Cost of zero emissions container freight shipping: a study on selected deep-sea and short-sea routes

December 2023

Authors

Camilo Velandia Perico
Dr Jean-Marc Bonello
Dr Nishatabbas Rehmatulla
Dr Eoin O'Keeffe

Publication data

Bibliographical details: Velandia Perico, C., Bonello, J., Rehmatulla, N., O'Keeffe, E., (2023) *Cost of zero emission container freight shipping: a study on selected deep-sea and short-sea routes*. UMAS, London.

Publication date: December 2023

This work has been funded by ClimateWorks Foundation and Quadrature Climate Foundation

Preface

This report has been written by a team of experts from UMAS. This work provides estimates of total cost of operation for zero carbon container freight shipping under different scenarios. The aim is to provide a method to explore the initial estimates of costs for zero emission container freight shipping.

Disclaimer

The information contained in this report is not an alternative to advice from an appropriately qualified professional. If you have any specific questions about any financial or technical matters you should consult an appropriately qualified professional. UMAS will not be liable for any business losses, including without limitation loss of or damage to profits, income, revenue, use, production, anticipated savings, business, contracts, commercial opportunities or goodwill.

About UMAS

UMAS delivers consultancy services and undertakes research for a wide range of clients in the public and private sectors using models of the shipping system, shipping big data, and qualitative and social science analysis of the policy and commercial structure of the shipping system. UMAS's work is underpinned by state-of-the-art data supported by rigorous models and research practices, which makes UMAS world-leading on three key areas; using big data to understand drivers of shipping emissions, using models to explore shipping's transition to a zero emissions future and providing interpretation to key decision makers. For more information visit: www.umas.co.uk

Contact person

If you require any further information on this report, please contact:
Dr Nishatabbas Rehmatulla
n.rehmatulla@ucl.ac.uk

Contents

List of figures

List of tables

List of abbreviations

coZEV	Cargo Owners for Zero Emission Vessels
DAC	direct air capture
EEDI	Energy Efficiency Design Index
EET	energy efficiency technology
EGR	exhaust gas recirculation
GHG	greenhouse gas(es)
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
LCA	levelised cost analysis
MEPC	Marine Environment Protection Committee
PEM	proton exchange membrane (electrolysis)
SBTi	Science Based Target initiative
SCR	selective catalytic reduction
SZEF	scalable zero emission fuel(s)
TCO	total cost of operation
TEU	twenty-foot equivalent unit

Executive summary

To set international shipping on an ambitious zero-emission trajectory, aligned to a Paris Agreement 1.5°C temperature target, the sector must transition away from using fossil fuels and consume scalable zero-emission fuels (SZEF). In the emergence phase of the transition, SZEF will be more expensive than the currently used fossil fuels leading to increased shipping costs. In the short term, before IMO policy levers enter into force, addressing the cost gap will require sharing this cost across the value chain, including end customers' willingness to pay for zero-emission shipping services. This report focuses on this as a mechanism to accelerate the emergence phase of shipping's transition to zero-emission, particularly because progressive shippers can operate ahead of global policy frameworks such as that of the IMO.

With the ambitious outcome at MEPC 80, committing IMO to achieve a 70-80% absolute reduction of international shipping GHG emissions by 2040, and committing IMO to adopt both GHG pricing and a GHG fuel standard by the end of 2025, there is now an urgent and unambiguous pressure for corporate and national action to rapidly decarbonise the shipping sector during the emergence phase.

This report estimates the potential costs associated with pre-regulation zero-emission container shipping, as a primer for setting up a zero-emission container shipping market. It is important to note that the estimates presented herein represent a worst-case scenario. They consider only the anticipated technology cost reductions through 2030, 2040, and 2050 and do not account for factors such as local subsidies on fuels (e.g. the US Inflation Reduction Act (IRA)) or the expected impact of regulatory measures, such as the EU's 'Fit for 55' or upcoming carbon pricing measures yet to be confirmed by the IMO, which are expected to take effect from 2027/8. Consequently, it can be anticipated that these measures would only lead to further cost reductions.

Method

The analysis starts by identifying routes with high potential for development into green corridors based on the volume of trade, a regular vessel operational profile and future access to a supply of SZEF. Once good candidate first-mover routes are identified, the fleet that currently operates on each route are analysed to define a typical vessel that satisfies the transport demand over the route, which in turn dictates vessel size and range. With a vessel specification, operating profile and route defined, a total cost of operation (TCO) analysis can be carried out to understand the costs related to building and operating a zero-emission vessel when compared to a reference fossil fuel vessel on specific routes. The TCO can then be used to determine a per-TEU (twenty-foot equivalent unit) cost differential for the decarbonisation of freight on the particular route in a given year.

As illustrative examples of the application of the above methodology, this study focuses on two of the high potential first-mover container routes: a transpacific route between Shanghai and Los Angeles (LA) for a 15,000 TEU vessel and a domestic route along the Chinese coastline for a 4,000 TEU vessel. The fuels considered are green ammonia and methanol derived from a renewable electricity feedstock[1], ensuring minimal greenhouse gas (GHG) emissions throughout the entire lifecycle. Their fuel costs were modelled using a levelized cost analysis (LCA) approach, incorporating local electricity input assumptions relevant to the routes under consideration. This analysis does not include subsidies, providing a conservative perspective on the outlook for fuel costs. Bio-methanol is also considered to provide a comparison; however, it is not considered a SZEF due to supply constraints and the impact of land use change associated with some biogenic feedstocks.

[1] Green ammonia is produced using renewable electricity to extract hydrogen from water via electrolysis (i.e. green hydrogen) and combining this with nitrogen from the atmosphere through a Haber-Bosch process. Green methanol is produced by combining green hydrogen with carbon retrieved from the atmosphere through carbon capture technology, often referred to as 'direct air capture'.

Key findings

The additional costs of a zero-emission ship in 2030 ranges between $90 to $450 per TEU on the transpacific route and $30 to $70 per TEU on the Chinese coastal route (see Figure 0-1). Considering this cost differential against average freight rates since 2010 (excluding the pandemic period), it suggests a potential increase of between 9% to 17% in freight rates (cost per TEU) for the Chinese coastal route[2] and between 17% and 50% increases in cost per TEU in the case of the Shanghai to LA route in 2030[3].

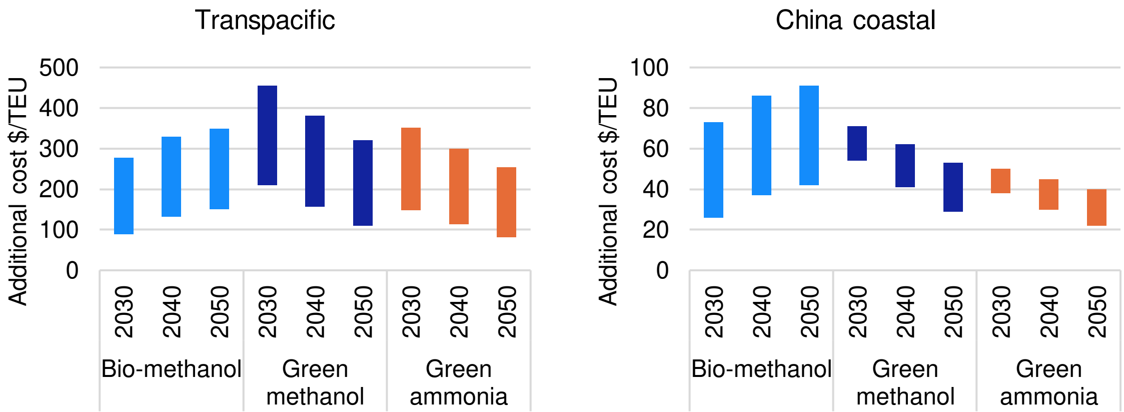


Figure 0-1 $/TEU cost differential for zero emission transport (low & high fuel price scenario)

Fuel cost plays the most prominent part in determining the overall cost; thus, this is the primary driver of the TCO, especially when considering regional differences in the cost of fuel production. In 2030, TCO for vessels on a transpacific route operating on green ammonia and methanol is two to four times that of a reference vessel operating on low sulphur heavy fuel oil (LSHFO) (See Figure 0-2). It's worth noting that these estimates are expected to decrease significantly if local subsidies, as provided by the US Reduction Inflation Act (IRA), are factored in. Early work suggests that the difference could drop as low as 1.6 to 2.4 times if subsidised hydrogen used for e-ammonia production ranged from $1 to $3/kg-H2. On the China coastal route, the TCO difference drops to 1.75 to 2.5 times for the low and high fuel cost scenarios respectively. These numbers would be significantly lower if further GHG policy is applied. Over time, the cost differential is expected to narrow due to declining SZEF fuel costs. In 2040, most scenarios show a TCO that is 2 to 2.5 that of conventional fuel, which goes down to 1.5 to 2 times the TCO in 2050.

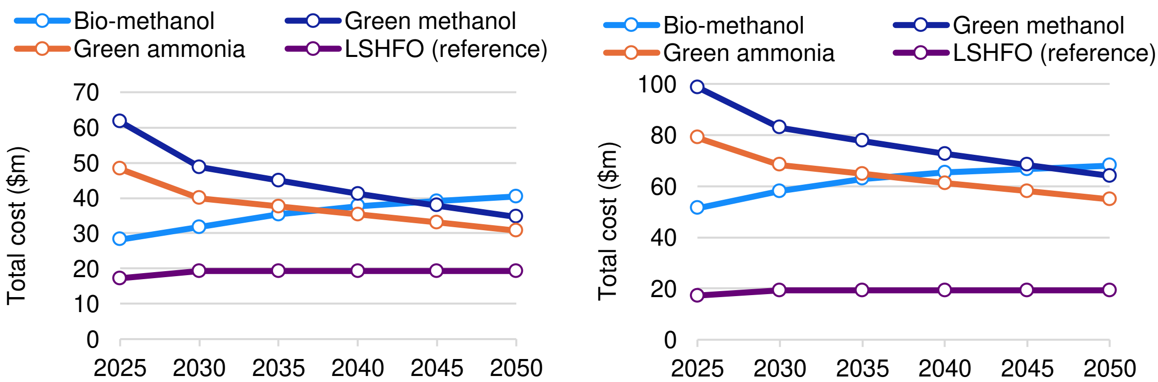


Figure 0-2 Annualised TCO under low (left) and high (right) fuel cost scenarios in the transpacific route

[2] When compared against the combined historical average of the Shanghai – Singapore, Shanghai-West Coast Japan and Shanghai-Korea (Pusan) SCFI Spot Freight rates indexes (https://en.sse.net.cn/indices/introduction_scfi_new.jsp).

[3] When compared against the historical average of the Shanghai – West Coast US SCFI Spot Freight rates index (https://en.sse.net.cn/indices/introduction_scfi_new.jsp

Two important clarifications are necessary when interpreting these numbers: These figures represent a worst-case scenario that considers expected savings from technology development only and does not account for potential reductions due to fuel subsidies or upcoming regional and global regulations. Secondly, the pandemic period has demonstrated the remarkable elasticity of demand for freight services. In 2022 alone, prices for freight surged by over 4 times the spot rates seen over the previous decade.

Implications

The TCO approach shows that by 2030, in the best-case scenario, to get a single vessel running on SZEF on the transpacific route would require an additional $20 to $30m per annum (of which $18 to $27m is fuel costs) and an additional $4.5m to $6.5m per annum (of which $3.6 to $5.2m is fuel costs) on the coastal China route. This indicates the magnitude of freight purchase commitments required in the early stages of the emergence phase. They also show the level of carbon prices needed to close the gap between the SZEFs and conventional fuels.

Early movers in the transition who are willing to pay an additional cost for lower GHG transport have a choice to make: to go for cheaper but non-scalable fuels such as bio-methanol, which will become more expensive as demand outstrips supply, or invest in fuels with a higher capital expenditure, thus stimulating a more likely long-term solution that will become cheaper as production ramps up and demand grows. There could be an argument to deploy a methanol pathway that begins with bio-methanol in the emergence phase (on the grounds of lower cost relative to SZEF), which gradually moves to DAC-methanol[4]. However, whilst this pathway is cheaper in the short-run, the initial use of bio-methanol does not significantly improve the long run costs of DAC-methanol. This is because they use different production pathways meaning that any early investments, learning and advantages of scale translate poorly from bio-methanol to DAC-methanol. As such, early movers, including cargo owners, should be acting now but taking a long-term view that enables the scaling up of production and reducing the cost gap of SZEF.

