost-lowering mechanisms need to go hand in hand with the development of collaborations and offtake agreements across the maritime value chain – from cargo owners to fuel providers – that will address the major market uncertainties associated with those projects. This is essential for 'first mover' pilots to provide a robust proof point of the commercial viability of zero-emission shipping.

Exhibit 4. Quantification of cost mitigation strategy for a green ammonia pilot project across the value chain



5. Recommendations to unlock the first wave of commercial-scale zero-emission shipping pilots

The global maritime industry finds itself at a critical juncture in its history as it commences a transition from a narrow range of high-carbon fossil-based fuels to multiple and competing zero-emission fuel options. At its core, the transition will see a transformation in how fuel is produced, bunkered, consumed and priced. The realisation in the next five to ten years of a first wave of commercial-scale zero-emission shipping pilots is essential to provide the technological and commercial proof points that will unlock deployment at scale in the 2030s.

Priorities for industry

Industry leaders across the maritime value chain hold the keys to several major cost-lowering and risk-mitigation opportunities for 'first mover' pilots. They should focus their attention on 5 key priorities:

1. **Join forces to fast-track technology trials** and regulatory approvals necessary to use new zero-emission fuels on a commercial scale in the maritime sector.

2. **Choose pilot locations that offer privileged access to low-cost renewable electricity and hydrogen**, opting for regions with large renewable energy potential, preferential prices and tax exemptions for major industrial electricity consumers, and industrial clusters where several transport and industry sectors will share energy infrastructure costs.

3. **Seize every opportunity to repurpose and retrofit existing infrastructure and assets**, especially for ammonia and methanol production, fuels storage and bunker vessels, to minimise upfront capital investment.

4. **Co-invest in critical equipment – especially at bunkering and vessel levels – to share costs and risks**, while also benefitting from the learnings that commercial-scale operations of new zero-emission fuels will bring to fuel producers, equipment and ship manufacturers, bunkering suppliers, port authorities, ship owners and operators.

5. **Form consortiums with key stakeholders across the value chain – from cargo owners to fuel producers – to put in place a chain of long-term voluntary offtake agreements**, which will leverage the ability of cargo owners to pass through increased freight costs to end consumers providing greater market certainty to ship operators/owners and subsequently to bunkering suppliers and fuel producers.

Recommended government actions

In parallel, governments will also have to create, extend, and enhance support mechanisms to the first wave of commercial-scale projects through both direct financial support and de-risking of private sector investment. 3 key sets of action will help unlock 'first mover' pilots:

1. **Provide targeted investment support in the form of direct subsidies as well as concessional/preferential loans and loss guarantees** for the key elements of capital expenditure required at each stage of the maritime value chain, in particular fuel provision capex (electrolysers and synthesis equipment), onshore and offshore bunkering infrastructure, equipment purchase (for new engines and fuel tanks), and vessel retrofitting.

2. **Facilitate access of the maritime sector to low-cost electricity**, generally by continuing to drive massive investment in renewable electricity provision and specifically by waiving electricity taxes and grid fees for zero-emission fuel providers.

3. **Create a mechanism that effectively contributes to bridging the cost differential between zero-emission marine fuel cost and HFO** – in the form of contracts-for-difference for fuel producers and/or of a carbon levy and feebate model benefitting ship operators.

This report illustrates that the ambition of getting zero-emission vessels on deep-sea routes by 2030 is feasible. We are confident that a first wave of commercial-scale end-to-end zero-emission pilots can be launched within the next five to ten years, informing and inspiring the scale-up of zero-emission shipping shortly thereafter. **Achieving this goal will require enhanced collaboration across the maritime value chain and targeted support from key governments to boost the technological and commercial viability of the projects. Success will bring a scale-up of zero-emission shipping into sight.**

Glossary

Biomass Energy with Carbon Capture and Storage (BECCS): A technology that combines bioenergy with carbon capture and storage to produce net negative greenhouse gas emissions.

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

Electrolysis: A process that uses electricity, passing through an electrolytic solution or other appropriate medium, to cause a reaction that breaks chemical bonds (e.g., electrolysis of water to produce hydrogen and oxygen). It can be zero-carbon if the electricity used is zero-carbon.

Engineering, Procurement and Construction (EPC): Common contracts used by the private sector when doing construction works on large-scale and complex infrastructure projects.

Feebate: A Combination of 'fee' and 'rebate', a system where energy-efficient or environmentally friendly practices are rewarded while failure to adhere to such practices is penalized.

Fuel Cell: An electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as by-products.

Heavy Fuel Oil (HFO): A fraction obtained from petroleum distillation, either as a distillate or a residue that is commonly used as primary fuel in large ship engines.

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

Liquefied Natural Gas (LNG): Natural gas (primarily methane) that has been liquefied by reducing its temperature to -162°C at atmospheric pressure.

Operating Expense (OPEX): Segment expenses related both to revenue from sales to unaffiliated customers and revenue from intersegment sales or transfers, excluding loss on disposition of property, plant, and equipment; interest expenses and financial charges; foreign currency translation effects; minority interest; and income taxes.

Scalability: ability to increase production by adding additional resources.

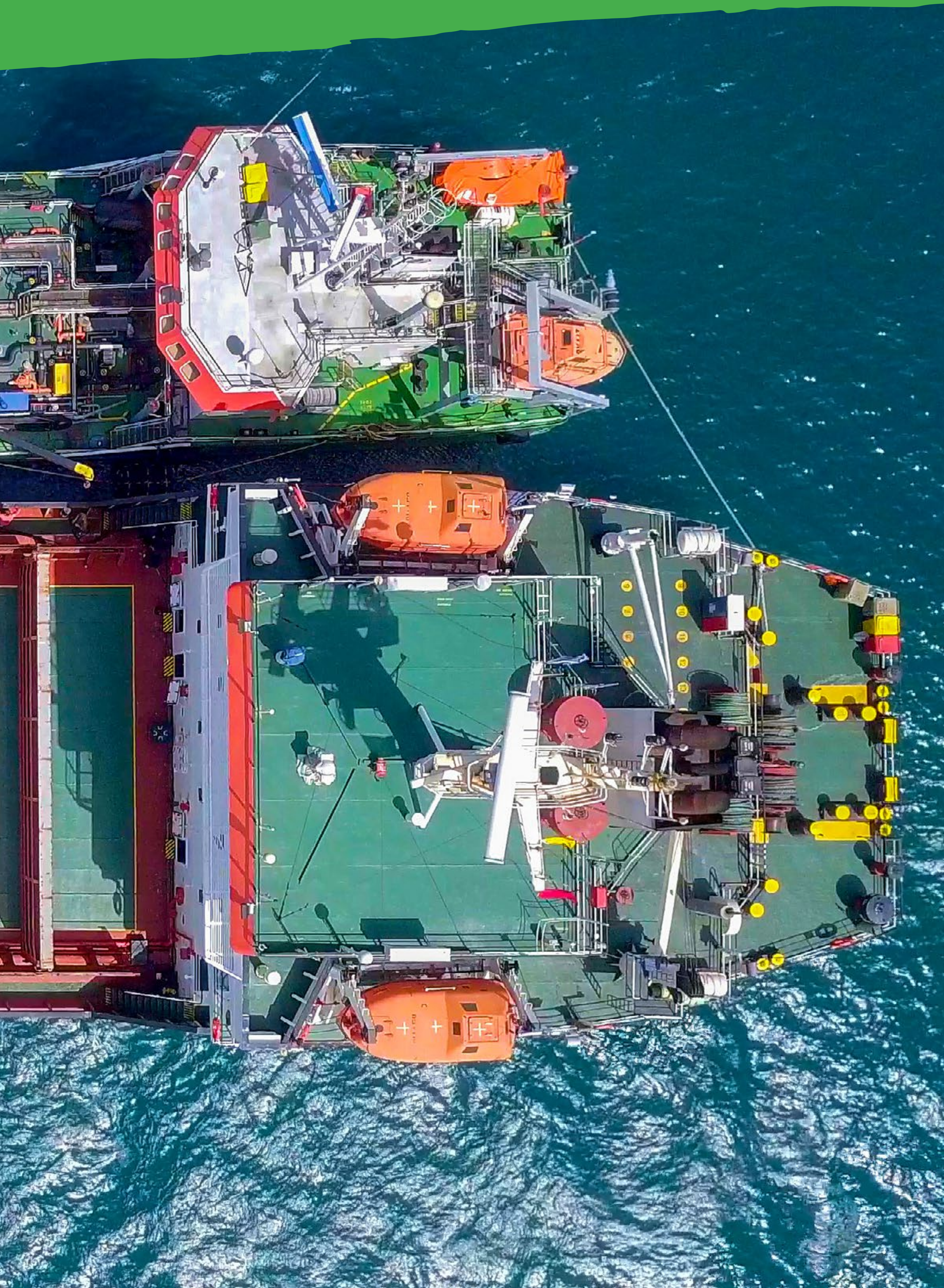
Twenty-foot Equivalent Unit (TEU): Standard unit for counting containers of various capacities and for describing the capacities of container ships or terminals.

What are Zero Emission Vessels?

Zero Emissions Vessels are vessels that operate on fuels from zero carbon energy sources. The definition for zero carbon energy sources used in this report is based on the IMO definition used in the 2018 Initial Strategy for GHG Reduction.

The Getting to Zero Coalition's "zero carbon energy sources" phrase is intended to be inclusive of fuels derived from zero carbon electricity, biomass and the use of CCS, but not of CCU derived energy sources based on the combustion of fossil fuels. The phrase "zero carbon energy sources" should be understood to cover energy sources and fuels that collectively have the potential to be scalable for supply of all of shipping's energy demand in 2050, taking into account foreseeable constraints of volumes available for shipping in recognition of the likely demand from other sectors. To read more, please see the technical footnote of the Coalition on this topic:

https://www.globalmaritimeforum.org/content/2019/09/Getting-to-Zero-Coalition_Zero-carbon-energy-sources.pdf



Introduction Unlocking the first wave of commercial-scale zero-emission shipping pilots

1. The importance of fuel switch for the decarbonisation of the maritime sector

The shipping sector is a key enabler of international trade, responsible for approximately 80% of the world's trade[1] . Although less intensive than other freight transport modes in terms of CO_2 emissions per tonne-kilometre, shipping represents about 3% of total global emissions from energy and industry today. Demand for shipping services is expected to continue to grow in line with global economic growth over the next three decades[2]. Without concerted collective efforts, greenhouse gas emissions from the sector could rise by as much as 50% above 2018 levels by 2050[3]. Given reaching the International Maritime Organisation's target of reducing total emissions from international shipping by 50% by 2050 - as compared to 2008 levels - will require an 85% reduction in emissions per vessel[4]. The deployment on a global scale of zero-emission vessels will be essential to reach the existing IMO target as well as to achieve the more ambitious objective of net-zero emissions by mid-century, which would be in line with the IPCC's scenarios to limit the rise of global temperatures to 1.5°C.

Greenhouse gas emission from shipping can already be reduced through a combination of efficiency strategies, leveraging existing technologies and solutions. These include:

- **System efficiency improvements:** Two key sources of system efficiency can be pursued in the maritime sector: reducing shipping demand through modal shifts to rail where this alternative exists – but trade routes on which such a modal shift is possible are very limited – and improving operational efficiency through logistics optimisation. Those levers combined could reduce emissions from the maritime sector by 4-5%[5].

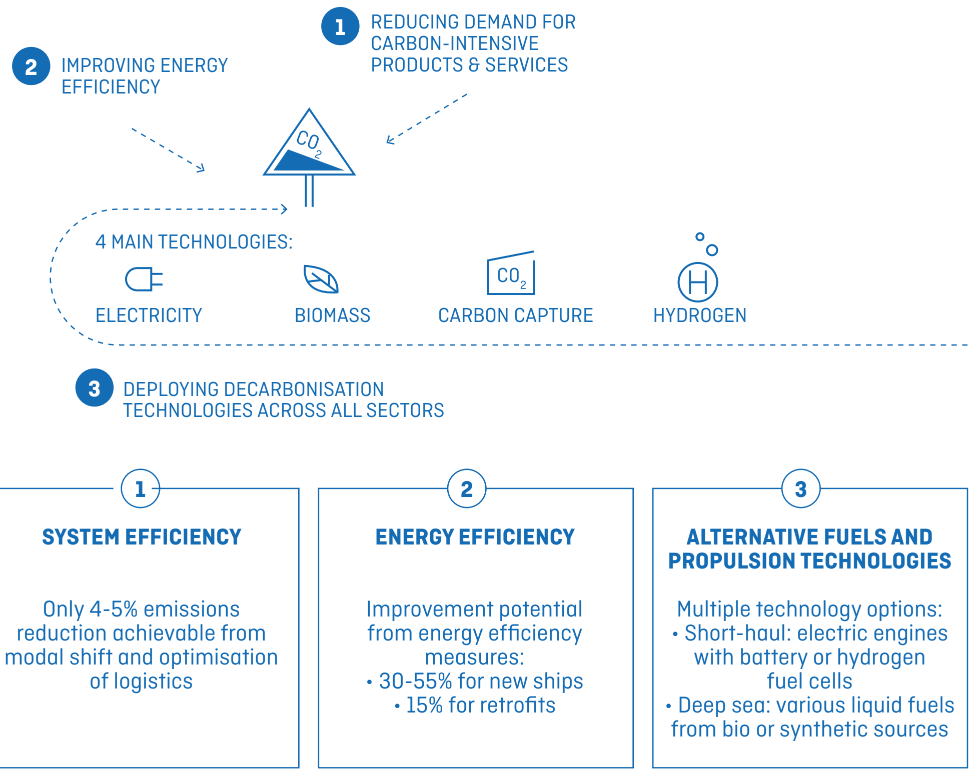
- **Energy efficiency improvements of existing ships and engines:** Energy efficiency improvements (through improved ship designs and propulsion systems) can in theory deliver overall energy efficiency improvements of 15% when retrofitting existing vessels and up to 55% for new ships[6], while unlocking cost savings for ship operators. Energy efficiency improvements have already resulted in emissions reductions of 20-30% since 2008 and will continue to contribute to the sector's decarbonisation. However, this progress has plateaued since 2015 as technical improvements have reached a saturation point through vessel fleets. Further emissions reductions from energy efficiency improvements could be more difficult to achieve, given the long lifetime of vessels (25-30 years) which slows down the adoption of design-efficient new builds. Accordingly, IMO projections indicate that future emissions reduction from energy efficiency could be offset by increases in global shipping volumes[7].

1 https://unctad.org/en/PublicationsLibrary/rmt2019_en.pdf
2 https://www.oecd-ilibrary.org/docserver/c013afc7-en.pdf?expires=1598487717&id=id&accname=guest&checksum=499085EAD9CE2156B25B6994025BC070
3 https://theicct.org/news/fourth-imo-ghg-study-finalreport-pr-20200804
4 https://www.u-mas.co.uk/LinkClick.aspx?fileticket=na3ZeJ8Vp1Y%3D&portalid=0
5 https://www.energy-transitions.org/publications/mission-possible-sectoral-focus-shipping/
6 https://rmi.org/wp-content/uploads/2017/06/RMI_Winning_the_Oil_Endgame_Book_2005.pdf
7 IMO GHG 4

A decarbonisation strategy focused on efficiency will therefore not be enough to meet the IMO's targets, nor a net-zero emissions objective. The decarbonisation of the maritime sector requires the deployment of vessels using zero-GHG-emitting fuels or energy sources (zero-emission vessels or ZEVs). These will need to be supported by the necessary fuel provision infrastructure for zero-carbon energy sources including production, distribution, storage and bunkering[8].

In that context, energy efficiency gains will still matter for the overall decarbonisation of the sector: by reducing fuel consumption significantly, they can both lower the additional fuel cost that a switch to zero-emission fuels currently entails and reduce the volume that might need to be dedicated to fuel storage on board of a vessel, which is important for zero-emission fuels with lower density than HFO, like ammonia and methanol.

Exhibit 1. Pathway to net-zero emissions in the maritime sector



Accordingly, the Getting to Zero Coalition, which brings together industry leaders from across the maritime value chain, has set an ambition to have commercially viable zero-emission vessels operating along deep-sea trade routes by 2030. This report forms part of a broad set of activities undertaken by the Getting to Zero community to accelerate the development and deployment of these zero-emission vessels.

2. Multiple fuel options for zero-emission vessels

The good news for the maritime sector is that several technology options for zero-emission vessels have been identified and are being developed, creating confidence that reaching the objective of net-zero emissions from international shipping by mid-century is technically achievable. However, consensus on which fuel or technology option might become dominant in the future has not yet been reached in the industry. The Getting to Zero community is currently undertaking complementary research focused on understanding the relative costs, benefits and challenges of the different candidate zero-emission energy sources and fuels for different parts of the fleet, including their technical feasibility and scalability, as well as their cost and commercial feasibility. Without pre-empting the conclusions of this analysis, we can draw an initial landscape of the major options under consideration and some of their specificities.

For deep-water shipping, several options are currently explored by the Getting to Zero Coalition as potential zero-emission marine fuels[9][10]:

- **Biofuels:** Certain biomass-based marine fuels can be used directly in existing engines and fuel infrastructure, precluding the need for any investments in new propulsion systems. Many biofuels are close to cost-parity with HFO[11] and initial commercial-scale operations have been initiated by industry leaders. Biofuels would continue to emit CO_2 at the point of use, but carbon emissions over their lifecycle could be significantly lower than HFO and potentially close to zero as the production of biomass absorbs carbon from the atmosphere. The calculation of lifecycle emissions reductions from biofuels is complex, and considers the speed of CO_2 absorption during biomass growth (which varies depending on the type of biomass), any indirect impact on land use change (including deforestation) as well as emissions from transportation and transformation of the bio-feedstock among other criteria. Concerns about the long-term scalability of biofuels remain, given known constraints on the truly sustainable supply of bio-feedstocks at both global and regional levels and expected competition from multiple sectors of the economy for this limited resource.

- **Hydrogen:** Hydrogen could potentially fuel the maritime sector in the long term, as it is already used as a fuel in other transport modes, notably some segments of road transport. Significant reduction in zero-carbon hydrogen production costs are expected in the next 10-15 years thanks to the development of a global hydrogen economy[12]. Hydrogen produced from electrolysis using zero-carbon electricity (i.e. "green hydrogen") is likely to be the most cost-competitive production route in the long term[13]. However, in the short term, production through steam methane reforming combined with carbon capture and storage (i.e. "blue hydrogen") would be a lower-cost option to access low-carbon hydrogen. Direct hydrogen use on deep-sea vessels – either in internal combustion engines or in fuel cells combined with electric engines – presents challenges relating to its low volumetric density (requiring larger hydrogen

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9 https://www.globalmaritimeforum.org/content/2019/09/Getting-to-Zero-Coalition_Zero-carbon-energy-sources.pdf
10 While synthetic LNG is – in theory – a potential fuel pathway, it has not been considered for the purpose of this report due to the high methane slip associated with LNG that limit its greenhouse gas mitigation potential.
11 https://www.ieabioenergy.com/wp-content/uploads/2013/10/IEA-Biofuel-Roadmap.pdf
12 https://www.energy-transitions.org/publications/mission-possible/
13 https://www.energy-transitions.org/publications/making-mission-possible/

storage), high volatility and flammability (requiring new safety and handling regulations for use as a marine fuel). Hence, hydrogen could also constitute the primary feedstock for various non-biomass based zero-emission marine fuels described below, which could circumvent some of these issues.

- **Ammonia:** Ammonia, produced from green or blue hydrogen, would benefit from higher volumetric density and relative ease of storage when compared to hydrogen, and could therefore constitute a more easily deployable option for deep-sea vessels. However, it would still require significant investment in engines, bunkering and fuel infrastructure, would still have a lower volumetric density than HFO, and would also require new safety and handling regulations for use as a marine fuel due to its toxicity[14]. Additionally, while ammonia propulsion systems are in the process of being developed, they are not currently commercially available[15].

- **Methanol:** Methanol, produced from a combination of hydrogen and CO or CO_2, could be more easily available than green or blue ammonia in the short term, as dual methanol-HFO engines are already commercially available. It is likely that the regulatory IMO framework for its fuel as a marine fuel will be standardised and approved in early 2021[16]. However, just like biofuels, methanol continues to emit CO_2 at point of use. To be truly zero-carbon over its lifecycle, CO_2 input should come from Direct Air Capture (DAC). This technology is still in its nascent stages and is only expected to be commercially available in the late 2020s. In the meantime, the capture of carbon from a process using bioenergy could also constitute a carbon-neutral source of CO_2 (although the small number of power or industrial plants using such a process would limit supply). The use of CO_2 captured on the back of industrial processes might be a lower-carbon – but not zero-carbon – transitional solution, which could allow for lower cost in the initial stages of technology deployment.

- **Synthetic diesel:** Synthetic diesel produced from a combination of hydrogen and CO_2 could, like biofuels, be 'dropped in' existing engines and preclude the requirement for investment in fuel infrastructure and new propulsion systems. It would, just like biofuels and methanol, continue to emit CO_2 at point of use and, to be truly zero-emission over its lifecycle, would face the same constraints in terms of CO_2 supply as methanol. However, this technology is still in its nascent stages and is only expected to be commercially available by 2030.High energy and capital expenditure requirements for its production make it the least economic option in the short term.

Meanwhile, for vessels operating shorter distances, the use of electric propulsion combined with batteries or hydrogen fuel cells could rapidly become cost competitive thanks to the rapid decrease in the price of renewable power, batteries and fuel cells[17]. Although initially limited due to battery and hydrogen storage density – which would make storage volume prohibitive for longer distances - the maritime market segments that could be served by these solutions will progressively expand with technology improvements.

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14 https://s2.q4cdn.com/255514451/files/doc_downloads/safety/Aqueous_Ammonia_HFC.pdf
15 https://www.motorship.com/news101/alternative-fuels/man-es-targets-2024-for-delivery-of-first-ammonia-engine
16 https://www.spglobal.com/platts/en/market-insights/latest-news/oil/072220-interview-methanol-bunkering-set-to-jump-after-regulatory-approval-methanol-institute-coo
17 https://www.energy-transitions.org/wp-content/uploads/2020/08/ETC-sectoral-focus-Shipping_final.pdf

3. Key hurdles to the deployment of new fuels

While the deployment of zero-emission fuels and vessels is achievable and critical to put the shipping industry on path to a net-zero emissions goal, multiple hurdles will need to be overcome to accelerate the deployment of those solutions.

The first set of challenges relates to the **reliability of zero-emission technologies**, which are currently at different stages of development. The use of alternative propulsion and storage systems has not yet been demonstrated at scale for some of the options with lower technology readiness, in particular the ammonia and hydrogen options. Both technology assessments and commercial-scale pilots will be essential to confirm their reliability and unlock large-scale deployment. Industry leaders will in particular need to address perceived fuel safety risks and regulatory hurdles.

- **Industry perception of fuel safety risk:** The physical properties of methanol, ammonia, and hydrogen make all three fuels either more flammable or more toxic than conventional HFO. Fuel-specific safety and handling procedures can mitigate against these risks: all three fuels are indeed already being transported by ships. Clear industry guidelines as well as more extensive experience of their use as marine fuels for commercial-scale operations should address remaining concerns.

