Zero-Emissions Shipping:

Contracts-for-difference as incentives for the decarbonisation of international shipping

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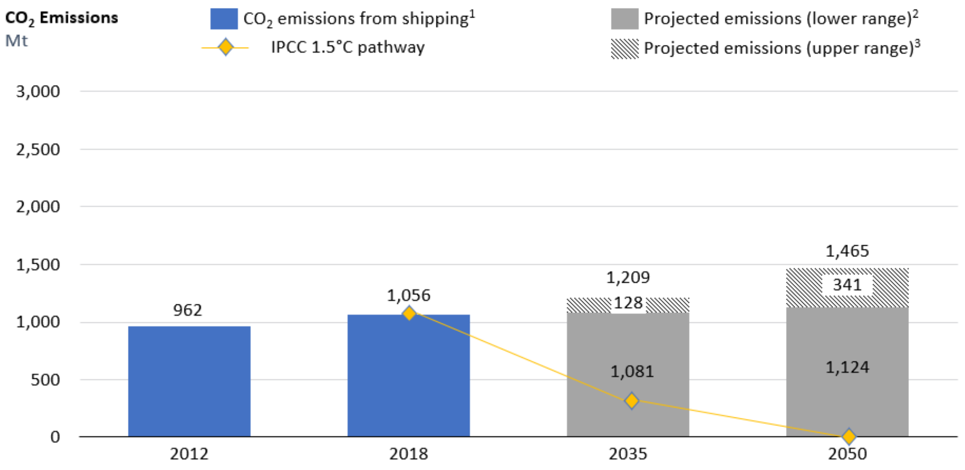
Executive Summary

Pressure is growing from multiple directions for the shipping industry to decarbonise. Alternative fuels do exist to reduce or remove all emissions from fuel use, but they are not yet competitive with fossil fuels, and face a range of barriers to entry. Calls for policy support for decarbonisation are increasing, but it is not yet clear what such support should entail. Our analysis looks at the feasibility of applying a policy instrument known as a 'contract-for-difference' (CfD), which has seen previous success in driving down the costs of renewable energy generation technologies in the electricity sector. We explore the application of this policy instrument to the decarbonisation of shipping, unpacking the important design and implementation decisions with feedback from a wide range of stakeholders, and provide initial legal documentation based on our findings, drawn up by legal experts Pinsent Masons.

The heavy transport sector is moving to the centre of attention for decarbonisation efforts. Pressure is increasing on governments to decarbonise all forms of transport – road, airborne and waterborne. The International Maritime Organisation (IMO) has agreed to reduce total GHG emissions from shipping by at least 50% by 2050 (from 2008 levels) and consultations are currently under way for the inclusion of shipping in an expansion of the European Union Emissions Trading Scheme. The shipping industry is looking to decarbonise with some major shipping firms, notably, Maersk (the world's largest container shipping line), announcing zero-carbon targets. Calls for policy support in this effort are increasing.



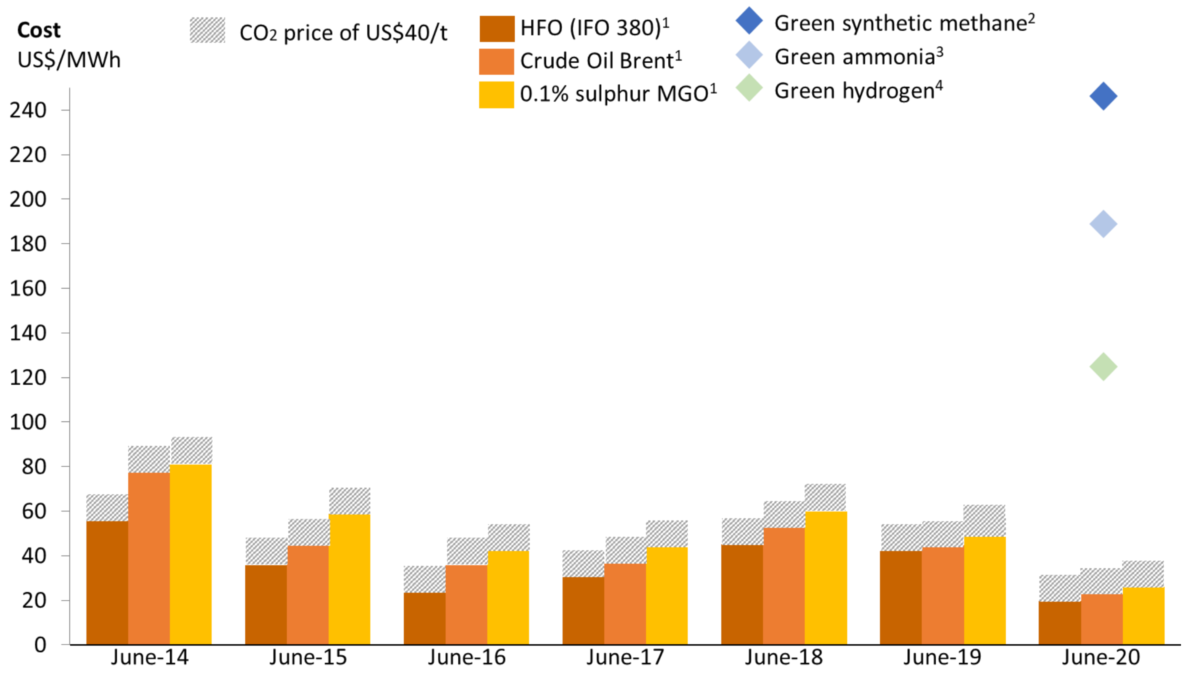
1. Total emissions from shipping in IMO 4th GHG Study (2020)
2. Lower range (SSP4, RCP 6.0) of long-term Paris-aligned scenarios, in which the land-based energy transition is consistent with the Paris Agreement and GDP growth is in line with recent projections.
3. Upper range (SSP2, RCP 2.6) of long-term Paris-aligned scenarios.

ES- 1: Current and projected CO2 emissions from shipping for long-term scenarios in which GDP growth tracks recent projections, and the land-based energy transition is consistent with 'well below 2 degrees', compared with the requirements of an IPCC 1.5 degrees pathway (Source: IMO 4th IMO GHG Study 2020)

Marine transportation accounts for an estimated 2.9% of global greenhouse gas (GHG) emissions. Even accounting for the COVID-19 pandemic, shipping emissions are expected to stay steady or increase significantly, with the IMO predicting that the sector's emissions could reflect 90-130% of 2008 levels by 2050 for the most plausible pathways identified in its Fourth GHG study (2020). As shown in ES- 1, the emissions gap between the range of projected shipping emissions and the requirements of the 1.5C pathway under the Paris Agreement are daunting.

Several potentially viable technologies for decarbonising shipping exist, with each at different stages of maturity in innovation and implementation. Options include batteries, biofuels, hydrogen-based fuels, carbon-based synfuels, nuclear, and wind power – although not all can meet the fuel energy density requirements of larger deep-sea vessels.

Technological advances have reduced the cost of clean fuels but still more progress will be required for zero-emissions shipping to become economically viable. As shown in ES- 2 the costs of clean fuels, such as green hydrogen and green ammonia are more than double their fossil fuel counterparts, even with a modest carbon price of US$40 per tonne**.** The key barriers to large-scale private investment and adoption of such clean fuels are well-known and include high perceived technology risks, lack of supporting infrastructure, lack of a project pipeline, lack of stable and scalable fuel supplies, and perhaps most importantly their costs in the absence of carbon pricing (or its equivalent) on existing fuels.



1. DNV.GL
2. Average of: IEA (2019) The Future of Hydrogen; Agora Energiewende (2018) The Future Cost of Electricity-Based Synthetic Fuels; and Gorre et al (2018) Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants in dynamic operation. Applied Energy 257.
3. Average of IEA (2019); Ash and Scarborough (2019) Sailing on Solar. EDF and Ricardo; and Nayak-Luke & Bañares-Alcántara (2020) Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production. Energy & Environmental Science 13.
4. Average of Van Hulst (2019) The clean hydrogen future has already begun; BNEF (2020) Hydrogen Economy Outlook; and IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal.

ES- 2: Cost estimates for common shipping fuels (HFO-Heavy Fuel Oil and MGO-Marine Gas Oil) and zero-emission alternatives green synfuels, green hydrogen, and green ammonia.

Cost obstacles have been dealt with successfully in other sectors in recent years. Most notably, in the UK offshore wind industry, a renewable obligations scheme, followed by three rounds of contract-for-difference (CfD) auctions has seen the 'strike' price of wind-derived electricity reduced to a third of its pre-CfD value and to a price below current baseload electricity prices (ES- 3). This remarkable result has been achieved at least partly by using CfDs to promote private sector investment and thereby stimulate technological progress and accelerate learning rates.

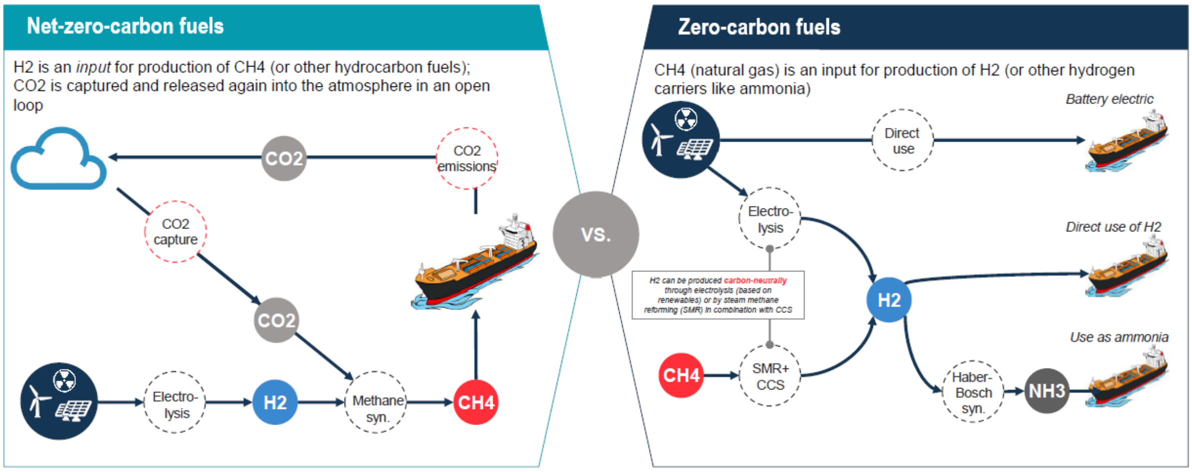
ES- 3: The UK offshore wind strike prices from 3 successive rounds of CfD reverse auctions compared to current baseload electricity price. Adapted from Grubb, M., Drummond, P., 2018, UK Industrial Electricity Prices: Competitiveness in a Low-Carbon World.

This report investigates the design and implementation of CfD mechanisms for international shipping to support the sector's decarbonisation. The purpose of such schemes is to incentivise investment in emerging technologies, to accelerate deployment and reduce costs to the point where they become economically competitive without support.

Incentivising private investment is key to the necessary scaling and adoption of clean shipping fuels. In its basic form, a CfD can help achieve this by allowing a public sector entity to meet the difference between the market price for a fuel or technology (the 'reference price'), and the 'strike price' required for its financial returns to be sufficiently attractive to developers and private investors. When the strike price is higher than the reference price, the scheme in effect subsidises the producer of the fuel or technology the difference. When the reverse is true, the producer repays the subsidy.

The viability of any incentive mechanism depends on both legal and economic feasibility as well as appetite for uptake by relevant stakeholders. Any CfD solution must be sensitive to the needs of the shipping community and providers of supporting infrastructure. Consequently, a key focus of the project was a stakeholder engagement process aimed at understanding the myriad viewpoints from shipping and energy industries, government and regulatory bodies, financial institutions, researchers, and civil society. In designing the CfD we strove to strike the right balance between stakeholder needs, political and practical feasibility, the need for technology neutrality and a level playing field, and the need for specificity in the policy mechanism.

The different technology options for shipping can be characterised as being either zero-carbon or net-zero-carbon fuels (ES- 4). These solutions each need very different, and potentially expensive infrastructure, which means it is potentially undesirable for all to exist at scale simultaneously. Certain technologies have a clear advantage for international shipping, but technology-neutrality is important to ensure the best long-term solution succeeds. There is however a trade-off between technology neutrality and the complexity of the CfDs, given the need to cater for the many and varied segments of the shipping industry.



ES- 4: Carbon-based vs non-carbon-based fuels. Note that production of hydrogen-based fuels from methane will likely require offsets on top of Carbon Capture and Storage (CCS) to ensure carbon neutrality. Adapted from ETH Zurich (2019) Towards net zero – comparison of zero-carbon.