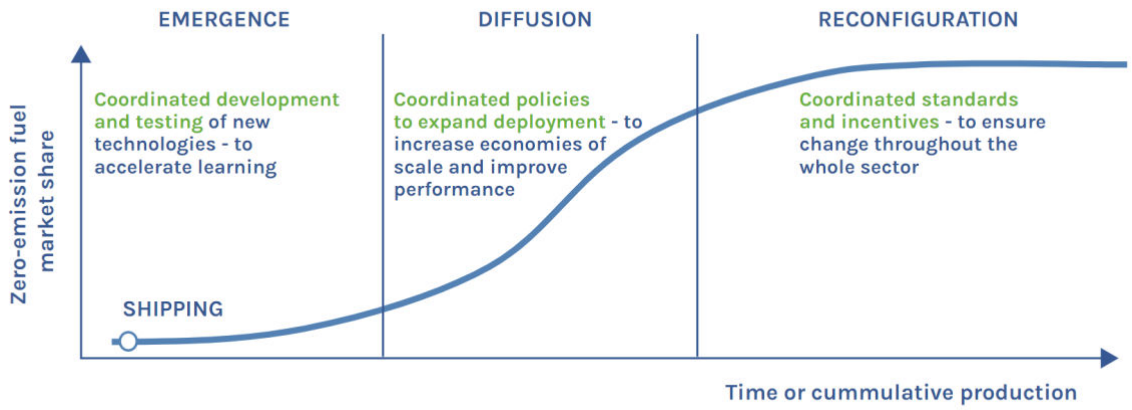
With that in mind, the findings presented in this study enables early movers to start informed discussions, better understand the cost of zero-emission shipping and take action. The cost burden can appear to be high during the emergence phase but there are already subsidies appearing that can close the gap between conventional fuels and SZEF. Notably, a combination of EU regulation (FuelEU Maritime and the inclusion of shipping in the EU Emission Trading Scheme) and the US IRA have the potential to cover much of the current cost difference along specific routes of US-EU routes[5]. Other initiatives such as the UK's Low-Carbon Hydrogen Agreement and Norway's Contracts for Differences for Hydrogen are examples of other upcoming support packages. Furthermore, the revision of the GHG strategy at MEPC 80 commits the IMO to adopt a policy package and a target of 5-10% zero and near zero emission fuel use by 2030. Both are mechanisms that can help to create a business case for early action. The window of opportunity for corporate action before regulation increasingly closes the gap is now only around a handful of years.

4 Methanol relies on carbon within its structure. Therefore, to be a genuine green alternative, carbon sourcing should avoid elevating atmospheric CO2 levels to achieve genuine environmental friendliness. DAC-based methanol production combines hydrogen from renewable electricity with CO2 captured from the air, thus is acknowledged as the only scalable long-term solution since it prevents the dependence on fossil resources and competition for biomass.

5 Policy pull and strategic opportunity scenarios from the NoGAPS Phase 2 report

1 Introduction

To set international shipping on an ambitious, zero emission trajectory aligned to 1.5°C, the sector must transition away from using fossil fuels, supported by the necessary technology and infrastructure to produce scalable zero-emission fuels (SZEF). Significant take-up of SZEF will be necessary for shipping to be on this trajectory. A general fuel transition can be considered to go through three distinct phases, ‘emergence’, ‘diffusion’ and ‘reconfiguration’. In the first phase research through pilots and innovation begins to increase the adoption of a novel fuel, which then rapidly increases in competitiveness through the ‘diffusion’ phase, to become the new dominant fuel in the ’reconfiguration’ phase, the shape of this transition is often referred to as the S-Curve shown in Figure 1-1.



Source: (Smith, Baresic, et al., 2021)

Figure 1-1 S-Curve relation to the decarbonization of maritime shipping

Currently, shipping is still in the emergence phase of the transition, and at least 5% of SZEF is required by 2030 (Osterkamp et al., 2021) to enable rapid scaling and mass adoption in the diffusion phase. This would equate to just over 0.6 EJ of energy demand which, depending on the green hydrogen-derived SZEF used, equates to either 29.8 MT of ammonia or 28.1 MT of methanol as examples. (Smith, Baresic, et al., 2021). This logic is embedded in the target-setting guidance for maritime transport published by the Science Based Targets Initiative (SBTi, 2023), which defines a sector-specific pathway that shipping needs to follow to remain below 1.5ºC of global temperature increase as defined by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018). More recently, the IMO has agreed an uptake target of at least 5%, striving for 10%, of zero and near-zero fuels and technologies by 2030 in the Revised Strategy on reduction of greenhouse (GHG) emissions from ships (IMO MEPC, 2023).

The Cargo Owners for Zero Emission Vessels[6] (coZEV) initiative is one example of early action in this emergence phase. CoZEV is a platform specifically designed for climate-leading customers of the shipping industry to come together to accelerate the transition to zero-emission maritime shipping. The coZEV 2040 Ambition Statement is a collective demand signal from over 20 cargo owners for a transition to zero-emission solutions on an SBTi trajectory - zero by 2040. The Zero Emission Maritime Buyers Alliance[7] (ZEMBA) is a first-of-its-kind buyers’ group within the maritime sector with the mission to accelerate commercial deployment of zero-emission shipping. ZEMBA's first request for proposals is seeking bids for shipping services that achieve at least a 90% reduction in greenhouse gas emissions compared to traditional fossil fuels on a lifecycle basis[8]. Fuel choice will address safety and land use concerns, particularly those that relate to biogenic substance.

[6] www.cozev.org
[7] www.shipzemba.org
[8] www.cozev.org/img/3.-Attachment-B-ZEMBA-LCA-Guidelines-and-Proposal-requirements.pdf

The role of freight purchasers in the emergence phase is important because it provides signals to the rest of the supply chain and enables them to commit to long-term goals while developing viable business models.

Another example is the First Movers Coalition launched at COP26 by the World Economic Forum and US special envoy John Kerry, which set a firm ambition for maritime carriers to shift at least 5% of deep-sea shipping to SZEF by 2030. Cargo owners also set the target of moving at least 10% of their volume of goods shipped internationally on zero-emission fuels by 2030 (US Department of State, 2021).

The IMO Revised Strategy on the reduction of GHG emissions from ships has resolved to have a net-zero target for international shipping by or around 2050, with interim reduction targets of 20%, striving for 30%, in 2030 and 70%, striving for 80%, in 2030 compared to 2008 levels on a well-to-wake[9] CO_2e basis (IMO MEPC, 2023). Although it may not be as ambitious as the 1.5ºC aligned SBTi, which received support from approximately 15 member states at ISWG-15 and requires reductions of 37% and 96% by 2030 and 2040 respectively (Shaw & Smith, 2023), this still sends a strong message to the industry that the only way forward is towards zero or near-zero emission assets. It is now riskier than ever before to not invest in such assets. Despite the positive signals and increase in levels of ambition, evidence shows that the window for shipping to achieve the 5% breakthrough target for SZEF is closing very quickly (Baresic et al., 2023).

As shipping is an international industry, decarbonisation will require a concerted global effort by all stakeholders. It will require significant changes in how bunker fuels are produced, delivered and used by ships. Financiers (PPA, 2023), investors (Climate Bonds Initiative, 2020), hull and machinery insurers (PPMI, 2023) and bulk charterers[10] (SCC, 2023) have started addressing this through industry-led initiatives driving accountability reduction and disclosure of carbon intensity of their activity.

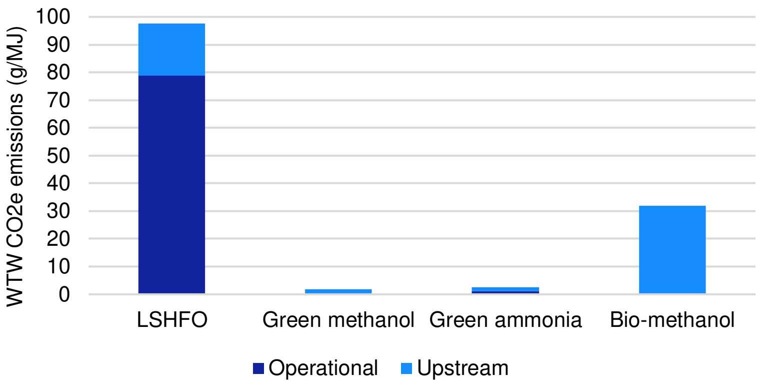
Several studies have shown that to achieve climate alignment of shipping, introducing and rapidly scaling the use of SZEF is required (DNV, 2021; Lloyd's Register & UMAS, 2019; MMMCZCS, 2021; Scarbrough et al., 2022; Smith, Baresic, et al., 2021). SZEFs contribute low or zero GHG emissions on a lifecycle basis and have good potential for supply and production scalability. One mechanism to reduce the cost gap between conventional fuels and SZEF is the introduction of market-based measures such as carbon pricing which the EU has implemented by including shipping within its emission trading scheme.

This study focuses on two SZEF as potential candidates: green ammonia and green methanol. Both of these fuels rely on renewable electricity for the production of their primary feedstock, green hydrogen. Unlike ammonia, which is a carbon-free fuel, methanol's molecular composition includes carbon. To prevent future additions of CO_2 to the atmosphere, the carbon required to form the fuel must be sustainably sourced, which can only be achieved through the still-developing technology of direct air capture (DAC).

Bio-methanol is also considered in this study for comparison purposes. However, it is not classified as a SZEF due to supply constraints and the impact of changes in land use associated with biogenic feedstocks (ETC, 2018) as shown in Figure 1-2. The same argument applies to the exclusion of biologically sourced carbon for methanol.

[9] Well-to-wake (WtW) refers to the inclusion of all lifecycle emissions related to the consumption of a fuel including production, transport and storage (referred to as upstream, or well-to-tank (WtT)) as well as the final onboard energy conversion (referred to as operational, or tank-to-wake (TtW)).

[10] Charterers hire vessels on a time or per voyage basis for transporting cargo.



Source: (IMO MEPC, 2022)

Figure 1-2 GHG emission comparison for maritime fuels

1.1 Study objective

The above-mentioned transition will have an associated cost due to several elements including new propulsion and fuel containment systems and increased cost of fuel. This report sets out to provide initial estimates around the potential costs associated with provision of zero emission container shipping. The key objectives of this report are:

- Identification of routes with high potential for green container shipping corridors.
- Definition of technical and operational characterisation of typical vessels operating on identified routes.
- Estimation of additional cost differential associated with zero emission shipping through total cost of operation (TCO) analyses from the present to 2050.
- Estimation of carbon price required to close price gap with conventional fuel.

2 Modelling methodology

In order to estimate the cost differential associated with switching to SZEF, the following steps were undertaken:

- Selecting container routes with potential for early adoption of SZEF based on shipping activity and domestic policy.
- Characterisation of a vessel and associated operating profile for a container liner on these routes.
- Running TCO analysis based on the inputs from the elements above to estimate a unit cost (per twenty-foot equivalent unit (TEU)) for decarbonising freight activity.

This section will describe the methods applied to undertake these steps.

2.1 Route selection

The routes selected come from the analysis of voyage-based activities of vessels with a view of identifying routes with the highest decarbonisation potential. This type of analysis builds an evidence base for policymakers, with the aim of informing decisions on optimal onshore investment and vessel technology based on current operational trends. Routes that are most likely to kick-start the transition are identified as first mover routes by analysing the geography of areas and ports, the vessel types and sizes, and energy demand for their decarbonisation.

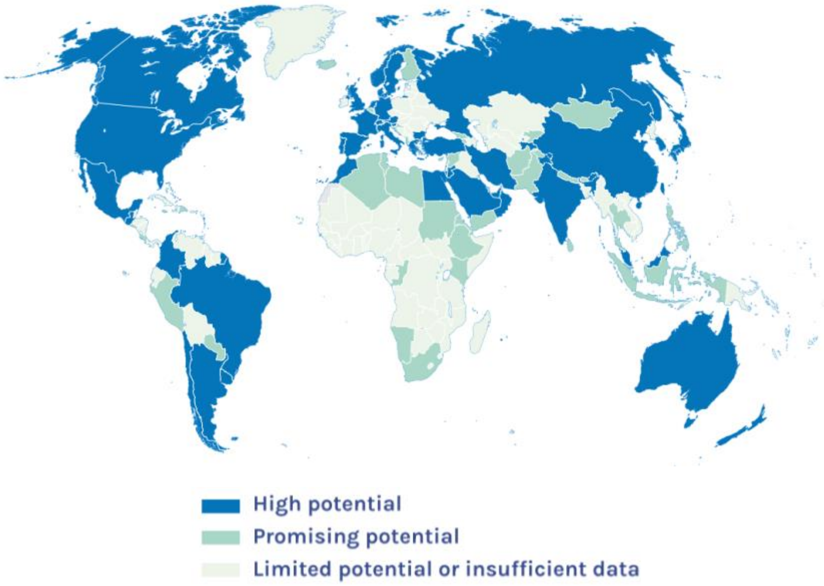
The likely key determinants for first mover action will be: 1) the cost and availability of SZEFs; and, 2) the nature of shipping operations, in terms of geography and complexity. There are geographical variations in the conditions for producing hydrogen and hydrogen-derived fuels (fundamental to SZEFs). Early action, therefore, will be enabled by a good potential to produce competitively priced, decarbonised (e.g., blue/green) hydrogen alongside access to significant shipping activity. This analysis was the focus of work undertaken by the World Bank and UMAS (Englert et al., 2021). A summary of some of the key results identifying countries well positioned for this pre-condition is shown in Figure 2-1).

However, production only constitutes the supply side and will not, in itself, enable emergence unless it can reach significant demand volumes. Matching this potential to feasible sources of demand is the next challenge. In practice, demand will likely come from multiple industries, with shipping in places "piggy-backing" on other sectors' need for green energy carriers and in some cases being the key off-taker of hydrogen (Smith, Shaw, et al., 2021). This analysis simplifies that reality by looking only at shipping demand.