- **Regulatory hurdles:** Safety and fuel handling regulations – established either by the International Maritime Organisation (IMO) or by domestic regulators – must be passed for any new marine fuel. This requirement has already been – or will soon be – met for biofuels and methanol. For ammonia and hydrogen, whilst they are already transported as cargo, those regulations are not yet in place and will need to account for the toxicity and flammability risks of each fuel, respectively.

The shift to zero-emission marine fuels also implies the **development of new land-based fuel production and bunkering infrastructure**. Fuel availability will be important in the short term for the development of the first wave of commercial-scale pilots. In the longer term, the scalability of those new fuel value chains will also be critical to underpin the deployment at scale of zero-emission vessels globally.

Finally, the deployment of zero-emission vessels faces a set of **market hurdles**, which are difficult to navigate in a globally competitive sector and will need to be addressed to launch a first wave of commercial-scale projects in the coming years:

- **Cost differential:** The cost of decarbonisation for the maritime sector could be as high as $200-300 per tonne of CO_2 saved by mid-century, which would entail a multiplication by 2-2.5 of shipping costs[18]. First movers are likely to face an even greater cost differential, as alternative fuels are not yet produced at scale. In a highly competitive and cost-sensitive sector, this cost differential will represent the most significant obstacle to a shift to zero-emission vessels, even if the impact on prices of consumer products traded internationally would often be minimal (<1%). A range of cost-lowering and cost-sharing solutions will therefore need to be pursued to overcome this challenge.

18 https://www.energy-transitions.org/publications/making-mission-possible/

- **Market structure:** The global nature of the maritime industry implies that policy interventions to drive decarbonisation (such as carbon prices or emissions reduction requirements) need to be agreed and implemented on either a global scale through the International Maritime Organisation or regional scale through supra-national entities such as the European Union. The negotiation and implementation of such regulations is by nature a lengthy process. First movers will therefore operate in a market that has not yet created a level playing field across all competitors.

Although significant, these hurdles are not insurmountable: early-stage technologies often face similar barriers and successfully overcome them over time. The history of transportation includes many such examples – from the invention of aviation to the deployment of electric vehicles on roads around the world. The overarching challenge facing the shipping sector today is one of speed: the climate imperative demands a fast transition from technology demonstration to deployment at scale.

4. The urgent need for commercial-scale zero-emission shipping pilots

The global shipping fleet should transition to zero-emission fuels and propulsion by mid-century if the sector is to contribute to the limitation of the rise in global temperatures to below 1.5°C. Given the average useful lifetime of vessels is 25-30 years, all new vessels launched after 2030 should be zero-emission vessels – or at least be conceived to be able to use zero-emission fuels with some retrofitting. This in turn implies that zero-emission vessels and fuels need to be technologically and commercially proven by 2030.

In that context, achieving the Getting to Zero Coalition aims would require that:

- **First-of-a-kind commercial-scale shipping pilots**, mobilising the entire shipping value chain end to end (from fuel producers to cargo owners), are implemented before 2025 to test and refine multiple technology options and the commercial models associated to those. The first wave of 'first mover' pilots would ideally encompass at least 10 large projects on different major deep-sea routes.

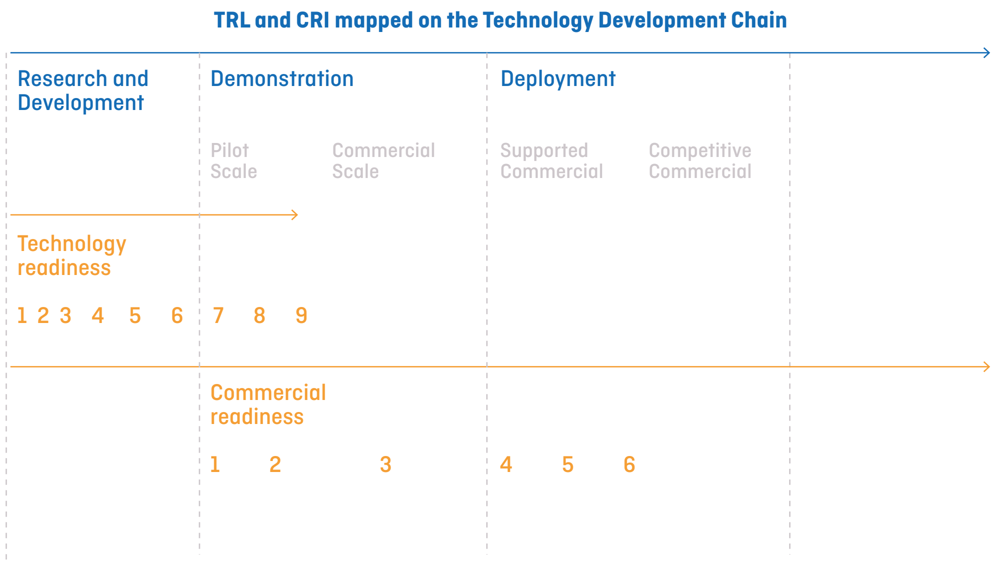
- **Early adoption** of zero-emission vessels accelerates between 2025 and 2030 in favourable segments of the market (for instance those with the greatest ability to pass through additional cost to end consumers) to reach 5% of the global energy consumption of the maritime sector. This initial scale – which would represent 15 million tonnes of HFO equivalent per annum[19] – is likely to trigger economies of scale and learning curve effects in both zero-emission marine fuel supply and vessel equipment manufacturing, which would facilitate an accelerated deployment of zero-emission shipping in the 2030s.

- **Diffusion** accelerates in the 2030s on a global scale and across multiple fleet segments, thanks to mechanisms, including IMO regulations, that would close the competitiveness gap between zero-emission options and HFO.

19 https://irena.org//media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Renewable_Shipping_Sep_2019.pdf

This report focuses on how to unlock the first wave of first-of-a-kind and second-of-a-kind commercial-scale zero-emission shipping pilots (or 'first mover' pilots) which would test both new technology and commercial models throughout the value chain in the next five years and constitute the critical proof point underpinning early deployment in the late 2020s and early 2030s. The objective of those 'first mover' pilots is to bring zero-emission shipping to technology readiness level 9 and commercial readiness level 3-4 (see Exhibit 2 below). These pilots are therefore distinct from technology validation exercises which are designed to prove the technological feasibility of a concept. They aim not only to test new vessels, but the full value chain required around those vessels for them to operate commercially on deep-sea routes, in particular the necessary fuel infrastructure. They would likely operate for several months or years to demonstrate the commercial viability of operations. They will therefore entail higher CAPEX and OPEX.

Exhibit 2. Technology readiness and commercial readiness framework



Source: IRENA (2014), Commercial readiness Index for Renewable Energy Sectors

5. A blueprint for commercial-scale zero-emission shipping pilots

This report explains how first movers from across the maritime value chain can come together to lower the technical, regulatory, and economic barriers facing the first wave of commercial-scale zero-emission shipping pilots. This work should be considered within the context of the broader programme of activities developed by the Getting to Zero Coalition, in particular the ongoing assessment of candidate zero-carbon energy sources and fuels from 2030. This report focuses on the necessary near-term actions to progress toward the 2030 ambition of achieving early deployment of zero-emission vessels on deep-sea routes, while parallel research will guide longer-term decisions by industry and policymakers to accelerate deployment in the 2030s and beyond.

- **Section 1** introduces the Blueprint, outlines the pros and cons of different design options for 'first-mover' pilots and describes the two examples analysed in greater details throughout this report.
- **Section 2** describes the end-to-end value chain that needs to be mobilised for a zero-emission vessel (ZEV) pilot to be successful and outlines the respective roles of different stakeholders in such pilots.
- **Section 3** illustrates the economics of an end-to-end pilot, highlighting the relative importance of CAPEX and OPEX at different stages of the value chain.
- **Section 4** focuses on the major cost drivers and cost reduction strategies for zero-emission fuel production.
- **Section 5** identifies the major cost drivers and cost reduction strategies at bunkering and vessel levels, beyond considerations related to fuel costs.
- **Section 6** addresses the major risks for 'first movers' across the value chain, in particular technology, regulatory and commercial risks.
- **Section 7** showcases the potential quantitative impact of cost-lowering and de-risking mechanisms for an end-to-end pilot.
- **Section 8** summarises key recommendations for private and public sector players to accelerate the development of the first wave of commercial-scale zero-emission shipping pilots.

Section 1

Scope of this blueprint: Navigating options for 'first mover' pilots

The objective of the first wave of commercial-scale zero-emission shipping pilots is to demonstrate the technical, operational and commercial feasibility of the zero-emission shipping value chain to facilitate rapid deployment thereafter. Multiple design choices are possible for those projects: commercial-scale pilots could be implemented with multiple fuel options, on different segments of the maritime sector, at different scales of operation. This blueprint purposefully focuses on a few options, which have been selected to illustrate the challenges and opportunities for 'first movers'. Many other design choices are possible – and should indeed be tested to inform early deployment in the late 2020s and early 2030s. We expect that the approach, analysis and recommendations developed in this blueprint will be transferrable to a wider range of potential projects and outline below the key similarities and differences that project partners would need to account for in different scenarios.

1.1 Choosing a fuel pathway

This blueprint focuses on two fuel options which are key contenders as long-term scalable zero-emission fuel options for the maritime sector but face multiple barriers to deployment in the short to medium term: ammonia and methanol. The availability of propulsion systems and the expected passing of safety and fuel handling regulations position methanol as more readily available than ammonia for projects today, but ammonia is attracting increasing attention from the industry[20]. These fuels are not 'drop-in' and therefore require investments in new engines and storage equipment, as well as new bunkering facilities. Their production and use in the maritime sector is still at an early stage, implying relatively high levels of technology uncertainty and relatively lower safety and handling experience as a fuel. They also present a significant cost differential compared to HFO. This combination of factors makes the development of commercial-scale pilots using those fuel options particularly challenging, thus providing a useful reference point for the industry.

The fuel production economics of hydrogen and synthetic diesel would have much in common with those of ammonia and synthetic methanol, given the use of hydrogen as a critical input and cost driver. By comparison, biofuels are already being used as marine fuels and are currently much lower cost than hydrogen-based fuels – indeed approaching parity with HFO in some cases – precluding the need for commercial-scale pilots.

The two worked examples in this blueprint – on ammonia and methanol – have been validated through extensive engagement with the Getting to Zero community, but do not represent investment-grade figures. Rather they aim to highlight the nature and scale of the investments and costs entailed by end-to-end commercial-scale shipping pilots, to illustrate challenges and potential solutions to facilitate their development. These assessments are sensitive to the underlying assumptions, which can be found in the appendix.

Both fuels use hydrogen as a key input and this blueprint specifically focuses on the use of 'green' hydrogen from electrolysis using primarily renewable electricity, as it is expected to be the most cost-effective and least carbon-intensive hydrogen production route in the long term. However, one should note that the usage of 'blue' hydrogen – or even fossil-based high-emission (e.g. 'grey') hydrogen – might be more economical in the short term and may constitute a way to lower cost in the initial stages of 'first mover' pilots.

Similarly, methanol requires a CO_2 input, which should ideally come from Direct Air Capture (DAC) to ensure that the fuel is truly zero-emission over its lifecycle. However, the technology is still in its nascent stages and is only expected to be commercially available by 2030. An alternative option is the use of CO_2 captured on the back of biomass combustion processes. However, in the short term, given the limited number of facilities providing this type of CO_2 input, 'first movers' may be constrained to using methanol with CO_2 from other industrial sources, which would not qualify as zero-emission, but would be more available and lower-cost as a transitional solution for the first wave of projects. For this blueprint, it is assumed that the carbon feedstock is procured from plants with biomass combustion processes. While the cost estimates for DAC facilities vary significantly, calculations using reasonable CAPEX estimates indicate that methanol production using DAC would increase cost by at least $200-300 per tonne for 'first movers'[21].

20 https://www.ft.com/content/2014e53c-531f-11ea-a1ef-da1721a0541e
21 https://www.sciencedirect.com/science/article/pii/S0959652619307772

Exhibit 3. Pros and cons of different fuel options for 'first mover' pilots

	Fuel production	Bunkering	Vessel	Comment
Green Ammonia	(+) Strong long-term scalability potential (+) Emerging consensus as most viable zero emissions-capable fuel	(!) High toxicity levels; lack of existing maritime handling regulations (!) Existing distribution, but not for fuel purposes	(!) Dual fuel ICE close to market but not yet commercially available (!) Lower volumetric density relative to HFO	• Likely to be the most scalable fuel option in the long-term
Green Methanol	(!) Carbon feedstock procurement can be difficult (!) Carbon capture technology still at nascent stage with uncertain costs	(+) Soon to be passed maritime handling regulation (+) Relatively easy to repurpose existing infrastructure	(+) Dual fuel ICE available (!) Lower volumetric density relative to HFO	• Proven technology with ease of use throughout value chain • Carbon procurement can be problematic
Biofuels	(+) Close to cost parity with HFO/MGO for select feedstocks (!) Long-term scalability concerns due to feedstock and sustainability constraints	(+) Limited/no new bunkering infrastructure required	(+) Drop-in fuel potential (+) ICE engines available with mature capex	• Proven technology with ease of use throughout value chain • Doubts about long-term scalability
Green Hydrogen	(+) Multi-sector demand to underpin scale and cost reductions	(!) Minimal transportation by ship at present (1-2 ships) (!) High flammability; lack of existing maritime handling regulations	(!) ICE options not commercially available (!) Cost-intensive storage options	• Low technology readiness • Low economic feasibility in short term
Synthetic Diesel	(!) Carbon feedstock procurement can be difficult (!) Carbon capture technology still at nascent stage with uncertain costs	(+) Limited/no new bunkering infrastructure required	(+) Drop-in fuel potential (+) ICE engines available with mature capex	• Lowest technology readiness • Low economic feasibility in short term

Focus for the Blueprint (Green Ammonia, Green Methanol)

1.2 Choosing a vessel type

Three major types of vessels are utilised for deep-sea transportation: containerships, bulk cargo ships, and tankers. These vessels are responsible for approximately 85% of emissions from the shipping sector[22]. While, zero-emission fuels will eventually need to be deployed across all segments of the global fleet, the unique operational characteristics of each vessel segment will have implications on the suitability of their use for 'first mover' pilots.

This blueprint focuses on **containerships**. A key advantage of containerships for the development of 'first mover' pilots is the predictability of their trade routes, which allows for the construction of production and port facilities to be limited to one or two locations, therefore lowering CAPEX numbers for first projects. Moreover, the ability to pass through cost to consumers through the development of a marketable "green shipping" offer is likely to be higher in containerships, which carry a higher proportion of 'high-end' consumer goods with larger margins than bulk cargo or tanker vessels. This segment is also likely to be presented with incentives to provide goods with low carbon footprints given increasing consumer scrutiny. Focusing shipping pilots on higher-margin finished and consumer goods would also ensure that shipping costs for critical price-sensitive sectors such as agriculture are not affected. Finally, from the perspective of ports and bunkering suppliers, the safety and handling regulations at a containership terminal are less stringent in comparison to regulations at a tanker terminal. In terms of type of vessels, we are considering 2,500 TEU vessels operating between three ports travelling a total of approximately 1,350 nautical miles. It is assumed that the vessels will be retrofitted with the appropriate engine and storage systems, as this would lower costs compared to new built vessels.

Other options could be considered, with a different set of advantages and disadvantages:

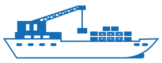
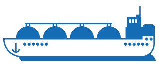
- **Bulk cargo ships:** The *ad hoc* nature of bulk cargo trade routes makes it more difficult to develop commercial-scale pilots with a limited number of production facilities and port infrastructure for new zero-emission fuels. Additionally, the tighter margins associated with bulk cargo transportation could hinder the ability of critical stakeholders to participate in 'first mover' pilots. Conversely, several sectors using bulk cargo shipping – for instance the mining and metals industry – are high-emitting sectors and are under pressure from governments and investors to reduce the carbon footprint of their products, which could create new incentives for their participation in 'first mover' pilots.

- **Tankers:** The use of tankers for 'first mover' pilots could usefully reduce expenses for fuel storage systems and crew training costs. Ammonia and methanol tankers specifically would be good candidates for 'first mover' pilots: as carriers, they are already transporting those fuels, applying safety and handling regulations specific to them, and by definition travelling between locations where they can access those fuels. It should be noted, however, that the ammonia or methanol usually used by those tankers would currently be fossil fuel based rather than zero-emission. Additionally, tankers transport homogenous products, usually for a single buyer, which can reduce the complexity of 'passing-through' the cost – while a containership would have to deal with multiple cargo owners. The potential unpredictability of voyage routes will likely make the usage of tankers for true 'zero-emission' pilots difficult.

22 IMO GHG 4

Regardless of the benefits and drawbacks of each vessel segment, the most important factor for the first wave of commercial-scale pilots will be limiting the number of locations where production facilities and bunkering infrastructure need to be developed.

Exhibit 4. Pros and cons of different vessel types for 'first mover' pilots

Vessel Segment	Description	Relevance for 'first mover' pilot
 Containership	Used to transport manufactured goods in intermodal containers	+ Known and predictability trade routes allow for the development of infrastructure at limited number of pre-determined ports + Higher potential of cost pass-through to end-use markets + Less stringent fuel handling procedures at containership terminals
 Bulk Cargo	Used to transport unpackaged bulk cargo in cargo hold	+ Increasing pressure for end-use sector to reduce Scope 3 emissions ! Variable trade route selection raises minimum level of infrastructure investment ! Tight margins limit potential of passing through cost to end-use markets
 Tanker	Used to transport liquids or gases in bulk	+ Lower expense related to fuel storage system and crew training costs + Homogenous cargoes and concentrated customer base simplifies cost pass-through ! Variable trade route selection raises minimum level of infrastructure investment ! Technical challenges in accessing engine and fuel storage systems increase complexity of testing and validation

Focus for the Blueprint

1.3 Choosing a scale of operation

The scale of an end-to-end pilot project can be determined by differing factors at various points in the value chain segment:

- Although for R&D projects, the use of one single vessel could be enough to prove technology reliability, demonstrating the commercial viability of zero-emission fuels will likely require the mobilisation of several vessels.
- Bunkering suppliers have only one offtake sector (the maritime sector) and must ensure that the scale of operations is sufficient to cover the fixed costs associated with the required bunkering facilities for a new zero-emission fuel.
- From a fuel producer perspective, the existence of multiple offtake options will reduce the importance of the scale of the shipping pilot, as a fuel production facility could diversify its offtakers beyond the shipping value chain

In this blueprint, we have therefore developed three worked examples which illustrate the relative importance of different cost elements of a 'first mover' pilot and how scale can affect the economics of such a project:

- A **'small' commercial-scale** pilot of **225 tonnes per day** (e.g. ~100 tonnes per day of HFO equivalent) at the fuel production segment of the value chain with **3 vessels** operating from the same port. The bunkering segment of the value chain will require a 5000-tonne storage tank along with two 1000 tonne storage tanks, as well as a bunker vessel.

- A **'large' commercial-scale pilot** of **950 tonnes per day** (e.g. ~400 tonnes per day of HFO equivalent) at the fuel production segment of the value chain with **12 vessels** operating from same port. The bunkering segment of the value chain will require a 30,000-tonne storage tank, as well as a bunker vessel.

- A **'reference' case** of **700 tonnes per day** (e.g. ~350 tonnes per day of HFO equivalent) the fuel production segment of the value chain with **9 vessels** operating from the same port. The bunkering segment of the value chain will require two 10,000 tonne storage tanks, as well as a bunker vessel. While the small and large scale worked examples will be used to illustrate how scale might affect the economics of a 'first mover' pilot, the 'reference' case will be used for analysis conducted for all other sections of the blueprint.

As methanol and ammonia are comparable from an energy density standpoint, the tonne per day production for the two fuel pathways can be considered equivalent.

1.4 Navigating possible cost and risk mitigation strategies

The objective of this blueprint is to map the key cost components of a commercial-scale blueprint for each value chain segment (at the level of fuel production, bunkering, vessel equipment and operation) to allow for a more informed assessment of the potential levers and mechanisms that can be used to reduce cost and facilitate the financing of the first wave of commercial-scale pilots.

Throughout this document, we therefore endeavour to identify and prioritise cost-lowering and de-risking strategies based on their potential impact and their ease of implementation. Solutions have been broadly divided into three catagories using this qualitative framework:

- **Quick Wins:** Mechanisms that are easy to implement but will likely have a more limited impact on pilot cost.

- **Game Changers:** Mechanisms that have the potential to yield significant cost reduction and are relatively easy to implement in the next 5 years.

- **High-Hanging Fruits:** Mechanisms that have the potential to yield significant cost reduction but are likely to be more difficult to implement and will require the mobilisation of the whole value chain. Their implementation might therefore not be fast enough to benefit first-of-a-kind commercial-scale pilots but could be critical to early deployment in the late 2020s and early 2030s.

Section 2

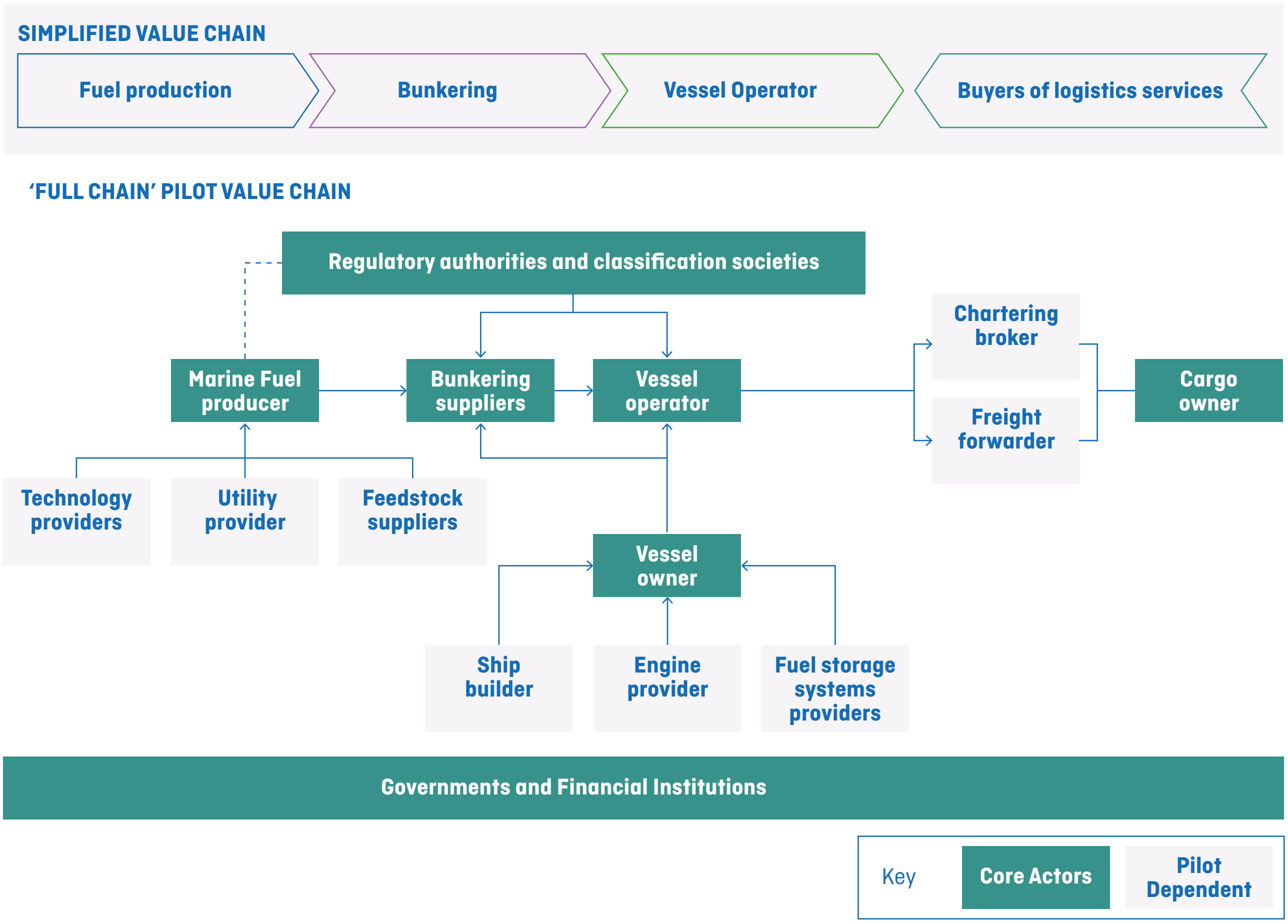
Mobilising the maritime value chain for the first wave of zero-emission pilots

The deployment of zero-emission vessels globally will require the creation of a new green shipping value chain, involving both old and new stakeholders, which will likely be underpinned by new forms of contractual relationships. Accordingly, a number of critical stakeholders will need to be involved in the first wave of commercial-scale pilots.