We develop a framework for designing CfDs for international shipping, based on implementation of this instrument in other sectors, the specific features of the shipping industry, and stakeholder views. We explore two CfD options in detail:

1) A "Fuel-only" CfD, which is the simplest and most popular solution among stakeholders, providing shippers with zero-carbon emission fuels at the same price as Marine Gas Oil (MGO) but may not cover 100% of the costs of switching from to zero-emission shipping or necessarily provide support for infrastructure and retrofitting costs. This CfD can be applied equally to all shipping segments but does not help promote 'non-fuel', highly capital-intensive options like nuclear-powered or wind-assisted ships.

2) A "Total Cost of Ownership" TCO-based CfD, which covers all costs associated with building and running a zero-carbon emission ship. This option is administratively much more difficult to manage and would likely require many variants to cover all shipping segments but is more technology-neutral, and potentially better for fostering competition, and for making progress on the cost of non-fuel components required to build and operate zero-emissions ships.

To provide industry stakeholders with a tangible legal product for use in taking the concept forward, the report concludes with draft "Heads of Agreement" for each of the two CfD options. These documents were drawn up by experienced law firm Pinsent Masons, based on the findings of the report. They are concise framework documents that can be used to outline an agreement in principle between parties and counterparties, laying out how each CfD would work and under what terms it would operate. They are intended to provide readers with an understanding of how the CfD might work in practice and enable industry stakeholders to see the concrete details of a basic CfD contract, locate points of agreement, and uncover issues that may require further negotiation.

In summary, this report provides readers with an in-depth understanding of the difficulties facing a shipping industry looking to decarbonise as well as a potentially powerful solution to enable it to do so. It is our hope that readers take from this analysis the belief that a zero-emissions shipping future is an economically viable possibility.

1. The aims of this report

An increasing number of large economies are committing to net-zero greenhouse gas (GHG) emissions by 2050 including major emitters such as the UK, EU, China, Japan, Korea, Canada, South Africa, Argentina and Mexico[1]. The shipping industry, under the guidance of the International Maritime Organisation (IMO), is not yet aligned with these goals. The IMO's current target of 40% GHG emissions reductions by 2030 and at least 50% by 2050 (over a 2008 baseline), falls short of these wider ambitions[2]. The IMO's Initial GHG Strategy for decarbonisation also contains a guiding principle of eventual alignment with the Paris Agreement, although meeting this objective remains some way off. More broadly, economies committing to net zero are facing increasing attention from the international community on the emissions of the heavy-transport sector, including shipping.

The decarbonisation[3] of international shipping (henceforth 'zero-emissions shipping'[4]) presents a formidable challenge. Electrification is emerging as the solution of choice for light duty road transport. It may also be appropriate for small, short-haul watercraft. Unfortunately, the energy density requirements and sheer size of the electric powertrain and batteries required to power a large ocean-going ship over long distances mean that electric shipping is unlikely to be a viable option without a series of major unexpected technological breakthroughs. Several alternative options for net-zero shipping remain. Almost all large ships currently use liquid fossil fuels to power an internal combustion engine. In principle, several net-zero-carbon fuel options are feasible for use in ships, including liquid hydrogen (H_2) or ammonia (NH_3) generated from electrolysers powered by renewable energy; synthetic carbon-based electro-fuels such as methanol (CH_3OH) or methane (CH_4) generated using renewable energy; hydrogen fuel cells; modular nuclear reactors; and wind power (in limited circumstances, and as a complement to a primary propulsion source).

All of these technologies are technically viable, but remain some distance away from full commercialisation, with some more advanced than others. The key barriers to large-scale private investment and adoption are well-known and include high perceived technology risks, lack of supporting infrastructure, lack of project pipelines, lack of stable and scalable fuel supplies, and perhaps most importantly the absence of carbon pricing (or its equivalent) on existing fuels. These are difficulties that have been faced and dealt with successfully in other

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[1] Carbon Brief (2020). UNEP: Net-zero pledges provide an 'opening' to close growing emissions 'gap'. https://www.carbonbrief.org/unep-net-zero-pledges-provide-an-opening-to-close-growing-emissions-gap

[2] IMO (2018) Initial IMO GHG Strategy. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

[3] 'Carbon' is used here as a proxy for greenhouse gas emissions. The Fourth IMO GHG study found that carbon dioxide accounted for 98% of greenhouse gas emissions from shipping, although upstream and operating emissions of methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, and nitrogen trifluoride can also be significant.

[4] This terminology is consistent with Getting to Zero coalition's description of 'zero carbon energy sources'. It includes zero-emissions fuels derived from zero-carbon electricity and carbon capture and storage; and fuels derived from biomass in which emissions from combustion are partially or fully offset in the production process. In all of these cases, there are still net positive upstream greenhouse gas emissions in most circumstances. This means the resulting fuels are not strictly 'net zero' on a well-to-wake basis unless combined with qualifying offsets, which should only be used subject to strict criteria. For further details on definitions, see Smith, T. (2019) 'Definition of zero carbon energy sources'. Getting to Zero Coalition.. For guidance on offset use, see University of Oxford (2020) 'The Oxford Principles for Net Zero Aligned Carbon Offsetting.' https://www.smithschool.ox.ac.uk/publications/reports/Oxford-Offsetting-Principles-2020.pdf

sectors in recent years, aided by policy and market instruments designed to promote private sector investment and accelerate technological progress and commercial deployment. Prominent examples include the use of feed-in-tariffs for solar energy in Germany, and the use of contracts for difference for offshore wind energy in the United Kingdom (UK).

In its basic form, a contracts-for-difference (CfD) scheme allows a public sector or administrative entity to meet the difference between the market price for a fuel or technology (the ‘reference price’) and the ‘strike price’ required for the financial returns to the project being financed to be sufficiently high for developers and private investors. When the strike price is higher than reference price, the scheme in effect subsidises the producer of the fuel or technology the difference, but when the reference price is higher, the producer pays back the difference to the scheme. A key difference from a typical subsidy is that a CfD has a fixed time limit, the “contract”, which avoids a common problem with removing subsidies once they have served their purpose. A CfD can also include a competitive ‘reverse auction’ element whereby suppliers bid against each other to establish the ‘winning’ strike price, and all bidders who offer a price below this strike price can win a contract with the scheme to supply the fuel or technology at the strike price.

This report investigates the design and implementation of CfD mechanisms for international shipping to support the sector’s decarbonisation. The purpose of such schemes is to incentivise private investment and the scaling of production to establish the emerging technologies and accelerate any potential for cost reductions. The primary requirements of such mechanisms are:

- a transparent and effective reference and strike price.
- a robust payment settlement framework able to manage the international dimension of shipping contracts.
- a credible enforcement mechanism for CfD obligations.
- an appropriate balance between competition, economic efficiency, technology neutrality, and practical feasibility.
- a clearly defined scope and set of beneficiaries.

This report builds on detailed examination of the technical elements of different zero-emissions shipping solutions carried out by others, past implementations of CfDs, and extensive consultation with experts in industry, government, advocacy, and research, to develop a workable CfD mechanism for promoting zero-emissions shipping.

Section 2 lays out the need for zero-emissions solutions in international shipping. Section 3 surveys the technology options currently being explored for zero-emissions shipping. Section 4 outlines the key barriers to adoption, and how similar barriers in other technologies have been addressed through CfD mechanisms. Section 5 provides a summary of the stakeholder engagement undertaken by the team to ensure that recommendations of this report are built on the experience of industry stakeholders and are cognisant of their views. Section 6 outlines the design features of a CfD for zero-emissions shipping, based on technology options, barriers to adoption, and the stakeholder engagement, to construct parameters for workable CfDs. Finally, Section 7 provides a legal blueprint for the implementation of two CfDs for international shipping, one based on fuel-only solutions and the other on total cost of ownership.

2. The need for zero-emissions shipping

2.1. Climate goals and the role of international shipping

The 2015 Paris Agreement sets out a global framework for the world's governments to limit the extent and impact of climate change. The Agreement's stated ambition of keeping global warming to well below 2°C above preindustrial levels, and to pursue efforts to limit the increase to 1.5°C, requires a rapid and sustained decline in emissions in the coming decades, reaching net-zero emissions between 2050 and 2070. To achieve limited overshoot of the 1.5°C target, global net anthropogenic CO2 emissions will need to decline by about 45% from 2010 levels by 2030, reaching net zero around 2050.[5]

In simple terms, by committing to reaching net zero, humans are committing to eventually removing as much anthropogenic greenhouse gas emissions as they produce each year. Reducing emissions is one of the more obvious means of achieving this goal but with hard-to-abate sources of emissions it may be more cost-effective to pull emissions from the atmosphere, or capture them during energy production from biomass sources, and store them underground. For example, a viable solution consistent with the aims of zero-emissions shipping would be to produce decarbonised shipping fuels from fossil fuels combined with 100% carbon capture and storage. It is, however, unlikely that this will be the most cost-effective path for zero-emissions shipping given the alternative technologies available (discussed further in Section 3).

Most global decarbonisation effort to date has focused on the power sector, which produces the largest share of emissions of all sectors and is considered one of the easier sectors to decarbonise. However, harder-to-abate sectors are increasingly coming under scrutiny as the next-largest sources of emissions with less clear pathways to net zero. The challenge of decarbonisation is particularly onerous for sectors that are hard to electrify or are dominated by long-term assets with lengthy cost recovery periods. International long-distance shipping falls cleanly into both these categories.

While the industry's supervisory body and regulator, the IMO, has announced 2050 decarbonisation targets, and some major shipping firms, notably, Maersk (the world's largest container shipping line), have done the same, the industry has not yet identified a universally accepted pathway to decarbonisation. Moreover, with lifetimes often exceeding 25 years, ships commissioned today are likely to be operating well into the 2040s, making the deployment of zero-emissions ships in the 2020s an imperative for the sector to align itself with the Paris goals[6]. This also means that the transition to true net-zero emissions across the shipping value chain must be realised within one-and-a-half generations of ships at

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[5] 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, sustainable development, and efforts to eradicate poverty".

[6] ITF (2020) *Future Maritime Trade Flows: Summary and Conclusions*, ITF Roundtable Reports, No. 178, OECD Publishing, Paris. https://www.itf-oecd.org/sites/default/files/docs/future-maritime-trade-flows.pdf

most.[7] The coming decade will therefore prove crucial in developing, piloting, scaling, and commercially incentivising the uptake of zero-emissions vessels.

Marine transportation[8] accounts for an estimated 2.9% of global greenhouse gas (GHG) emissions[9,10]. Even accounting for the COVID-19 pandemic, shipping emissions may increase significantly from this (already high) baseline by 2050. The IMO's Fourth GHG Study predicts that under a range of plausible scenarios, the sector's total emissions could sit at 90-130% of 2008 emissions by 2050.[11] Around 80% of global trade by volume took place by sea in 2018,[12] and shipping is likely to remain the dominant transport mode for traded products. Its growing contribution to global GHG emissions and lack of commercially viable decarbonisation options suggest efforts to decarbonise should be urgently accelerated.

Requirements for decarbonising the various shipping sectors vary substantially between short-sea, medium-distance, and deep-sea vessels. Since the international deep-sea shipping segment produces more than 80% of global CO_2 emissions from shipping[13] and will be hardest to decarbonise, it is sensible to focus on this sector.

The international container shipping industry and its supporting infrastructure is highly concentrated both geographically, and in terms of ownership. Trade in containers is often expressed by volume, in twenty-foot-equivalent units (TEU). In TEU terms, the world's five largest ports (all in China) controlled 19.5% of the 793 million TOE in global container freight handled by ports in 2018.[14] Over 60% of world container port throughput was estimated to have gone through Asia in 2019.[15] The top ten ports globally controlled 31% of freight, and the top 20, 44%.[16] The Asia-North America trade route was the world's busiest in 2017, followed by the Asia-Northern Europe and Asia-Mediterranean route.[17] Five container ship operators also control more than half of total global fleet capacity.[18] As measured by the

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[7] Lloyd's Register (2019) "Zero-Emission Vessels: Transition Pathways, https://www.lr.org/en-gb/insights/global-marine-trends-2030/zero-emission-vessels/

[8] Marine transportation includes domestic and international cargo-carrying and non-cargo commercial shipping, and fishing vessels.

[9] International Maritime Organisation (2020): "Fourth Greenhouse Gas Study 2020". International Maritime organisation, London: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf

[10] ETH Zürich, Amplifier (2019): "Towards net-zero. Innovating for a carbon-free future of shipping in the North and Baltic sea". https://fe8dce75-4c2a-415b-bfe4-e52bf945c03f.filesusr.com/ugd/0a94a7_47fc75affb6e41768a6c3e5f3a970039.pdf

[11] IMO (2020): "Fourth Greenhouse Gas Study 2020."

[12] UNCTAD (2018) *Review of Maritime Transport 2018*. United Nations, New York. https://unctad.org/system/files/official-document/rmt2018_en.pdf (p. 23).

[13] DNV.GL (2019) "Energy Transition Outlook 2019".