Based on the analysis as described above carried out using UMAS' green corridor algorithm, four routes were identified to be prime candidates for decarbonisation due to the high volume and regularity of container transport work, identified using Automatic Identification System (AIS) data as presented in Smith, Baresic, et al., 2021.These can be divided into deep sea and short sea shipping routes (Table 2.1). This report will present results for the Asia - US route and the Chinese coastal routes as they are suitable representations of deep-sea and short-sea shipping.

Table 2.1 Route characterisation

Deep sea	Short sea
Transpacific: Shanghai – LA	China domestic: Coastal China
Asia – Europe: Vietnam – Rotterdam	US domestic: Hawaii – LA



Source: (Englert et al., 2021)

Figure 2-1 Analysis of different countries' hydrogen production potential

The two routes that will be focused on in this report are shown below in Figure 2-2 and Figure 2-3. These profiles are very different in terms of length and more importantly, the type of vessel that operate on each.

Figure 2-2 Transpacific: Shanghai – LA

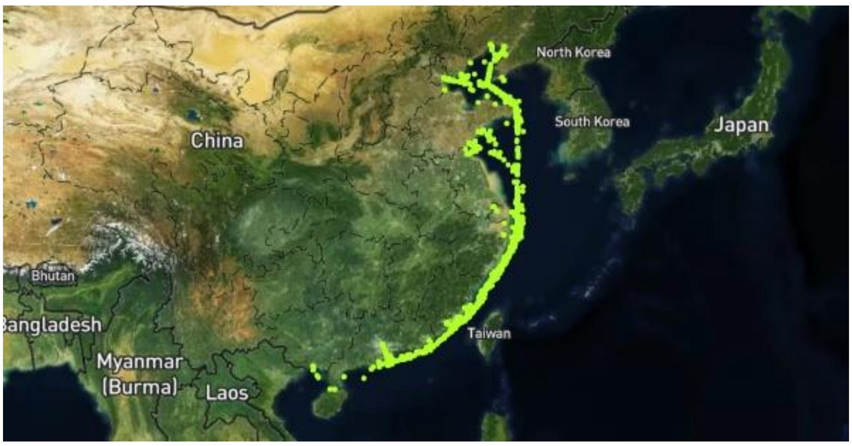


Figure 2-3 Asia domestic: China coastal route

2.2 Route based vessel characterisation

Having selected the routes under analysis, vessels with typical characteristics are defined based on existing operational trends and assumed performance into the future. The transpacific route analysis is carried out for a 15,000 TEU vessel while for the route in China it is carried out for a small feeder container vessel with a capacity around 4,000 TEU.

Table 2.2 Vessel technical characteristics based on route

Vessel	Transpacific 15,000 TEU	China coastal 4,000 TEU
Size (TEU)	14,568	3,856
Installed power (kW)	49,000	18,310
Design speed (kn)	22.5	21.8
Operational speed (kn)	19.01	12.29
Range (nm)	14,110	2,948
Voyages per year	17	48
LSHFO consumption (tpd)	99.3	16.0
MDO consumption (tpd)	21.8	8.3
Ammonia consumption (tpd)	198.2	40.7
Methanol consumption (tpd)	186.4	38.3

Table notes: 1. The fuel consumption values for ammonia and methanol do not include pilot fuel that is required for operation. Consumption values are presented in tonnes per day (tpd). 2. Marine diesel oil (MDO) consumption includes that from operation in emission control areas as well as in auxiliary engines and boilers. 3. Range is defined as "the longest distance covered in a single year by any of the vessels that operated the route"

2.3 Total cost of operation modelling

The economic viability of SZEF expressed through TCO is the sum of the additional costs relative to a reference vessel operating under the same conditions. Given the purpose of this analysis is to consider different fuelling options, the reference vessel is one that operates using conventional heavy fuel oil to power a two-stroke slow speed diesel engine. The TCO is a function of the additional annualised capital (CAPEX) and operational (OPEX) expenditures when compared to the reference vessel per year as follows (Figure 2-4):

- Annualised CAPEX:
  - Machinery installed, e.g., main engine and auxiliary engine
  - Energy efficiency technology installed (e.g., hydrodynamic technologies such as contra-rotating propellers and air lubrication)
  - Onboard bunker storage
  - Pollution control devices[11] if not included in the machinery costs

- Annualised OPEX:
  - Alternative fuel costs
  - Carbon costs under market-based measures such as carbon pricing
  - Revenue loss due to reduction of cargo carrying capacity due to fuel storage
  - Operation cost of the pollution control devices (e.g. urea)

[11] These may include selective catalytic reduction (SCR) or exhaust gas recirculation (EGR)

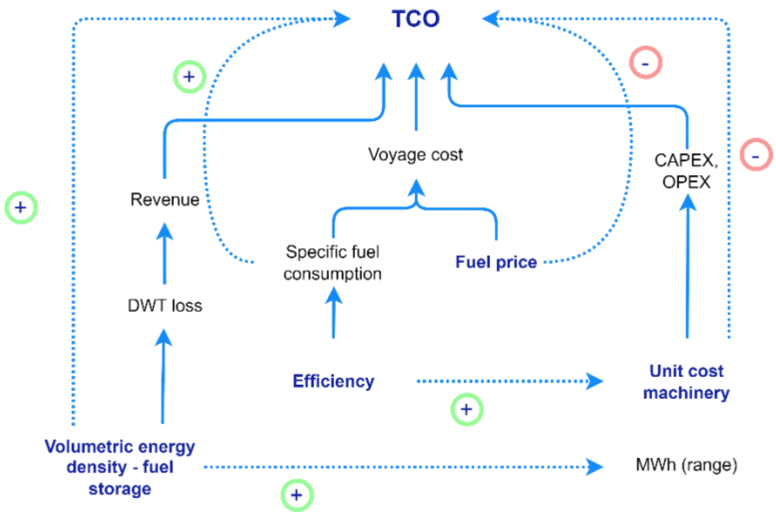


Figure 2-4 Cost components considered in TCO modelling

Thus, TCO can be described as illustrated below in Figure 2-5. Applying this method to different scenarios of cost, policy, fuel availability and other variables, the viability of different fuel and technology alternatives can be evaluated and compared. Further details about each of these cost components and variables can be found in Appendix A.

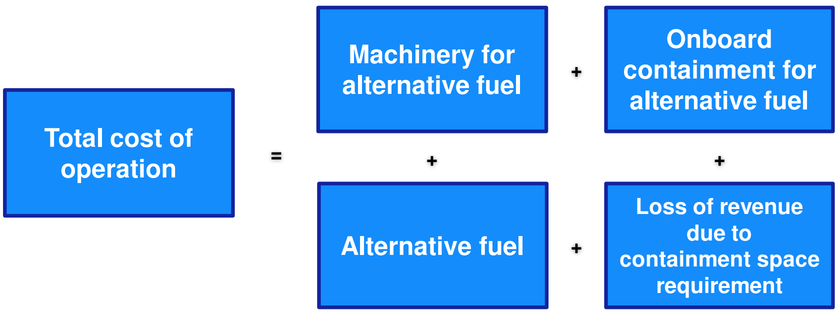


Figure 2-5 Components of cost considered in TCO analysis

2.4 Decarbonisation unit cost impact determination

For this study, the fuels considered are green methanol and green ammonia. Therefore, in order to obtain an estimated additional unit cost for zero emission freight, once the annual TCO is established, this is divided across the total annual number of TEU transported on the route being considered. The number of TEUs is estimated based on the number of voyages that can be completed where the voyage length is the maximum voyage length derived from AIS data and the average utilisation. The cost impact can be expressed as shown in Figure 2-6

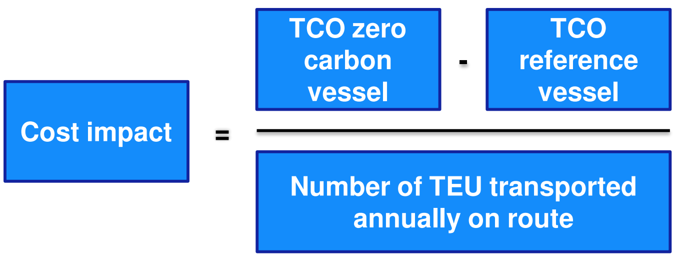


Figure 2-6 Components of unitised TCO cost per TEU

3 Results

3.1 Asia – US Transpacific: Shanghai – LA

The results of the TCO analysis (Figure 3-1) show that the cost differential between the reference vessel and zero-emission vessels is highest between 2020 and 2030 due to the fuel cost which then becomes less expensive between 2030 and 2050. The fuel cost from green methanol is consistently higher than that for green ammonia mostly due to the cost of DAC.

The drop in price for green ammonia and methanol in this decade is attributed to the assumption that the price of renewable electricity will continue to decline rapidly especially in countries like the US and China which have been identified as prime candidates for renewable hydrogen production (Englert et al., 2021).

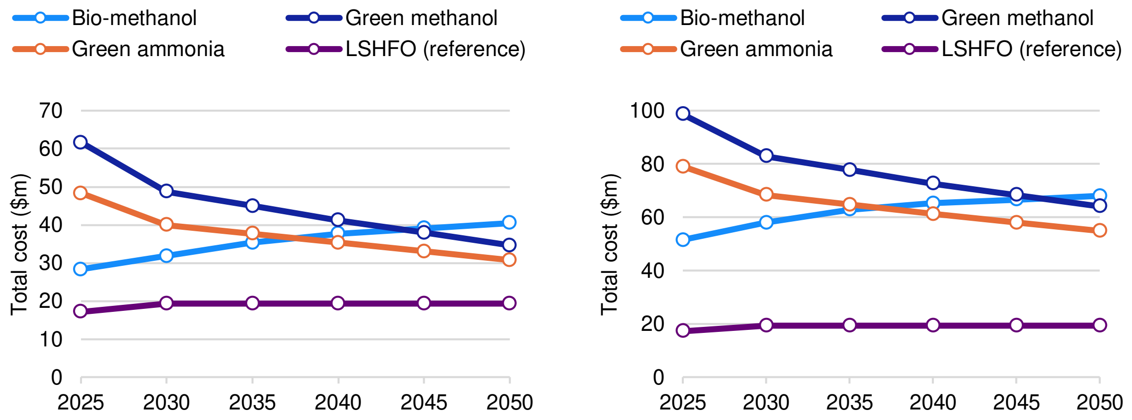


Figure 3-1 Transpacific - annualised TCO under low (left) and high (right) fuel cost scenarios

Beyond 2030, the constraints around bio-based fuels due to increased demand and restricted supply will make all biofuels vulnerable to high cost increases which makes them less viable than green ammonia by around 2035 (IMO MEPC, 2022). Figure 3-2 illustrates the assumed regional fuel cost assumptions with specific projections for renewable electricity costs in the US (IEA, 2021). It should be noted that fuel costs are derived from a technology based levelized cost perspective that does not include subsidies. It is understood that government support such as the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act in the US may greatly reduce the cost of hydrogen production (Zhou, 2023).

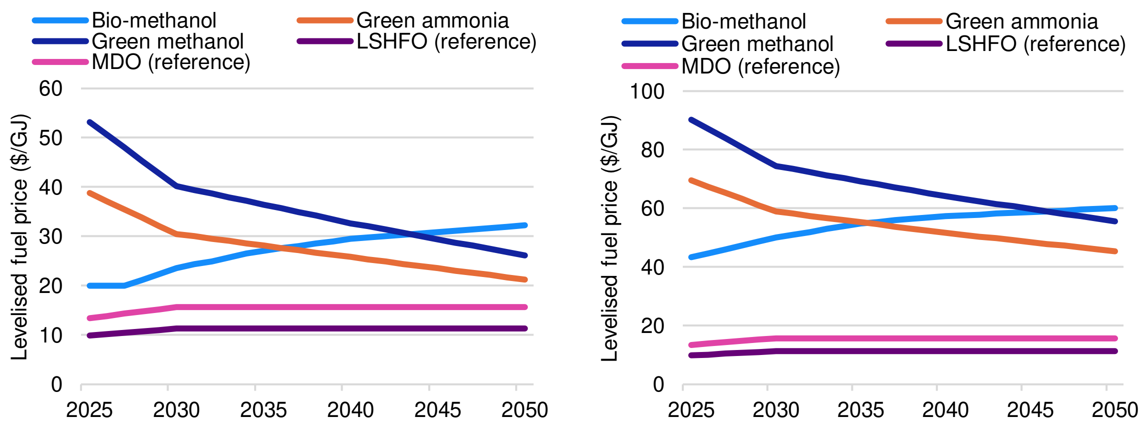
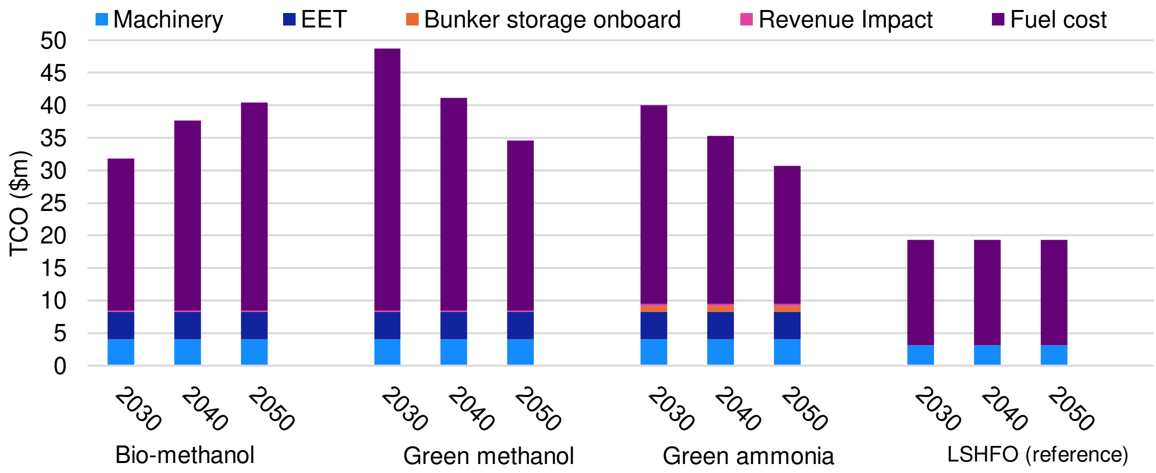


Figure 3-2 Transpacific - regional fuel cost projections for low (left) and high (right) price scenarios

A significant spread between low and high fuel cost scenarios is attributed to uncertainties surrounding fuel production costs, notably renewable electricity costs, and to a lesser extent, the rate at which technologies scale. Breaking down the cost components of TCO, it is evident that fuel cost is the main driver under both low and high fuel cost scenarios (Figure 3-3). For green fuels, bunker costs account for 75% to 90% of TCO at 2030 across low and high fuel cost scenarios whilst for LSHFO this is stable at 85%. Further details regarding CAPEX costs and revenue impact can be found in Section 3.3.1.