2.1 Critical stakeholders across the maritime value chain

The deployment of zero-emission vessels globally will require the creation of a new green shipping value chain, involving both old and new stakeholders, which will likely be underpinned by new forms of contractual relationships. Accordingly, a number of critical stakeholders will need to be involved in the first wave of commercial-scale pilots.

Exhibit 5. Key partners to be involved in an end-to-end pilot



The specific set of partners involved in an end-to-end pilot will vary by fuel pathway and vessel type, but a set of core actors will always need to be involved:

- **Fuel producers** need to build a first wave of zero-emission maritime fuel production facilities to allow the first zero-emission ships to operate. Given the use of new feedstocks and technologies, the participation of new entrants into marine fuel production market is likely. It is also possible that partnerships between traditional marine fuel producers and new entrants will be formed.

- **Bunkering suppliers** need to build appropriate bunkering infrastructure for new fuels and handle the fuelling process at ports. Given the low-margin nature of the industry, it is likely that the infrastructure investments will have to be heavily subsidised by the public sector, or that the bunkering portion of the value chain will be vertically integrated by fuel producers with robust balance sheets.

- **Classification societies and regulatory authorities** will need to be involved for any zero-emission vessel pilot. For green ammonia pilots in particular, the involvement of classification societies and regulatory authorities will be essential to develop necessary safety and fuel handling standards, whereas those are close to completion for methanol already.

- **Vessel operators** are obviously key stakeholders in pilots, as they will ultimately face the operating costs of zero-emission shipping and will need to develop new commercial models accordingly. While cost remains the most significant barrier, the technical and regulatory hurdles for 'first mover' vessel operators will also be significant. The involvement of additional market intermediaries will depend on the vessel type and market segment the cargo owners operate in.

- **Vessel owners** will make the investments in acquiring or retrofitting a zero-emission vessel, while **vessel operators** will face the extra operational cost related in particular to higher fuel costs. Although, in the maritime industry, vessel ownership and operation can be done by two distinct corporations, pilots are most likely to involve vessels both owned and operated by the same entity, as this would reduce the complexity of the stakeholder play. For the purposes of this blueprint, therefore, the term 'vessel operator' will be assumed to refer to an operator that also owns its vessel.

- **Engine and fuel storage equipment providers as well as ship builders** will be dependent on the chosen fuel pathway. They need to collaborate with the marine fuel producer, bunkering supplier and vessel operator to ensure coherence of the zero-emission propulsion system on an end-to-end basis.

- **Cargo owners** will likely need to absorb and pass on the additional cost of green shipping to customers. For the purposes of the blueprint, we are assuming the use of containerships by **vessel operators** for pilots. The structure of the containership market segment, wherein each vessel carries cargo for a range of different companies, implies that a coalition of buyers would need to be involved.

- **Financial institutions** will be required to provide funding for zero-emission vessel pilots at each step of the value chain. The risk-averse nature of traditional banking institutions will make it difficult to procure funding for zero-emission vessels and fuel infrastructure without forms of public de-risking.

2.2 The importance of public financial support for the first wave of commercial-scale pilots

Given the extent of the cost differential between zero-emission fuels and HFO, the level of technology and commercial risks, and the complexity of the maritime value chain, public support, especially public financial support to investment, will be critical to launch the first wave of commercial-scale pilots.

Public support to investment will be important at different stages of the value chain to lower the financial burden for 'first movers' as well as de-risk private investments, in particular debt provision, therefore facilitating the financing of the projects and potentially lowering the cost of capital facing different stakeholders involved in such pilots. The next sections highlight the specific elements of CAPEX in end-to-end zero-emission shipping pilots that could particularly benefit from public support to investment. A range of mechanisms could be leveraged – which we are detailing here and referred to throughout this blueprint. These include (but are not limited to):

- **Direct grants:** Direct subsidies for equipment purchases are the most obvious mechanism that governments can use to facilitate 'first mover' pilots. For pilots based in Europe, for example, there are several EU funds, such as the EIC Fast Track to Innovation and Connecting Europe Facility, that focus specifically on high-risk sustainability projects[23]. However, direct grants do not allow for any return on investment for taxpayers and limit the potential to crowd in private capital.

- **Concessional loans:** Governments can also facilitate the financing of investments by providing concessional loans to 'first mover' projects through public financial institutions, which enable key stakeholders to access capital at a lower financing cost than what would have been offered by a private debt provider. From a public finance point of view, such a mechanism allows for a regular recycling of taxpayers' money in projects as loans get reimbursed and reinvested.

- **Loan guarantees:** Public finance tools can also unlock the financing of investments by private financial institutions through mechanisms that lower the risk for those investors, therefore creating higher leverage for the same amount of public money invested. Loan guarantees are an example of one such mechanism.

- **Public-Private Partnership:** Securing co-investment by a public sector entity would lower the amount of investment required from the shipping value chain itself. It might sometimes be preferred by public entities, as it creates an opportunity for the public funder to get potential returns on the funds that have been invested. Public co-investment can also be designed to crowd in private capital by ensuring that the public entity assumes a higher level of risk than private investors.

- **Investment tax credits:** By allowing capital expenditure related to 'first mover' projects to be claimed as tax credit, governments can create an incentive for corporate players to invest in 'first mover' projects using corporate balance sheets.

Additional public support to zero-emission operations, for instance in the form of direct or indirect subsidies to fuel costs or to staff training costs, will likely be required in addition to investment support to lower the impact of a switch to zero-emission fuels on shipping prices and therefore facilitate the absorption of the additional cost of 'green shipping' by cargo owners and end consumers.

23 https://www.eesc.europa.eu/sites/default/files/files/energy_investment.pdf

Section 3

Major cost drivers in a 'first mover' pilot: the dominance of fuel costs

The development of end-to-end commercial-scale pilots will present a completely new set of investments and operating costs for the maritime industry. There will be a cost differential at each stage of the value chain. To understand the economics of a zero-emission vessel pilot, we set out below industry-validated worked examples that illustrate the relative importance of different cost components and the effect of scale on investment and operating economics.

3.1 CAPEX in an end-to-end pilot: primarily land-based investment

The capital outlay for a 'first mover' pilot will not be split proportionally across the value chain: the majority of CAPEX for an end-to-end pilot will be related to land-based fuel production infrastructure. In the case of both green ammonia and green methanol, a large proportion of that land-based CAPEX will be attributable to the cost of electrolysers and the equipment required for ammonia and methanol synthesis. These investments in fuel production make up between 75-90% of overall capital outlay of a pilot for both fuel options considered here. The remainder of the CAPEX relates to the fuel bunkering and vessel fuel storage and engine systems. This conclusion corroborates with those of an earlier insight note published by the GMF in partnership with UMAS and the ETC[24].

Capital expenditure would be lower for a green methanol project than for a green ammonia project at small scale. The difference can be attributed to lower storage-related costs, as methanol is easier to handle than ammonia; and to lower propulsion system costs, as learning curve effects have already been achieved on dual fuel methanol engines, whereas ammonia equipment is more likely to be first-of-a-kind and purpose-made, so will not yet benefit from economies of scale. In practice though, the differences in CAPEX between the two fuel options are unlikely to make a significant difference to the total cost of 'first mover' pilots given that opportunity-specific circumstances might significantly alter project-specific costs and that CAPEX only represents a limited share of total project cost (see below). Additionally, the CAPEX differential between the two pathways reverses as scale increases, due to the methanol production process requiring a greater number of electrolysers than the ammonia production process to deliver a similar amount of marine fuel[25].

Capital expenditure for both green ammonia and green methanol is variable and increases with the scale of the pilot. In both cases, the number of electrolysers required for hydrogen production, storage tanks for bunkering, and vessels that need to be equipped with new engines and storage tanks will vary with the scale of the pilot. The only fixed cost is the cost of the bunkering vessel itself, as one vessel would be enough to serve the different potential scales of pilot projects we are considering, with different types and combinations of fuel tanks. From a per unit cost perspective, scale will therefore have limited effect on the CAPEX of a project for either a green ammonia or green methanol pilot:

- **For green ammonia**, CAPEX would vary between $240 million and $940 million depending on the scale of the pilot, with fuel production tripling and vessel costs quadrupling for a 'large-scale' projects compared to a 'small-scale' project, while bunkering costs would see a smaller increase.

- **For green methanol**, CAPEX would vary between $225 million and $945 million depending on the scale of the pilot, with both fuel production and vessel costs quadrupling in a 'large-scale' project compared to a 'small-scale' project, while bunkering costs would also see a smaller increase.

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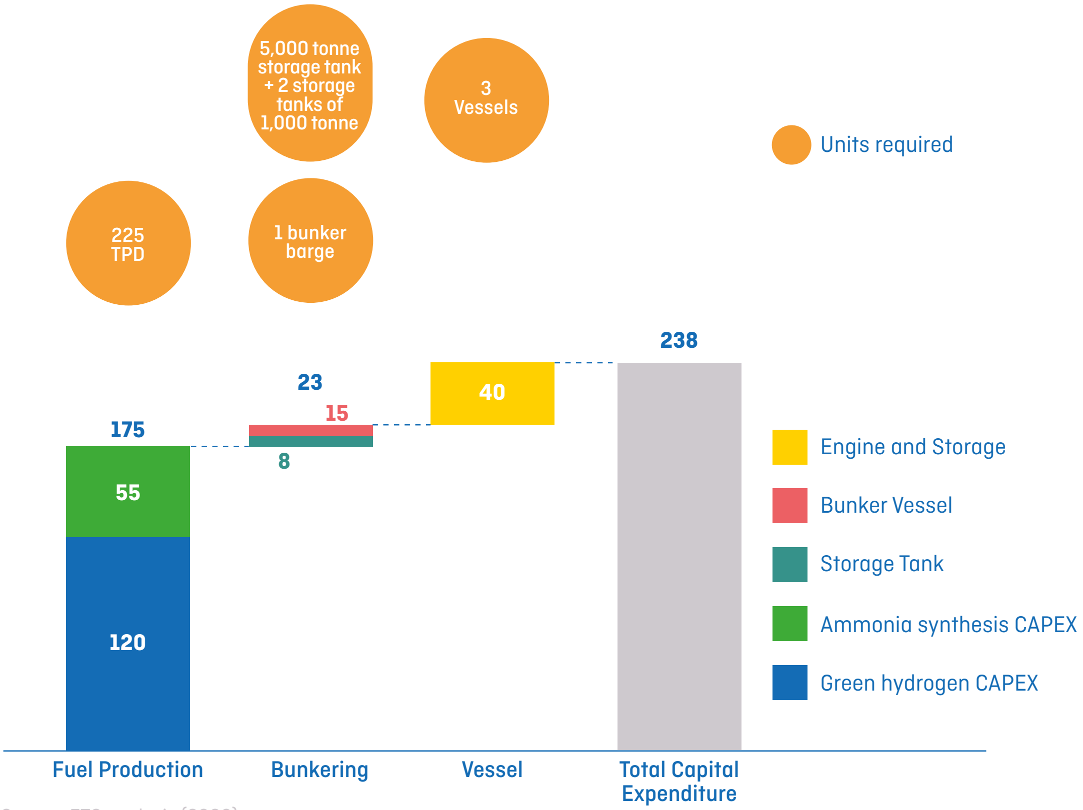
24 https://www.globalmaritimeforum.org/news/the-scale-of-investment-needed-to-decarbonize-international-shipping

25 The green methanol pathway has the potential to fully integrate renewables as a result of the operating flexibility of the methanol reactor. Lower renewable energy capacity factors will mean, however, that proportionally more electrolyser capacity is needed to service the same number of vessels.

Exhibit 6. Total CAPEX for 'small-scale' green ammonia 'first mover' project

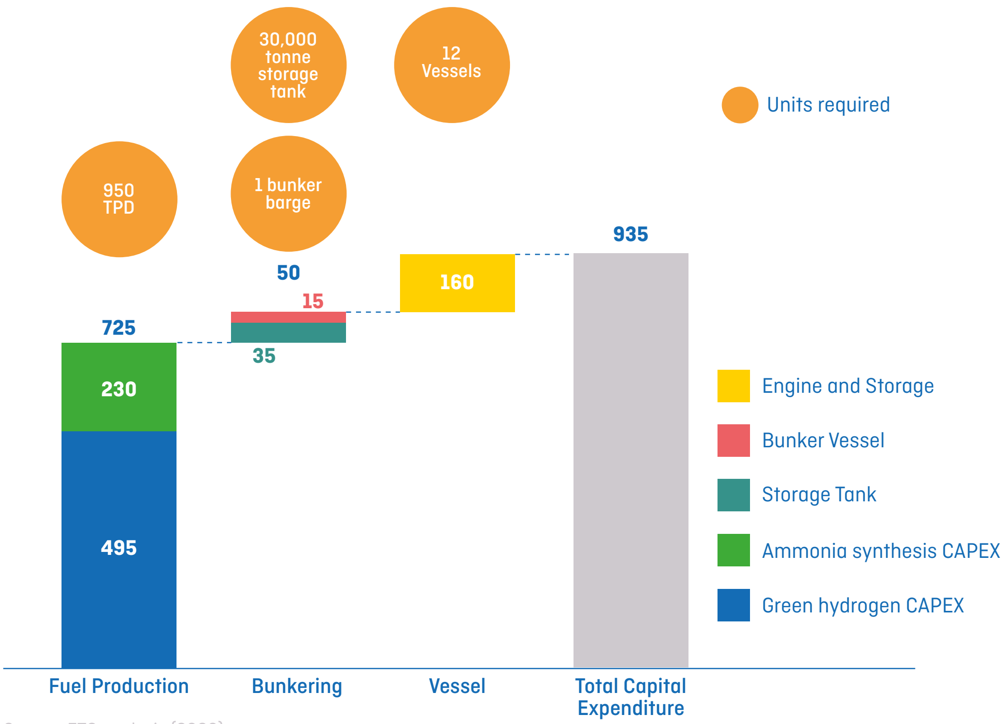
'SMALL SCALE FULL CHAIN' 225 TPD GREEN AMMONIA PILOT
Capital expenditure needed across value chain, $m



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Exhibit 7. Total CAPEX for 'large-scale' green ammonia 'first mover' project

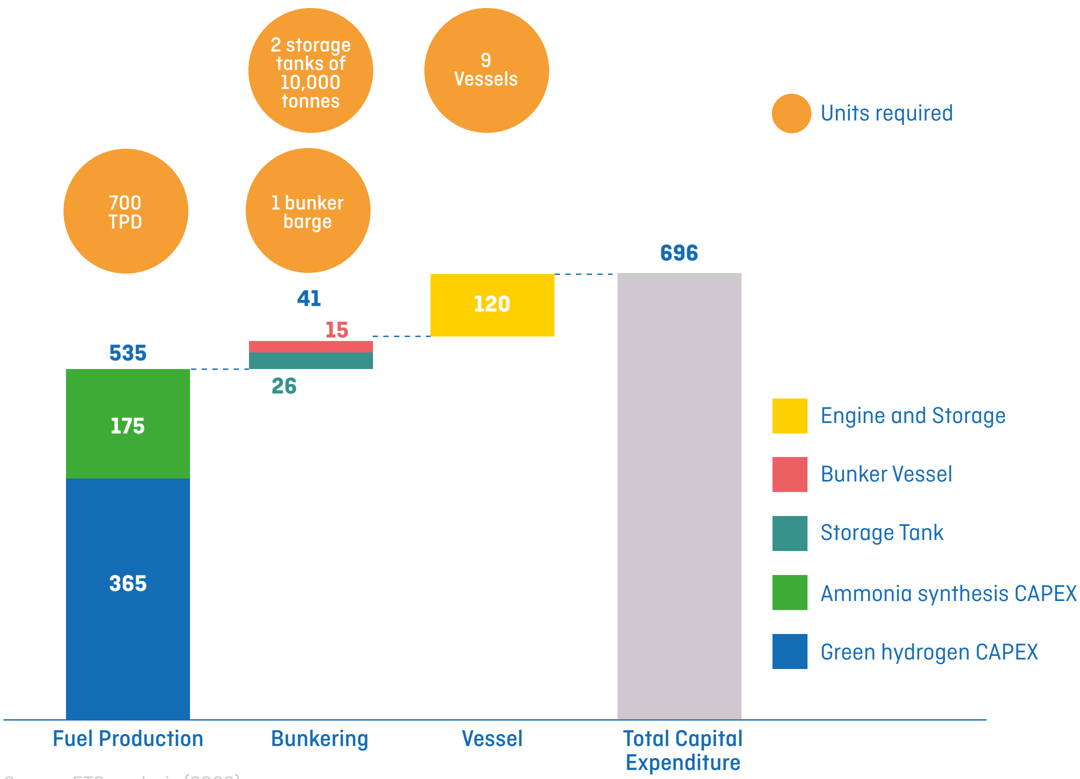
'LARGE SCALE FULL CHAIN' 950 TPD GREEN AMMONIA PILOT
Capital expenditure needed across value chain, $m



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Exhibit 8. Total CAPEX for 'reference-case' green ammonia 'first mover' project

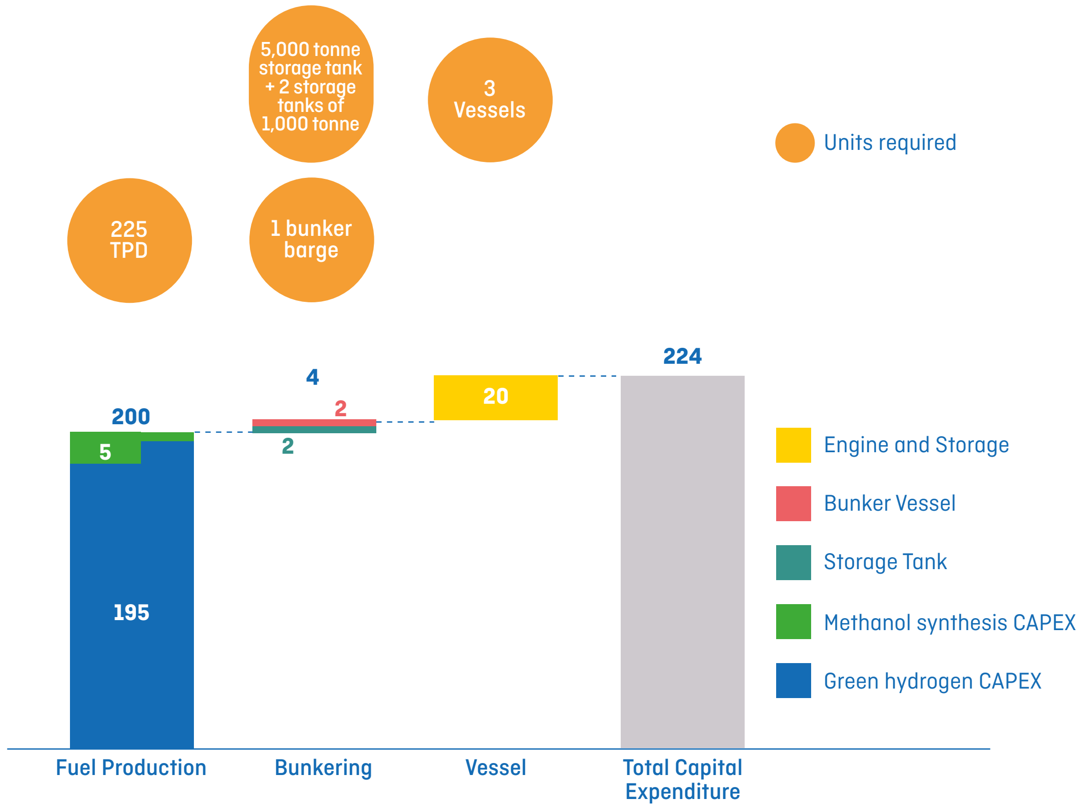
'REFERENCE CASE FULL CHAIN' 700 TPD GREEN AMMONIA PILOTCapital expenditure needed across value chain, $m



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Exhibit 9. Total CAPEX for 'small-scale' green methanol 'first mover' project

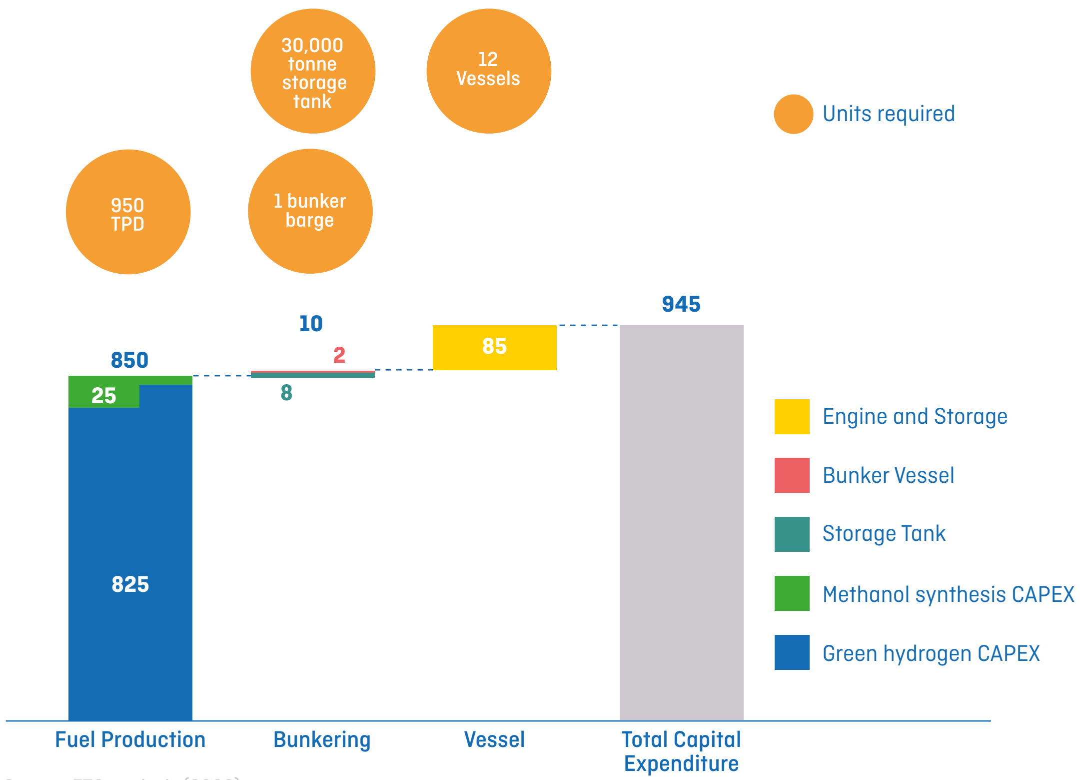
'SMALL SCALE FULL CHAIN' 225 TPD GREEN METHANOL PILOT
Capital expenditure needed across value chain, $m