[14] Authors' calculations, based on World Shipping Council (2021) *Top 50 World Container Ports* (http://www.worldshipping.org/about-the-industry/global-trade/top-50-world-container-ports); and UNCTAD (2020) UNCTADStat Database (https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=13321)

[15] UNCTAD (2020) *Review of Maritime Transport 2020.* (p.17, Figure 1.10).

[16] Of the top 10, 7 are in China; the other three are in Singapore, South Korea, and the United Arab Emirates. Of the top 20 ports, 10 are in China, 2 in the US and 3 in Europe (Rotterdam, Antwerp, and Hamburg). The only UK port in the top 50 is Felixstowe.

[17] World Shipping Council (2021) *About the Industry: Trade Routes.* http://www.worldshipping.org/about-the-industry/global-trade/trade-routes

[18] UNCTAD (2020) Review of Maritime Transport 2018.

Herfindahl-Hirschman Index, industry concentration among container ship line operators has increased steadily since at least 2010, with the sharpest annual increase seen from 2015-2018 amid a surge of consolidation.[19] In 2000, the ten largest container companies enjoyed a market share of 12%; by mid-2019, this figure was 82%.[20] Amid the economic strain associated with the COVID-19 pandemic, further consolidation may well be expected.

The major non-container shipping segments, notably bulk and tanker shipping, have more fragmented ownership structures, and voyage patterns that respond more readily to changes in commodity prices and demand. In terms of physical ships, 43% of deadweight tonnage (a measure of maximum weight a ship can carry) is in bulk carriers, 29% in oil tankers and just 13% in container ships.[21]

Two key international regimes currently regulate the environmental effects of shipping: the IMO's International Convention for the Prevention of Pollution from Ships (MARPOL), and the UN Convention on the Law of the Sea (UNCLOS). Further voluntary performance indicator frameworks have been selectively adopted, including the European Sea Ports Organization, EcoPorts, Port Environmental Review System and the Green Marine Environmental Program.[22] Some ports, to reduce local pollution (e.g., Vancouver), require certain berthed ships to use onshore electricity supplies instead of onboard generators, allowing some degree of electrification (which can be net-zero-carbon if the electricity is zero-carbon). Nonetheless, current measures to improve energy efficiency, use 'shore power', use cleaner fossil fuels, and to capture some CO_2 emissions through onboard systems, appear insufficient if the industry is to realise net-zero-carbon by 2050.

The voluntary financial sector-led 'Poseidon Principles', targeting the container shipping segment, were launched in 2019, with signatories committing to invest in support of the IMO's GHG emissions reduction goal and to revise their targets and expectations over time in response to technological and policy change.[23]. In October 2020, the 'Sea Cargo Charter' was launched as an equivalent for the bulk charter segment.[24]

Existing mandatory environmental initiatives in shipping are largely governed by, or tied to, IMO frameworks. The IMO Initial Strategy on the reduction of GHG emissions from ships[25] was first adopted in 2018 and is due to be reviewed in 2023. It includes three components:

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[19] Charlampowicz, J. (2018) "*Analysis* of the market concentration of the container shipping markets – selected issues". SHS Web of Conferences 58(01005). https://doi.org/10.1051/shsconf/20185801005

[20] Lasater, L. (2019, 25 July) "*Is Market Concentration Leading to an Oligopoly?"* Red Arrow Logistics. https://www.redarrowlogistics.com/shipping/is-market-concentration-leading-to-an-oligopoly/

[21] UNCTAD (2020) *Review of Maritime Transport 2020*. United Nations, New York. https://unctad.org/system/files/official-document/rmt2020_en.pdf (p.37)

[22] Walker, T.R., Adebambo, O. et al. (2019) "Environmental Effects of Marine Transportation". In Sheppard, C. (ed.) *World Seas: An Environmental Evaluation, 2nd Ed.* Academic Press, pp. 505-530. https://doi.org/10.1016/B978-0-12-805052-1.00030-9

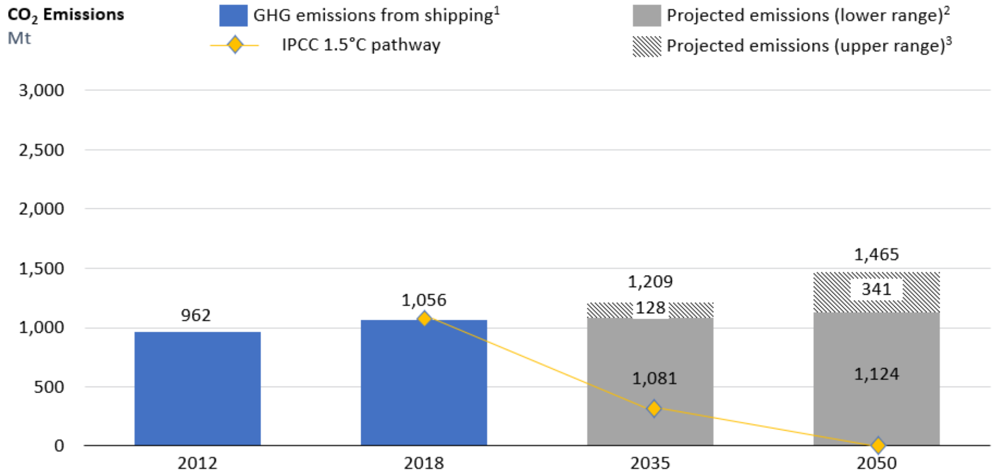
[23] Poseidon Principles (2020). "How did we get there". https://www.poseidonprinciples.org/about/how-did-we-get-there/

[24] Sea Cargo Charter (2021). "About: A global framework for responsible ship chartering". https://www.seacargocharter.org/about/

[25] IMO (2018, 13 April) "UN body adopts climate change strategy for shipping". https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

- Implementation of further phases of the Energy Efficiency Design Index (EEDI), introduced in 2011[26], which mandates minimum energy efficiency levels for different ship types and size segments. As the regulation only affects new builds, and lifetimes range between 25 and 30 years[27], its emissions impact is slow to materialise and relatively marginal.[28]
- Reduction of CO_2 emissions intensity (per 'transport work') by at least 40% by 2030 on average, pursuing efforts to each 70%, against a 2008 baseline
- Reduction of total GHG emissions from international shipping by at least 50% by 2050 against a 2008 baseline, pursuing efforts to decarbonise fully in alignment with the temperature goals of the Paris Agreement.

As Figure 1 shows, the changes required to achieve even these modest goals for CO_2 emissions alone, particularly given projected emissions rises under business-as-usual, are very substantial. The means by which the remaining 50% of emissions will be mitigated to bring the sector in line with IPCC pathways is not clear.



1. Total emissions from shipping in IMO 4th GHG Study (2020)
2. Lower range (SSP4, RCP 6.0) of long-term Paris-aligned scenarios, in which the land-based energy transition is consistent with the Paris Agreement and GDP growth is in line with recent projections.
3. Upper range (SSP2, RCP 2.6) of long-term Paris-aligned scenarios.

Figure 1: Current and projected CO_2 emissions from shipping for long-term scenarios in which GDP growth tracks recent projections, and the land-based energy transition is consistent with 'well below 2 degrees', compared with the requirements of an IPCC 1.5 degrees pathway (Source: IMO 4th IMO GHG Study 2020)

In 2016, the IMO introduced a data collection system mandating the standardised collection and reporting of a range of operational and emissions data from all ships exceeding 5,000

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[26] Marine Environment Protection Committee [MEPC] (2011, 15 July). Resolution MEPC.203(62): "Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973. As Modified by the Protocol of 1978 Relating Thereto." https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.203(62).pdf

[27] ETH Zürich (2019) "Towards net-zero. Innovating for a carbon-free future of shipping in the North and Baltic sea".

[28] Technically and commercially mature efficiency measures, such as route and speed optimisation, improved hull and surface designs, and wind assistance, have all been used to increase the efficiency of the current fleet for largely economic reasons; these measures are however marginal relative to the ultimate net-zero target, and insufficient to substantially reduce emissions in the medium term without emissions-free forms of propulsion.

gross tonnage from 2019 onwards.[29,30] It does not include any requirement to reduce reported emissions, but by measuring them, supports the tracking and management of shipping emissions. In addition, IMO sulphur content regulations were introduced in January 2020 to enforce a maximum sulphur content of 0.5% on marine fuels.[31] This effectively prevents shipping from using the dirtiest forms of fuel, notably some forms of Heavy Fuel Oil (HFO), without on-board scrubber technology. It does not, however, preclude the use of other widely used oil-based fuels, such as Very Low Sulphur Fuel Oil (VLSFO) and Marine Gas Oil (MGO).

Since the electricity sector has a clear path towards decarbonisation and the cost of renewable electricity is likely to continue to fall[32], the use of clean electricity to produce fuels has been identified as a way forward for zero-emissions shipping. Such zero-carbon fuels include ammonia and hydrogen and battery power generated using zero-carbon electricity sources such as solar, wind and nuclear. Synthetic methane/methanol are carbon based but can be “carbon-neutral” or “net-zero-carbon” fuels if direct air capture of CO_2 is used in their production (Figure 2). Biofuels are also a “net-zero-carbon” fuel option and can be used in existing engines. Other fuel options include nuclear powered ships[33], and sail- or sail-assisted designs[34]. Few of these options, if any, are currently technologically and economically viable (see Section 3 for more details), and none are operating at sufficient scale, raising the need for supporting policies to accelerate progress towards cost parity with oil- and gas-based fuels.

2.2. Setting course in time: avoiding stranded carbon assets in the shipping industry

Given its significant contribution to global emissions and projected future growth, accelerating efforts to achieve zero-emissions shipping is urgent from a climate and environment perspective. The Getting to Zero coalition and UMAS estimates that enabling decarbonisation in line with Paris goals would require 5% of the international shipping fuel mix to come from zero emission fuels by 2030.[35] Making progress towards decarbonisation is also in the long-term interests of the industry in avoiding stranded costs and assets, particularly as the likelihood of climate policy tightening increases. Some orders for zero-emissions-capable vessels (primarily ammonia-ready and dual-fuel ships allowing operators to switch to green fuels only once market conditions allow) are starting to be placed, but the

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[29] MEPC (2016, 28 October) *Resolution MEPC.278(70): “Data collection system for fuel oil consumption of ships”.* https://marsig.com/data/_uploaded/downloads/MEPC.278(70).pdf

[30] There are more regulations in place (EEDI, SEEMP) and currently under discussion (EEXI and CII).

[31] PWC (2019). “IMO 2020 Regulation.” https://www.pwc.com/ng/en/publications/imo-2020-regulation.html

[32] Farmer, J. D., & Lafond, F. (2016). “How predictable is technological progress?” Research Policy, 45(3), 647–665. https://doi.org/10.1016/j.respol.2015.11.001

[33] Liang, L.H. (2020, 4 November) “A nuclear option - Molten Salt Reactor to reduce shipping’s GHG emissions”. Seatrade Maritime News. https://www.seatrade-maritime.com/environmental/nuclear-option-molten-salt-reactor-reduce-shippings-ghg-emissions

[34] Hellenic Shipping News (2019, 25 October). “Norsepower Rotor Sails Confirmed Savings Of 8.2% Fuel And Associated CO2 In Maersk Pelican Project”. Hellenic Shipping news. https://www.hellenicshippingnews.com/norsepower-rotor-sails-confirmed-savings-of-8-2-fuel-and-associated-co2-in-maersk-pelican-project/

[35] Getting to Zero Coalition (2021) “Five percent zero emission fuels by 2030 needed for Paris-aligned shipping decarbonization”. https://www.globalmaritimeforum.org/content/2021/03/Getting-to-Zero-Coalition_Five-percent-zero-emission-fuels-by-2030.pdf

industry as a whole is not yet at the point where regulatory uncertainty outweighs the costs of investing in relatively unproven, expensive, clean technologies. The current policy environment - limited regulation and support schemes - further reduces the incentive for individual shipping firms to act.

At present the wider regulatory environment is not conducive to ambitious decarbonisation efforts. Shipping has so far been excluded both from direct obligations under the Paris Agreement, and from major regional carbon-pricing systems. However, while the European Union Emissions Trading System (ETS) has historically excluded marine transportation, the industry is widely expected to be included in the ETS, with formal proposals to be published in July 2021. These are expected to clarify whether just intra-EU emissions, or extra-EU emissions as well (most relevant for international long-haul shipping), will be counted. The UK's draft Sixth Carbon Budget commits to reducing national emissions by 78% by 2035 against 1990 levels, including emissions from aviation and shipping for the first time.[36] The UK Department for Transport has also published a 'clean maritime plan' laying out its roadmap for the transition to zero-emission shipping. It does not commit to a new headline target, instead aligning itself with the IMO strategy of 50% emissions reductions by 2050.[37]

The adoption of legally binding emission reduction targets – either through regulation by the IMO or by inclusion of parts of the shipping fleet into regional carbon-pricing systems – has been on the horizon for some time.[38,39] However, whilst the sector is expecting future regulation (including becoming subject to the EU-ETS), and the IMO Initial Strategy provides a clear target of at least halving total annual emissions by 2050, there is still no clear outlook on emission pathways, carbon pricing, or other measures to reach even this, intermediate, goal in the transition to zero-emissions shipping.[40] The absence of clear signals creates considerable ongoing planning and investment uncertainty that is hampering the development, commissioning and adoption of non-fossil fuel options.