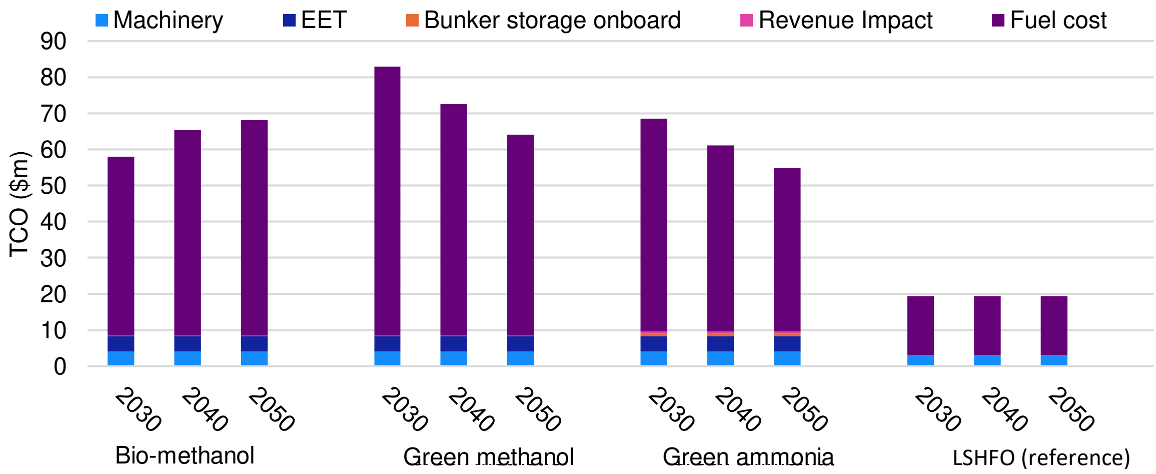


Figure 3-3 Transpacific - annualised TCO component costs under low (top) and high (bottom) fuel cost scenarios

The additional cost associated with switching to zero-emission transport translates to a unit cost increase in container transport as illustrated in Figure 3-4. Therefore, the cost differential for zero emission freight transport per TEU ranges between $90 to $450 per TEU above the reference values for conventional freight in 2030. This gap consistently closes to a range of $115 to $380 in 2040 and below $100 to $350 at 2050.

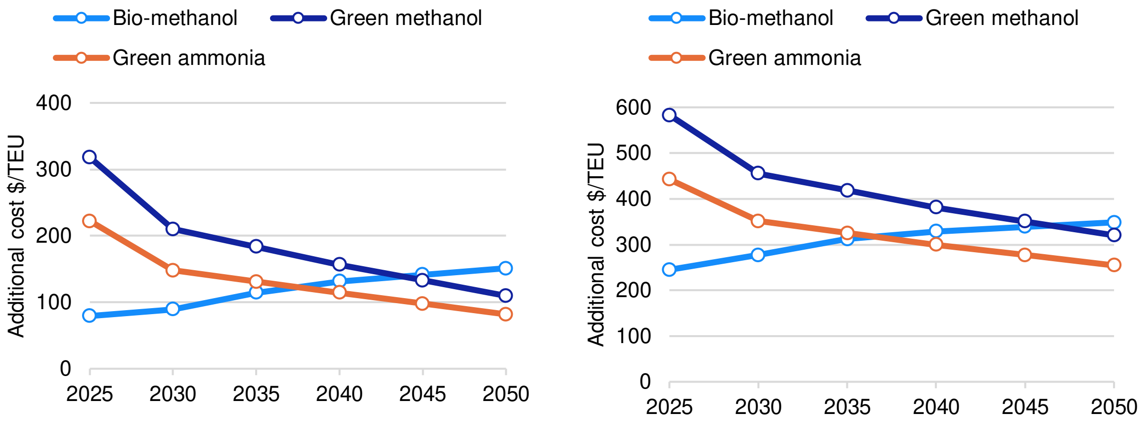
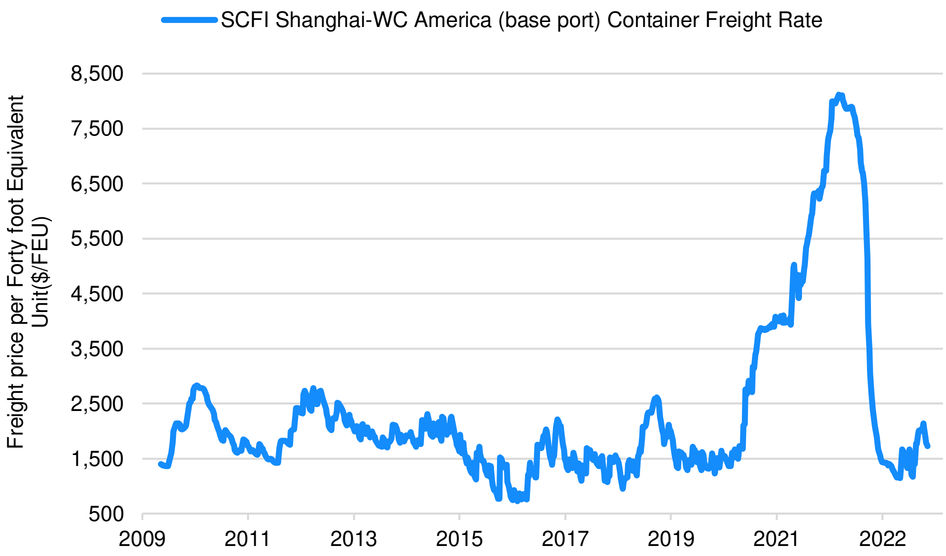


Figure 3-4 Transpacific - cost impact on TEU transportation under low (left) and high (right) fuel cost scenarios

To provide an indication of the impact that these costs would have in the container freight market, the Shanghai Containerized Freight Index (SCFI) Shanghai to West Coast of America Container Freight Rate $/FEU (forty-foot equivalent unit) spot freight price index can be used as a reference. Its average for the period covering between 2010 and 2023 (excluding the pandemic period between March 2020 to October 2022) can be estimated at $1746 per FEU. For the purposes of this report it will be assumed that the price per TEU is half that reported by the index, which gives us an average of $873 per TEU see Figure 3-5.



Source: Clarkson Research Services Limited 2023

Figure 3-5 Historical values of the "Shanghai Containerized Freight Index -SCFI " for the spot rates of the Shanghai to US West Coast ports of LA, Long Beach and Oakland in USD/FEU.

This means that a 2030 range of additional total operation costs between $90 – 450$/TEU, represents between 17% and 52% of the freight rates reported in the index (Figure 3-6). As mentioned previously, these estimates don't include fuel subsidies or regulatory incentives, thus can be seen as a worst case scenario that relies exclusively on projected technology savings. Furthermore, it is worth considering that the high costs seen through the pandemic illustrate the high elasticity of the freight markets to absorb dramatic increments in costs. Increases that in the future are likely to be driven by the continuous stepping up of regulations.

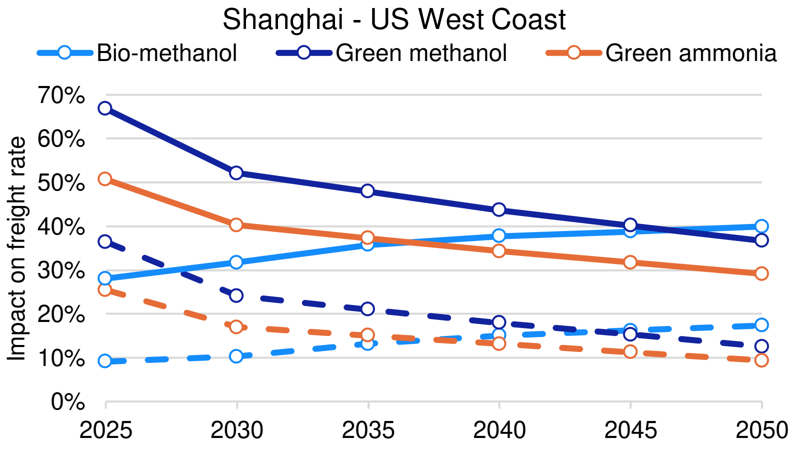


Figure 3-6 Transpacific (Shanghai - US West Coast) - impact on freight rates under low (dashed) and high (solid) fuel cost scenarios

A $150 to $550 per t$CO_2$ carbon price would be required in 2030 depending on the fuel cost assumptions applied. Findings from other work suggest that a price of $250 to $350 would be enough to close this gap which fits with this study as these figures lie in the middle of the range considered (MMMCZCS, 2021; Trafigura, 2020). By 2035, green ammonia is more viable than bio-methanol in both high and low fuel cost scenarios. At higher fuel costs, bio-methanol is not economically viable beyond the mid-2020s. This study shows a declining carbon price as it only considers the difference between zero emissions fuel and conventional fuel TCO based on geographic, fuel and ship related constraints in the modelling. Analysis carried out on a system/sector wide perspective, carbon price is usually shown to be increasing over time (Baresic et al. 2022) because a higher carbon price is required to reduce emissions from more costlier abatement options and last remaining opportunities.

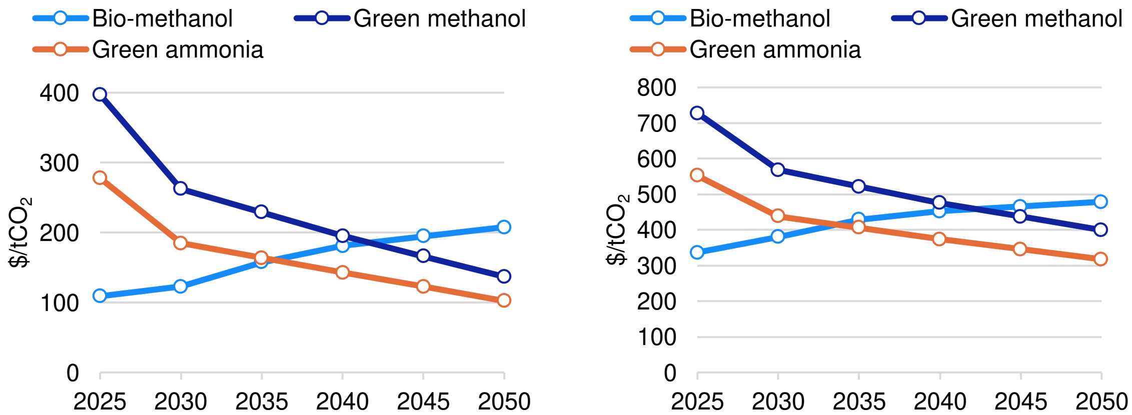


Figure 3-7 Transpacific - carbon price to close gap between LSHFO and green fuels under low (left) and high (right) fuel cost scenarios

3.2 Asia domestic: China coastal route

Being a smaller vessel, the TCO costs are lower overall than for larger vessels however, fuel cost trends are similar due to the base costs associated with production which are not significantly altered with the exception of the price of renewable electricity which continues to decrease over time. The results of the TCO analysis (Figure 3-8) show that the cost differential between the reference vessel and zero-emission vessels is highest between 2020 and 2030 due to fuel cost which then becomes less expensive between 2030 and 2050.