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Exhibit 10. Total CAPEX for 'large-scale' green methanol 'first mover' project

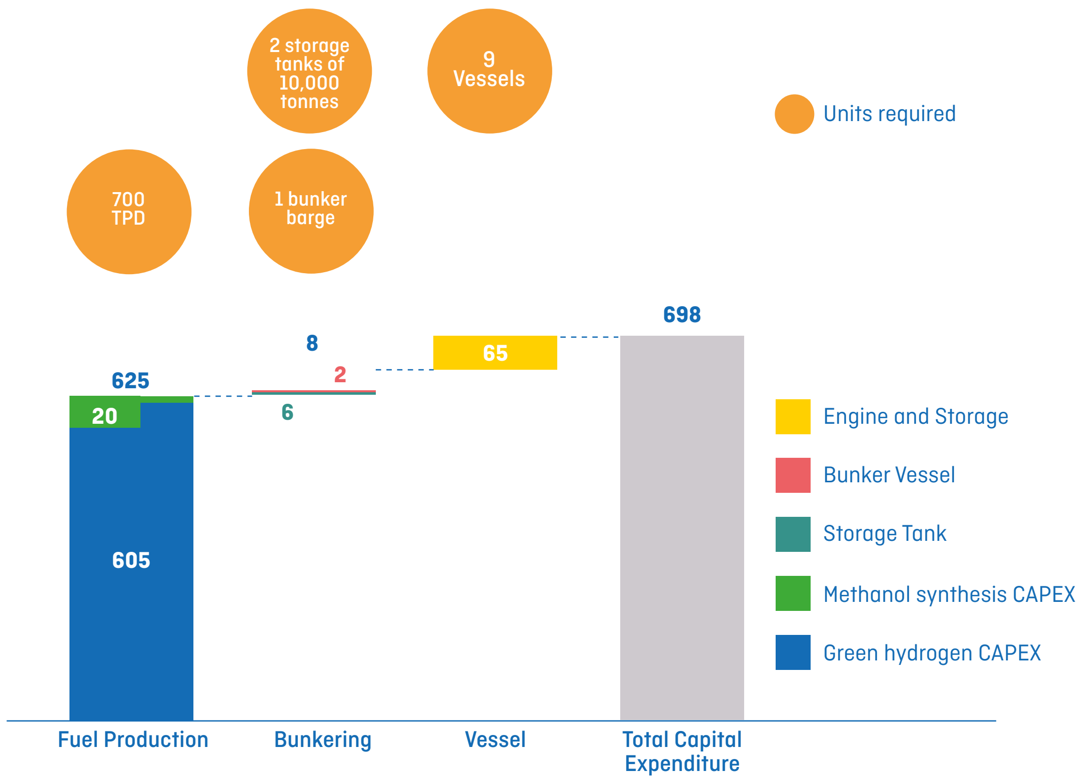
'LARGE SCALE FULL CHAIN' 950 TPD GREEN METHANOL PILOT
Capital expenditure needed across value chain, $m



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Exhibit 11. Total CAPEX for 'reference-scale' green methanol 'first mover' project

'REFERENCE CASE 'FULL CHAIN' 700 TPD GREEN METHANOL PILOT
Capital expenditure needed across value chain, $m



Source: ETC analysis (2020)
Key assumptions listed in Appendix

3.2 Total cost of an end-to-end pilot: the significance of fuel costs

While sizeable investments are required for commercial-scale pilots, especially in the fuel production infrastructure, capital outlay is, in fact, a relatively small contributor to the total cost of a pilot. The higher fuel costs cascade across the value chain to represent more than 90% of the total cost at both bunkering and vessel stages. And the energy intensity of green hydrogen production makes electricity the dominant cost driver of fuel costs for both the green ammonia and methanol routes.

- For green ammonia, around 70% of the final fuel cost relates to electricity. On a per tonne basis, the cost of green ammonia is approximately 2.5 times the cost of conventional HFO fuel[26]. Correcting for energy density means that green ammonia is around 5 times the cost of HFO today.

- The results are similar for green methanol, although the share of electricity prices in final fuel cost is slightly lower than for ammonia (60%). The methanol synthesis process also requires carbon as an input, and this CO_2 input (especially if procured from sources that truly enable zero emission over the lifecycle of the fuel) will drive up fuel costs. The total increase in fuel cost to the vessel operator will be between 5-5.5 times the cost of HFO, accounting for the lower energy density of the fuel.

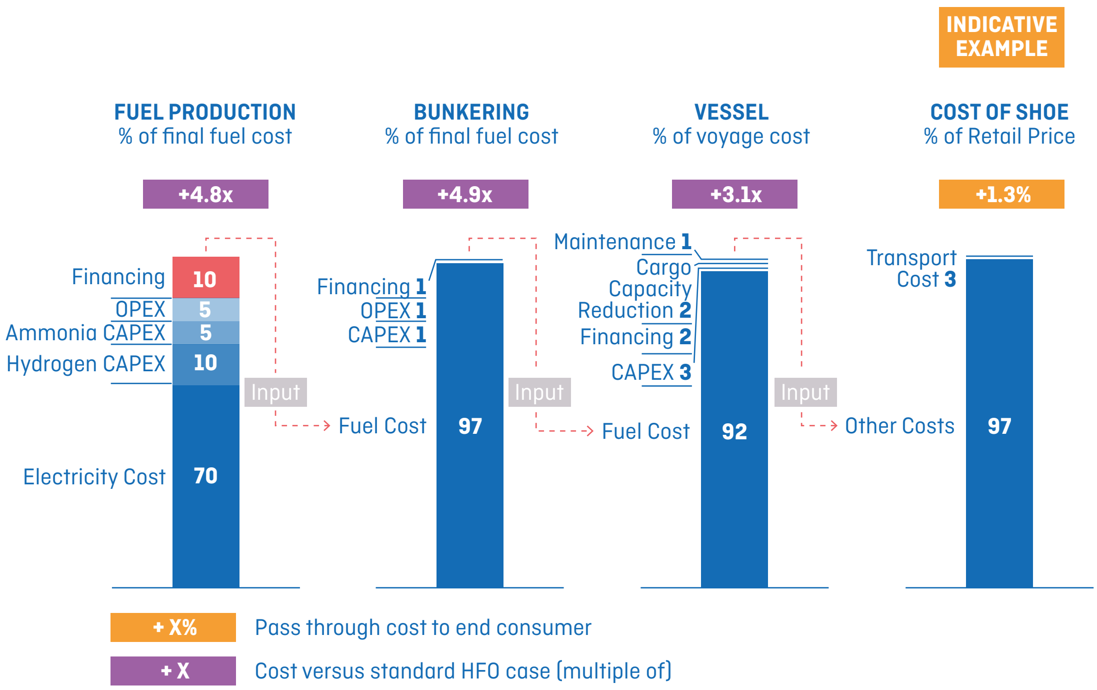
While these costs are expected to come down over time, thanks in particular to the continued decrease in renewable electricity prices and in flexibility provision to complement the variability of renewables, as well as to economies of scale and learning curve effects in hydrogen production (including reduction in CAPEX of electrolysers), this is unlikely to happen before the late 2020s and will therefore not benefit the first wave of commercial-scale pilots.

With targeted measures, it will be possible to lower costs – both CAPEX and OPEX – at each segment of the value chain, yielding significant cost reduction for end-to-end pilots overall. Sections 4 and 5 detail potential measures, which comprise both proven and novel interventions.

26 HFO price is calculated as an average across Top 20 global bunker ports for the first six months of 2020

Exhibit 12. End-to-end economics for green ammonia 'first mover' project

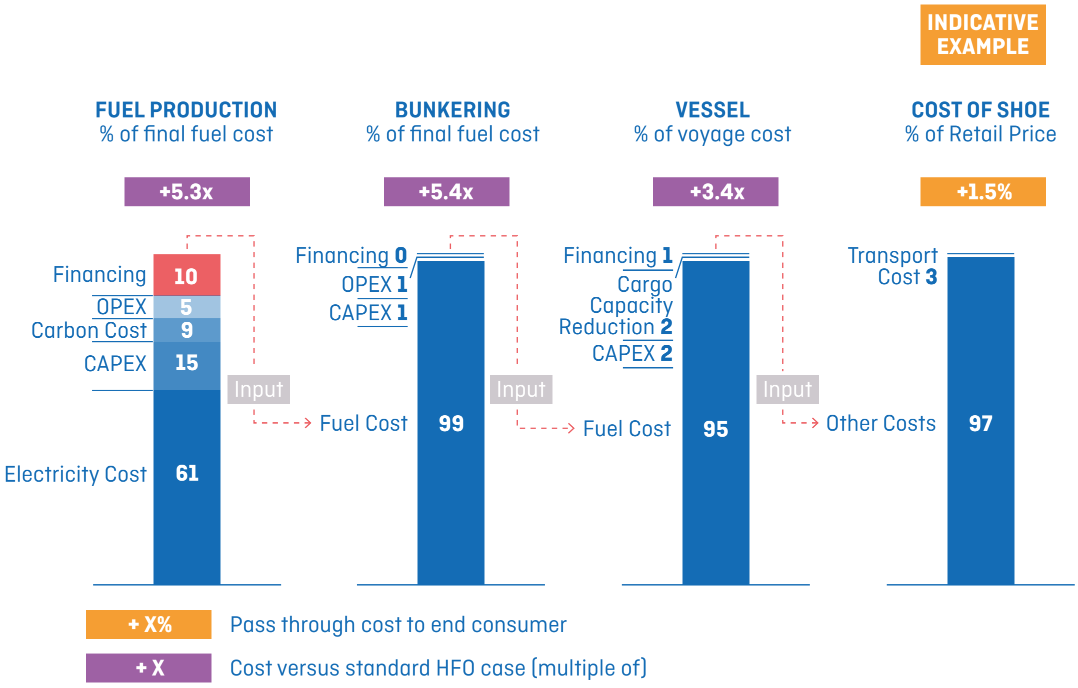
'FULL CHAIN' 700 TPD GREEN AMMONIA PILOT
Breakdown of cost at each step of the value chain



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Exhibit 13. End-to-end economics for green methanol 'first mover' project

'FULL CHAIN' 700 TPD GREEN METHANOL PILOT (w/ BECCS)
Breakdown of cost at each step of the value chain



Source: ETC analysis (2020)
Key assumptions listed in Appendix

3.3 Cost to the end consumer: a limited impact

Despite the significant cost difference of operating zero-emission vessels relative to operating with HFO – i.e. about three times more expensive for the first wave of zero-emission shipping pilots - the impact on end consumer prices would actually be relatively low. This is because shipping usually represents a very small proportion (often less than 1%) of the final retail price of consumer goods, especially high-end consumer goods. For instance, the cost increase to a $100 pair of shoes imported from halfway around the world would be less than +1.5%, regardless of the fuel option considered for the pilot[27].

This limited impact on end consumer prices suggests that the cost of decarbonisation of the maritime sector – even for the first wave of commercial-scale pilot projects – can be managed through relatively modest price increases for end-use markets and consumers. However, passing through cost to cargo owners would be difficult in a competitive global market in the absence of international regulation. To achieve that objective in the short term, first movers would need to benefit from voluntary commitments from cargo owners to absorb and pass through cost. This could be underpinned by the development of a standardised 'green shipping' offer that some market segments, in particular the high-end consumer goods manufacturing sector, could advertise to their end consumers as part of a broader strategy to reduce the carbon footprint of their products. We explore this option in further details in Section 6.

27 https://solecollector.com/news/2014/12/how-much-it-costs-nike-to-make-a-100-shoe

Section 4

How to reduce the cost of zero-emission marine fuels

Fuel costs represent more than 90% of the total cost of a commercial-scale zero-emission pilot. It is therefore the most critical cost driver to tackle, to reduce the cost and facilitate the implementation of 'first mover' projects.

4.1 Fuel cost drivers: the importance of electricity prices

For both green ammonia and green methanol fuel production, fuel production costs are overwhelmingly related to electricity costs, which account for 60-70% of total fuel cost. Additional cost drivers include:

- CAPEX related to hydrogen production, which accounts for 10-15% of fuel cost;
- Non-hydrogen-related costs, in particular synthesis equipment for ammonia production and carbon feedstock for methanol production, which account for an additional 10%; and
- The cost of capital.

Cost of electricity

Electricity represents a higher proportion of the cost for green ammonia than for green methanol. This is due to the plant operating constraints of the Haber-Bosch process[28]:

- In the absence of hydrogen storage, some proportion of higher-cost grid electricity is needed to complement cheaper variable renewable input in order to ensure continuous production of ammonia. This precludes ammonia producers from leveraging least-cost power from captive renewables for 100% of their power needs. Green methanol, in comparison, will have a lower proportion of cost attributed to electricity due to the ability of the methanol reactor to operate flexibly and therefore rely exclusively on low-cost renewables[29].
- At the same time, the fact that methanol production is likely to operate with variable electricity supply implies that production could require proportionally more electrolyser capacity to produce the same amount of fuel as an ammonia plant with electrolysers operating with higher load factors.

Project-specific economics will be highly dependent on a number of factors, including location of the pilot which dictates local renewable and grid electricity prices, availability of natural hydrogen storage options (which could reduce the need to rely on grid connection for ammonia production) and contractual terms with power providers.

28 Research is underway to enable the ammonia synthesis process to be ramped up and down efficiently , which could enable the use of intermittent renewables for green ammonia production without having to use costly battery or hydrogen storage; it is unlikely, however, that the technology will be available for first movers
29 https://cordis.europa.eu/project/id/637016/reporting

Other cost drivers

In addition to electricity prices, the following cost drivers also need to be addressed:

- Of particular importance to both fuels will be the capital costs of electrolysers. Based on 2020 market pricing, the costs can vary significantly and exhibit large variation in pricing structure, particularly in relation to the stack replacement interval. Some datapoints indicate that Chinese producers might already produce electrolysers with significantly lower CAPEX than Western producers, but the ability of fuel producers around the world to purchase this lower-cost equipment remains unclear[30].

- Non-hydrogen costs represent approximately 10% of the final fuel cost for both fuel pathways.

    - The most important non-hydrogen cost for the ammonia pathway is the CAPEX related to the Haber-Bosch synthesis process, which is technologically and commercially mature. Fundamental cost reductions to the equipment or process are not currently anticipated.

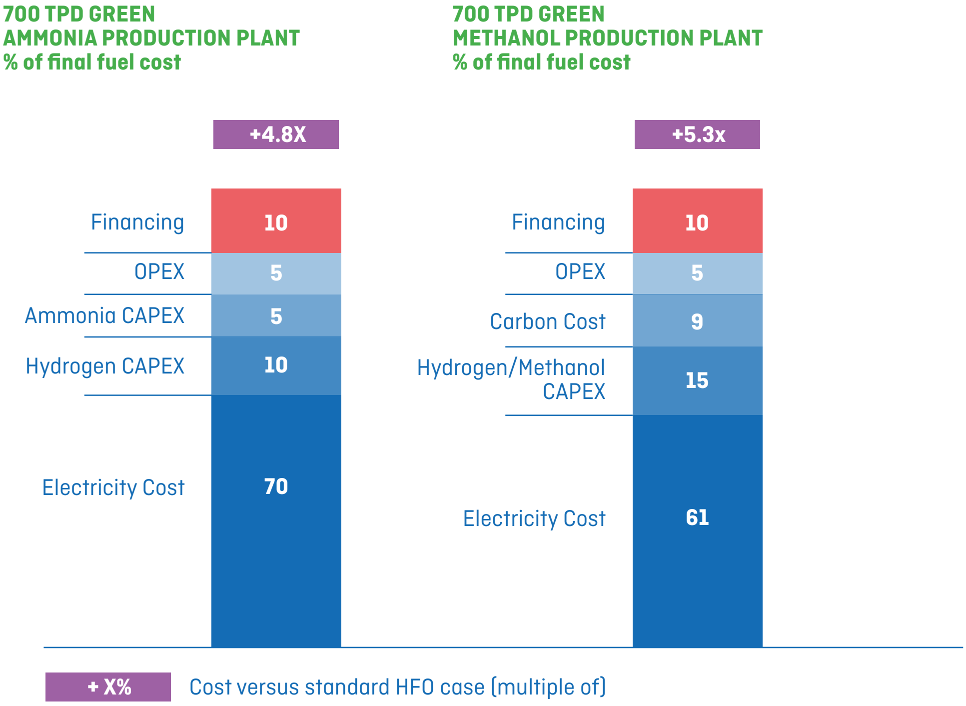
    - For the methanol synthesis process, the cost of procuring carbon feedstock is uncertain and would vary significantly depending on the source of CO_2. The cost of true zero-emission carbon feedstock sourced from direct air capture (DAC) is currently estimated at $250-320 per tonne of CO_2[31], but the technology is still at pre-commercial stage and availability of CO_2 from this source is highly uncertain before 2030. The price of CO_2 from biomass combustion varies widely depending on the end use sector[32], and transportation costs must also be accounted for. The use of CO_2 captured on the back of industrial processes might be a lower-carbon – but not zero-carbon – transitional solution, which could allow for lower cost[33] in the initial stages of deployment of methanol as a marine fuel.

- First-movers will also likely have to account for increased cost of capital because of uncertainty over the technological scalability of the production process. While the proof of concept for 'green' production exists for both green ammonia and green methanol, there are currently no medium to large scale facilities under operation. It will likely be difficult for project developers to secure funding from traditional lenders without government intervention or a significant risk premium. Balance sheet-based funding represents an option for lowering the risk premium but will be restricted to large corporations given the scale of capital required.

- The operating expenses for both fuel pathways will be similar, driven by operating and maintenance costs, as well as staff costs.

30 Hydrogen - The Economics of Production From Renewables, BloombergNEF (2019)
31 https://www.sciencedirect.com/science/article/pii/S0959652619307772
32 https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_18-March.pdf
33 https://www.globalccsinstitute.com/wp-content/uploads/2018/12/2017-Global-Status-Report.pdf

Exhibit 14. Cost drivers for green ammonia and green methanol production



4.2 Cost-lowering strategies: multiple options to access low-cost electricity

Gaining access to lower-cost electricity through location-based cost minimisation, power purchase agreements, and tax exemptions and waivers on power network charges are the most impactful cost mitigation strategies that can be pursued at the fuel production level. This single driver could reduce total cost of commercial-scale pilots by 15-20%. Reducing capital outlay by repurposing existing facilities and utilising direct public support mechanisms will also be significant levers to reduce the total cost of 'first mover' pilots.

Game Changers

Given the energy intensity of the fuel production process, **lowering electricity cost will have the largest impact on the economics of a pilot**. Access to power at $35/MWh instead of $60/MWh would reduce the cost of zero-emission fuels by 30-35%. Several 'game changing' industrial strategies and policies can be applied:

- **Location-based electricity cost optimisation**: First movers have the ability to lower electricity costs by siting fuel production activities in locations with a combination of high renewable energy potential, low industrial power prices and natural hydrogen storage:
    - Ideal locations for green hydrogen production, and therefore for the production of hydrogen-based fuels, will be areas with high renewable resource potential and supportive policy environments where the cost of renewable electricity is the lowest. Regions like Australia, Chile or North Africa, but narrower spots – for instance around areas with a high offshore wind potential – could also offer favourable conditions.

- Some jurisdictions also offer low industrial electricity rates which can reduce the cost of grid electricity for the periods when production facilities cannot utilise renewables due to variability. Regions currently known for low industrial electricity rates include the Nordics (Denmark, Sweden, Finland), some Latin American countries like Argentina and the United States among others[34].

- Finally, while man-made hydrogen storage solutions are expensive, naturally forming salt caverns provide an efficient and economical alternative. Using salt caverns to store hydrogen can reduce the need to use grid-connected electricity and lower overall electricity costs for a production facility. Regions with natural hydrogen storage availability include the Nordic region, Australia, and North Africa[35].

- **Long-term corporate PPAs**: 'First movers' can also benefit from lower electricity costs by signing long-term purchase power agreements (PPAs) with renewable energy producers which typically represent the lowest-cost power price available to a corporate buyer. The longer duration of the contract would allow zero-emission fuel producers to procure electricity at a discounted rate while also ensuring price certainty for a major cost component of their product.

- **Exemptions and waivers on grid connected electricity**: Governments also have a role to play to support zero-emission fuel producers and through them the full shipping value chain. Two major types of exemptions can lower the cost of grid connected electricity for fuel production facilities:

    - Almost all governments impose taxes and levies on electricity, which can, depending on the region, represent as much as 50% of final power price[36]. The cost of grid connected electricity can be lowered significantly if fuel production facilities are exempted from paying these taxes. The precedent for similar exemptions exists for energy-intensive industries across most of the developed world[37].

    - There is precedent in many countries for allowing 'grid exemptions' for key or strategic industrial-scale projects. Electricity network costs can represent as much as 25% of final electricity price[38].

In addition to lowering electricity cost, zero-emission marine fuel producers have the opportunity to reduce their capital outlay by:

- **Re-purposing existing infrastructure for low-emission fuel production:** By re-purposing an existing ammonia plant (which would likely have served the fertiliser market in the past) re-using the existing assets for ammonia synthesis (and therefore foregoing new ammonia synthesis investment), while replacing the 'grey' hydrogen production assets on site by an electrolyser for 'green' hydrogen production, a first mover could reduce fuel production CAPEX by as much as 33% in comparison to an entirely greenfield green ammonia plant. Precedent for the process exists, as the process is already being implemented at small scale by industry[39].

34 https://www.iea.org/reports/energy-prices-2020
35 http://www.energnet.eu/sites/default/files/3-Hevin-Underground%20Storage%20H2%20in%20Salt.pdf
36 https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_205&lang=en
37 https://www.edfenergy.com/large-business/buying-energy/energy-intensive-industries
38 https://www.enerdata.net/about-us/company-news/energy-prices-and-costs-in-europe.pdf
39 https://arena.gov.au/projects/yara-pilbara-renewable-ammonia-feasibility-study/

- **Acquiring equipment – and electrolysers specifically – from least-cost international vendors:** This strategy could result in significant fuel production CAPEX reduction. Based on quoted market prices, electrolyser prices in China are 50 to 80% lower on a per kilowatt basis than comparable prices in Europe[40]. This difference is the result of relatively lower labour and materials costs and higher production utilisation rates. Strategies for accessing the least-cost prices could include reverse auctions to source equipment pricing from international vendors.

Quick Wins

In addition to the potential game changers described above, **public support mechanisms** such as direct grants specifically dedicated to 'first movers' entering the zero-emission marine fuel market can lower investment requirements at a crucial step of the value chain, which defines costs for zero-emission shipping pilots end-to-end. Specific mechanisms like concessional/preferential loans and loan guarantees can also reduce interest rates and help crowd-in private capital to finance the necessary capital expenditure at fuel production level. Multi-party risk sharing agreements with multiple parties jointly guaranteeing a project can also reduce the probability of default/non-payment of loans from a lender's perspective with precedent existing in the form of joint ventures between early generation wind power producers[41].