The multi-decadal lifetime of shipping assets aggravates this problem. Without regulatory support for green shipping technologies, investors face an unattractive choice. Investing in

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[36] S&P Global Platts (2021, 20 April). "UK targets 78% cut in GHG emissions by 2035, to include aviation, shipping". https://www.spglobal.com/platts/en/market-insights/latest-news/coal/042021-uk-pm-johnson-to-back-78-cut-in-co2-emissions-by-2035-report

[37] Department for Transport (2019) *Clean Maritime Plan*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815664/clean-maritime-plan.pdf

[38] In laying out her 2020 agenda during her successful campaign for President of the European Commission, Ursula von der Leyen noted "I will propose to extend the Emissions Trading System to cover the maritime sector". This was repeated in discussions around a European Green Deal and further details are expected in July 2021. See Von der Leyen, U. (2021). *A Union that strives for more: My agenda for Europe.* https://ec.europa.eu/commission/sites/beta-political/files/political-guidelines-next-commission_en.pdf Accessed 10 July 2020.

[39] IMO (2020) "IMO Action to reduce Greenhouse gas emissions from international shipping: Implementing the Initial IMO Strategy on Reduction of GHG Emissions from Ships". International Maritime Organisation. https://sustainabledevelopment.un.org/content/documents/26620IMO_ACTION_TO_REDUCE_GHG_EMISSIONS_FROM_INTERNATIONAL_SHIPPING.pdf

[40] It is possible in principle to calculate a net-zero pathway in shipping by allocating a portion of the remaining global carbon budget to the shipping sector and converting this budget into a trajectory for emissions intensity per nautical mile, or per tonne-mile of freight transport, using a range of possible emissions pathways. Shipping firms would then be allocated shares based on current activity and projected future market share. However, the utility of this analysis depends on the assumed carbon budget restrictions being reflected in national and sectoral policies.

conventional technology is economically preferable in the short term but heightens stranded asset risks in the medium term. Meanwhile, investing in new technologies that are yet to be scaled commercially creates both technology and project delivery risks, and the high cost of the resulting technology creates market risks for investors, since the alternatives are unable to compete with fossil fuels. Even if parts of the shipping industry were to fall under regional carbon pricing systems, uncertainty around the level of future carbon prices remains. Unless investors take the expected carbon price over the lifetime of the vessel (rather than the current carbon price) into account, incentives to invest in technology development remain suboptimal (a phenomenon described elsewhere as "dynamic inefficiency").[41,42] Visibility on emissions reduction pathways, and support for the implementation and scaling of new technologies, are therefore in the interest of government, the shipping industry, and its long-term financial backers.

In 2019, a consortium of five shipping associations including the International Chamber of Shipping (ICS), which represents ship owners and operators, formally proposed an industry-wide bunker fuel levy of US$2 per tonne to promote clean fuel use and raise modest research and development funding for low-carbon vessels.[43] In April 2021, a similar group reiterated this call, and submitted a further proposal to the IMO calling for discussions on the use of market-based-mechanisms to be brought forward by several years.[44] In a sign of tension between industry bodies and states in which a large number of ships are registered, the Marshall and Solomon Islands demanded early in 2021 that the IMO impose a universal levy on emissions starting at US$100 per tonne of CO_2 equivalent, both as a price signal to stimulate decarbonisation, and a source of R&D funds.[45]

There is considerable variance in ambition across individual firms. Some major shipping companies, such as Maersk and CMB, have pledged to have commercially viable zero-emissions vessels operating by 2030, and to be fully carbon neutral by 2050.[46,47] Engine producers like MAN already have approved marine fuel-gas systems for liquified hydrogen on the market and are currently working on ammonia engines,[48] while Mitsubishi has

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[41] Fankhauser, S. and Hepburn, C. (2010) "Designing carbon markets, part I: Carbon markets in time". Energy Policy 38(8): 4363-4370. https://doi.org/10.1016/j.enpol.2010.03.064

[42] del Rio, P. (n.d.) "The dynamic efficiency of ETS". Consejo Superior de Investigaciones Científicas. http://www.unife.it/economia/lm.economia/insegnamenti/economia-e-politiche-ambientali/materiale-didattico/delrio.pdf

[43] Chambers, S. (2019, 13 November). "Decarbonisation levy on bunker fuel under discussion at IMO." Splash 247. https://splash247.com/decarbonisation-levy-on-bunker-fuel-under-discussion-at-imo/

[44] International Chamber of Shipping (2021). "Shipping bodies call on world leaders to bring forward discussions on global market-based measures". International Chamber of Shipping. https://www.ics-shipping.org/press-release/shipping-bodies-call-on-world-leaders-to-expediate-global-market-based-measures/

[45] The Maritime Executive (2021, 12 March) "Marshall and Solomon Islands Demand IMO Set $100/Ton Levy on Emissions". The Maritime Executive. https://maritime-executive.com/article/marshall-and-solomon-islands-demand-imo-set-100-ton-levy-on-emissions

[46] See, for example, Maersk (2019), "Towards a zero-carbon future". Maersk. https://www.maersk.com/news/articles/2019/06/26/towards-a-zero-carbon-future

[47] Hellenic Shipping News (2020, 25 January). "CMB's CO2 Pledge: Net Zero As From 2020 – Zero In 2050". Hellenic Shipping News. https://www.hellenicshippingnews.com/cmbs-co2-pledge-net-zero-as-from-2020-zero-in-2050/

[48] Brown, T. (2019, 25 January). "MAN Energy Solutions: an ammonia engine for the maritime sector". Ammonia Energy Association. https://www.ammoniaenergy.org/articles/man-energy-solutions-an-ammonia-engine-for-the-maritime-sector/

announced commercialisation of a turbine able to run on pure ammonia by 2025 that may ultimately see applications in shipping.[49]

In a two-volume report released by the World Bank in April 2021, green ammonia and hydrogen are described as having the most promising balance of favourable features relative to other options for zero-emissions shipping.[50] The report also finds that LNG is unlikely to play a significant role in decarbonisation, including as a transitional fuel.[51] In a recent report published by the Environmental Defense Fund (EDF), "Sailing on Solar", green ammonia is presented as the most likely candidate for net-zero-carbon shipping fuel.[52] Both reports also caution that being able to use ammonia for rapid decarbonisation is conditional on the timely implementation and support of policies promoting the adoption of green ammonia-based technologies. A 2021 academic study concluded that meeting IMO 2050 goals would require "a quantum leap in energy saving technologies and alternative fuels" which would require the proper incentives to facilitate,[53] echoing the conclusion of Balcombe et al's 2019 study, which finds that "decarbonisation will require stronger financial incentives".[54] This sentiment was echoed by a majority of those we interviewed across all segments: shipping and energy, industry bodies, research institutions, financial institutions, and government and NGOs.

In another report developed by the Global Maritime Forum and UMAS, the most effective decarbonisation pathways for shipping adopted ammonia as the most feasible and cost-effective fuel to meet the IMO emissions reduction targets.[55] Lloyd's Register and UMAS have also published recent analysis on zero-emission vessels, weighing up a range of scenarios, and highlighting pros and cons for all technology options.[56,57,58] Finally, the IEA's flagship Energy Technology Perspectives report also contains a useful overview for maritime shipping, including analysis on technology readiness and zero-emissions pathways.[59]

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[49] Mitsubishi Power (2021, 1 March). "Mitsubishi Power Commences Development of World's First Ammonia-fired 40MW Class Gas Turbine System". Mitsubishi Power. https://power.mhi.com/news/20210301.html

[50] Englert, D., Losos, A., Raucci, C., and Smith, T. (2021a). The Potential of Zero-Carbon Bunker Fuels in Developing Countries. World Bank, Washington, DC. World Bank. https://openknowledge.worldbank.org/handle/10986/35435 .

[51] Englert, D., Losos, A., Raucci, C., and Smith, T. (2021b). The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping. World Bank, Washington, DC. World Bank. https://openknowledge.worldbank.org/handle/10986/35437

[52] Ash, N. and Scarborough, T. (2019). "Sailing on Solar: Could green ammonia decarbonise international shipping?" London. Environmental Defense Fund and Ricardo Energy & Environment. https://europe.edf.org/file/399/download?token=agUEbKeQ

[53] Psaraftis, H.N. and Kontovas, C.A. (2021) "Decarbonization of Maritime Transport: Is There Light at the End of the Tunnel?" Sustainability 13(1):237. https://doi.org/10.3390/su13010237

[54] Balcombe, P. et al (2019) "How to decarbonise international shipping: Options for fuels, technologies and policies". Energy Conversion and Management 182(15): 72-88. https://doi.org/10.1016/j.enconman.2018.12.080

[55] Raucci, C., Bonello, J.M., Suarez de la Fuente, S., Smith, T., and Søgaard, K. (2020) "Aggregate investment for the decarbonisation of the shipping industry". UMAS. https://www.globalmaritimeforum.org/content/2020/01/Aggregate-investment-for-the-decarbonisation-of-the-shipping-industry.pdf

[56] International Chamber of Shipping (2021). "Shipping bodies call on world leaders to bring forward discussions on global market-based measures". International Chamber of Shipping. https://www.ics-shipping.org/press-release/shipping-bodies-call-on-world-leaders-to-expediate-global-market-based-measures/

[57] Lloyd's Register (2018) "Zero-Emission Vessels 2030. How do we get there?". https://www.lr.org/en-gb/insights/articles/zev-report-article/.

[58] Lloyd's Register (2020) "Zero-emission vessels: Transition Pathways". https://www.lr.org/en-gb/insights/global-marine-trends-2030/zero-emission-vessels/

[59] IEA (2020) Energy Technology Perspectives 2020. https://www.iea.org/topics/energy-technology-perspectives

A 2020 ICS report indicated that while the shipping industry is acutely aware of the need to decarbonise, a technologically neutral financing approach allowing for the development of multiple zero-emissions solutions is favourable.[60] This report looks to the UK offshore wind industry, which has seen substantial successes in turbine adoption, cost reduction, and technological innovation through the implementation of CfDs.[61] This report seeks to bridge the financing gap between the potential producers of green fuels and the broader maritime industry through an approach not dissimilar to that used in the UK offshore wind industry.

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[60] International Chamber of Shipping (2020). "Catalysing the fourth propulsion revolution". Marisec Publications. https://www.ics-shipping.org/wp-content/uploads/2020/11/Catalysing-the-fourth-propulsion-revolution.pdf

[61] Jennings, T., Andrews Tipper, H., Daglish, J., Grubb, M. and Drummond, P. (2020). *Policy, innovation and cost reduction in UK offshore wind.* Bartlett Institute for Sustainable Resources and Carbon Trust. https://prod-drupal-files.storage.googleapis.com/documents/resource/public/Policy-innovation-offshore-wind-report-2020.pdf

3. Zero-emissions shipping technology options

The shipping industry's current fuel profile remains almost exclusively dominated by emission-intensive fossil fuels. The most common marine fuels (HFO, VLSFO and MGO[62]) are all used in internal combustion engines (ICEs). More recently, the use of liquified natural gas (LNG), offering GHG emission reductions of up to ~20%[63] has been increasing.[64] Switching to less polluting fossil fuels is not, however, is unlikely to achieve the IMO goal of 50% GHG emissions reductions, and extremely unlikely to enable zero-emissions shipping by 2050.

This menu of alternatives includes technologies at different stages of maturity in innovation and implementation. All zero-emissions fuels can be characterised as either zero-carbon or net-zero-carbon (Figure 2). Zero-carbon fuels include ammonia and hydrogen (in compressed form for use in internal combustion engines or stored in fuel cells) and battery power given they are generated using zero-carbon electricity sources such as solar, wind, and nuclear. Other zero-carbon fuel options include nuclear powered ships[65], and sail- or sail-assisted designs[66], are feasible in principle, although nuclear powered ships are likely to face technological, regulatory, and political barriers not faced by other net-zero-carbon options, and sails would be expected to only operate alongside a complementary means of propulsion.

Net-zero-carbon fuels contain carbon but do not increase the total anthropogenic carbon balance in the atmosphere. Examples include synthetic fuels (synfuels) such as methane/methanol where direct air capture of CO_2 is used in their production, and biofuels which are attractive since they can be used in existing engines. However, synfuels are expensive considered and biofuels may not scale well in the long run due to the pressures they could place on arable land needed for food production.