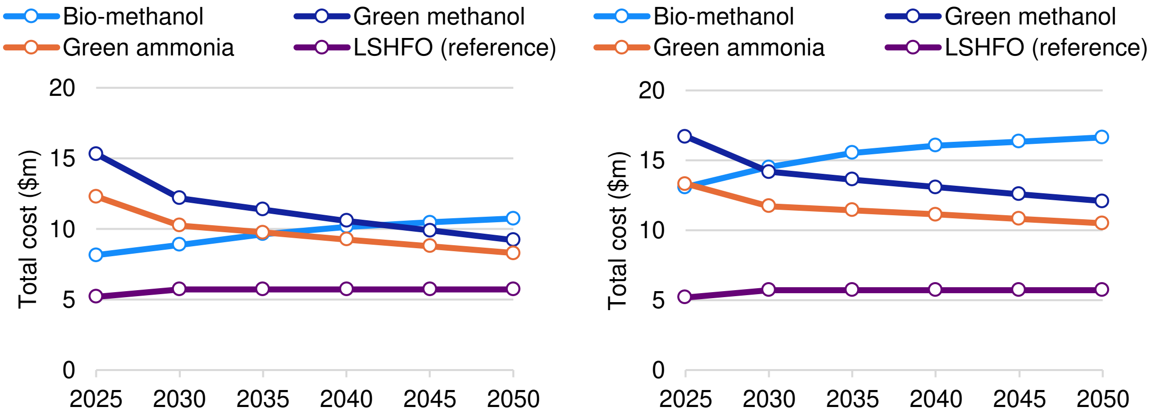


Figure 3-8 China coastal - annualised TCO under low (left) and high (right) fuel cost scenarios

Once again, the fuel cost from green methanol is consistently higher than that for green ammonia due to the cost of DAC. Bio-methanol is restricted by supply in any part of the world and will therefore become less affordable as competition increases from other sectors especially at the high cost scenario (Figure 3-9). The cost difference for other fuels is less due to envisaged drop in renewable electricity prices especially considering the steep ramp up of production seen in China. Energy supply from wind and solar in China increased by 670% between 2010 and 2020 compared to just 275% over the same period in the USA (IEA, 2023a, 2023b). This increase in production has been seen despite the policy and regulatory environment being lacking in several areas that could increase the rate of capacity building (Song et al., 2022).

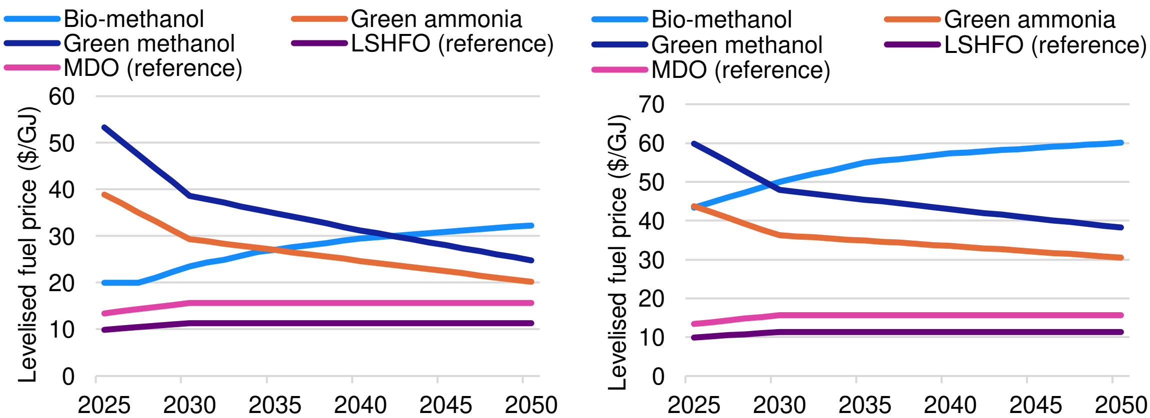


Figure 3-9 China coastal - regional fuel cost projections for low (left) and high (right) price scenarios

Fuel costs account for the majority of TCO as expected however, due to the lower price gap between conventional fuels and SZEF especially in the low cost scenario, the proportion of TCO estimated for fuel is similar across fuels (Figure 3-10). For example, fuel accounts for 66% of TCO under for the reference vessel and goes from 61% to 52% in the case of ammonia between 2030 and 2050. Thus, while CAPEX will be higher, OPEX would only be marginally higher thus reflected in a smaller cost differential on transport cost.

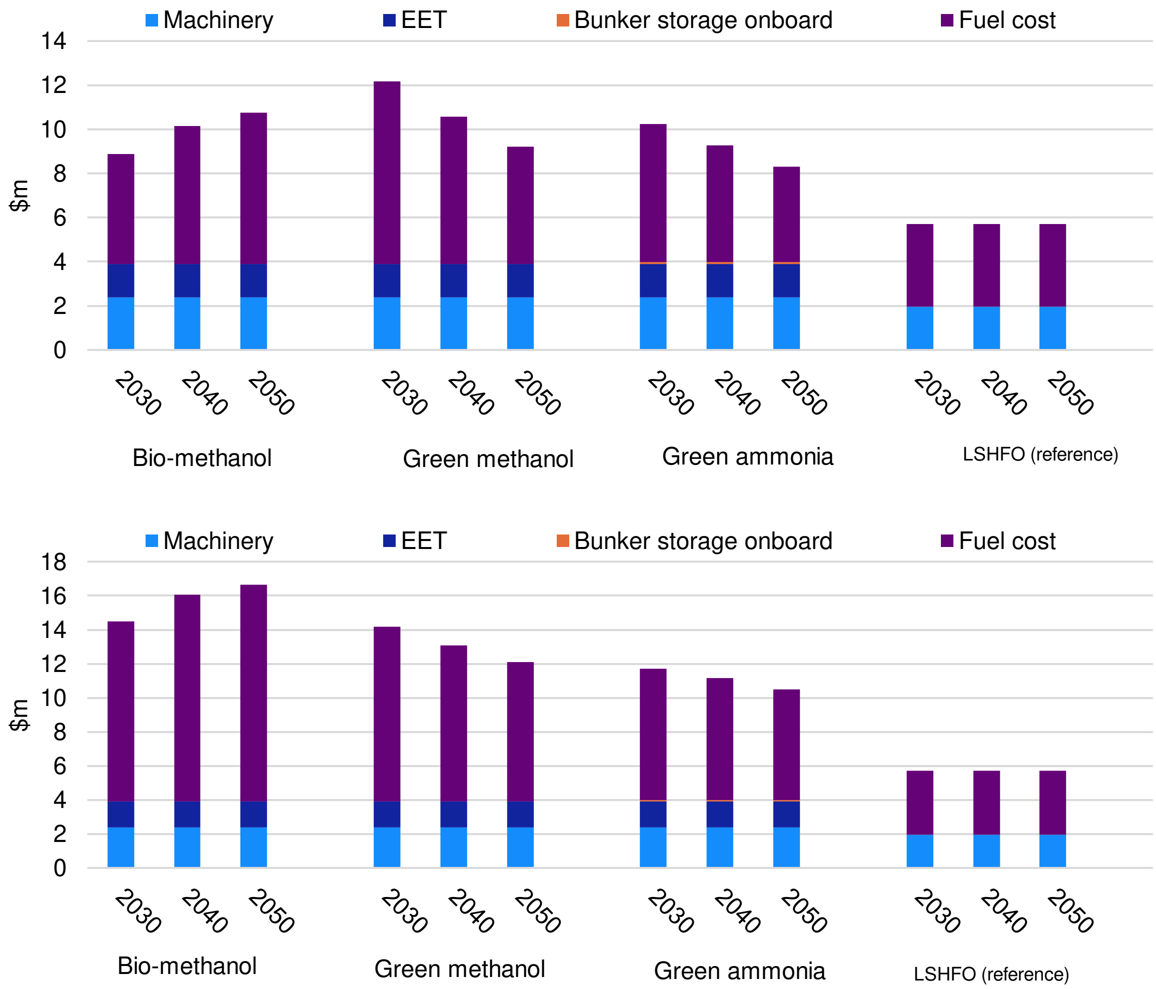


Figure 3-10 China coastal – annualised TCO component costs under low (top) and high (bottom) fuel cost scenarios

Considering this cost differential, the additional cost associated with switching to zero-emission transport translates to a unit cost increase in container transport as illustrated in Figure 3-11.

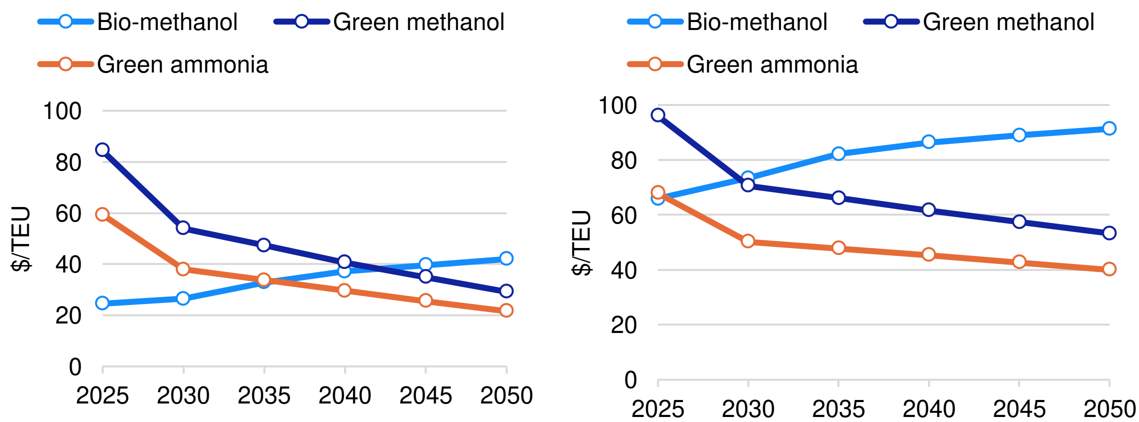
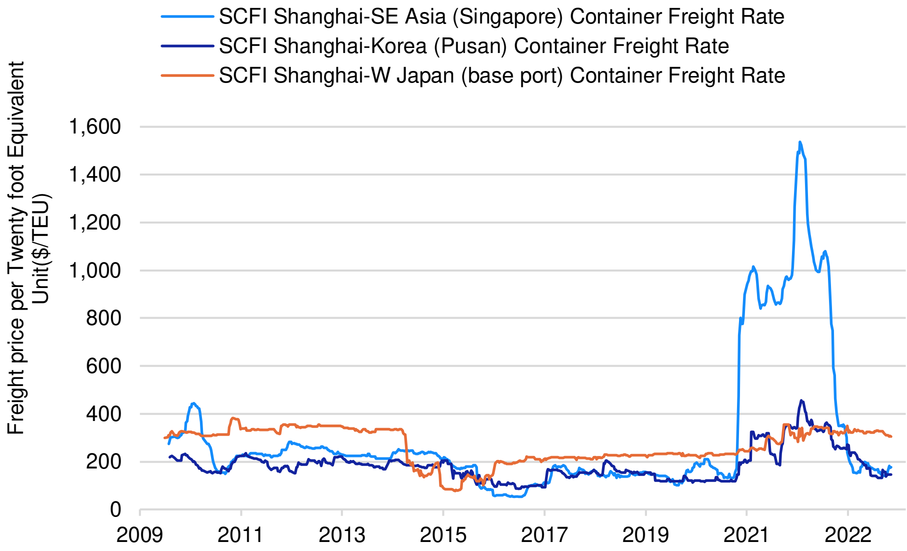


Figure 3-11 China coastal – cost impact on TEU transportation under low (left) and high (right) fuel cost scenarios

To provide a reference for comparing the estimated additional Total Cost of Ownership (TCO) costs, we examined three SCFI container freight rate indexes in the region: Shanghai – Singapore, Shanghai – West Japan, and Shanghai – Korea. While these may not precisely reflect domestic freight prices in China, they are considered to provide an indication of freight price ranges in the region.



Source: Clarkson Research Services Limited 2023

Figure 3-12 Historical values of the "Shanghai Containerized Freight Index -SCFI" for the spot rates of the Shanghai to SE Asia (Singapore), Shanghai to Korea (Pusan) and Shanghai West Japan (Osaka/Kobe) in USD/TEU.

Excluding the pandemic period from March 2020 to October 2022, we can calculate an average of $206 per TEU over the last decade for all three intra-Asian routes. Using this value as the reference freight price and incorporating the TCO costs for the China coastal route (as shown in Figure 3-12), we can estimate the additional proportion that decarbonizing the route would contribute to this historical freight price estimate. The results indicate that achieving decarbonization for the route would require a freight increase ranging between 9% and 17% by 2030 (Figure 3-13). When compared to the results from the Transpacific route, these findings demonstrate that efficiently operated routes in regions with strong renewable energy potential and low fuel costs could experience lower additional operating costs for decarbonization, potentially aligning with shippers' willingness to pay thresholds estimated to be between 5% and 10% (van Gogh et al., 2022).