Transitional Quick Wins

For the purpose of testing the reliability of new marine fuels throughout the shipping value chain, there might be a case for **a transitional use of ammonia and methanol produced from "blue hydrogen"** (i.e. from gas reforming combined with carbon capture) **or even from "grey hydrogen"** (i.e. high-carbon conventional hydrogen), which would currently be respectively 25% and 40% cheaper[42] than "green hydrogen" from renewable power electrolysis. However, such use of fossil-fuel derived grey hydrogen should be clearly time-bound (e.g. 1-2 years) and only serve as an initial step before a transition to "green" fuels.

Similarly, for green methanol pilot projects, carbon feedstock costs could be significantly reduced through **sourcing from least-cost capture facilities**, which rely on fossil fuel combustion. CO_2 from those industrial sources could be as much as 70% cheaper than CO_2 from biomass combustion and would also be more readily available as the number of carbon capture facilities operating on fossil plants is higher than those operating on biomass-based processes[43]. This choice would result in the production of a lower-carbon – but not zero-carbon – methanol.

High-Hanging Fruits

Finally, the shipping industry should seize on the opportunity to participate in **industrial clusters**, in particular hydrogen clusters, currently being developed across several regions of the world. This model brings together zero-emission energy producers as well as various energy-consuming markets across the transport, industry and sometimes residential heating sectors that they can serve. Through cross-sectoral collaboration, energy producers can generally achieve CAPEX reductions (through bulk pricing and engineering, procurement, and shared infrastructure construction), reduce offtake risks through a diversification of potential markets beyond shipping, and secure lower electricity costs through

40 Hydrogen -The Economics of Production From Renewables, BloombergNEF (2019)
41 https://www.swissre.com/dam/jcr:0bb55d9a-68ba-4997-aefb-5ade2c07dc4f/EIU_SwissRe_ManagingRiskRenewableEnergy_Nov11.pdf
42 Hydrogen - The Economics of Production From Renewables, BloombergNEF (2019)
43 https://www.globalccsinstitute.com/wp-content/uploads/2018/12/2017-Global-Status-Report.pdf

access to high-volume industrial power pricing[44]. Whilst such clusters represent a complex set of commercial relationships, the capital and operating expense benefits for fuel producers could potentially reduce zero-emission fuel costs for zero-emission shipping pilots by up to 20%.

Implementing the game changer and quick win mechanisms described above could result in a 40% reduction in electricity prices, while CAPEX could potentially be reduced by 25-50%. The cost of capital would also be lowered by as much as 60%. Once combined, **such measures could see zero-emission marine fuel costs reduced to 2-2.5 times relative to the cost of HFO** on an energy content basis, instead of a factor of 5 in the absence of such cost-reductions strategies.

44 https://orsted.com/en/media/newsroom/news/2020/05/485023045545315

Exhibit 15. Quantification of cost mitigation strategy for Green Ammonia pilot at fuel production segment

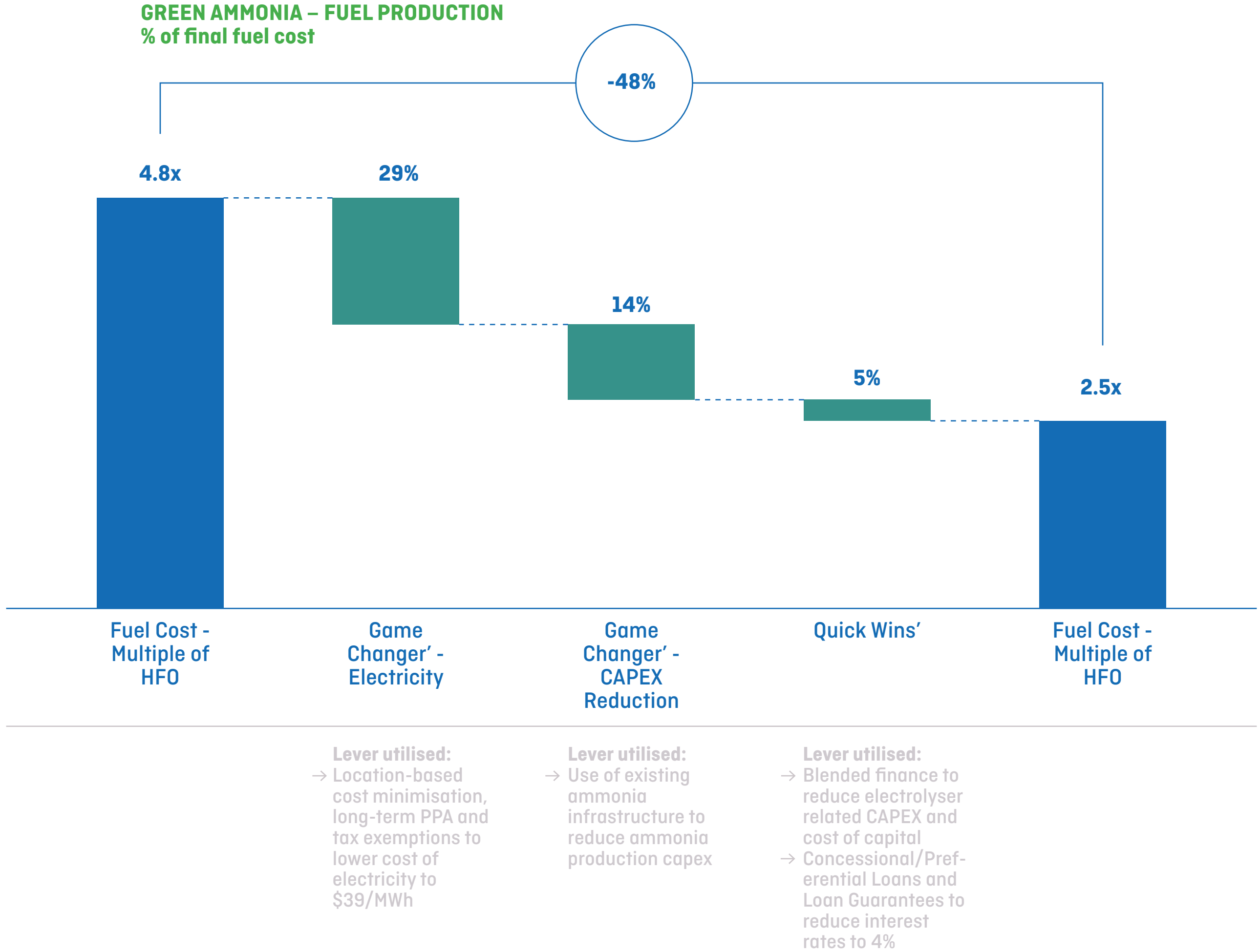
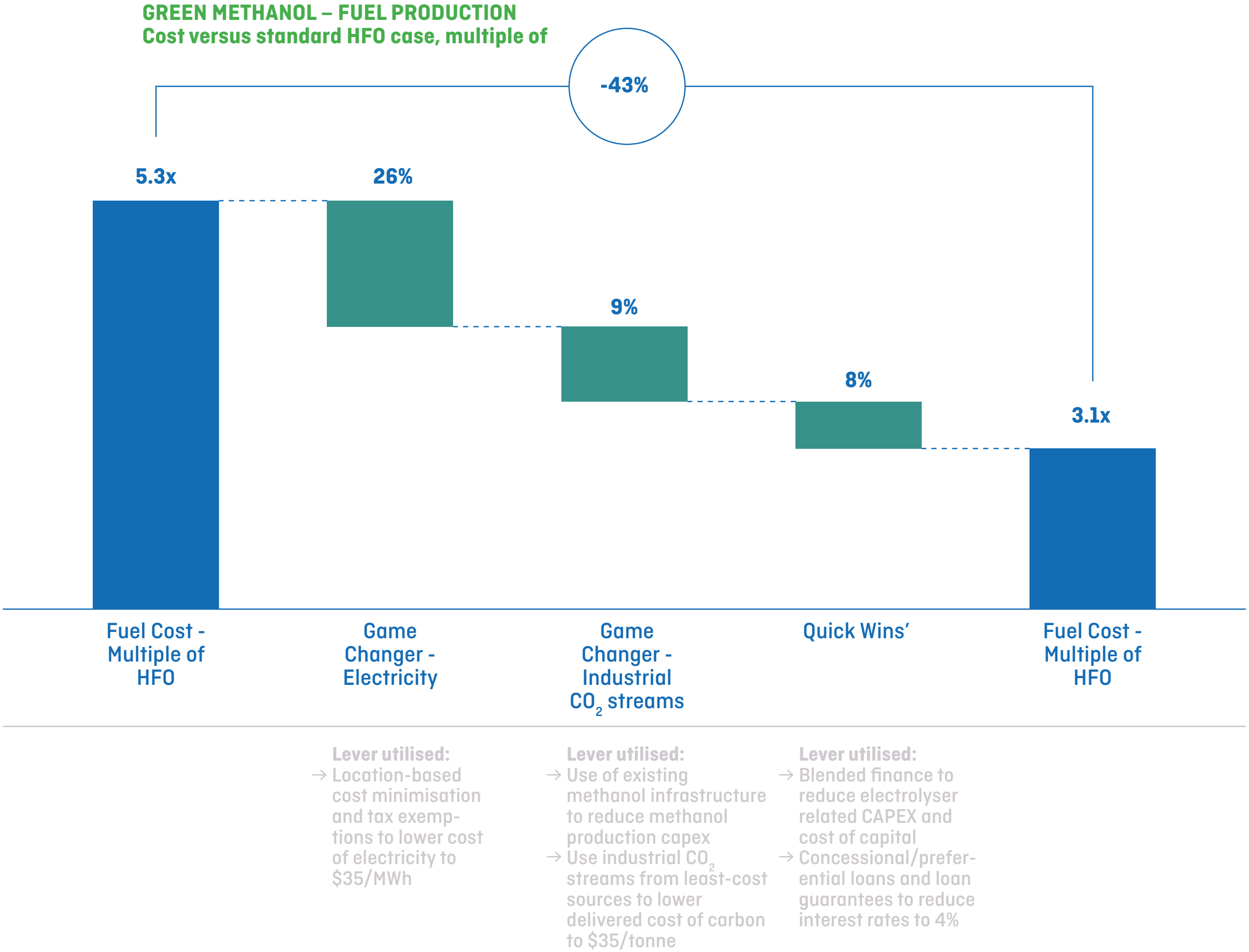


Exhibit 16. Quantification of cost mitigation strategy for Green Methanol pilot at fuel production segment[45]



45 Electricity price for green ammonia includes percentage of power procured through grid connected electricity as compared to green methanol which assumes use of renewables only.

Section 5

How to reduce costs at bunkering and vessel levels

While zero-emission fuels are the dominant cost driver for an end-to-end zero-emission pilot, there are additional costs at the bunkering and vessel operating levels of the value chain that are significant for the stakeholders involved and could be prohibitive if not addressed – potentially preventing the development of pilots. Targeted investment support for bunkering suppliers and vessel owners/operators will therefore likely be required to support pilot project development.

5.1 Reducing bunkering costs through repurposing and public support to investment

Key cost drivers beyond fuel at bunkering level

Beyond fuel, the dominant cost for bunkering suppliers involved in zero-emission pilots is the on-shore storage tank and the bunker vessel CAPEX, as well as the related cost of capital – which jointly represent up to 50% of their non-fuel costs. These costs are significantly higher for an ammonia pilot than for a methanol pilot, given the greater technical challenges related to ammonia storage: they would amount to roughly $600,000 per year for a medium-sized methanol pilot versus $3.5 million per year for a similar-size ammonia project.

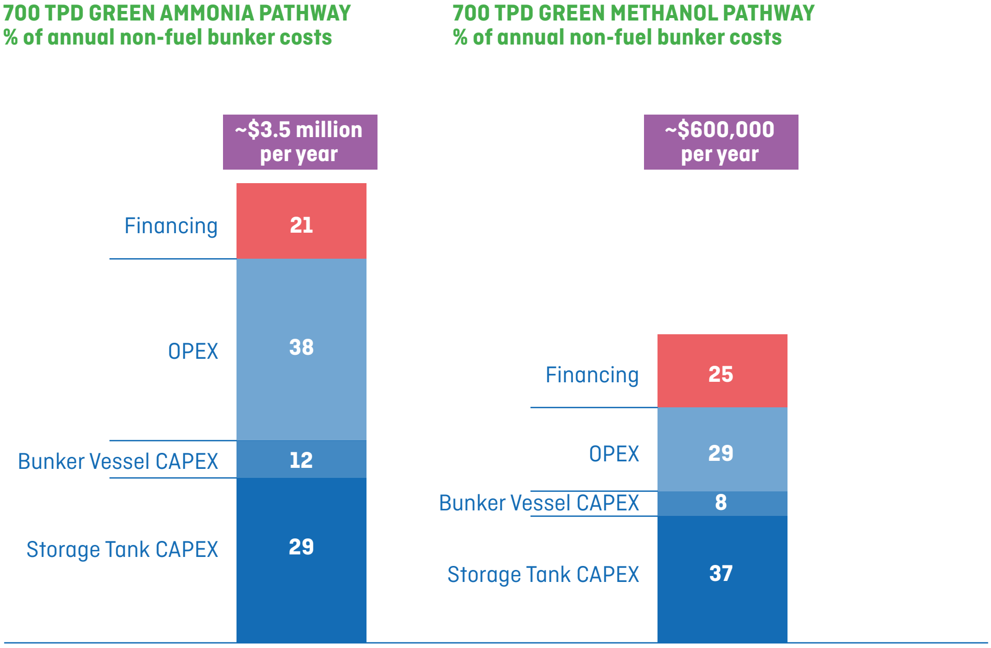
- **On-shore storage CAPEX:** The need to hold ammonia in a liquified stage – which can be done through compression or refrigerated storage – makes ammonia storage tanks more expensive than traditional storage containers. By contrast, methanol can be stored in traditional HFO facilities, with minor retrofits to account for corrosion. As such, the cost of storage is comparatively lower at the bunkering stage for a methanol 'first mover' pilot than for an ammonia one.

- **Bunker vessel CAPEX:** The higher cost of storage applies to ammonia bunker vessels as well. In addition, it is quite difficult to retrofit HFO bunker vessels with refrigerated storage tanks. An ammonia-based 'first mover' pilot would, therefore, require either the commissioning of a specialised refrigerated bunker barge or the acquisition of an existing small-scale ammonia tanker that could be repurposed as an ammonia bunker vessel. Comparatively, the similarities in physical properties between methanol and HFO make it relatively simple for a traditional bunker vessel to be retrofitted for a methanol-based pilot.

- **Financing costs:** Financing costs will also likely be greater for bunkering suppliers involved with ammonia pilots due to comparatively higher toxicity levels and greater perceived safety risks, although the prevalence of ammonia terminals at most major ports could mitigate this risk and enhance the confidence of debt providers.

- **OPEX:** Finally, operating expenses for both ammonia and methanol bunkering suppliers largely consist of maintenance and upkeep of the storage tanks and bunker barge, as well as staff training costs for the handling of new fuels. The operating and maintenance costs of an ammonia bunker barge are forecast to be higher than for methanol due to the greater complexity of the refrigerated storage systems. Training costs are also likely to be higher to ensure that employees are able to safely handle ammonia. Additionally, ammonia storage tanks have higher energy requirements during operation due to the requirements of the compression/storage process, resulting in substantial additional electricity costs.

Exhibit 17. Annual non-fuel bunker costs for medium sized green ammonia and methanol pilot project



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Cost-lowering strategies at bunkering level

The single most effective measure to reduce costs at bunkering level is to lower storage tank and bunker vessel CAPEX, as well as lower the cost of capital and de-risk private investment to facilitate the financing of the onshore and offshore equipment. Accordingly, Game Changers at bunkering level all relate to investment:

- **Utilising existing infrastructure:** The most impactful mechanism to reduce CAPEX for a bunkering supplier is the repurposing and retrofitting of existing storage facilities and bunker vessels. While this is the default assumption for the green methanol fuel pathway, it can also be applied to green ammonia. Most major global ports have ammonia terminals with existing storage facilities. Repurposing an underutilised facility with the valves, hoses, and pumps needed to turn it into a bunkering facility could result in annual cost savings of 50% for a bunkering supplier. Additionally, repurposing and retrofitting a small ammonia tanker to be used as a bunker barge could reduce the need for a bunkering supplier to make a significant investment in a new ammonia bunker vessel.

- **Using truck to ship fuelling:** While it is likely not necessary for the green methanol pathway, using the truck to ship fuelling method can help bunkering suppliers avoid making a costly investment in a bunker vessel and reduce costs by approximately 25%. Truck to ship refuelling allows a vessel to be refuelled by several tanker trucks which transport the marine fuel from the land-based storage tank to the shore and then load the fuel onto the vessel using specialised equipment. Precedent for the use of truck to ship fuelling has been established by LNG ships and is likely to be easily replicable for green ammonia.

- **Direct grants, blended finance mechanisms and co-investment models** can be effective mechanisms to support bunkering suppliers participating in commercial-scale pilots by splitting total investment amounts across multiple parties. For bunkering suppliers, port authorities may act as a natural partner through public private partnerships to jointly invest in zero-emission bunkering assets, especially onshore infrastructure[46]. Zero-emission fuel providers could also be interested in co-investing in bunkering as this would enable them to play a more active role in creating a market for themselves in the shipping sector. Finally, while financing costs could be significant for bunkering suppliers (between 20-25% of annual non-fuel costs), interest rates can be reduced thanks to the range of public investment support mechanisms mentioned in Section 2 such as concessional/preferential loans and loan guarantees, while tax investment credits on bunkering equipment can also provide potential indirect incentives on CAPEX. It will be important for such support mechanisms to extend to both new and retrofitted investments.

These different cost-lowering mechanisms will not make a profound difference on the overall pilot economics, representing a potential reduction of 1-5% of total pilot cost. However, from the perspective of bunkering suppliers faced with major investments in long-lasting assets, avoiding and defraying costs will be key to progressing the first wave of pilot projects.

46 https://www.mpa.gov.sg/web/portal/home/maritime-singapore/green-efforts/maritime-singapore-green-initiative

Exhibit 18. Quantification of cost mitigation strategy for Green Ammonia pilot at bunkering segment

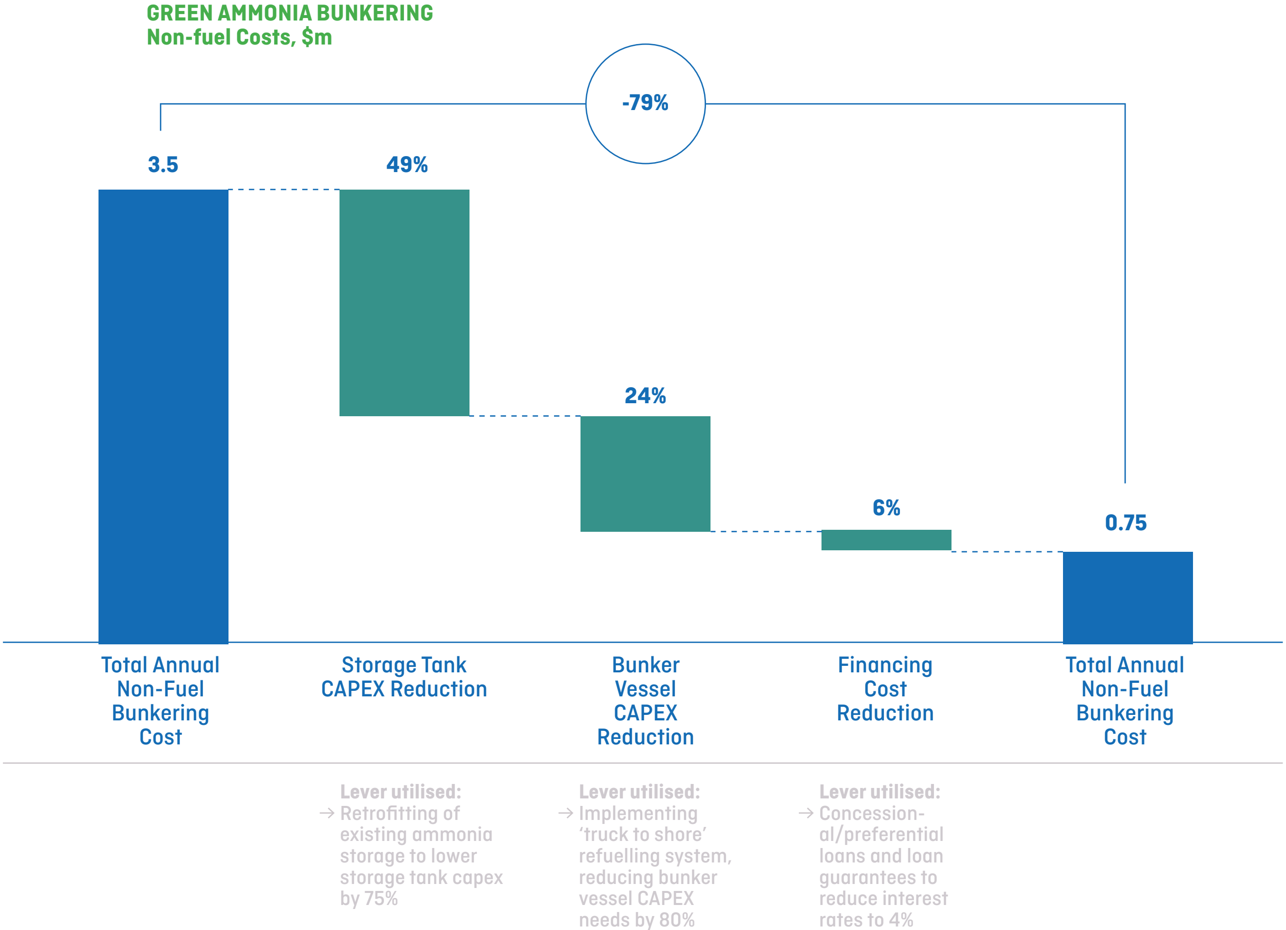
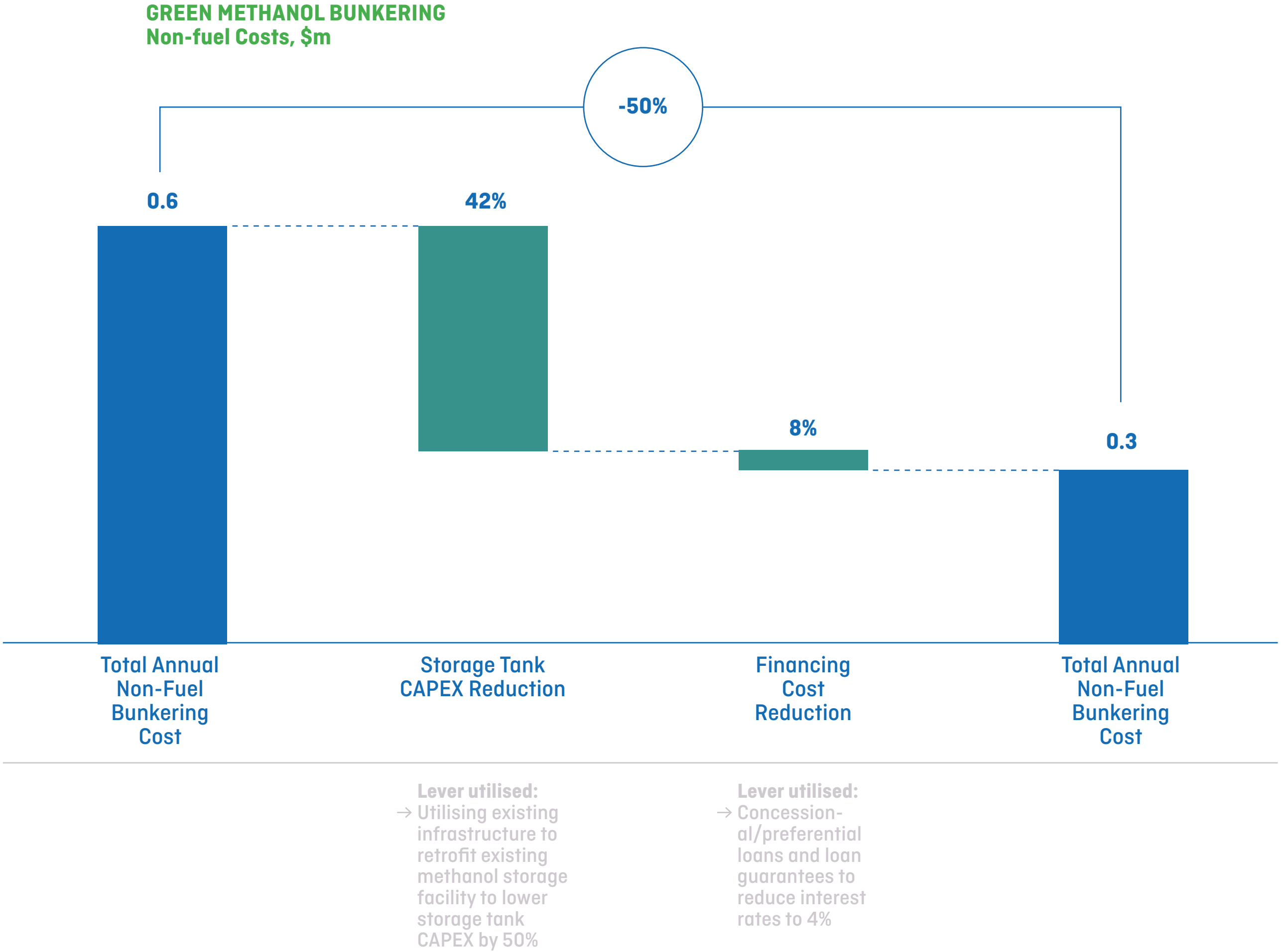


Exhibit 19. Quantification of cost mitigation strategy for Green Methanol pilot at bunkering segment



5.2 Reducing costs for vessel owners and operators through repurposing and public support to investment

Key cost drivers beyond fuel at vessel level

At the level of the vessel, non-fuel costs related to the shift to zero-emission fuels comprise of engine and storage costs (and related financing costs), cargo capacity losses, and new operating expenses (for instance related to training of staff for the handling of new fuels). Overall, additional CAPEX and associated financing costs could represent up to 60-70% of non-fuel voyage costs. Similarly to what we have observed at bunkering level, the relative technology maturity of methanol propulsion systems and the storage requirements of ammonia will result in higher vessel costs for an ammonia pilot than for a methanol pilot, although costs will remain in the same order of magnitude for both fuel options: they would amount to roughly $900,000 per year for a methanol-fuelled feedermax containership versus $1.3 million per year for a similar-sized ammonia-fuelled vessel.