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[62] Speirs, J., Balcombe, P., Blomerus, P. Stettler, M., Brandon, N. and Hawkes, A. (2019) "Can natural gas reduce emissions from Transport? Heavy good vehicles and shipping" Sustainable Gas Institute, Imperial College London. https://www.imperial.ac.uk/sustainable-gas-institute/research-themes/white-paper-series/white-paper-4-can-natural-gas-reduce-emissions-from-transport/

[63] This refers to direct emissions from combustion. Depending on the extraction, refining and supply of LNG, total process emissions may be more or less than those for standard fuels.

[64] DNV.GL (2019) "Energy Transition Outlook 2019" DNV.GL. https://eto.dnv.com/2019/index.html

[65] Liang, L.H. (2020, 4 November) "A nuclear option - Molten Salt Reactor to reduce shipping's GHG emissions". Seatrade Maritime News. https://www.seatrade-maritime.com/environmental/nuclear-option-molten-salt-reactor-reduce-shippings-ghg-emissions

[66] Hellenic Shipping News (2019, 25 October). "Norsepower Rotor Sails Confirmed Savings Of 8.2% Fuel And Associated CO2 In Maersk Pelican Project". Hellenic Shipping news. https://www.hellenicshippingnews.com/norsepower-rotor-sails-confirmed-savings-of-8-2-fuel-and-associated-co2-in-maersk-pelican-project/

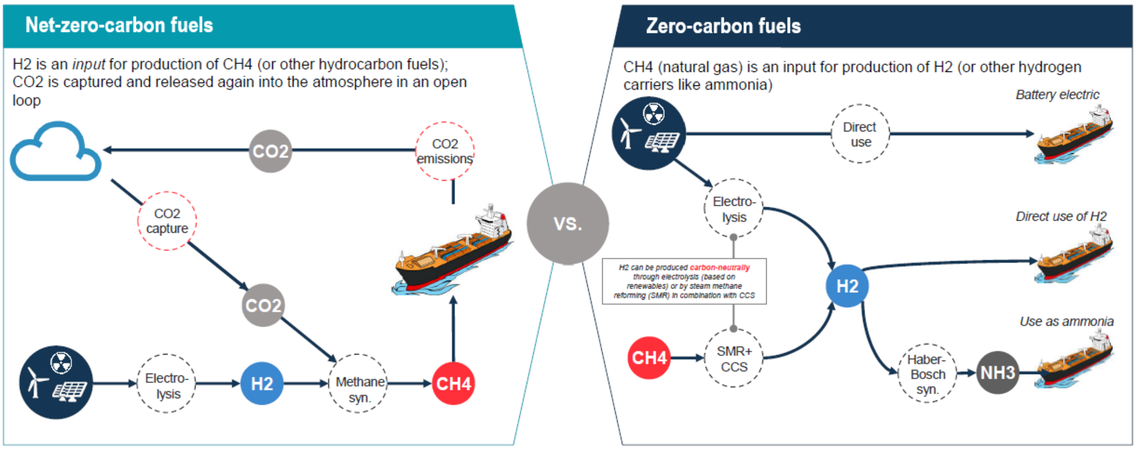

Figure 2: Carbon-based vs non-carbon-based fuels. Note that production of hydrogen-based fuels from methane will likely require offsets on top of Carbon Capture and Storage (CCS) to ensure carbon neutrality. Adapted from ETH Zurich (2019) Towards net zero – comparison of zero-carbon

Energy density, safety, and volume requirements limit the range of potential net-zero-carbon fuels suitable for shipping. Six key approaches or combinations thereof are conceivable for application in different industry segments:

- Direct use of renewable electricity through batteries (for smaller ships and shorter distances).
- Indirect use of renewable electricity through carbon-based synthetic fuels (methanol/methane) with CO_2 sourced from atmospheric capture or from the combustion of biomass/biogas.
- Indirect use of renewable electricity through non-carbon-based synthetic fuels produced through electrolysis (hydrogen/ammonia); [67]
- Bioenergy-derived carbon-based biofuels.
- Nuclear-powered shipping or using nuclear energy to generate clean fuels such as hydrogen or ammonia
- Carbon-based fuels with 100% carbon capture and storage (CCS)

Figure 3 compares International Energy Agency (IEA) estimates of the total ownership cost of different fuels, including supporting infrastructure, for a new ship including an estimate for a nuclear fuelled ship provided in Appendix A2. Based on cost alone (measured in TCO terms), ammonia appears the most promising option. The analysis also suggests that ammonia is the cheapest net-zero-carbon option on a TCO basis; and that the storage costs of hydrogen are very high. The nuclear fuel option is for a ship powered by a nuclear reactor. An alternative that might be more cost-competitive is to produce ammonia by extending the life of existing nuclear power plants, which can have a very low cost of electricity since their capital costs have already largely been recovered (discussed in more detail in Appendix A2). The cost of synthetic fuels using direct air capture to offset CO_2 emitted in combustion represents the largest cost uncertainty.

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[67] We do not consider hydrogen produced from landfill gas with steam reformation, as it is not scalable to the required volumes.

Even for ammonia a significant cost gap remains between the two fossil fuel options (VLSFO and LNG) and the net-zero-carbon ones, as shown in Figure 3. VLSFO requires almost no infrastructure costs, while LNG has similar infrastructure costs but negligible storage costs and the lowest fuel cost of all currently available options.

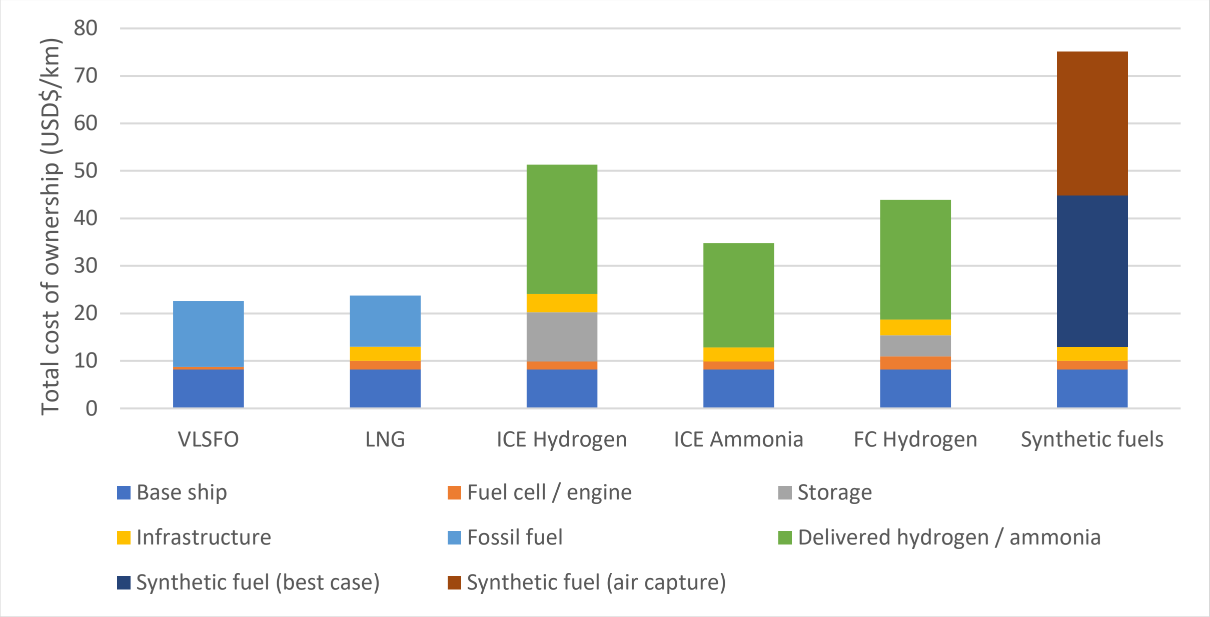

Figure 3: Current total cost of ownership of fuel and powertrain alternatives for large bulk carrier ships. ICE = Internal Combustion Engine, FC = Fuel Cell. Sources: IEA (2019)[68]

While decarbonisation of the maritime industry will likely be achieved through the development of numerous technologies simultaneously, including batteries and hydrogen, ammonia was identified in most reports and by interviewees as the top contender for the decarbonisation of international shipping. Other solutions including fuel cells and batteries, nuclear, and to a lesser extent sail or wind-assist, and carbon capture and storage (CCS), which may play a role in the decarbonisation of the cruise, short-haul, and ferry segments.[69]

3.1. Batteries

Batteries are electrochemical systems that store electric power with very high responsiveness. They are technically attractive both because they represent a direct use of electricity, which is more efficient in terms of propulsion than other technologies, and because if the electricity source is renewable, they have the potential to be zero-carbon. Battery power is an established, commercially viable technology, already relatively cheap with still-declining costs. For short-distance vessels, battery-electric power has already demonstrated a positive business case and is being deployed in certain niche markets such

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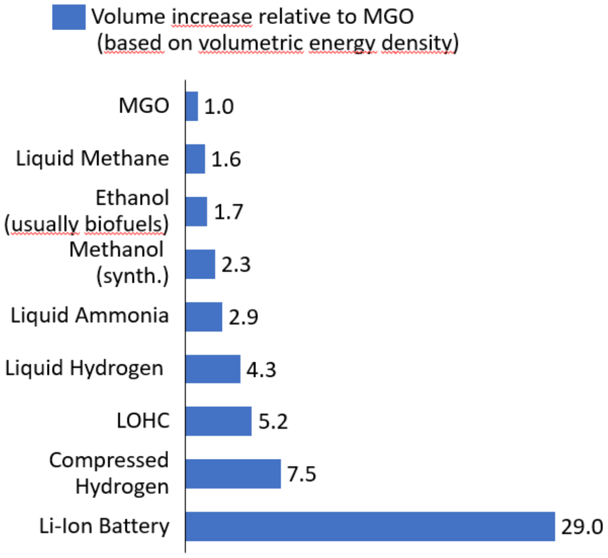
[68] IEA (2019) "Current and future total cost of ownership of fuel/powertrain alternatives in a bulk carrier ship". International Energy Agency, Paris. https://www.iea.org/data-and-statistics/charts/current-and-future-total-cost-of-ownership-of-fuel-powertrain-alternatives-in-a-bulk-carrier-ship

[69] De Beukelaer, C. (2020, 5 November). "Sail cargo: Charting a new path for emission-free shipping?" UNCTAD Transport and Trade Facilitation Newsletter No. 88. https://unctad.org/news/sail-cargo-charting-new-path-emission-free-shipping

as short-distance ferries, tug, and work boats. Near full-electric vessels are increasingly being used in the Scandinavian short-haul ferry market.[9]

However, battery propulsion has its limitations: Lithium-Ion batteries have around 1/30th of the volumetric energy density of MGO (see Figure 4), effectively ruling out any full-battery system on deep-sea vessels based on weight and space requirements. Since most shipping emissions come from deep-sea vessels and they are the focus of this report, batteries are not discussed further as a decarbonisation option.



	Energy density [GJ/m^3]	Storage pressure [bar]	Storage temperature [°C]
MGO[1]	36.6	1	20
Liquid Methane[1]	23.4	1	-162
Ethanol[1]	21.1	1	20
Methanol[1]	15.8	1	20
Liquid Ammonia[1]	12.7	1 or 10	-34 or 20
Liquid Hydrogen[1]	8.5	1	-253
LOHC[2]	7	0	20
Compressed Hydrogen[2]	4.9	700	20
Li-Ion Battery[3]	1.26	1	20

1. De Vries (2019) "Safe and effective applications of ammonia as marine fuel" (2019)
2. Rivard, Trudeau, and Zaghib (2019) "Hydrogen Storage for Mobility: A Review." Materials 12(12). https://europepmc.org/article/PMC/6630991
3. Clean Energy Institute Washington (2020) Lithium-Ion Battery. https://www.cei.washington.edu/education/science-of-solar/battery-technology/

Figure 4: Relative volumetric energy density of shipping fuel alternatives

3.2. Biofuels

Alongside batteries, biofuels are the only other currently commercially available alternative for zero-emissions shipping.[12] Biofuels are made from organic feedstock such as oils, sugars, or waste, and include HVO (hydrogenated vegetable oil), BTL (biomass-to-liquids), bioethanol, biodiesel and LBG (liquefied biogas, mainly methane). Biofuels can be considered carbon-neutral where enough CO_2-equivalent is sequestered in production to offset emissions from combustion.[70] This ignores net emissions from land use change, which can be significant for fuel crops, and the possibility significant environmental damage such as biodiversity loss. Studies looking at lifecycle-emissions from manufacturing biofuel further challenge the assumption of inherent carbon-neutrality.[71]

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[70] Svanberg, M. Ellis, J., Lundgren, J. and Landälv, I. (2018) "Renewable methanol as a fuel for the shipping industry," Renewable and Sustainable Energy Reviews 94:1217-1228.