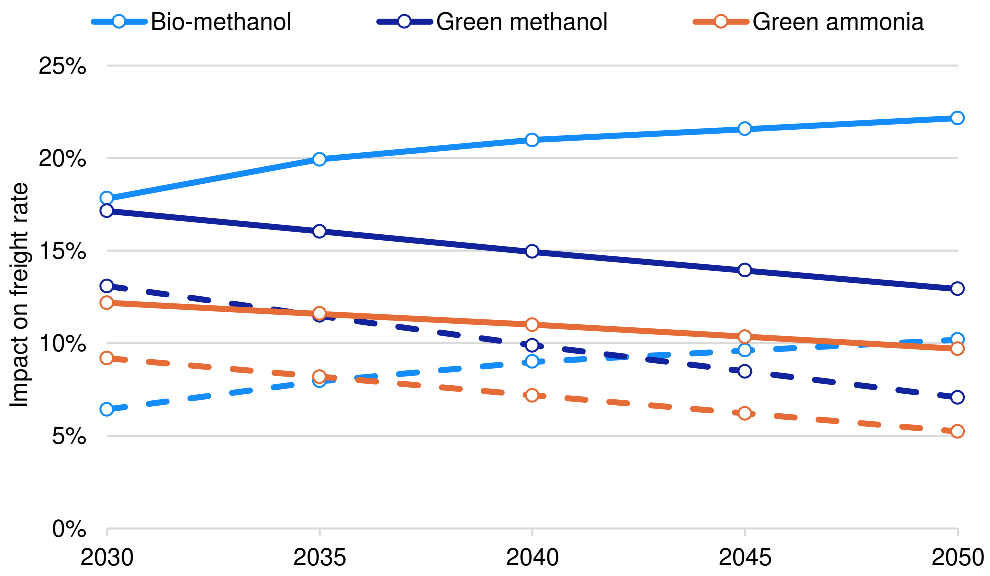


Figure 3-13 China coastal – impact on freight rates under low (dashed) and high (solid) fuel cost scenarios

When considering the scale of a carbon tax that could close the gap between conventional and SZEF, Figure 3-14 presents modelled findings for the candidate fuels up to 2050. Due to its potential price competitiveness, green ammonia would require the smallest carbon price to close the gap which would be around \$250 per tCO_2 on average and more cost competitive than bio-methanol by 2035.

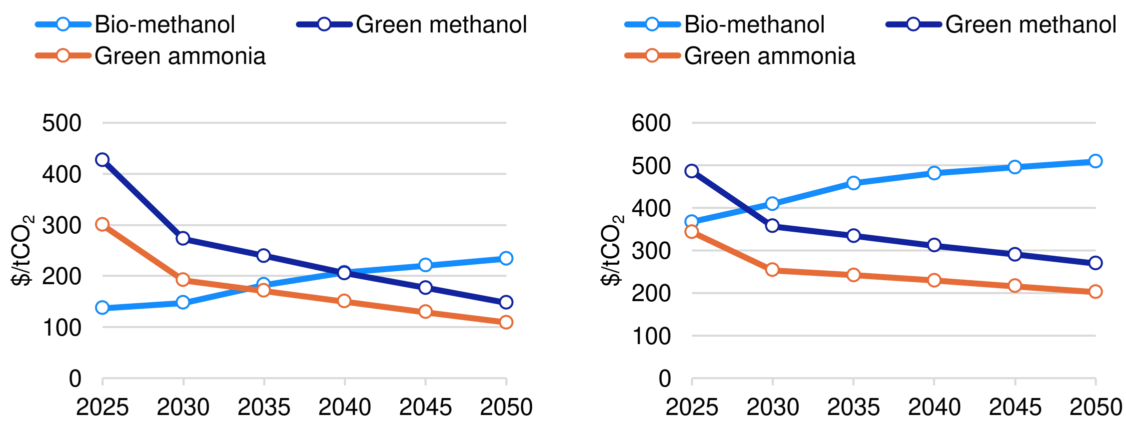


Figure 3-14 China coastal – carbon price to close gap between LSHFO and green fuels under low (left) and high (right) fuel cost scenarios

3.3 Further analysis of cost drivers/exploring sensitivities

3.3.1 Vessel capex costs

Figure 3-15 gives more details around the CAPEX values assumed for building vessels with the specifications that would be suitable for the routes discussed in this study. For the larger transpacific vessel, EETs and fuel storage (in the case of green ammonia) are the distinguishing costs when comparing to the reference fossil fuel vessel which make vessels 2.4 to 2.7 times more expensive to build. The difference in cost for the smaller vessel is in the range of 1.8 times that of the cost a conventional fuel vessel. It should be noted that Figure 3-15 does not include the impact of revenue loss from increased requirement for fuel storage space.

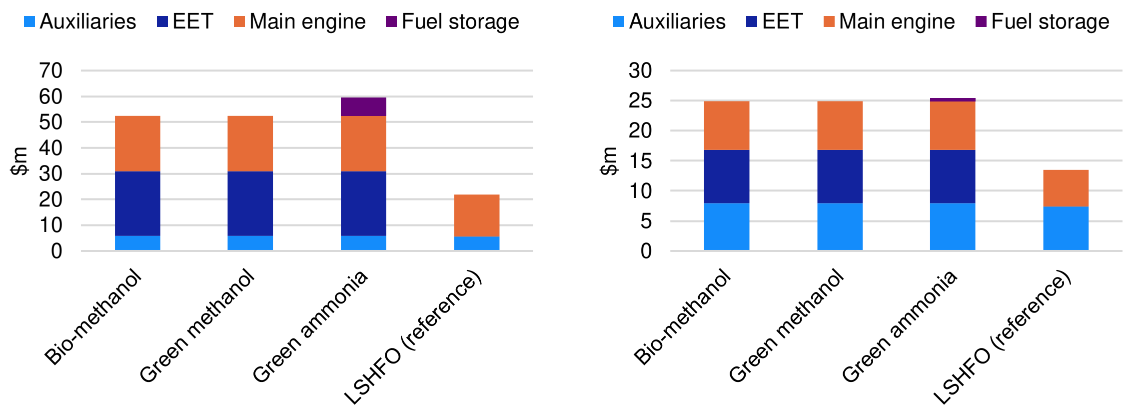
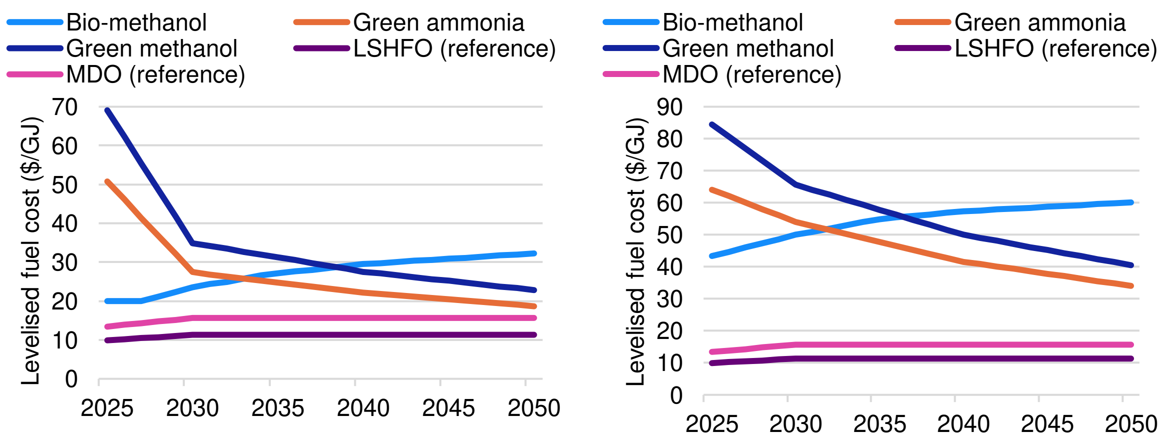


Figure 3-15 Vessel CAPEX cost components for transpacific (left) and Asia domestic (right) routes

3.3.2 Fuel cost breakdown

Throughout this study, green methanol has been shown to have a higher cost when compared to green ammonia due to the requirement of DAC. This is yet an immature technology whose associated costs and performance remain highly uncertain. This makes the cost ranking of green ammonia vs green methanol vessel a trade-off between the additional capex of a green ammonia vessel configuration vs the additional fuel cost of green methanol. Figure 3-16 presents the assumed global trends with regards to fuel cost for a low and high cost scenario. No carbon prices are included in this study which provides an opportunity to quantify the required carbon price to close the gap for SZEF as shown in Section 3.1 and 3.2. Similarly, no subsidies were included in the modelling of fuel costs.



Source: IMO MEPC (2022)

Figure 3-16 Global fuel cost projections for low (left) and high (right) price scenarios

Figure 3-17 presents the different cost elements associated with the production of green fuels from renewable electricity in 2030. For both the fuels, the major cost component is around the cost of electricity and the electrolysis process, and a reduction in these costs is associated with the declining total cost of the fuels over the next two decades (Figure 4-2). As can be seen, DAC makes up around 15% of the total cost of production for green methanol which leads to high uncertainty around fuel cost due to its technical maturity. Technologies involved in green ammonia production are already operating at scale in other industries such as fertiliser production which reduces the uncertainty around cost.

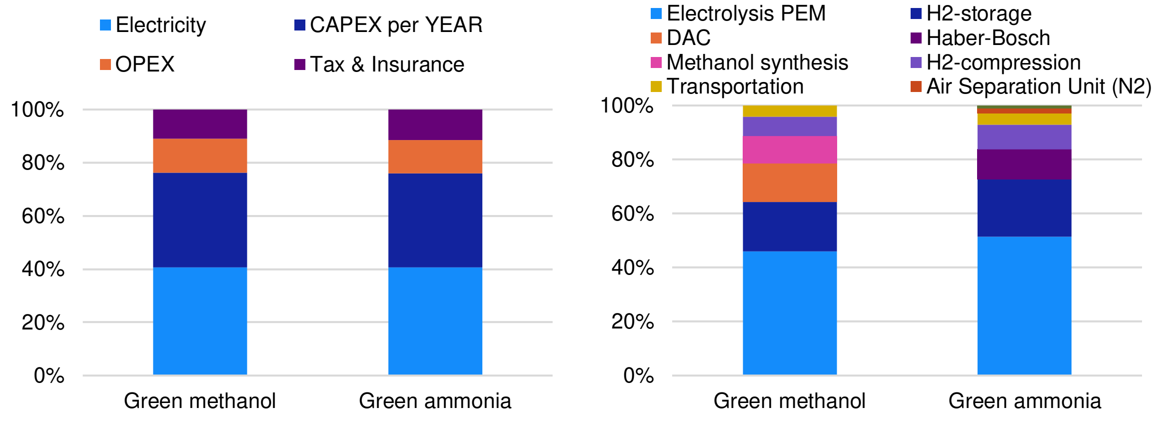


Figure 3-17 Fuel cost (left) and production cost (right) components of green fuel

4 Discussion

In the early phases, especially the emergence phase of the transition, the cost for zero emission shipping will be shared across the maritime value chain. In particular, cargo owners' willingness to pay for zero emission shipping services will be a key driver in kickstarting the market for these services, while regulation that would reduce the cost gap (either in the form of standards or economic instruments – see Baresic et al., 2022) lags behind. As confidence builds in the transition and international and regional regulation catches up, the share of the cost burden would be expected to reduce over time (Figure 4-1). It is crucial that the stand-off on stakeholders' (industry, policy) actions, where each stakeholder places conditions on other stakeholders, is resolved (Smith, Baresic, et al., 2021). The IMO has agreed having a specific zero emission fuel uptake targets in 2030 as well as interim targets at 2030 and 2040 for emission reduction in the Revised Strategy which will support the shift from emergence into diffusion and reconfiguration (IMO MEPC, 2023).

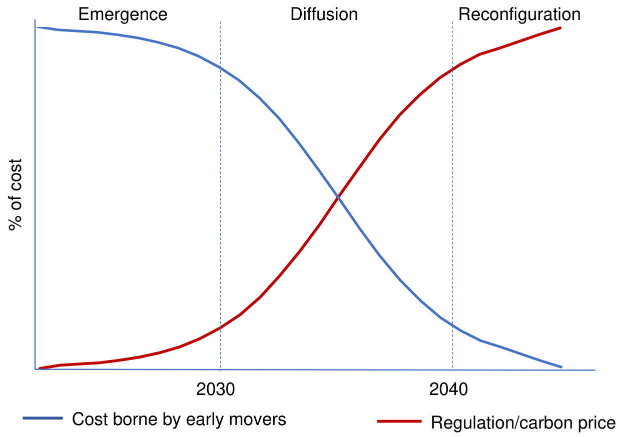


Figure 4-1 Illustrative spread of cost over time as transition to zero emission shipping evolves

The results from the modelling presented in this report set out to evaluate estimated costs for early movers as well as the price gap that would need to be filled by a carbon price or command and control measures. The cost differential for transport customers can be applied per TEU based on the route with a spread that represents a range of high and low fuel cost scenarios over time for different SZEF (Figure 4-2). The cost differential between a conventional low sulphur heavy fuel oil (LSHFO) fuelled ship and a zero-emission ship for decarbonising container transport in 2030 ranges between $90 to $450 per TEU between Shanghai to LA and $30 to $70 per TEU on the Chinese coastal route. The cost differential between the two fuels in the deep-sea route results in approximately $60/TEU in the low fuel cost scenarios and $100/TEU in the high fuel cost scenarios, with green ammonia consistently being cheaper than green methanol.