Specific cost drivers include:

- **Engine and storage CAPEX:** It is likely that engine and storage costs will be the largest non-fuel cost for a green ammonia 'first mover' pilot due to the first-of-a-kind nature of the technology. While cost reductions can be expected through learning curve effects, 'first movers' will have to incur initially higher costs. The need for a specialised fuel storage system to store liquid ammonia will also lead to higher costs for those vessels. In comparison, the commercial availability of the propulsion systems and the relative ease of retrofitting conventional engine and storage system will result in comparatively lower vessel related costs for green methanol pilot projects. A methanol propulsion system will still cost approximately $3 million more than a standard HFO engine[47].

- **Financing cost:** The use of a first-of-a-kind propulsion system will almost certainly result in a higher cost of capital for green ammonia pilots. Comparatively, the established technological reliability of the methanol propulsion system will likely be reflected in a lower comparative cost of capital.

- **Reduction of cargo capacity:** Due to lower energy density, green ammonia and methanol pilot projects will require at least twice the volume of fuel, relative to HFO. To account for the increased fuel consumption, additional fuel storage facilities will be required, which will reduce the amount of cargo that can be carried by a 'first mover' vessel by approximately 5%[48] (and therefore impact the vessel's revenue-making potential). New vessels designs can reduce potential impact on cargo carrying capacity, but are unlikely to be available for 'first movers' in the next five years. As a result, a meaningful proportion of the non-fuel costs for a 'first mover' will likely represent this lost revenue.

- **OPEX:** In addition to increased operating and maintenance costs, the potential toxicity of ammonia will result in higher crew training costs. While methanol is corrosive, its lower toxicity level can be expected to be less demanding in terms of specialised crew training.

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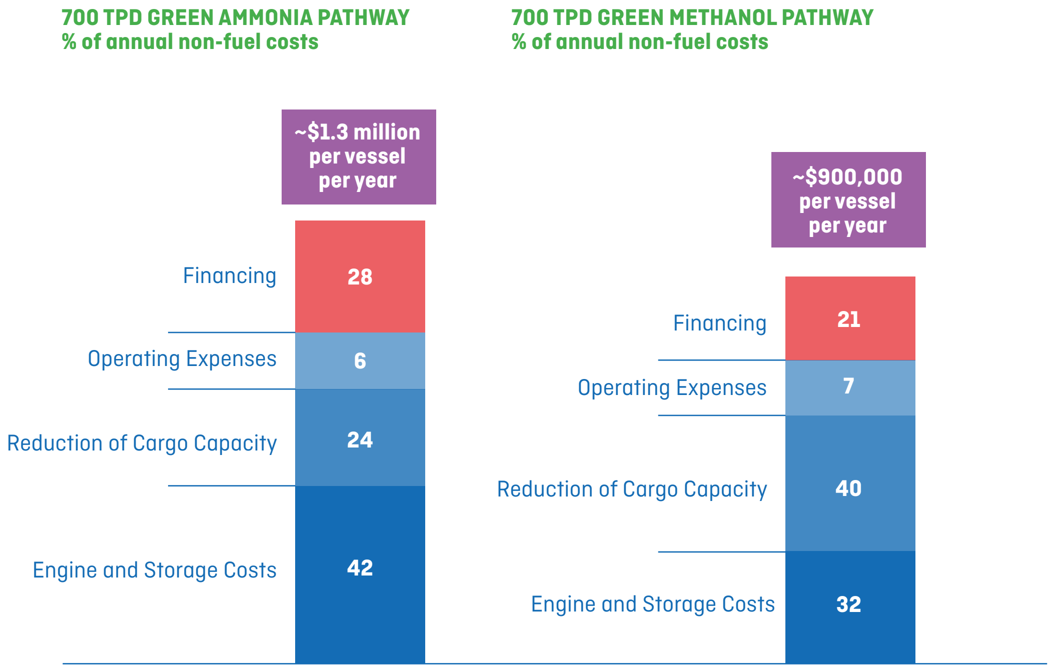
47 https://marine.man-es.com/docs/librariesprovider6/test/5510-0196-01_18-1039-man-es_costs-and-benefits-l4_web.pdf?sfvrsn=72a018a2_38
48 https://www.mdpi.com/2077-1312/8/3/183

Exhibit 20. Annual non-fuel voyage costs for medium sized green ammonia and methanol pilot project



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Cost-lowering strategies at vessel level

Games Changers at the vessel level will be aimed at reducing the CAPEX requirements of vessel operators/owners, which could amount to 50-70% of non-fuel costs, through both government support and cost sharing with other actors in the value chain. Potential Quick Wins for pilots will involve securing public support mechanisms to reduce operating expenses, especially one-off crew training costs while repurposing existing ammonia or methanol tanker vessels (rather than using containerships) could represent an Extra Opportunity.

Game Changers

Governments can facilitate the necessary capital expenditures through different forms of **targeted public support to investment** dedicated to vessel owners and operators. This public support should be particularly focused on the retrofitting of zero-emission engines and fuel tanks on existing deep-sea vessels. Although significant for individual ship owners, total amounts to cover 50% of the cost of new equipment for 10 pilots would not be higher than $30-70 million in total. Vessel operators/owners that have strong links with key governments interested in the decarbonisation of the maritime sector are most likely to benefit from direct support to investment. In parallel, a number of non-governmental stakeholders could play a key role in providing a similar type of financial support to vessel owners and operators operating from other regions or under different flags, including development banks, as well as philanthropic funders (including corporate foundations from major consumer good companies that have a particular interest in the decarbonisation of freight) and impact investors such as the Breakthrough Energy Coalition.

For the first wave of commercial-scale pilots, which aim to prove the operational reliability of new engines and fuel tanks when operating on commercial deep-sea routes, **equipment manufacturers, ship manufacturers and zero-emission marine fuel producers could also have an interest in co-investing** in on-ship equipment, following a similar model to that described at bunkering level. This would enable those different stakeholders to share costs and risks – and could be combined with offtake agreements as described in Section 6. Importantly, it would enable manufacturers and fuel producers to gain privileged information on how fuels and equipment sustain commercial-scale operations, and build on this knowledge to push their comparative advantage.

Quick Wins

In addition to supporting investments, **governments could also decide to financially support some of the extra operating cost** faced by 'first movers', in particular one-off costs like the re-training of the workforce participating in the pilots with regards to safety and handling of zero-emission fuels. Time-bound fuel subsidies for participants in the first wave of commercial-scale pilots may be envisioned, but would likely be more difficult to establish, as financial implications for public authorities could become difficult to manage as soon as zero-emission shipping starts scaling up.

High-Hanging Fruits

Although direct fuel subsidies for zero-emission marine fuels are unlikely to be implemented in national jurisdictions, given the international and fragmented nature of the shipping industry, proposals for **a global carbon levy and feebate system** to subsidise zero-emission fuels appear to gain traction. Such a system may initially be tested on a voluntary basis. It would, however, reach maximum impact if scaled up under the auspices of the IMO. A proposal developed by industry[49] suggests a carbon tax of $250-300 per tonne of CO_2 levied on shipping fuels, with the funds primarily re-routed to support vessel operators using zero-emission fuels. While the system would catalyse the decarbonisation of international shipping, implementation is difficult due to the fragmented nature of the sector. The passing of 'IMO 2020'[50] provides a hopeful signal that the maritime sector is capable of quickly adapting to stringent environmental regulations. A global carbon levy and feebate system could therefore be in the realm of possibility. If this type of policy was put in place, the costs related to zero-emission shipping, including CAPEX, could possibly be brought down for ship operators regardless of their flag.

49 https://www.trafigurainsights.blog/responsible-sourcing/time-for-a-carbon-levy-on-shipping-fuel/
50 IMO regulation to reduce sulphur oxides (SOx) emissions from ships

Extra Opportunity

Commercial-scale pilots developed with **ammonia or methanol tankers** rather than containerships could benefit from a slight cost advantage when it comes to vessel CAPEX, as they could circumvent costs related to the fuel storage system, while also avoiding costs related to training of crew. Using tankers rather than containerships for pilots could also have the additional advantage of lowering the complexity of a 'first mover' pilot, if a vertically integrated company is both producing and transporting the fuel. As discussed in Section 1, however, tankers' trade routes are more unpredictable than containership trade routes and are likely to operate with "grey" ammonia or methanol.

Exhibit 21. Quantification of cost mitigation strategy for Green Ammonia pilot at vessel segment

'FULL CHAIN' 700 TPD GREEN AMMONIA PILOT
otal voyage cost, $m

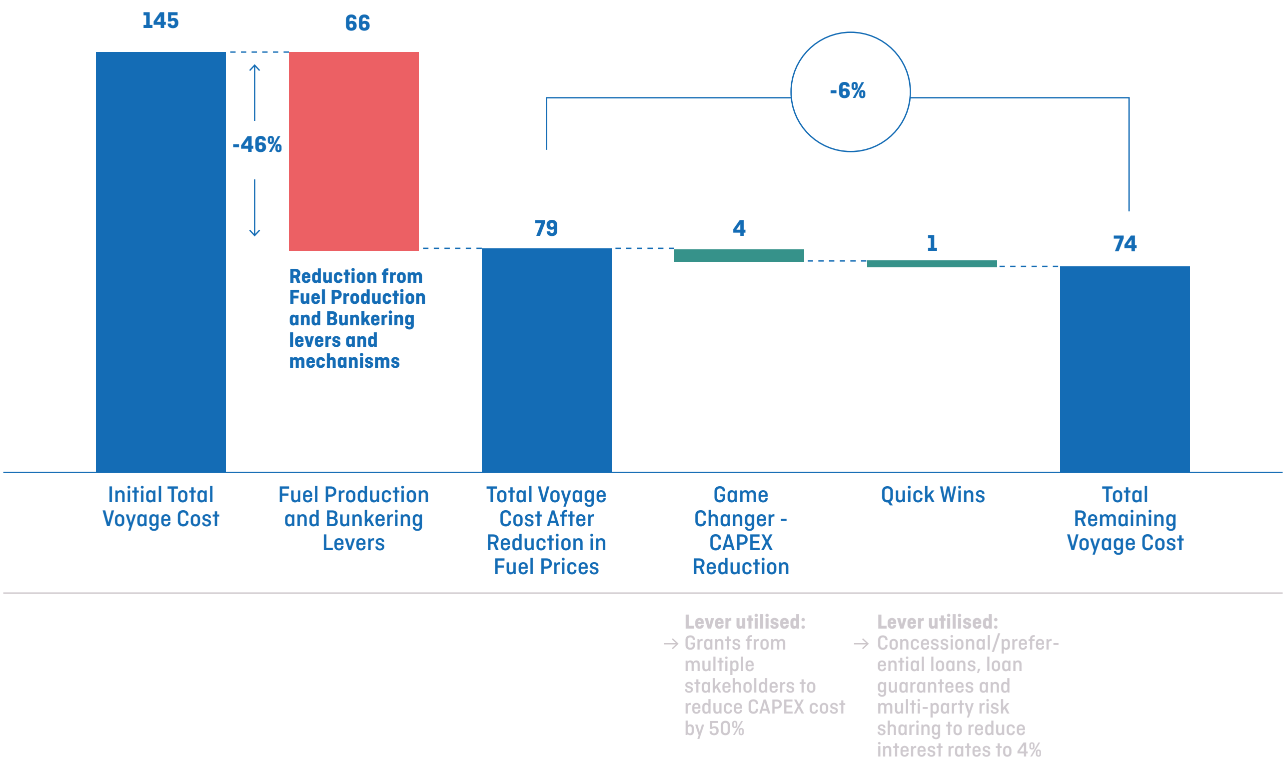
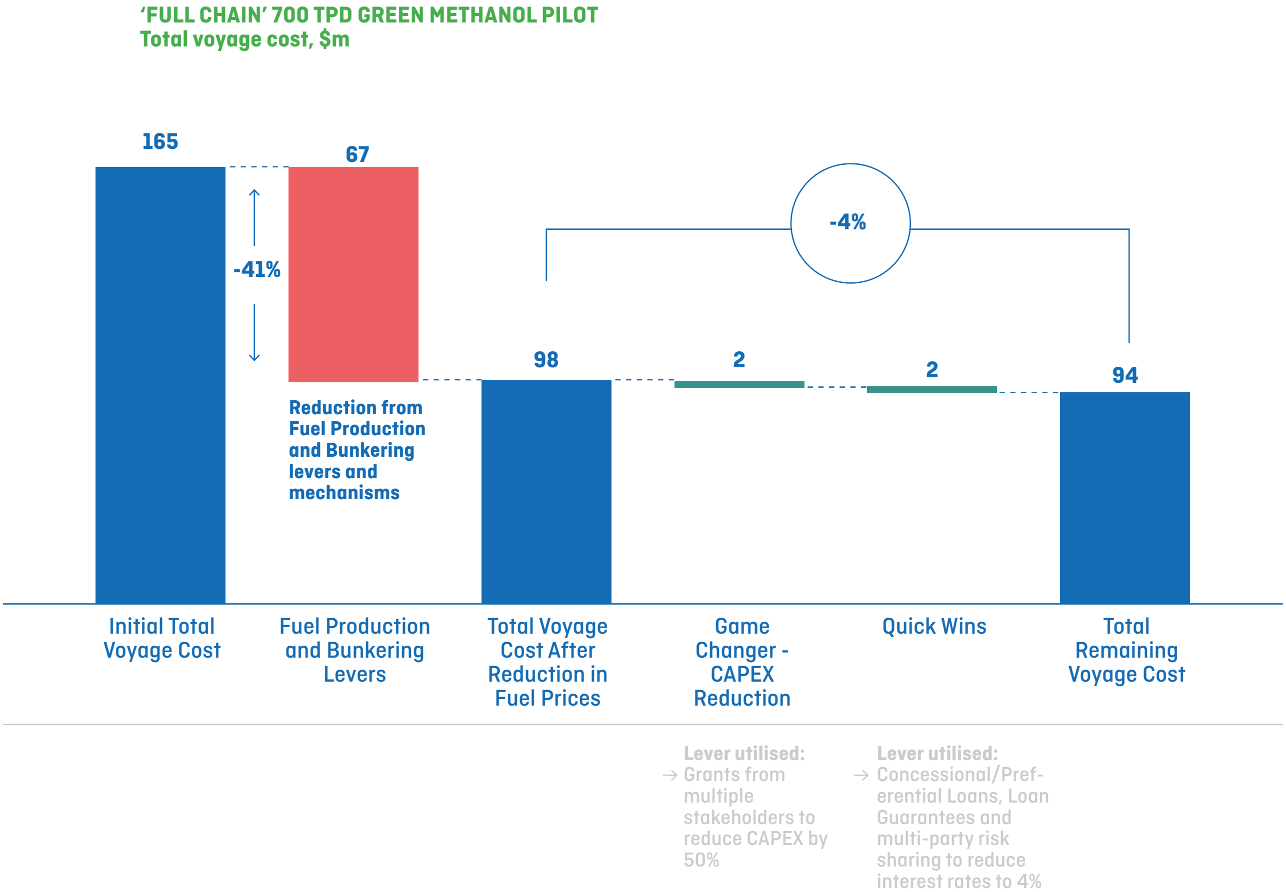


Exhibit 22. Quantification of cost mitigation strategy for Green Methanol pilot at vessel segment



Given the dominance of fuel costs in voyage costs, the Quick Wins and Game Changers available at the level of the vessel would only have a limited impact on voyage costs (1-5%), but they would make a significant difference in terms of the level of investment required from shippers with highly leveraged balance sheets, and therefore considerably facilitate the launch of commercial-scale zero-emission pilots.

Section 6

How to navigate major technical, regulatory and commercial risks

First-of-a-kind projects are, by nature, high-risk projects. Risk levels – both real and perceived – can increase the cost of capital for stakeholders involved (by up to 5-7%[51 52]). In the case of first-of-a-kind commercial-scale zero-emission shipping pilots, the cost of capital can represent a significant share of the cost faced by stakeholders at key stages of the shipping value chain – up to 25% for bunkering suppliers, for example. High levels of technical, regulatory and commercial risks may even preclude the implementation of entire projects. By collaborating across the maritime value chain, stakeholders can mitigate those risks, unlock financing of pilot projects and reduce the cost of capital.

51 Angelopoulos, Dimitrios, et al. "Risks and Cost of Capital for Onshore Wind Energy Investments in EU Countries." Energy & Environment, vol. 27, no. 1, 2016, pp. 82–104.
52 https://www.globalccsinstitute.com/resources/global-status-report/

6.1 Addressing technology reliability through joint technical evaluation

Uncertainties on the reliability of zero-emission fuels newly used in the maritime sector and of the fuel-specific equipment required for both bunkering and vessel operation will be pronounced for novel propulsion systems. New fuels must be stress-tested on an engine to flag potential 'wear and tear' issues that could lead to eventual engine failure. New maritime engine technologies therefore need to be validated over a defined number of operating hours and complete tests spanning a range of conditions (e.g. running at high rates for extended periods) to rule out potential failure of key components. The risks associated with technology reliability are mostly applicable to ammonia pilot projects, as methanol engine and storage systems have reached industrial benchmarks that mark technological reliability for a propulsion system[53].

To overcome this hurdle, stakeholders across the value chain – in particular engine and equipment manufacturers, fuel providers, vessel owners, vessel operators, bunkering suppliers and port authorities – should collaborate on assessment, and, in particular, pool resources to jointly fund technical evaluation studies. As technical evaluation and testing on First-of-A-Kind propulsion systems can be time-consuming, a potential solution is to conduct collaborative testing with engine manufacturers and operators (along with universities, academic centres and labs during the initial stage) to rapidly build the necessary performance benchmarks. Given the high cost of testing, grant funding – accessible to both public institutions like universities and private stakeholders (especially consortiums) could also accelerate that process.

6.2 Addressing fuel regulation issues via national regulations

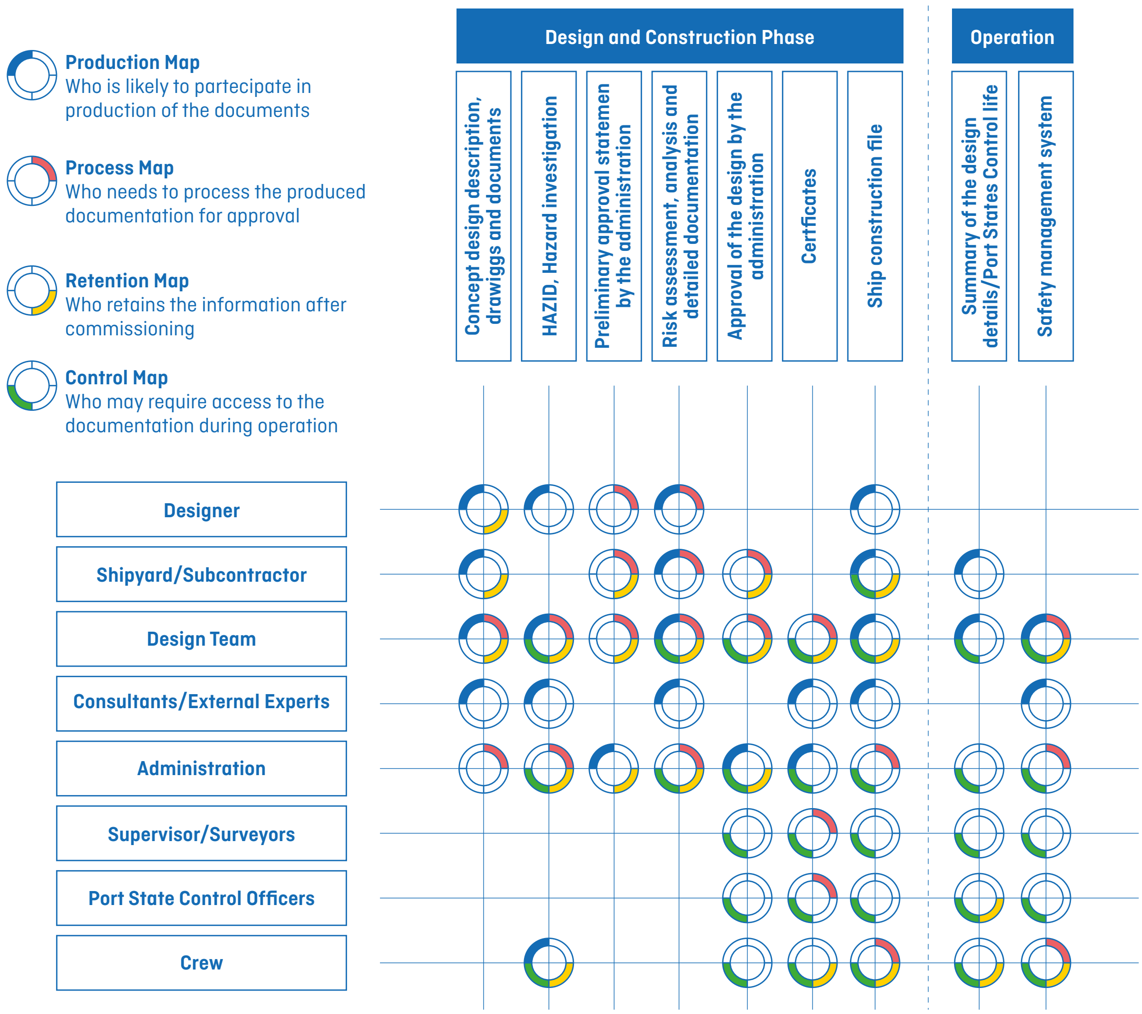
Safety in ports and at sea is paramount for the industry. Marine fuels can therefore not be transacted at ports or handled on ships without approval from relevant regulatory authority. The development of IMO regulations can be a relatively lengthy process. In the short term, it is possible to overcome this hurdle by gaining approval for an 'alternative design' from the regulatory authorities of the host country of a given pilot. For green ammonia, conducting such an 'alternative design' process will be necessary. For the methanol fuel pathway, it will likely not be needed if pending IMO regulation certifying its use as a marine fuel is passed[54].