[71] DeCicco et al. (2016): "Carbon balance effects of U.S. biofuel production and use". Climatic Change 138>667-680. https://link.springer.com/content/pdf/10.1007%2Fs10584-016-1764-4.pdf

Biofuels are logistically attractive because, as with road transport, they can be easily integrated into existing systems without significant modifications. As they are compatible with existing engines, onboard systems, and bunkering infrastructure[72] they form part of the 'bridging philosophy'[73] of decarbonised shipping, which holds that it is optimal to invest in the most decarbonisation-flexible solutions in the short term. So far, high costs have limited the uptake of biofuels, but several large-scale demonstrations projects are active, including the CMA CGM White Shark container vessel (bunkered with biofuel in 2019)[74]; the Van Oord and Shell marine biofuel pilot (HAM 316)[75]; and the Norwegian Hurtigruten and Biokraft commitment to supply biogas at scale by 2027[76].

Well-founded scalability concerns limit the role of biofuels in the longer term. There is already steep competition for land between agriculture and fuel-crop production. The many other useful applications of biofuels (including in road transport, aviation, and industry) intensify this competition. A 2019 Sustainable Shipping Initiative inquiry concluded that "there remains no clear consensus on whether there is sufficient sustainable biomass for shipping as well as other sectors", "a biomass-based decarbonisation pathway for shipping comes with considerable supply risks" and that purpose-grown crops would need to be "certified using leading sustainability standards and […] sourced within regions with strong land governance, carbon and biodiversity credentials" to be considered sustainable in the first place.[77] While water-efficient plants grown on non-agricultural land[78] may loosen these constraints somewhat, we do not currently consider biofuels a viable long-term and large-scale solution for decarbonising shipping.

3.3. Fossil fuels with carbon capture and storage

An option with support from several stakeholders interviewed for this report is the use of hydrogen-based shipping fuels produced from fossil fuels coupled with carbon capture and storage (CCS). This involves using fossil fuels to convert water to hydrogen (electrolysis) and then using CCS to pull the CO_2 out of the exhaust generated by burning the fossil fuel use and injecting it into subsurface geological formations for permanent storage. Fuels produced in this manner are referred to as 'blue' hydrogen and 'blue' ammonia. They are mostly considered interim measures, designed to help decarbonise the shipping industry in

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[72] Ash, N., Sikora, I. and Richelle, B. (2019) "Electrofuels for shipping: How synthetic fuels from renewable electricity could unlock sustainable investment in countries like Chile". Environmental Defense Fund and Ricardo Energy & Environment. https://www.edfeurope.org/file/519/download?token=3VSQ5LR6

[73] DNV.GL: (2019) "Energy Transition Outlook 2019".

[74] Bioenergy International (2019, 25 March) "CMA CGM White Shark bunkers green marine biofuel oil in Rotterdam trial". Bioenergy International. https://bioenergyinternational.com/storage-logistics/cma-cgm-white-shark-bunkers-with-green-marine-biofuel-oil-in-rotterdam-trial Accessed 30 July 2020.

[75] Van Oord (2019, 19 September) "Van Oord and Shell together in biofuel pilot for vessels". Van Oord. https://www.vanoord.com/news/2019-van-oord-and-shell-together-biofuel-pilot-vessels. Accessed 30 July 2020.

[76] Biokraft (2019, 24 May). "Hurtigruten partners with Biokraft in record-breaking biogas deal". Biokraft. https://www.biokraft.no/press-release-hurtigruten-partners-with-biokraft-in-record-breaking-biogas-deal/ Accessed 30 July 2020.

[77] Sustainable Shipping Initiative (2019). "The role of sustainable biofuels in the decarbonisation of shipping". Sustainable Shipping Initiative. https://www.ssi2040.org/wp-content/uploads/2019/12/SSI-The-Role-of-Sustainable-Biofuels-in-the-Decarbonisation-of-Shipping-Full-report.pdf

[78] See, for example, Mason, M. (2020, 10 March) "At the Glasgow climate conference, the UK could kickstart a green tech revolution". *The Guardian*. https://www.theguardian.com/commentisfree/2020/mar/10/glasgow-climate-conference-uk-green-tech-revolution-cop26

the nearer term and facilitate a move to truly ‘green’ alternatives, buying time for green fuel production to grow to sufficient scale to compete economically with conventional fuels. Several problems have been associated with such an approach including upstream emissions from the production of fossil fuels generally not being captured, the difficulty of fully capturing carbon emissions from combustion, and the potential for further investment in gas & CCS infrastructure diverting investment away from genuine net-zero-carbon energy technologies (i.e., solar and wind) that have much greater potential for medium-and long-term cost declines.

A similar option that is technically feasible but not seriously considered by the shipping industry is for carbon-based fossil fuels to continue as the main source of propulsion energy, coupled with their emissions being offset by some form of negative emissions technologies (NET). NETs normally involve pulling CO_2 from the atmosphere and injecting it into subsurface geological formations for permanent storage, as with CCS, but other carbon offsetting options have been explored including enhanced weathering and nature-based sequestration. We have mentioned this option here for completeness but there are significant drawbacks associated with this solution, notwithstanding that such negative emissions technologies are currently extremely expensive (approx. $600/ton of carbon[79]) and have yet to be tested at scale.

3.4. Synthetic carbon-based electro-fuels

Synthetic electro-fuels (“synfuels” henceforth) can be carbon- or hydrogen-based. Carbon-based synfuels include a wide range of synthetic hydrocarbons produced from hydrogen and carbon oxides and are made using several different chemical processes.[80] These include synthetic methane, methanol, and diesel (often referred to as e-methane, e-methanol, etc)[81]. “Green” synfuels conventionally refer to fuels produced using renewable electricity, and whereby enough CO_2 is captured from the atmosphere to offset emissions from combustion.[82]

Like biofuels, e-fuels can generally be directly substituted for conventional petroleum-derived hydrocarbons. Their volume and energy density are comparable to conventional fuels, and they can make use of existing bunkering infrastructure. Successful engine conversion from MGO to (conventional) methanol has been demonstrated in a dual-fuel medium speed engine application on the “Stena Germanica”, in operation since 2015[83], although it is not clear how widely other ship and engine types can be viably retrofitted this way.

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[79] Tollefson, J. (2018) Sucking carbon dioxide from air is cheaper than scientists thought, Nature News, 07 June 2018, https://www.nature.com/articles/d41586-018-05357-w

[80] Ash, Sikora, and Richelle (2019) “Electrofuels for shipping”.

[81] Hänggi, S., Elbert, P., Bütler,T., Cabalzar,U., Teske, S., Bach, C., Onder, C., (2019). “A review of synthetic fuels for passenger vehicles”. Energy Reports 5: 555-569. https://doi.org/10.1016/j.egyr.2019.04.007

[82] The Royal Society (2019) “Policy Briefing: Sustainable synthetic carbon-based fuels for transport”. The Royal Society. https://royalsociety.org/-/media/policy/projects/synthetic-fuels/synthetic-fuels-briefing.pdf

[83] Stefenson, P (2016). “Methanol: The marine fuel of the future. Updates from the Stena Germanica” http://www.methanol.org/wp-content/uploads/2016/07/Updates-from-Stena-Germanica-Per-Stefenson.pdf Accessed 30 July 2020.

The major obstacle to synfuels' use for large-scale shipping decarbonisation is that carbon-based synfuels generally need to include direct air capture to be carbon neutral, which is currently only provided at high cost by a handful of companies. Consequently, methane and methanol synfuels, and direct air capture of CO_2 are not yet available in sufficient commercial quantities or at competitive prices.

3.5. Green hydrogen

Unlike carbon-based synfuels, hydrogen does not emit any CO_2 when combusted to generate power. Green hydrogen production from water (through electrolysis powered by renewable electricity) uses commercially mature technologies that have been proven at scale.[84] The one-step production process makes it less energy-intensive to produce than synfuels or ammonia and gives it a cost advantage over ammonia and synfuels on an energy content basis. Each MWh of energy stored as hydrogen requires around 16% less input energy than ammonia, and 60-70% less than e-methanol.

The main obstacle for hydrogen is storage and transportation. One representative of the shipping and energy sector suggested that "transporting hydrogen destroys the business case for it". Even liquified or bound to an organic carrier (as LOHC), hydrogen has lower volumetric energy densities than ammonia and carbon-based synfuels (by a factor of 2-4; see Figure 4). Liquid hydrogen requires cryogenic storage, greatly increasing the costs of on-board and onshore storage (see Appendix A3). Hydrogen is also highly flammable, and safe storage is cost-intensive. Storage demands also reduce the overall process efficiency on an energy basis. and there is no existing distribution and bunkering infrastructure.

Like all fuels produced using renewable electricity, green hydrogen can be produced without generating additional GHG emissions. This does not account for the embodied carbon in renewable electricity generation equipment and infrastructure, however, which can vary considerably depending on the context.

3.6. Green ammonia

Green ammonia has been identified as a promising long-term net-zero-carbon fuel in the shipping sector.[85] Ammonia is produced from hydrogen combined with atmospheric nitrogen through the energy-intensive Haber-Bosch process. Although ammonia is already widely produced and traded for use in fertiliser and other industrial applications, it is predominantly produced using hydrogen derived from fossil fuels ('grey ammonia').

Ammonia has more than double the volumetric energy density of liquid hydrogen and can be stored in liquid form, at atmospheric pressures and relatively normal temperatures (see Figure 4). It poses a much lower fire risk than hydrogen and hydrocarbon fuels. Although it is highly toxic and corrosive, established standards for safe handling, storage, and transport of ammonia in bulk already exist. It is less energy- and cost-intensive to store and transport than hydrogen; and, since ammonia supply chains already exist, is supported by an existing

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[84] Ash, Sikora, and Richelle (2019) "Electrofuels for shipping".

[85] De Vries, N. (2019). "Safe and effective application of ammonia as a marine fuel". TU Delft. http://resolver.tudelft.nl/uuid:be8cbe0a-28ec-4bd9-8ad0-648de04649b8.

global logistical infrastructure. Despite its two-stage production process, therefore, ammonia provides a potentially faster route to decarbonisation than hydrogen. One interviewee remarked that “ammonia is the best vector for exporting hydrogen” and that that it is the “most promising due to the scalable market”. Another representative of the shipping industry concluded that “the hydrogen future we see is actually an ammonia future”, a sentiment echoed by many interviewees.

Ammonia is not very compatible with existing bunkering infrastructure and cannot be burned in existing internal combustion engines without modifications. Fully ammonia-burning engines or fuel cells are estimated to be commercially viable within 3-5 years.[86] Ammonia’s high auto-ignition temperature means it requires co-firing with a ‘pilot’ fuel in both compression and spark ignition engines. This function could be served by breaking down or ‘cracking’ the ammonia to produce hydrogen using cracking equipment onboard the ship. Green ammonia shipping fuels can be virtually carbon-free on a lifecycle basis if there is no embodied carbon in the infrastructure required to produce the energy [87]. Although ammonia is not as dense as synfuels, its energy production efficiency, at 50-60%, is greater than for synfuels (around 40%), meaning that less renewable input is required per unit of fuel.[31]

Several green ammonia projects are at development and pilot stages, both in fuel production, and its use in ships. The Yara Pilbara plant in Australia uses renewable electricity to produce carbon-neutral ammonia,[88] while MAN Energy Solutions is expected to build an ammonia engine for use by 2022,[89] and an Equinor and Eidesvik offshore project aims to test ammonia fuel cells on deep sea sailing by 2024.[90]

3.7. Nuclear

Nuclear energy provides two options for zero-emissions shipping. Firstly, as a zero-carbon energy source for producing green fuels such as hydrogen/ammonia and synfuels, and secondly as a direct source of energy for propulsion onboard ships. The key benefit of nuclear is that once a reactor is built it can have a long lifetime with relatively low operating costs, enabling low-cost generation of clean fuels, or propulsion for vessels that never need refuelling. However, while maritime nuclear propulsion is technologically mature, the adoption of nuclear reactors onboard civilian, commercial shipping vessels poses several unique and significant challenges. The capital costs associated with the implementation of generators are substantial while the risks pertaining to safety, environment, disposal, public perception, and regulation are substantial.

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[86] ETH Zürich, Amplifier (2019): “Towards net-zero. Innovating for a carbon-free future of shipping in the North and Baltic sea”.

[87] If the production of the solar panels and wind farms uses fossil fuel-based energy, then there will be ‘embodied emissions’, but in the future even this energy can come from renewable sources.

[88] Brown, T. (2020, 9 April). “Green ammonia plants win financing in Australia and New Zealand”. Ammonia Energy Association. https://www.ammoniaenergy.org/articles/green-ammonia-plants-win-financing-in-australia-and-new-zealand/. Accessed 30 July 2020.

[89] Brown, T. (2019). “MAN Energy Solutions: an ammonia engine for the maritime sector”.

[90] Equinor (2020, 23 January). “The world’s first carbon-free ammonia-fuelled supply vessel on the drawing board”. Equinor. https://www.equinor.com/en/news/2020-01-23-viking-energy.html. Accessed 30 July 2020.