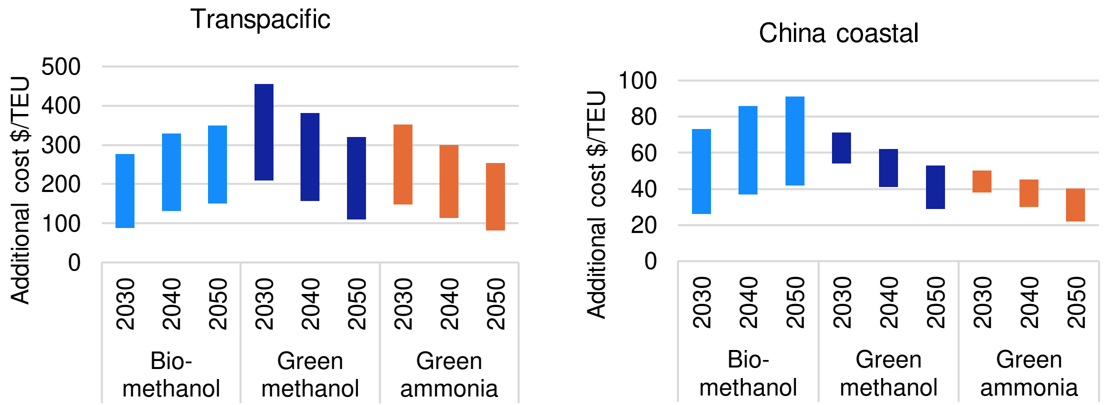


Figure 4-2 Summary of findings in $/TEU cost differential for zero emission transport

Figure 4-3 gathers the prospective carbon prices required to close the gap between conventional fossil fuels and SZEFs on the two routes for the prospective fuels. This becomes increasingly important as the IMO discusses the basket of measures that are to be implemented from 2025 onwards in order to ensure the Revised Strategy is achieved. A carbon pricing mechanism has good potential for having a two-fold effect of closing the cost gap while raising funds for in-sector technological development and ensuring a just and equitable of the transition (Baresic et al., 2022). It should be noted that the cost of carbon to close the gap with zero emission fuels is related to fuel consumption while the cost differential considers all the TCO cost element.

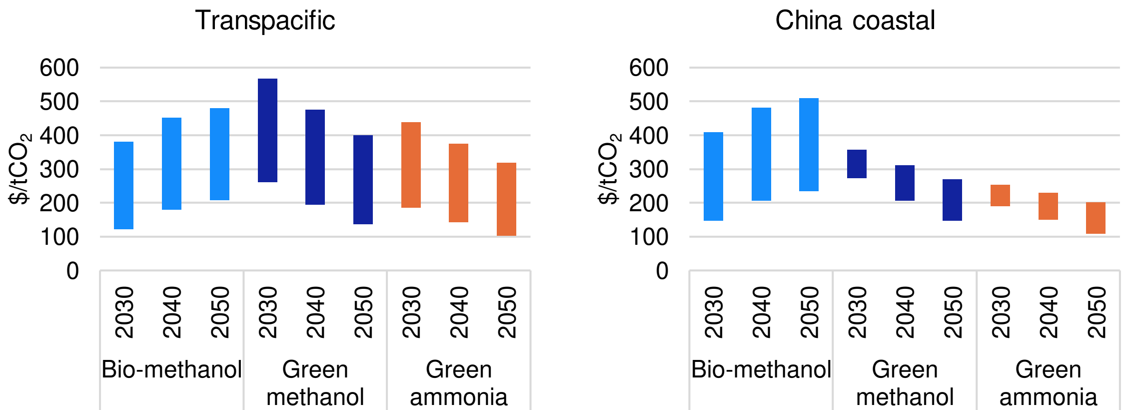


Figure 4-3 Summary of findings in $/$CO_2$ carbon price to close gap between LSHFO and zero emission fuel

4.1 Comparison with other studies

The TCO analysis was compared with a recent comprehensive study by EMSA (Laursen et al., 2022). The study estimated TCO for ammonia internal combustion engine (ICE) powered vessels for 2021, 2030 and 2050 for various regional estimates of production cost of green ammonia. In their analysis, they estimated that TCO for ammonia powered vessels is between 2 and 3.5 times that of LSHFO reference vessel in 2030, which is broadly aligned with the analysis conducted in this study (between 2 and 4 times).

Comparing absolute estimates of TCO, there are significant differences between this study and Laursen et al. (2022). Looking specifically at the Vietnam-Rotterdam route, the same class vessel from Laursen et al. (2022) is approximately twice the TCO cost of that estimated in this study. This is driven by two key factors: vessel specification and fuel cost. For the former, Laursen et al. (2022) used the average vessel from the Fourth IMO GHG Study (Faber et al., 2020), albeit with an improved energy efficiency performance. In this study, a best-in-class vessel operating similarly to the current vessels on the route is assumed along with installed energy efficiency technologies (EET). The effect of choosing best in class was a reduction in installed power of approximately 30% as compared the average installed in the fleet in 2018. This is supported by a comparison of the Honololu route vessel, where the projected TCO is broadly aligned with (Laursen et al., 2022) as the vessel operating that route is a relatively high-powered vessel coupled with a high operational speed.

The second impacting factor, fuel cost, also shows significant differences on the projected minimum price of ammonia. Laursen et al. (2022) estimates a minimum price about 50 to 60% greater than those used in this study. The regions they focus on are different to those used in this study. Regional variations in fuel costs are of the same scale in both this study and Laursen et al. (2022) as the differences between the studies. For example, the maximum production cost of ammonia and methanol in the USA in this study is significantly (up to 50%) higher than the global average price.

The next comparison we undertook was to benchmark fuel costs projections against other studies beyond the study above. MMMCZCS' NavigaTE model (MMMCZCS, 2022a) provide a single global price for ammonia which is about mid-range of this study's estimates in 2030 and 2050 but aligned with the minimum price of those Laursen et al. (2022). It should be noted that Laursen et al. (2022) minimum prices for ammonia vary by up to $10/GJ depending on the region of production. For green methanol, MMMCZCS (2022b) provide a single global price of $65/GJ in 2030 which is closer to the maximum price of that used in this study, although still within the range. This is similarly the case for 2050. Using point source rather than DAC in the production of green methanol, (MMMCZCS, 2022b) estimates(MMMCZCS, 2022b) estimates that the price of green methanol reduces by $11/GJ in 2030 and $5/GJ in 2050, but still within the range of prices provided in this study. The key driver of the price of fuel, highlighted in both (Laursen et al., 2022) and (MMMCZCS, 2022b) is the price of renewable electricity which could vary significantly between regions.

In summary, our comparison shows that absolute estimates of TCO can vary significantly, but these variations are explainable and they align along a similar narrative: the estimation of TCO is dependent for the most part on geographic factors that affect both the specification and operation of the typical vessel that is expected to operate a route but also the regional production price of the fuel. For the former, although our estimates of TCO for ammonia vessels are lower than Laursen et al. (2022) this is most likely explained by the specific characteristics of the vessels expected to operate on the routes selected and associated expected fuel costs. For the latter, although this study's ammonia fuel costs are lower than those in Laursen et al. (2022) they are more aligned with MMMCZCS (2022a, 2022b). Moreover, the price spread of green ammonia and green methanol is similar in this study to that provided in MMMCZCS (2022a, 2022b).

4.2 Practical implementation of zero emission shipping market

The total cost of operation and the cost per TEU are helpful in understanding the scale of transport demand that a maritime transport aggregation initiative would have to put together to have a meaningful catalysing effect in creating a zero-emission shipping market. This is crucial while the sector waits for the implementation of supportive policy interventions. In addition, these metrics shed light on the respective cost differentials associated with zero-emission transport. Considering the cases in this study, a minimum TCO of around $10m would have to be raised for zero emission transport for small sized container vessel operating in short-sea routes under the best-case scenario and $40-$50m for a large containership in the deep-sea route, in the best-case scenario. When translating this to costs per TEU, it should be noted that this study only considers the cost rather than the market price i.e. the freight which may come with an additional mark-up.

The estimations from the modelling can provide the basis for the implementation of a zero-emission shipping market under the structure of a book-and-claim system as a form of industry insetting. Book-and-claim enables customers 'willingness to pay' to purchase zero emission freight without being geographically connected to the transport activity. The system enables companies to invest in emission reductions within their value chains and link them to the organisation's actual transport activity. It is imperative that there is a robust system of tracking emissions to avoid any double counting and the risk of greenwashing through the implementation of such a scheme[12]. Once one vessel is built and starts operating using SZEF, shippers can pay for an amount of TEUs or tonnes of CO_2 which they can claim against their own activity. TCO modelling therefore provides grounds for an initial estimate to understand the scale of investment that is required upfront in order to have access to zero emission vessels and guide decision-making around asset investment.

[12] Details about such systems available in the insight brief: "*Accelerating Maritime Decarbonisation: A Book and Claim Chain of Custody System for the early transition to Zero-emission Fuels in Shipping*"

References

Agora Verkehrswende, Agora Energiewende, Frontier Economics, Perner, J., Unteutsch, M., & Lövenich, A. (2018). The future cost of electricity-based synthetic fuels. *Agora Energiewende*.

Baresic, D., Prakash, V., Stewart, J., Rehmatulla, N., & Smith, T. (2023). *Climate action in shipping. Progress towards Shipping's 2030 Breakthrough*. https://www.u-mas.co.uk/wp-content/uploads/2023/10/UMAS-GMF-RtZ-2023-Climate-Action-in-shipping-2023-report.pdf

Baresic, D., Rojon, I., Shaw, A., & Rehmatulla, N. (2022). *Closing the Gap. An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel Transition in Shipping*. Getting to Zero Coalition, UMAS.

Dagmar Nelissen, Japer Faber, Reinier va der Veen, Anouk can Grinsven, Hary Shanthi, & Emiel van den Toorn. (2020). *Availability and costs of liquefied bio- and synthetic methane*. https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_190236_Availability_and_costs_of_liquefied_bio-_and_synthetic_methane_Def.pdf

Climate Bonds Initiative (2020) The Shipping Criteria for the Climate Bonds Standard & Certification Scheme, https://www.climatebonds.net/standard/shipping

DNV. (2021). *Maritime Forecast To 2050. Energy Transition Outlook 2021*.

Englert, D., Losos, A., Raucci, C., & Smith, T. (2021). *Volume 1: The Potential of Zero-Carbon Bunker Fuels in Developing Countries.* https://openknowledge.worldbank.org/handle/10986/35435

ETC. (2018). *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century*. Energy Transitions Commission.

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., Schim van der Loeff, W., Smith, T., Zhang, Y., Kosaka, H., Adachi, M., Bonello, J. M., Galbraith, C., Gong, Z., Hirata, K., Hummels, D., Kleijn, A., Lee, D. S., Liu, Y., … Xing, H. (2020). *Fourth Greenhouse Gas Study 2020*. International Maritime Organization. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth IMO GHG Study 2020 - Full report and annexes.pdf

Fasihi, M., & Breyer, C. (2017, August 23). Synthetic Methanol and Dimethyl Ether production based on hybrid PV-Wind Power plants. *Neo-Carbon Energy 8th Researchers's Seminar*.

Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO 2 direct air capture plants. *Journal of Cleaner Production*, *224*. https://doi.org/10.1016/j.jclepro.2019.03.086

Huisman, G. H., Van Rens, G. L. M. A., De Lathouder, H., & Cornelissen, R. L. (2011). Cost estimation of biomass-to-fuel plants producing methanol, dimethylether or hydrogen. *Biomass and Bioenergy*, *35*(SUPPL. 1). https://doi.org/10.1016/j.biombioe.2011.04.038

ICCT. (2020). Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe. *International Council on Clean Transportation (ICCT)*.

IEA. (2021). *Net Zero by 2050 A Roadmap for the Global Energy Sector*. IEA Publications. https://doi.org/10.1787/c8328405-en

IEA. (2023a). *China - Countries & Regions - IEA*. https://www.iea.org/countries/china

IEA. (2023b). *United States - Countries & Regions - IEA*. https://www.iea.org/countries/united-states

Ikäheimo, J., Kiviluoma, J., Weiss, R., & Holttinen, H. (2018). Power-to-ammonia in future North European 100 % renewable power and heat system. *International Journal of Hydrogen Energy*, *43*(36). https://doi.org/10.1016/j.ijhydene.2018.06.121

IMO MEPC. (2022). *MEPC 79/INF.29 - Review of evidence on emissions reduction pathways (United Kingdom)*.

IMO MEPC. (2023). *2023 Strategy on reduction of GHG emissions from ships MEPC.377(80)*. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/2023%20IMO%20Strategy%20on%20Reduction%20of%20GHG%20Emissions%20from%20Ships.pdf

IPCC. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,* (V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. Robin Matthrews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield, Eds.). In Press. https://doi.org/10.1038/291285a0

IRENA. (2020). Green Hydrogen Cost Reduction. In */publications/2020/Dec/Green-hydrogen-cost-reduction*. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

Laursen, R., Barcarolo, D., Patel, H., Dowling, M., Penfold, M., Faber, J., Király, J., van der Ven, R., Pang, E., & van Grinsven, A. (2022). *Potential of Ammonia as Fuel in Shipping*. American Bureau of Shipping, CE Delft, Arcsilea.