A 'first mover' can ensure that the correct safety standards have been adhered to for the pilot through thorough planning, collaborating with multiple actors across the maritime value chain and partnering with maritime classification society to progress through the multi-step process described in Exhibit 23. It is also necessary to ensure the involvement of the relevant regulatory authority from the outset to ensure maximum efficiency in the approval process. While obtaining 'alternative design' approval can be a resource-intensive process, precedent for the process does exists – as evidenced by the case of LNG and methanol.

53 https://japan.man-es.com/news/news-details/2019/07/30/dual-ships-pass-dual-fuel-methanol-milestone
54 https://www.spglobal.com/platts/en/market-insights/latest-news/oil/072220-interview-methanol-bunkering-set-to-jump-after-regulatory-approval-methanol-institute-coo

Exhibit 23. Multiple value chain actors are needed at each step of the 'alternate design' process

Involvement Map



Source: Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments MSC.1/Circ.1455 24 June 2013

6.3 Addressing market uncertainty through a chain of offtake agreements

The cost differential between zero-emission fuels and HFO creates a chain of market uncertainty throughout the maritime industry. Fuel providers face uncertain offtake from the shipping sector – although this can be partly mitigated through a diversification of their offtakers across multiple transport and industry sectors using similar fuels. The lack of certainty and diversity in offtake options can also increase revenue-risk for bunkering suppliers. The same market uncertainty applies to vessel operators who are unlikely to invest in new technologies and buy zero-emission fuels at a significant premium without assurance of the existence of a market that will be willing to pay a 'green premium' for cargo delivery.

These market uncertainties would be resolved if international regulations from the IMO were either imposing use of zero-emission fuels through a fuel mandate or implementing a high enough carbon price which would alter the cost trade-off between zero-emission marine fuels and HFO. However, in the short term and in the absence of such international regulations, the first wave of commercial-scale pilots will necessarily need to be underpinned by additional risk mitigation mechanisms. Voluntary offtake agreements across the shipping value chain represent a critical Game Changer, while carbon contracts for difference supported by governments can be an impactful High-Hanging Fruit.

Game Changer

Voluntary offtake agreements constitute an essential tool to provide greater certainty on both volume and price of offtake at different levels of a zero-emission pilot and therefore reduce commercial risks for all actors involved.

- These can be concluded between the fuel producer and the bunkering supplier to guarantee fuel offtake to the fuel provider. The Fuel producer might also be able to secure offtake agreements from multiple buyers beyond the shipping sector (for instance from other transport sector or from heavy industry using same or similar zero-emission fuels).

- Similar agreements can also be found between the bunkering supplier and the vessel operator to reduce commercial risks for the bunkering supplier.

- However, the essential prerequisite for this chain of offtake agreements to be established is that vessel operators pass through the extra cost of zero-emission shipping to cargo owners. Agreements between cargo owners and vessel operators by which cargo owners commit to paying a premium for "green shipping" services is therefore the cornerstone upon which commercial-scale zero-emission shipping projects need to be built.

Fortunately, as discussed in Section 3, the low impact of higher shipping costs on retail prices of consumer goods, in particular high-end goods, makes such an agreement commercially feasible for many cargo owners. The precedent for cost pass-through mechanisms already exist in the containership industry, which has been using Bunker Adjustment Factors to levy additional surcharges on consumers to mitigate against fluctuations in fuel prices for more than 50 years[55]. Other logistics sectors (including trucking and air cargo) are also debating the implementation of cost pass-through mechanisms to support their own decarbonisation.

To be able to market the reduction in the lifecycle carbon footprint of their products related to zero-emission shipping, cargo owners would, however, need reliable fuel traceability protocols to allow for verification of fuel use and related CO_2 emissions for the corresponding voyage. While this may be achieved in a relatively *ad hoc* way for the first wave of projects, implementing it at scale will likely require the creation of a **standardised "green shipping" offer**. Given that similar ideas are currently explored by other freight transport sectors, the shipping sector might want to partner with other sectors to develop an integrated and coherent traceability protocol for the whole logistics value chain.

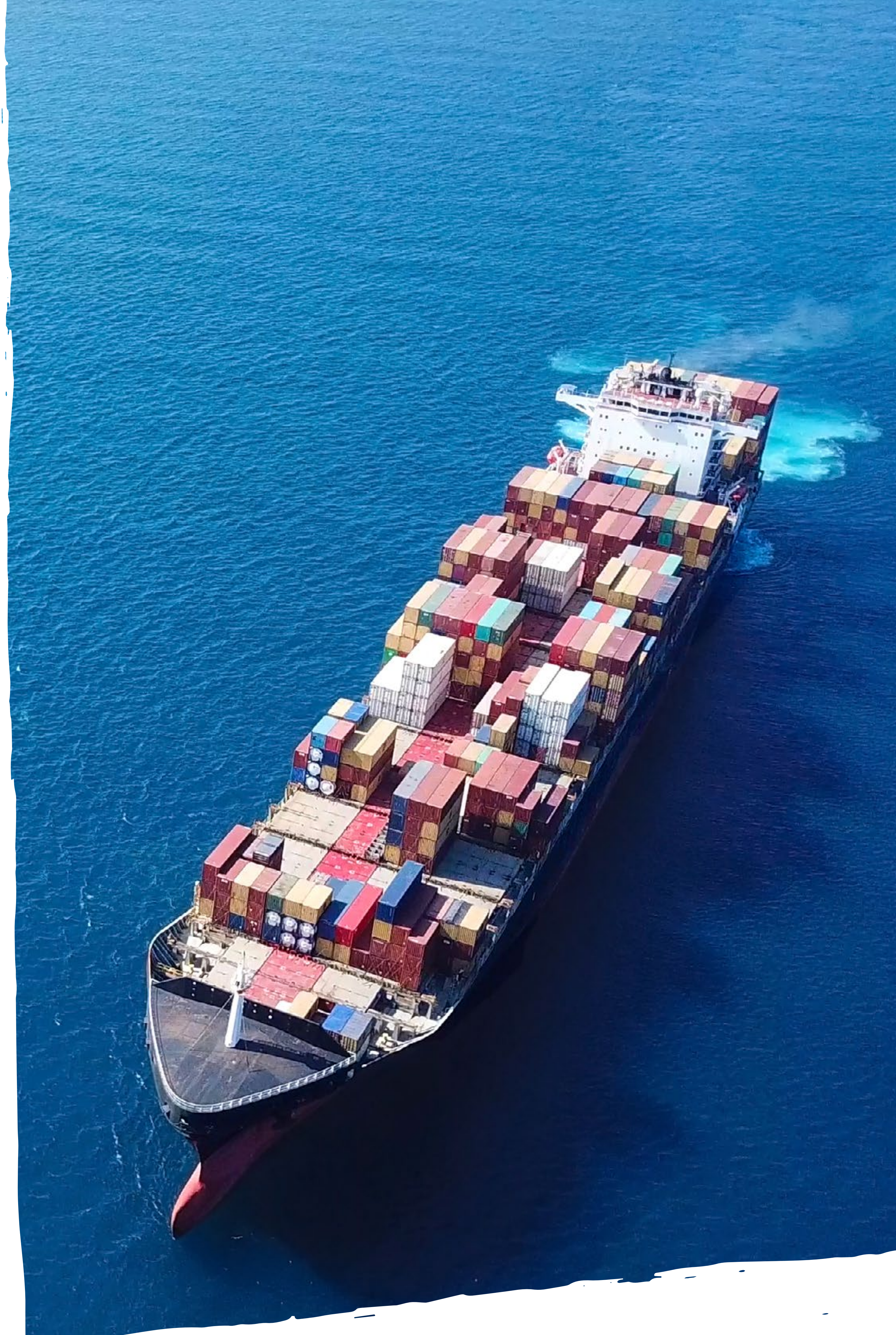
The multiplicity of cargo owners served by a single containership route adds a layer of complexity to the implementation of such a "green shipping" offer. Rather than trying to secure offtake agreements from all cargo owners served by a certain vessel, vessel operators will likely prefer a dematerialised system – by which the cargo owner pays a premium corresponding to the amount of zero-emission fuel that would be used by the vessel operator to carry its cargo, while the vessel operator ensures that the same amount of zero-emission fuel is effectively used in its operations, but not necessarily on the exact same vessel. Such a system would be easier to implement from a practical and logistical point of view, but would require more developed traceability mechanisms.

High-Hanging Fruit

In addition to voluntary mechanisms developed through private sector collaboration, project-based contracts-for-difference (CfDs) could also reduce offtake risk by contributing to bridging the cost gap between zero-emission fuels and HFO. These mechanisms, underpinned by government funding, are adapted from renewable power auctions: they would take the form of subsidised auctions guaranteeing a certain price to zero-emission marine fuel producers which would compensate for the difference between production costs and the prevailing benchmark price for conventional fuel or what the shipping industry is able to pay.

CfDs are currently considered by policymakers across Europe as a tool to support early-stage low-carbon technology deployment, with the mechanisms under consideration for green hydrogen and low-emission basic materials production. Their extension to the maritime sector is possible. Implementation of this type of policy intervention is likely to require at least a couple of years. CfDs would result in lower zero-emission fuel costs for the shipping industry – and lower "green premia" for cargo owners – while providing greater certainty to investors in fuel supply. While the initial level of public subsidy would likely be significant, over time the learning rate cost-reductions would progressively reduce the cost differential, limiting the long-term liability placed on taxpayers.

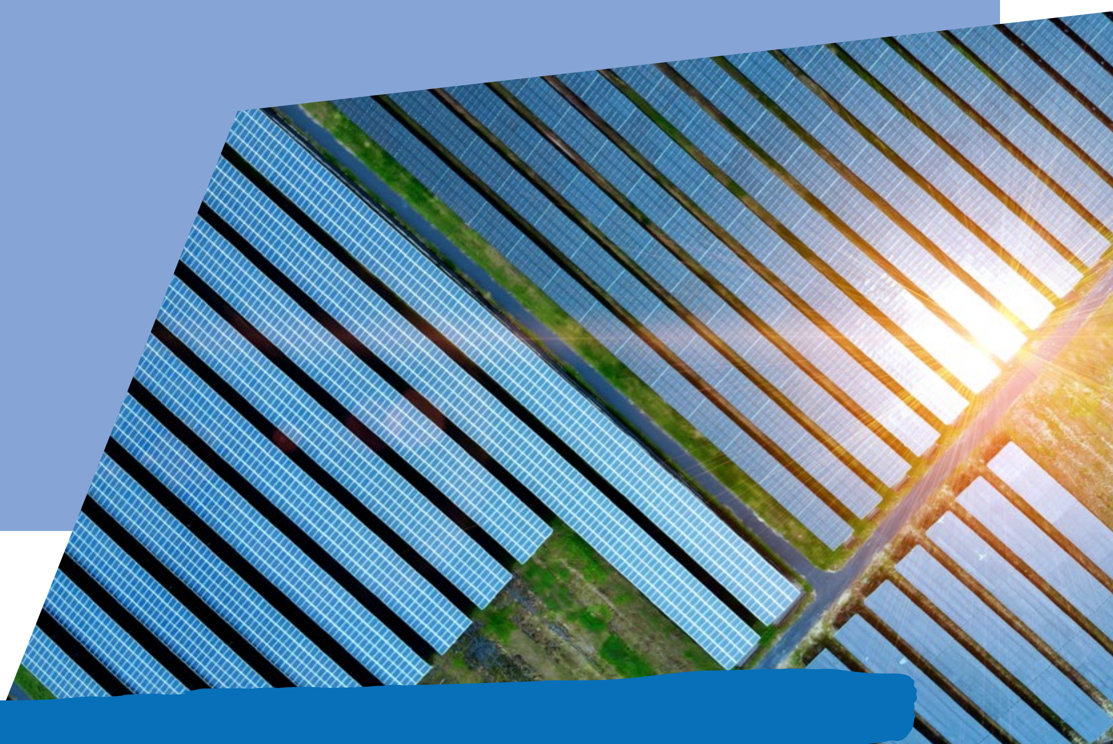
55 Wang, Dong-Hua & Chen, Chung-Ching & Lai, Cheng-Sheng. (2011). The rationale behind and effects of Bunker Adjustment Factors. Journal of Transport Geography - J TRANSP GEOGR. 19. 467-474. 10.1016/j.jtrangeo.2009.11.002.



Section 7

Potential impact of cost-lowering and de-risking mechanisms on ‘first-mover’ pilots

The implementation of a suite of cost-lowering and de-risking mechanisms at the different stages of a commercial-scale zero-emission pilot can significantly alter the economics of such a project. This section illustrates how a combination of the mechanisms described as Quick Wins and Game Changers across this report could lower the total cost of ammonia and methanol pilots by 30-50%. This would in turn divide by two the cost premium associated with zero-emission shipping that cargo owners might have to pay. It would make it even easier to pass through this extra cost to end consumers given how minimal the impact on the retail price of many consumer goods, especially high-end goods, would be – i.e. in the order of 0.5-0.8%.



The reduction of fuel costs constitutes the most significant lever to reduce the total cost of 'first mover' pilots. We estimate that fuel production costs could be reduced by up to 40% for both green ammonia and green methanol. Achieving these major cost reductions for zero-emission fuels would require that the following measures be jointly implemented:

- Access to renewable electricity at a price of $35/MWh instead of $60/MWh thanks to a combination of location optimisation, long-term power purchase agreements and waivers on network/grid taxes;
- Reduction in CAPEX through the use of existing infrastructure;
- Public support to investment providing $65 million of subsidy to fuel providers and lowering the cost of capital from 10% to 4%

Additional, smaller cost reductions can then be achieved at bunkering and vessel levels: 1-3-% on bunkering costs and 2-3% on costs for vessel operators and owners. These are mostly the result of:

- Repurposing and retrofitting existing storage facilities and bunker barges – which can by itself reduce bunkering costs by 40-50%;
- Public support to capital expenditure at vessel levels, which could represent a total capex reduction of roughly 50% for vessel owners.

Combined, those different mechanisms can drastically alter the economics of a 'first mover' pilot. They will, however, be **insufficient to fully compensate for the cost differential between zero-emission fuels and HFO**. The development of a "green shipping" offer, at a premium price, will therefore be indispensable to pass through the additional cost to the consumer. This will likely start with ad hoc agreements between cargo owners and vessel operators ensuring fuel and emission traceability, but the expansion of this practice will probably be contingent upon the development of a standard traceability and certification scheme recognised by the entire industry.

The cost-lowering and risk-mitigation strategies described in this report are essential to unlock the realisation of the first wave of commercial-scale pilots, but **they also prefigure the nature of the support mechanisms that will likely be required to underpin early deployment of zero-emission shipping** in the late 2020s and early 2030s.

Exhibit 24. Quantification of the impact of cost and risk mitigation strategies for a green ammonia pilot

'FULL CHAIN' 700 TPD GREEN AMMONIA PILOT
Total voyage cost, $m

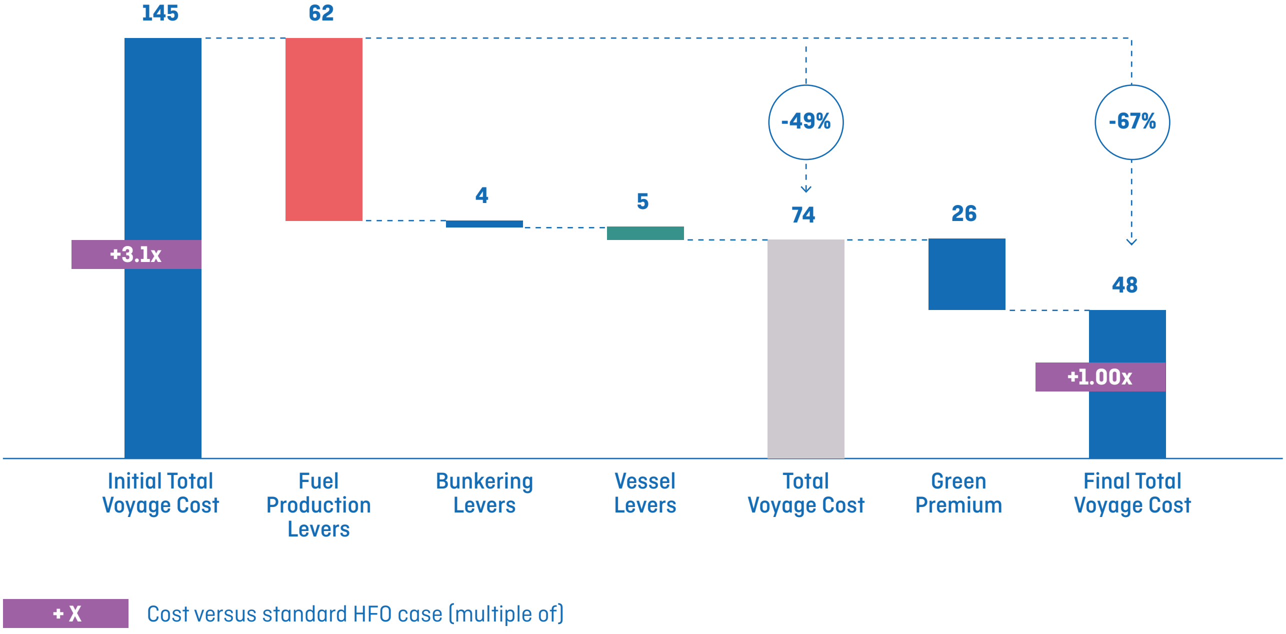
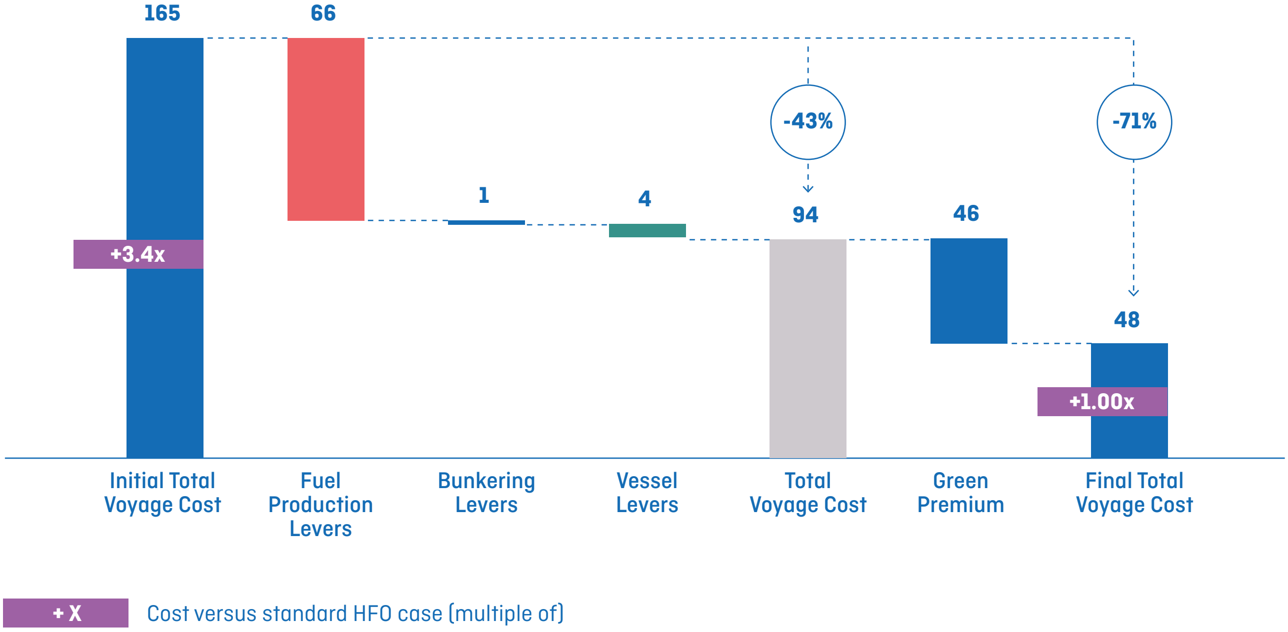


Exhibit 25. Quantification of the impact of cost and risk mitigation strategies for a green methanol pilot

'FULL CHAIN' 700 TPD GREEN METHANOL PILOT
Total voyage cost, $m



Section 8

Key recommendations for private and public sector actors

The global maritime industry finds itself at a critical juncture in its history as it commences a transition from a narrow range of high-carbon fossil-based fuels to multiple and competing zero-emission fuel options. At its core, the transition will see a transformation in how fuel is produced, bunkered, consumed and priced. The realisation in the next five to ten years of a first wave of commercial-scale zero-emission shipping pilots is essential to provide the technological and commercial proof points that will unlock deployment at scale in the 2030s.

Industry leaders willing to engage in the first commercial-scale end-to-end projects will benefit from technology leadership, operational understanding, and early-mover partnerships, which will represent significant competitive advantages as the global maritime industry undertakes the transition to zero emissions. At the same time, a new set of cost drivers and risks will need to be navigated to get the first wave of projects off the ground.

Five critical cost and risk drivers need to be addressed in priority to unlock the first wave of 'first mover' pilots:

1. **Access to low-cost renewable electricity:** For both green ammonia and green methanol pilot projects, renewable electricity represents the single largest cost driver, representing more than 60% of the total project cost. It is also potentially the most variable, as multiple strategies can be implemented to reduce this energy bill with a major impact on the end-to-end economics of any pilot.