Nuclear technology appears to be in a state of flux with many of the earlier reactors built for commercial purposes either retired or nearing the end of their lifetime (i.e., typically ~30 years), but with a potentially positive future given climate change concerns.[91] While a number of advanced economies with nuclear energy are experiencing near-term closure of a large number of nuclear plants (the IEA found that 25% of existing nuclear capacity in advanced economies is expected to be shut down by 2025)[92], life-extension to 80 and even 100-years of lifetime are feasible.[93] A few countries have chosen not to build any new reactors, notably Japan and Germany, but the Asian nuclear industry is in rapid growth, with China's recently doubling its nuclear capacity during their 13th Five-Year Plan period from 2016 to 2020.[94]

To account for the full scope of nuclear options and the evolving nature of the industry, the following scenarios were considered when evaluating the viability of nuclear energy for green shipping:

1. Current nuclear reactor technology as a source of indirect energy for production of hydrogen and/or ammonia
2. New nuclear reactor technology as a source of indirect energy for production of hydrogen and/or ammonia
3. Current nuclear reactor technology used as a direct source of energy for steam propulsion within a ship
4. New nuclear reactor technology (small modular reactors) used as a direct source of energy for steam propulsion

The most viable option at present for the nuclear energy in international shipping appears to be scenario 1 - the production of hydrogen or ammonia from existing nuclear plants. A certain subset of current reactor technologies could be used as a cost-effective source of indirect energy for production of hydrogen and/or ammonia. Specifically, nuclear plants that have operated for more than 30-years of operation, in certain markets, which are capable of supplying energy for as low as $25/MWh, making them close to producing hydrogen at a cost competitive with fossil fuels.[95]

New nuclear plants, scenario 2, including plants that have operated for less than 30 years generally have a much higher energy cost (i.e., >$50/MWh and up) and are currently not cost-competitive with renewable energy unless they can be dedicated to purely generating clean fuels. It should be noted that the direct or indirect production of hydrogen or ammonia from nuclear energy is not currently a commercial activity, with only some states exploring technological development (see Appendix A2). Early research in the US suggested that

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[91] International Atomic Energy Agency (2021) "Safe Long Term Operation of Nuclear Power Plants." https://www.iaea.org/publications/7871/safe-long-term-operation-of-nuclear-power-plants.

[92] IEA (2019) "Nuclear Power in a Clean Energy System". https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system

[93] Bandyk, M. (2021) "How long can a nuclear plant run? Regulators consider 100 years". Utility Dive. https://www.utilitydive.com/news/how-long-can-a-nuclear-plant-run-regulators-consider-100-years/597294/

[94] Conca, J. (2021). "China Will Lead the World in Nuclear Energy, along with All Other Energy Sources, Sooner than You Think." *Forbes Magazine*, April 23, 2021. https://www.forbes.com/sites/jamesconca/2021/04/23/china-will-lead-the-world-in-nuclear-energy-along-with-all-other-energy-sources-sooner-than-you-think/.

[95] Bakirov, M., A. Cserhati, Y. Dou, Esquivel Estrada, S. Hercberg, J. J. Kwon, Ž. Tomšić et al. (2018) "Economic Assessment of the Long Term Operation of Nuclear Power Plants: Approaches and Experience.". IAEA Nuclear Energy Series. https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1813_web.pdf

nuclear generation of hydrogen / ammonia might only be competitive in certain applications.[96] More recent research has pointed to the fact that advanced nuclear technologies are also capable of providing high quality steam to newer generations of electrolysers (i.e., Solid-Oxide Electrolysis Cell (SOEC) technology) potentially supporting higher rates of efficiency in hydrogen and ammonia production. A 2020 IRENA analysis found that once the costs of electrolyser technology fall to $130 kW/hr (USD) at 5 TW installed capacity, hydrogen costs could be less than $5/kg, competitive with fossil fuel-based hydrogen production (see Appendix A2). However, engineering risks remains with relying on new nuclear for clean fuel production given that renewables have achieved a much more convincing learning rate compared to nuclear over the last two decades.[97]

Nuclear technology ships (scenario 3) are reasonably prevalent today, in the form of nuclear-powered submarines for military application, with an estimated 150 in operation today.[98] There have been four commercial nuclear surface vessels, one in which remains in operation today, the Russian Sevmorput. However, as noted in a 2019 assessment from Imperial College London and University of London, "this ship experiences restrictions in which ports it can visit, due to civilian evacuation plans and fears at docks."[99] Other commercial ships built using existing nuclear technology have been retired due to similar restrictions and failure to achieve economic parity with conventional fuels.

Advanced nuclear technology ships operate more safely, efficiently and, once the technology is implemented at scale, are expected to have reduced capital costs. As such, they could be a commercially viable prospect for decarbonising shipping. Ships powered with advanced nuclear technology (scenario 4) are currently still only in a research and development phase with newer small modular reactors not likely to achieve cost parity with alternatives, such as ammonia-powered ships, until at least 2030 (i.e., in comparison to scenarios 1 and 2 above). Nonetheless, it is reasonable to assume that advanced nuclear technology could be beneficial in commercial shipping in the future.

While the technical realization and deployment of advanced small modular reactors for nuclear powered ships unfolds, the regulatory path for operation must also be navigated. Due to political and environmental concerns, nuclear vessels often are left with a limited number of ports that they may call upon.[100] Widescale adoption of reactors aboard commercial vessels would require updates to the IMO Code of Safety for Merchant Nuclear Ships and International Atomic Energy agency agreements consistent with international norms and politics surrounding the distribution of nuclear fuels and technologies.[101] The rapid adoption of

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[96] Keuter, D. (2010), "Nuclear H2 production–a utility perspective.", Fourth Information Exchange Meeting Oakbrook, Illinois, USA 14-16 April 2009. p289-298 https://read.oecd-ilibrary.org/nuclear-energy/nuclear-production-of-hydrogen_9789264087156-en

[97] Way, R., Mealy, P. & Farmer, J. D. Estimating the costs of energy transition scenarios using probabilistic forecasting methods. (2020), https://www.inet.ox.ac.uk/publications/no-2021-01-estimating-the-costs-of-energy-transition-scenarios-using-probabilistic-forecasting-methods/

[98] World Nuclear Association (2021) "Nuclear-Powered Ships". https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx

[99] Balcombe et al (2019) "How to decarbonise international shipping".

[100] Halim, R. A., Kirstein, L., Merk, O., Martinez, L.M. (2018). "Decarbonization Pathways for International Maritime Transport: A Model-Based Policy Impact Assessment" Sustainability 10(7): 2243. https://doi.org/10.3390/su10072243

[101] *Ibid.*

nuclear-based fuels as a means of meeting decarbonisation targets would require rapid international agreements and treaty amendments that would almost certainly prevent meaningful adoption before 2030. As a result of the international politics of nuclear energy and its applications, nuclear shipping may be best managed through bespoke bilateral agreements where political will already exists.[102]

In terms of funding nuclear technologies through contracts for difference, clean fuels produced by nuclear energy could enter into both a fuel-only or total cost of ownership CfD format. As a nuclear-powered ship would require a very specific build and does not require refuelling over its lifetime, only a total cost of ownership format of a CfD would work (see section 6 for more details).

3.8. Wind and Sail

In addition to nuclear, wind propulsion technologies have been proposed and utilised on a small-scale basis to improve energy efficiency and reduce emissions in the shipping sector. Wind technologies are estimated to reduce fuel consumption in the range of 10-30% with CO_2 abatement reductions in the range of 10-60% dependent on the wind technologies.[103]

A variety of wind technologies exist serving multiple functions at various stages of development ranging in levels of maturity.[104] Sails, both soft and rigid as well as kites and rotors offer an intermittent supply of propulsion requiring the pairing with other technologies while turbines and rotors support electric propulsion or battery recharge.[105]

Development and installation costs vary drastically based on technology type and will require pairing with other net-zero-carbon fuel solutions to meet the energy demands of modern shipping vessels.[106]

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[102] *Ibid.*

[103] *Ibid.*

[104] ClearSeas 2020. “Back to the Future: Wind Power and the Decarbonisation of Shipping.” Accessed 29 March 2021. https://clearseas.org/en/blog/back-to-the-future-wind-power-and-the-decarbonization-of-shipping/

[105] Halim, Ronald A.; Kirstein, Lucie; Merk, Olaf; Martinez, Luis M. (2018). "Decarbonization Pathways for International Maritime Transport: A Model-Based Policy Impact Assessment" Sustainability 10, no. 7: 2243. https://doi.org/10.3390/su10072243

[106] Bonduelle, A., Métivier, S., and Rynikiewicz, C. (2015). “Sail into a sustainable future: Roadmap for Sail Transport”. http://www.nsrsail.eu/wp-content/uploads/2015/12/Roadmap-SAIL-Transport-WEB-Bonduelle-WP4.pdf. Accessed 29 March 2021.

4. Supporting the adoption of zero-emissions solutions in shipping

Even as the cost of alternative fuels declines and the technical feasibility of their use rises, major challenges remain. The shipping industry is used to capital-intensive, long-lifetime investments, but it is also intensely competitive.[107] Although ships themselves are essentially regulated by a single body, the IMO, the vast complexity of ownership, leasing, financing, and operation structures complicate efforts to coordinate decarbonisation investments effectively.

Barriers standing in the way of a fast adoption of green shipping technologies can be broken down into three main categories – economic, technological, and environmental – all of which will need to be effectively addressed by regulatory and market-based instruments for net-zero-carbon fuels to succeed. The UK government commissioned a report on barriers to commercial deployment of emission reduction options, which is a useful complement to the analysis presented here[108].

4.1 Economic barriers

All net-zero-carbon shipping fuel alternatives described in Section 3 are currently more expensive than conventional VLSFO and MGO fuels (see Figure 5). HFO, a refinery residual, generally trades below the Brent crude oil price and remains the most widely used engine fuel on ships.[109] Annex VI of the IMO MARPOL Convention introduced sulphur content regulation in 2005, leading to gradual, ongoing replacement of HFO by MGO and other higher quality alternatives requiring minimal operational changes.[110] The reduction in sulphur content limits to 0.5% mandated by IMO 2020 is accelerating this shift.[111] MGO has historically traded around 20% above the Brent crude oil price[112] and, with IMO 2020 in place, is the most appropriate benchmark price against which net-zero-carbon fuels should be assessed.

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[107] Monacelli, N. (2018) “Improving maritime transportation security in response to industry consolidation”. *Homeland Security Affairs* 14. https://www.hsaj.org/articles/14257.

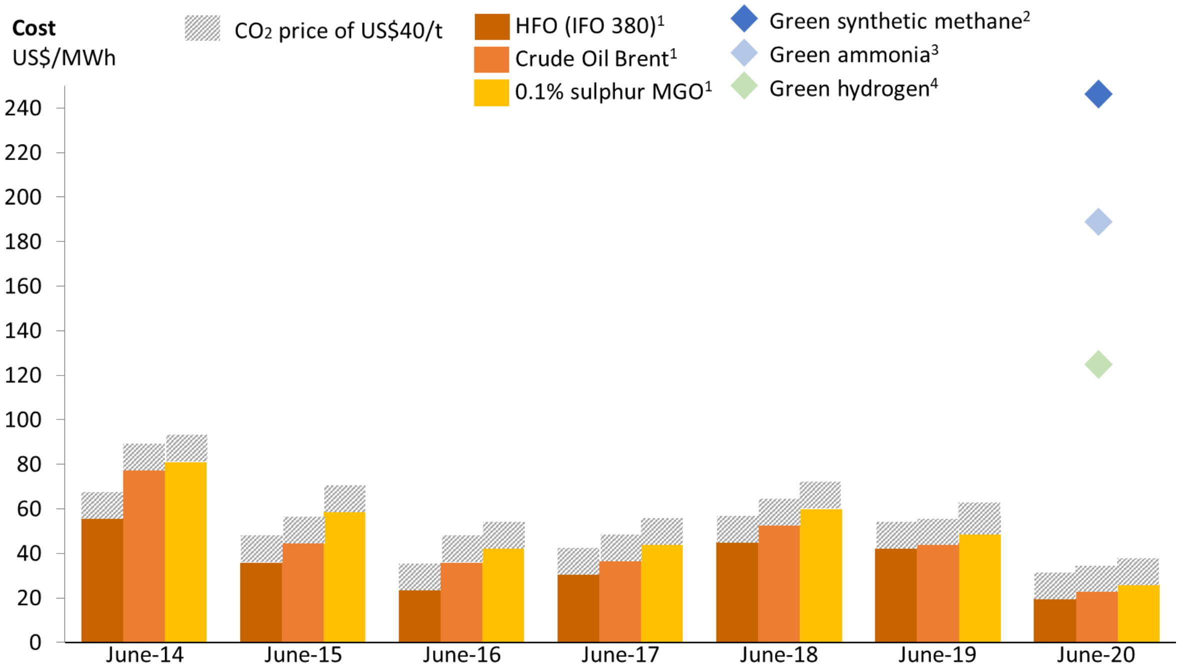
[108] Fitzpatrick, N. et al (2019). “Reducing the Maritime Sector’s Contribution to Climate Change and Air Pollution”. UK Department for Transport. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815671/identification-market-failures-other-barriers-of-commercial-deployment-of-emission-reduction-options.pdf

[109] IMO (2020) “IMO 2020 – cutting sulphur oxide emissions”. International Maritime Organisation. http://www.imo.org/en/mediacentre/hottopics/pages/sulphur-2020.aspx Accessed 27 July 2020.