Lloyd's Register, & UMAS. (2019). *Zero-Emission Vessels: Transition Pathways*. Lloyd's Register, UMAS.

MMMCZCS. (2021). *We show the world it is possible. Industry Transition Strategy* (Issue October).

MMMCZCS. (2022a). *Ammonia as a marine fuel. Documentation of assumptions for NavigaTE 1.0 (2021)*. Maersk Mc-Kinney Møller Center for Zero Carbon Shipping.

MMMCZCS. (2022b). *Methanol as a marine fuel. Documentation of assumptions for NavigaTE 1.0 (2021)*. Maersk Mc-Kinney Møller Center for Zero Carbon Shipping.

Nayak-Luke, R., Bañares-Alcántara, R., & Wilkinson, I. (2018). "green" Ammonia: Impact of Renewable Energy Intermittency on Plant Sizing and Levelized Cost of Ammonia. *Industrial and Engineering Chemistry Research*, *57*(43). https://doi.org/10.1021/acs.iecr.8b02447

Osterkamp, P., Smith, T., & Søgaard, K. (2021). *Five percent zero emission fuels by 2030 needed for Paris-aligned shipping decarbonization* (Issue March). UMAS, Getting to Zero Coalition.

PPA. (2023). *Poseidon Principles - A global framework for responsible ship finance*. Poseidon Principles Association. https://www.poseidonprinciples.org/finance/poseidon_principles/

PPMI. (2023). *Poseidon Principles - A global framework for responsible marine insurance* (Version 4.0). Poseidon Principles for Marine Insurance. https://www.poseidonprinciples.org/insurance/wp-content/uploads/2021/12/Poseidon-Principles-for-Marine-Insurance-Technical-Guidance.pdf

SBTi. (2023). *Science Based Target Setting for the Maritime Transport Sector*. https://sciencebasedtargets.org/resources/files/SBTi-Maritime-Guidance.pdf

Scarbrough, T., Longva, T., MacLean, G., Endresen, Ø., & Campbell, M. (2022). *Study on the readiness and availability of low- and zero-carbon technology and marine fuels*. https://wwwcdn.imo.org/localresources/en/MediaCentre/WhatsNew/Documents/MEPC80.INF10.pdf

SCC. (2023). *Sea Cargo Charter - Aligning global shipping with society's goals*. Sea Cargo Charter Association. https://www.seacargocharter.org/wp-content/uploads/2020/10/SCC-Brochure-V09.pdf

Shaw, A & Smith, T. (2023) An overview of the discussions from IMO ISWG-GHG 15: Readout from UMAS, London, UK https://www.u-mas.co.uk/wp-content/uploads/2023/06/ISWG-GHG-15-overview-UMAS-1-1.pdf

Smith, T., Baresic, D., Fahnestock, J., Galbraith, C., Velandia Perico, C., Rojon, I., & Shaw, A. (2021). *A Strategy for the Transition to Zero-Emission Shipping*. UMAS, Getting to Zero Coalition. https://www.u-mas.co.uk/wp-content/uploads/2021/10/Transition-Strategy-Report.pdf

Smith, T., Shaw, A., & Fahnestock, J. (2021). *The Role of the Energy Sector in Shipping's Fuel Transition* (Issue October).

Song, D., Liu, Y., Qin, T., Gu, H., Cao, Y., & Shi, H. (2022). Overview of the Policy Instruments for Renewable Energy Development in China. In *Energies* (Vol. 15, Issue 18). MDPI. https://doi.org/10.3390/en15186513

Tarud, J., & Phillips, S. (2011). Technoeconomic comparison of biofuels: Gasoline, methanol, and ethanol from gasification of woody residues. *ACS National Meeting Book of Abstracts*.

The Royal Society (2020). (2020). Ammonia: zero-carbon fertiliser, fuel and energy store. Policy Briefing. *The Royal Society*, *Accessed August 25, 2020*.

Trafigura. (2020). *A proposal for an IMO-led global shipping industry decarbonisation programme*. Trafigura.

US Department of State. (2021). *Launching the First Movers Coalition at the 2021 UN Climate Change Conference*. US Department of State. https://www.state.gov/launching-the-first-movers-coalition-at-the-2021-un-climate-change-conference/

van Gogh, M., Farrag-Thibault, A., Hausmann, L., Liu, S., Mohr, D., Weber, B., & Wolff, C. (2022). *Driving decarbonization: Accelerating zero-emission freight transport* (Issue July). McKinsey & Company.

Zhou, Y. (2023, January 3). *Can the Inflation Reduction Act unlock a green hydrogen economy?* The ICCT. https://theicct.org/ira-unlock-green-hydrogen-jan23/

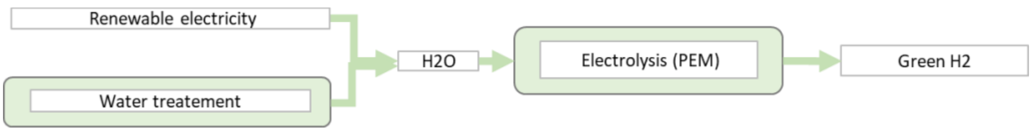
Appendix A - Assumptions

Onboard containment

- The tanks are sized to service a round trip on the maximum transpacific voyage length requiring significant addition bunker volume (50 to 75% more). However, the impact on revenue (due to reduced cargo carrying capacity) and CAPEX cost of tanks remains small (<5%).

Fuel

- Green fuels production prices are currently high but expected to steeply decrease until 2030 (approx. 5% per year), from which point the decrease will be more gradual (approx. 2% per year).
- The bio-methanol in this analysis is produced through wood gasification. How the prices will vary in the future is a very open question. Using the low and high costs for current availability favours bio-methanol over the alternatives. Further details can be found in IMO MEPC 79/INF.29 (IMO MEPC, 2022)
- In order to account for the flexibility of bunkering on either coast, this study calculates the fuel costs for the transpacific route by taking the average of fuel costs in the United States and China. The China coastal route only uses fuel cost prices derived from China.
- High and Low fuel production costs for China and for the low fuel production costs for US for green ammonia and green methanol assumed a common production pathway for green hydrogen as presented below:



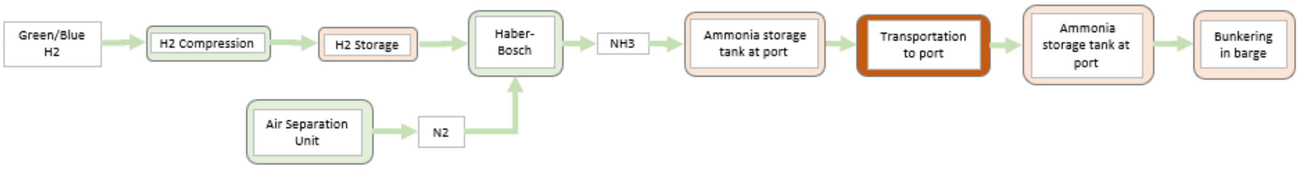
Parameter	Unit	2020	2030	2040	2050	Reference
Electricity (low-China)	USD/kWh	0.04	0.025	0.02	0.015	(IEA, 2021)
Electricity (high-China)	USD/kWh	0.045	0.04	0.04	0.04	(IEA, 2021)
Electricity (low-US)	USD/kWh	0.035	0.03	0.025	0.02	(IEA, 2021)
PEM electrolysers (size)	MW	300	300	300	300	User selected
PEM electrolysers (CAPEX)	USD/kW	1400	652	476	300	(ICCT, 2020; IRENA, 2020; Noordende & Rison, 2020)
PEM electrolysers (efficiency)	%	60	67	71	74	(IRENA, 2020)
Utilisation	%	87.4	87.4	87.4	87.4	User selected

High prices for Hydrogen in the US were derived from ICCT (2020) as follows

Parameter	Unit	2020	2030	2040	2050	Reference
Hydrogen	$/kg	10.61	8.27	6.92	5.97	(ICCT, 2020)

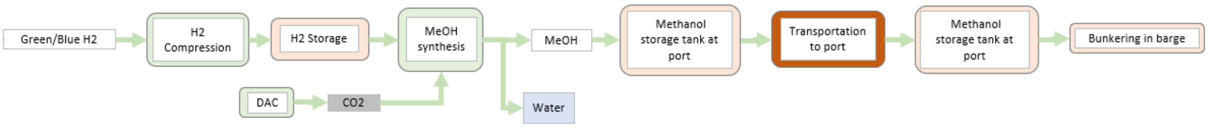
Following the estimation of Hydrogen costs, the pathways and assumptions for the production of Green Ammonia and green methanol are as follows:

Green Ammonia:



Parameter	Units	2020	2030	2040	2050	Reference
H2 compression (CAPEX)	USD/kg H2/y	7,800	7,800	7,800	7,800	(ICCT, 2020)
Haber-Bosch (energy demand)	kWh/kg NH3	0.4	0.4	0.4	0.4	(Nayak-Luke et al., 2018)
Ammonia storage (CAPEX)	USD/t	3,000	3,000	3,000	3,000	(The Royal Society, 2020)
Transportation (tanker)	USD/t-km	0.003	0.003	0.003	0.003	(The Royal Society, 2020)

Green Methanol:



Parameter	Units	2020	2030	2040	2050	Reference
H_2 storage (CAPEX)	USD/t	469,141	456,016	429,766	416,641	(Ikäheimo et al., 2018)
DAC (CAPEX)	USD/tCO_2/year	819	296	195	159	(Agora Verkehrswende et al., 2018; Fasihi et al., 2019; Fasihi & Breyer, 2017)
DAC (Thermal demand)	kWh(thermal)/ tCO_2	250	225	203	182	(Agora Verkehrswende et al., 2018; Dagmar Nelissen et al., 2020; Fasihi et al., 2019; Fasihi & Breyer, 2017)
DAC (electricity demand)	kWh/tCO_2	1,750	1,500	1,286	1,102	(Agora Verkehrswende et al., 2018; Fasihi et al., 2019; Fasihi & Breyer, 2017)
Methanol synthesis (CAPEX)	USD/MWh output $MeOH_{HHV}$	782,093	671,925	584,089	496,252	(Fasihi et al., 2019; Fasihi & Breyer, 2017; Huisman et al., 2011; Tarud & Phillips, 2011)

Vessel specification

- As fuel costs are the main driver of TCO for green vessels, it is optimum to design the vessel propelling configuration and install a bundle of technology that increases the vessel efficiency. This is typically not the case for fossil fuel vessels, where CAPEX is a more significant component of TCO. It is likely to see regulation forcing the improved efficiency of fossil fuel vessels.
- These differences in "profit optimum" technology configuration for a green vs fossil fuel vessel is an important consideration for "ammonia ready" or "methanol ready" vessels.
- SCR/EGR are required for all options but their costs are included in the cost of machinery.
- The vessel specification is informed by both vessels that currently operate the route and the assumption that vessels built will be similar in specification to the most recently built vessels with a similar capacity. The latter assumption is required as in most cases the vessels that currently operate the route would have an Energy Efficiency Design Index (EEDI) that would fail EEDI regulation in 2025. Therefore, we use an average of the technical specification of vessels built between 2016 and 2018 (this limit is due to the limit of data available in this study), whose capacity is approximately the same as the average vessels on the route. An example impact of this

assumption is that the installed main engine power of the vessel used in the study for the China domestic route is approximately half that of vessels currently operating on the route. We couple this technical specification with the operational characteristics (specifically operational speed) of the vessels on the route. The TCO estimate and derived metrics use this baseline specification as the specification for newbuild in each year that the estimation is carried out. For ammonia and methanol vessels, the vessels are also fitted with EET.

- EET configuration of installed tech includes air lubrication, a contra rotating propeller, wind assist (kite), waste heat recovery (organic Rankine cycle) and block coefficient reduction. It is likely that the EET installed on each vessel would vary and be different to what is specified below.
- In all but the 15k TEU transpacific route, the vessel EEDI is above the allowable threshold as set out in MEPC regulations, and therefore vessels of that specification would not be compliant. In order to meet the regulations, the vessel would need engine derating and/or EET installed. For the purposes of this analysis, we have not made such adjustments to vessel specification.

Further Assumptions

- The maximum voyage length is derived from reported AIS. This is used both in the estimation of the range (round trip) for bunker capacity sizing, and; in combination with the AIS estimated utilisation rate is used to estimate the number of TEUs delivered.
  - Revenue impact is based on a voyage charter rate estimated from time charter rate and fuel costs for the reference vessel.
- We use the vessel specification for a typical vessel on each route currently and not what it would be at a future point in time, and therefore these current reference vessels would likely (and indeed have to, to meet regulation) be different in the future. A further study would be required to define what the future base vessel would be. For example, the Honolulu route operates at a high speed so derating the engine and lowering design speed may not be an option. Using current vessels as the basis for new green fuels means that our fuel consumption is very high (even with EET), except for the 15k TEU vessels which are newer. This augments the TCO delta of green fuels.
- All investment use the same amortization period for calculation for annualised costs. It is most likely that EET would require a shorter return period (3 years) rather than the 15 years used for onboard machinery and storage. The impact of this assumption is that our annualised cost of EET is higher than it is likely to be.