2. **Land-based CAPEX requirements:** Most of the CAPEX for an end-to-end pilot is land-based and relates to the production of zero-emission fuels. This investment will exceed $200 million even for a small-scale pilot and the cost of capital associated with it could be further increased by offtake uncertainties. It is therefore particularly important to identify shortcuts to reduce CAPEX requirements and secure public support for those investments.

3. **Bunkering and vessel CAPEX requirements:** Although capital expenditure at the level of bunkering facilities and vessels represent a small proportion of total pilot costs, they are significant for the stakeholders who need to bear those costs who should therefore benefit from various forms of support as they engage in 'first mover' pilots.

4. **Technology and regulatory risks.** Safety in both ports and at sea is paramount for the industry. Marine fuels cannot be transacted at ports or handled on ships without proper safety assessments and approval from the relevant regulatory authority. These processes can be lengthy, and value chain collaboration to expedite these processes are essential to enable the realisation of 'first mover' pilot projects.

5. **Offtake risks:** In a competitive global market like shipping, launching zero-emission operations that would result in a significant price premium compared to conventional offers necessarily entails major market uncertainties. This risk cascades across the value chain from cargo owners all the way to fuel producers and could be a major impediment to the launch of commercial-scale pilots. Fortunately, the limited impact of increased shipping costs on end consumer products opens the door to innovative collaboration models that can mitigate this commercial risk.

Industry leaders across the maritime value chain hold the keys to several major cost-lowering and risk-mitigation opportunities for 'first mover' pilots. They should focus their attention on 5 key priorities:

1. **Join forces to fast-track technology trials and regulatory approvals** necessary to use new zero-emission fuels on a commercial scale in the maritime sector.

2. **Choose pilot locations that offer privileged access to low-cost renewable electricity and hydrogen**, opting for regions with large renewable energy potential, preferential prices and tax exemptions for major industrial electricity consumers, and industrial clusters where several transport and industry sectors will share energy infrastructure costs.

3. **Seize every opportunity to repurpose and retrofit existing infrastructure and assets**, especially for ammonia and methanol production, fuels storage and bunker vessels, to minimise upfront capital investment.

4. **Co-invest in critical equipment** – especially at bunkering and vessel levels – to share costs and risks, while also benefitting from the learnings that commercial-scale operations of new zero-emission fuels will bring to fuel producers, equipment and ship manufacturers, bunkering suppliers, port authorities, ship owners and operators.

5. **Form consortiums with key stakeholders across the value chain** – from cargo owners to fuel producers – to put in place a chain of long-term voluntary offtake agreements, which will leverage the ability of cargo owners to pass through increased freight costs to end consumers to providing greater market certainty to ship operators/owners and subsequently to bunkering suppliers and fuel producers.

In parallel, governments will also have to create, extend, and enhance support mechanisms to the first wave of commercial-scale projects through both direct financial support and de-risking of private sector investment. 3 key sets of action will help unlock 'first mover' pilots:

1. **Provide targeted investment support** in the form of direct subsidies as well as concessional/preferential loans and loss guarantees for the key elements of capital expenditure required at each stage of the maritime value chain, in particular fuel production capex (electrolysers and synthesis equipment), onshore and offshore bunkering infrastructure, equipment purchase (for new engines and fuel tanks), and vessel retrofitting.

2. **Facilitate access of the maritime sector to low-cost electricity**, generally by continuing to drive massive investment in renewable electricity provision and specifically by waiving electricity taxes and grid fees for zero-emission fuel providers.

3. **Create a mechanism that effectively contributes to bridging the cost differential** between zero-emission marine fuel cost and HFO – in the form of contracts-for-difference for fuel producers and/or of a carbon levy and feebate model benefitting ship operators.

This report illustrates that the ambition of getting zero-emission vessels on deep-sea routes by 2030 is feasible. We are confident that a first wave of commercial-scale end-to-end zero-emission pilots can be launched within the next five to ten years, informing and inspiring the scale-up of zero-emission shipping shortly thereafter. Achieving this goal will require enhanced collaboration across the maritime value chain and targeted support from key governments to boost the technological and commercial viability of the projects. Success will bring a scale-up of zero-emission shipping into sight.

Model Methodology and Assumptions

Exhibit A1 and A2 gives an overview of the cost model methodology showing user inputs, internal calculations, and cost outputs. Assumptions are laid out in the table following the Exhibits.

Exhibit A1. High level model methodology – Fuel Production

High level methodology of the model – Fuel Production

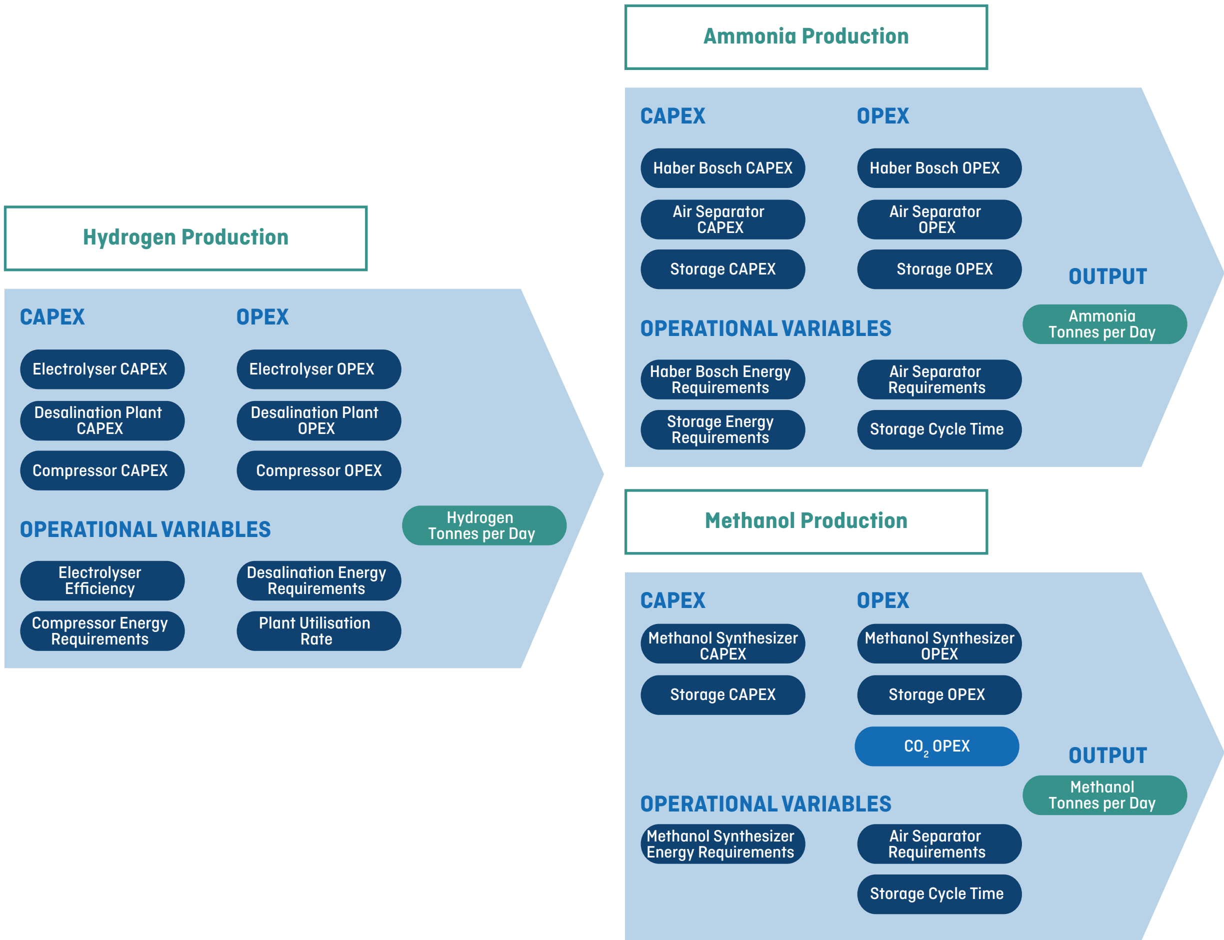
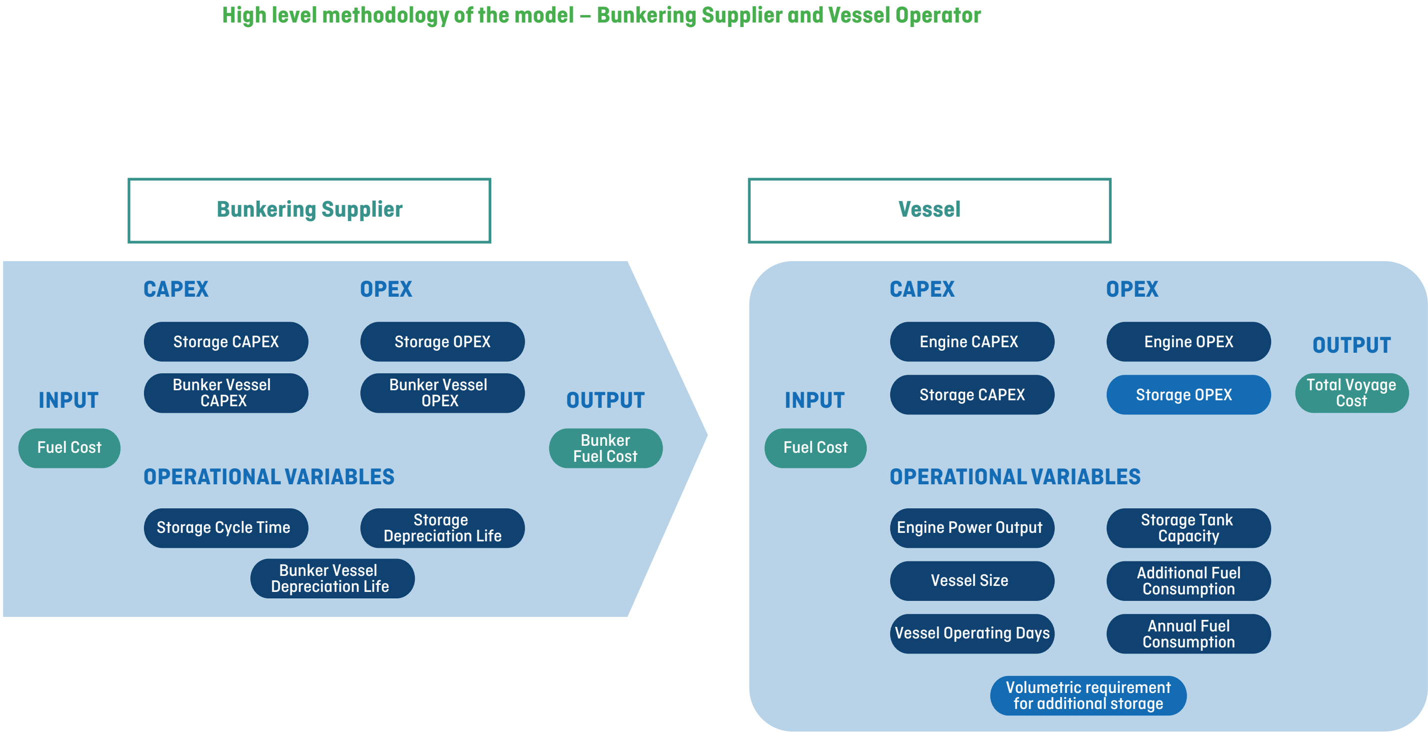
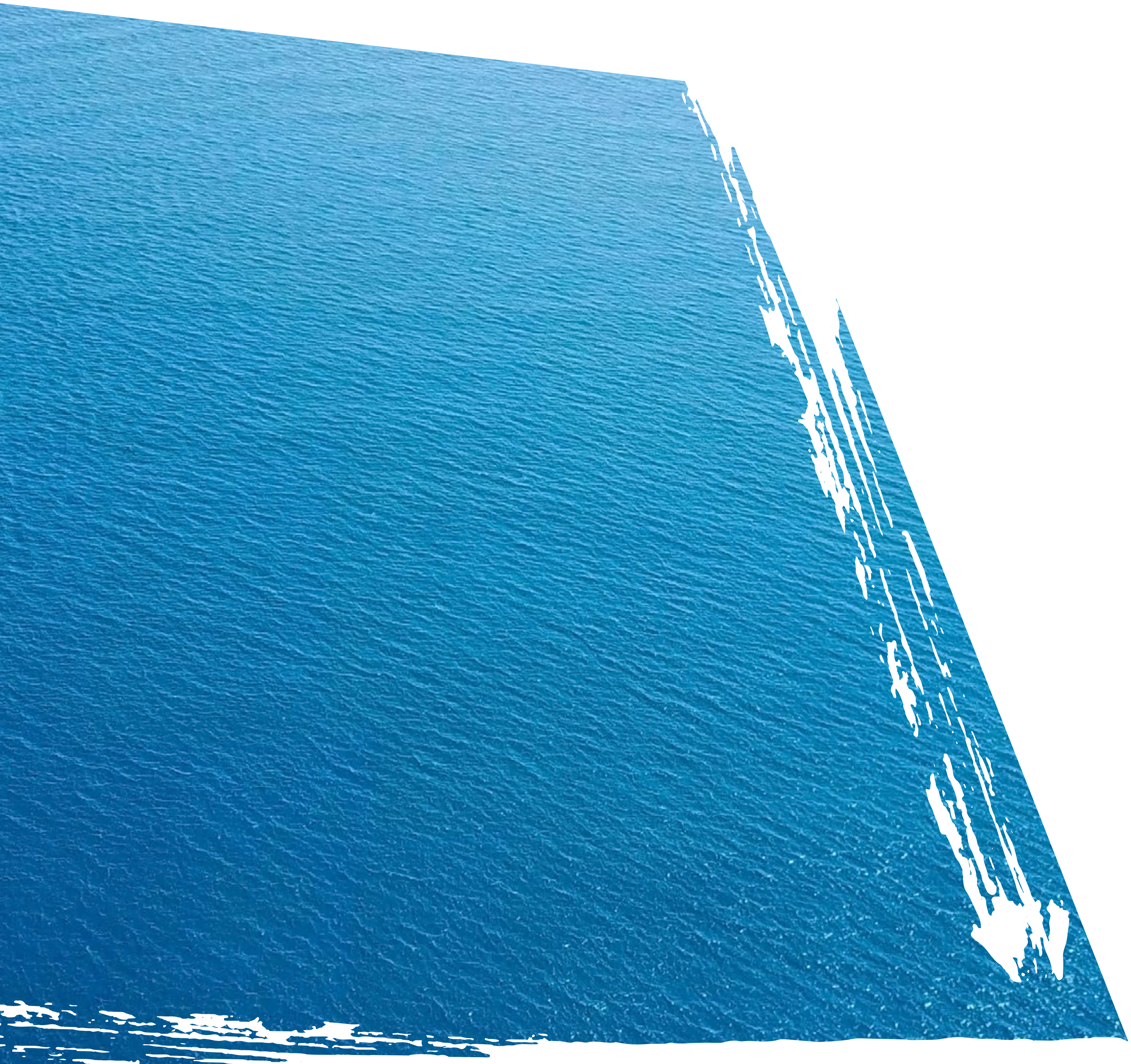


Exhibit A2. High level model methodology – Bunkering Supplier and Vessel Operator





Hydrogen Production Data			
Variable	Unit		**Source**
Electrolyser CAPEX	USD / kW	1,200	BloombergNEF - Hydrogen: The Economics of Production From Renewables (2019)
Desalination Plant CAPEX	$ / m3 day	1,150	Morgan, Eric R., "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind" (2013). Open Access Dissertations. 697.
Compression CAPEX	$ / kg	0.965	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Electrolyser OPEX	%	2%	BloombergNEF - Hydrogen: The Economics of Production From Renewables (2019)
Desalination Plant OPEX	%	4%	Morgan, Eric R., "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind" (2013). Open Access Dissertations. 697.
Compression OPEX	%	3%	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Electrolyser Efficiency	%	63.0%	BloombergNEF - Hydrogen: The Economics of Production From Renewables (2019)
Desalination Energy Requirement	kWh / m3	4.10	Morgan, Eric R., "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind" (2013). Open Access Dissertations. 697.
Compression Energy Requirement	kWh / kg	2.85	BloombergNEF - Hydrogen: The Economics of Production From Renewables (2019)
Plant Life	Years	30.00	EDF - Sailing on Solar (2019)
Ammonia Production Data			
Air Separator CAPEX	$ / kg N2	0.16	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Haber Bosch CAPEX	$ / kg NH3	0.51	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Refrigeration and Storage CAPEX	$ / kg NH3	1.06	BloombergNEF - Hydrogen: The Economics of Production From Renewables (2019)
Air Separator OPEX	%	4%	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Haber Bosch OPEX	%	2%	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)

Storage OPEX	%	4%	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Air Separator Energy Requirement	kWh / kg N2	0.108	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Haber Bosch Energy Requirement	kWh / kg NH3	0.44	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Storage Energy Requirement	kWh / kg NH3	0.04	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Storage Cycle Time	Days	30.00	BloombergNEF - Hydrogen: The Economics of Transport & Delivery (2019)
Ammonia Bunkering Data			
Refrigeration and Storage CAPEX	$ / kg NH3	1.06	BloombergNEF - Hydrogen: The Economics of Transport & Delivery (2019)
Ammonia Barge CAPEX	$ / Vessel	15,000,000	National Academies of Sciences, Engineering, and Medicine. 2012. Marine Highway Transport of Toxic Inhalation Hazard Materials. Washington, DC: The National Academies Press.)
Storage OPEX	%	4%	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Bunker Vessel OPEX	%	3%	National Academies of Sciences, Engineering, and Medicine. 2012. Marine Highway Transport of Toxic Inhalation Hazard Materials. Washington, DC: The National Academies Press.)
Bunker Vessel Depreciation Life	Years	18.00	IRS - Pub 946 (2020)
Storage Tank Depreciation Life	Years	22.00	IRS - Pub 946 (2020)
Bunkering Infrastructure Useful Life	Years	30.00	National Academies of Sciences, Engineering, and Medicine. 2012. Marine Highway Transport of Toxic Inhalation Hazard Materials. Washington, DC: The National Academies Press.)
Ammonia Carrier Data			
Main Engine CAPEX	$ / kW	550	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.

Genset CAPEX	$ / kW	500	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Cracker CAPEX	$	670000	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Converter CAPEX	$ / kW	200	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
SCR CAPEX	$ / kW	44	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Main Engine OPEX	$ / kW / year	5.2	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Genset OPEX	$ / kW	5.2	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.

Cracker OPEX	% of CAPEX	1%	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Converter OPEX	$ / kW / year	2	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
SCR OPEX	% of CAPEX	3%	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Annual Fuel Consumption	tonnes	25505.70	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Main Engine Capacity	kW	13500	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Genset Capacity	kW	4500	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.

Converter Capacity	kW	300	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
SCR Capacity	kW	18000	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
NH3 Engine and Fuel Storage System Volume	m3	3984	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Vessel Useful Life	Years	25.00	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Depreciation On Board CAPEX	Years	7.00	IRS - Pub 946 (2020)
Annual Vessel Operating Days	Days	280.00	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Annual Number of Trips	Trips	47.00	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.

Vessel Size	TEU	2500.00	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Methanol Production Data			
Methanol Synthesizer CAPEX	$ / kW	857	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Carbon OPEX	$ / kg CO2	0.07	GCI - Perspective: Bioenergy and Carbon Capture and Storage (2019)
Storage CAPEX	$ / kg	0.32	FCBI Energy - Methanol as a Marine Fuel (2015)
Methanol Synthesizer OPEX	%	4%	Fasihi, Mahdi. (2017). Synthetic Methanol and Dimethyl Ether Production based on Hybrid PV-Wind Power Plants.
Storage OPEX	%	3%	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Methanol Synthesizer Energy Requirement	kWh / kg / MeOH	0.22	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Storage Energy Requirement	$/kg	0.14	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Methanol Bunkering Data			
Storage CAPEX	$ / kg MeOH	0.32	FCBI Energy - Methanol as a Marine Fuel (2015)
Methanol Barge CAPEX	$ / Vessel	1500000.00	FCBI Energy - Methanol as a Marine Fuel (2015)
Storage OPEX	%	2%	LR/UMAS - Techno-economic assessment of zero-carbon fuels (2020)
Bunker Vessel OPEX	%	3%	FCBI Energy - Methanol as a Marine Fuel (2015)
Bunker Vessel Depreciation Life	Years	18.00	IRS - Pub 946 (2020)
Storage Tank Depreciation Life	Years	22.00	IRS - Pub 946 (2020)
Bunkering Infrastructure Useful Life	Years	30.00	FCBI Energy - Methanol as a Marine Fuel (2015)
Methanol Carrier Data			
Main Engine CAPEX	$ / kW	300	FCBI Energy - Methanol as a Marine Fuel (2015)

Fuel Supply System CAPEX	$ / kW	40	Brynolf, Selma & Taljegard, Maria & Grahn, Maria & Hansson, Julia. (2017). Electrofuels for the transport sector: A review of production costs. Renewable and Sustainable Energy Reviews. 10.1016/j.rser.2017.05.288.
Main Engine OPEX	$ / kW / year	5.2	FCBI Energy - Methanol as a Marine Fuel (2015)
Annual Fuel Consumption	tonnes	26471	The Engineer Toolbox
Main Engine Capacity	kW	18000	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Vessel Useful Life	Years	25.00	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Depreciation On Board CAPEX	Years	7.00	IRS - Pub 946 (2020)
Annual Vessel Operating Days	Days	280.00	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Annual Number of Trips	Trips	46.67	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.

Vessel Size	TEU	2500.00	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
HFO Equivalent Fuel Consumption	tonnes	13507.00	Kim, Kyunghwa & Roh, Gilltae & Kim, Wook & Chun, Kangwoo. (2020). A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. Journal of Marine Science and Engineering. 8. 183. 10.3390/jmse8030183.
Financial Assumptions			
Cost of Debt	%	10%	Author's assumption
Debt to Capital Ratio	%	80%	Author's assumption
Loan Term - Fuel Production and Carrier	Years	20	Author's assumption
Loan Term - Bunkering	Years	15	Author's assumption
Tax Rate	%	30%	Author's assumption
IRR Requirement	%	7%	Author's assumption
Discount Rate	%	5%	Author's assumption
HFO Cost	USD / tonne	394.00	Average from Jan 1, 2020 to Jul 1, 2020 for top 20 global ports from shipandbunker.com
Levelised Cost of Electricity – Renewables	$	60.00	Komušanac, Ivan. (2018). Wind energy in Europe in 2018. 10.13140/RG.2.2.12678.63049.
Capacity Factor – Renewables	%	60%	Komušanac, Ivan. (2018). Wind energy in Europe in 2018. 10.13140/RG.2.2.12678.63049.
Cost of Grid Connected Electricity	$	100.00	EuroStat - Electricity prices for non-household consumers

By the Energy Transitions Commission

Energy Transitions Commission

For the Getting to Zero Coalition

GLOBAL MARITIME FORUM

FRIENDS of OCEAN ACTION

WORLD ECONOMIC FORUM

About the Getting to Zero Coalition

The Getting to Zero Coalition is an industry-led platform for collaboration that brings together leading stakeholders from across the maritime and fuels value chains with the financial sector and other committed to making commercially viable zero emission vessels a scalable reality by 2030.

Learn more at:
www.globalmaritimeforum.org/getting-to-zero-coalition