[110] Billing, E., Fitzgibbon, T. and Shankar, A. (2018) “IMO 2020 and the outlook for marine fuels”. McKinsey & Company. https://www.mckinsey.com/~/media/McKinsey/Industries/Oil%20and%20Gas/Our%20Insights/IMO%202020%20and%20the%20outlook%20for%20marine%20fuels/IMO-2020-and-the-outlook-for-marine-fuels.pdf

[111] IMO (2019) “Frequently Asked Questions: The 2020 global sulphur limit” http://www.imo.org/en/MediaCentre/HotTopics/GHG/Documents/2020%20sulphur%20limit%20FAQ%202019.pdf. Accessed 27 July 2020.

[112] DNV.GL. (2018) “Assessment of selected alternative fuels and technologies”. DNV-GL Maritime. https://sustainableworldports.org/wp-content/uploads/DNV-GL_2018_Assessment-of-selected-alternative-fuels-and-tech-report.pdf



1. DNV.GL
2. Average of: IEA (2019) The Future of Hydrogen; Agora Energiewende (2018) The Future Cost of Electricity-Based Synthetic Fuels; and Gorre et al (2018) Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants in dynamic operation. Applied Energy 257.
3. Average of IEA (2019); Ash and Scarborough (2019) Sailing on Solar. EDF and Ricardo; and Nayak-Luke & Bañares-Alcántara (2020) Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production. Energy & Environmental Science 13.
4. Average of Van Hulst (2019) The clean hydrogen future has already begun; BNEF (2020) Hydrogen Economy Outlook; and IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal.

Figure 5: Cost estimates for different brown and green shipping fuels

The cost drivers for net-zero-carbon fuels vary by fuel type and are divided into a marginal fuel production cost differential, and upfront investment requirements.

For green hydrogen, both the fuel cost differential and upfront investments are cost drivers. Whilst green hydrogen is the cheapest fuel to produce on an energy-content basis, it is much less energy-dense and carries additional requirements on board a ship in terms of bunkering infrastructure and transport. To be used, hydrogen needs to either be liquified (requiring energy-intensive cryogenic storage) or bound to organic carriers (LOHC). Even in liquid or organic form, hydrogen is still less energy-dense than the alternatives, requiring fuel tanks on board to be 4-6 times larger than on conventional vessels (Figure 4). Additional costs are incurred in onshore transport and bunkering. If used in fuel cells to provide electric propulsion, hydrogen has the potential to lower operating costs, but competitiveness remains some way off.

For synthetic carbon-based fuels and liquid ammonia, the fuel itself is the main cost driver. Whereas carbon-based synfuels can be employed with few changes to bunkering systems and ship engines, liquid ammonia requires changes to handle its corrosive properties (see Appendix A3). Ammonia used in fuel cells, like hydrogen, has the potential to lower operating costs in the longer-term.

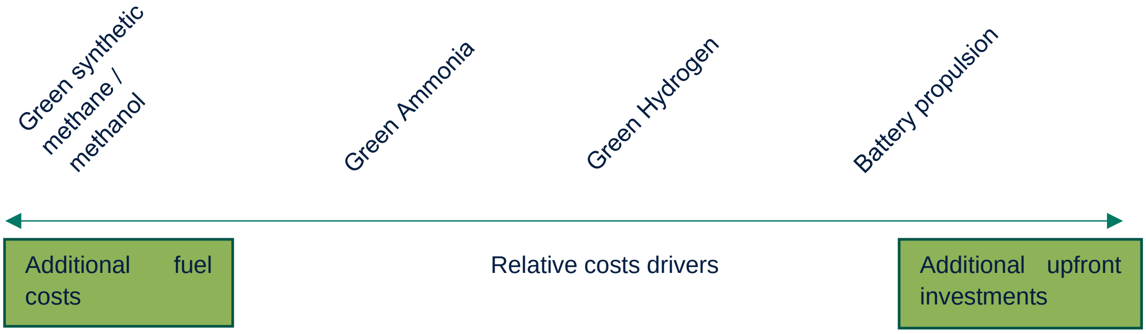


Figure 6: Relative cost drivers for different net-zero-carbon fuel options.

Fuel-cost ranges are highly uncertain, since they depend on the cost of electricity, electrolyser technology, methane synthesis technology, carbon capture technology, transportation, and bunkering cost, with the relative importance of each depending on the fuel. Costs for green hydrogen, green ammonia and green synthetic methane vary substantially across studies. The lower bounds of future cost estimates generally reflect (widely expected) declines in the cost of renewable electricity, as well as more uncertain cost declines for electrolyser capacity. Upper bounds on future costs of traditional fuels are driven by carbon prices or equivalent regulation.

By surveying a range of studies on the current costs of alternative fuels, we estimate green hydrogen energy costs at around $147/MWh[58], green ammonia at $181/MWh[59], and green synthetic methane costs of around $244/MWh[60], compared to $40-70/MWh for MGO from 2015-2020 (see Figure 5). Costs for green hydrogen are forecasted to drop rapidly in the next ten years. Price estimates for 2030 range from 30% (IEA) to 60% (Hydrogen Council) lower than today in real terms, bringing it into a similar range to MGO with no carbon price on a fuel-only basis[113]. Green ammonia is expected to see similar declines using similar key technologies (e.g., electrolysers),[114], although by less given the additional steps required.

On a total cost basis, green hydrogen is likely to remain more expensive than MGO and green ammonia, given the greater need for upfront investment and opportunity costs from lost storage space. Estimates including crew, engine, storage, fuel, and opportunity cost could see hydrogen around 30% more expensive than ammonia solutions.[115]

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[113] IRENA (2019) *Renewable Power Generation Costs in 2018*. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/%20Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf

[114] Cesaro, Z., Ives, M., Nayak-Luke, R., Mason, M. & Bañares-Alcántara, R. (2021) "Ammonia to power: Forecasting the levelized cost of electricity from green ammonia in large-scale power plants." Applied Energy 282, 116009. https://doi.org/10.1016/j.apenergy.2020.116009

[115] ETH Zürich, Amplifier (2019): "Towards net-zero. Innovating for a carbon-free future of shipping in the North and Baltic Sea".

Regardless of ultimate fuel choice, the adoption of net-zero-carbon fuels in shipping will raise costs for operators, although industry professionals suggest demand for shipping is sufficiently inelastic that this will have little effect on demand, and that the primary concern expressed in stakeholder interviews was with the maintenance of a level playing field in the transition from one set of fuels to another. A complication for the widespread adoption of green ammonia and hydrogen, and to a lesser extent synfuels, is the absence of standardised certification processes, regulatory standards, and large-scale fuel suppliers. Until these fuels are competitively priced, cohesive standards are essential to support a market. This in turn requires industry or regulatory agreement on standards for blue, grey, and green hydrogen, ammonia, and e-fuels such that buyers can be confident in fuels meeting low- or net-zero-carbon criteria. The international nature of the fuel supply and bunkering industry is likely to further complicate certification efforts.

Decarbonised shipping also has implications for geopolitics and trade. The sensitivity of net-zero-fuels to electricity prices incentivises production near high-resource renewable energy sites. While this does not pose a problem for low-volume production (the UK can, for example, site hydrogen-producing electrolysers near North Sea offshore wind resources), space and load factor constraints will emerge as the fuel supply market expands and becomes more competitive. Regulatory or market instruments for net-zero shipping should encourage cost-effective production of net-zero-carbon fuels, with potential implications for existing shipping corridors, which may adapt to allow refuelling or bunkering in locations where these fuels are cheapest.

A final challenge – and potentially an opportunity – is the structure of the shipping industry itself. The many stakeholders in a ship's construction and operational activity mean its interaction with different sovereign and corporate entities is diverse. The container segment is highly concentrated among large firms and has a higher proportion of owner-operators, while ownership structures in the bulk and tanker segments are more fragmented. The vested interests of dominant shipowners and operators, and oil majors supplying shipping fuels (particularly large LNG suppliers looking to sell into shipping markets), can slow progress, but equally, commitments by a small number of large firms, particularly in the container segment, can accelerate investment in net-zero-carbon fuel supply and infrastructure and generate positive externalities by lowering cost for smaller players. Concentration of marine traffic through a relatively small number of major ports presents similar opportunities for policies and instruments adopted by a small number of individual governments or ports to have an outsize impact on industry trends.

4.2 Technological barriers

Renewable electricity-powered electrolysis is a key technology for all synthetic fuels, as green hydrogen is required for both green ammonia and synthetic methane production. Whilst hydrogen is an established feedstock, only around 4% of global hydrogen supply is produced via electrolysis.[116] Most existing capacity is based on chlor-alkali (ALK)

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[116] IRENA (2018): "Hydrogen from renewable power: Technology outlook for the energy transition". International Renewable Energy Agency, Abu Dhabi. https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

electrolysers, but prototypes and demonstration projects of solid oxide electrolyser cells (COEC) and proton exchange membranes (PEM) are being explored.

ALK technology has been in use for decades (albeit in small volumes). PEM electrolysers have become commercially available in recent years and are gaining market traction[117] due to their flexibility and smaller lifecycle footprint. Flexible operation and higher efficiencies at lower load factors are helpful in working with intermittent renewable electricity supply. While further improvements are widely expected, more research and larger-scale operation are required to fully understand the scope for further cost and material declines, higher efficiencies, and higher load factor flexibilities.

The step from green hydrogen to green ammonia – nitrogen fixation through a Haber-Bosch process – has been technologically mature for more than a century, with existing research focusing on agile Haber-Bosch processes (e.g., at the Thyssen-Krupp Port Lincoln Pilot project in Australia) to optimise use with intermittent electricity supply. The production of green synthetic methane (and other, carbon-based e-fuels) from green hydrogen involves two additional processes, neither of which is established at scale: direct capture of atmospheric CO_2[118] and large-scale methane synthesis. Learning curves here are more difficult to predict than for electrolysers, due to the nascent nature of the technologies and the lack of deployment to scale.

A range of demand-side technologies are also required in ship engine design, on-board storage, on-board safety, bunkering and onshore transport. Green hydrogen and ammonia can be burned in ICEs and fuel cells. As the shipping industry predominantly uses large diesel engines, ICEs are an easier initial entry point for new fuels. MAN Energy Solutions, a major ship engine designer, is developing ammonia ICEs.[119] Ammonia has a narrow flammability range with combustion conditions becoming more unstable at very low and high engine speeds. Increased usage will no doubt promote solutions including the use of hydrogen as a ignition fuel.[120] Hydrogen, in contrast to ammonia, is highly flammable, potentially creating safety problems on board. In the medium term, hydrogen and ammonia fuel cells have the potential to reduce overall energy use and operating costs through electric propulsion (offsetting the additional energy conversions required with the far greater efficiency of electric motors). ETH Zürich and Amplifier anticipate commercialisation within 5-10 years.[121]

4.3 Environmental and Safety barriers

Environmental impact and safety are critical issues for marine fuels. Spills and leakages of oil, and of hazardous and noxious substances (HNS), pose potentially catastrophic environmental risks with long-term effects, while fires, explosions and exposure to toxins

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[117] *Ibid.*

[118] Two companies currently provide commercial direct air-capture (Carbon Engineering in Canada, and Climeworks in Switzerland), at a cost of approximately US$ 600 per tonne of CO2 https://www.nature.com/articles/d41586-018-05357-w

[119] Brown, T. (2019). "MAN Energy Solutions: an ammonia engine for the maritime sector".

[120] Comotti, M.; Frigo, S. (2015) "Hydrogen Generation System for Ammonia–Hydrogen Fuelled Internal Combustion Engines". International Journal of Hydrogen Energy 40(33):10673-10686. https://doi.org/10.1016/j.ijhydene.2015.06.080

[121] ETH Zürich, Amplifier (2019): "Towards net-zero. Innovating for a carbon-free future of shipping in the North and Baltic sea".

pose risks to those handling fuels.[122] The last decade has seen ten marine fuel spills exceeding 700 tonnes.[123] Measures for reducing the risk of these occurrences, such as the double hulling of ships, are well established. By contrast, there is a relative underdevelopment of safety standards for other HNS, including ammonia, despite similar levels of attributable accidents between such chemicals as cargo and oil-based fuels.[124]

While standards exist for the transport and treatment of all of the net-zero-carbon fuels under consideration, each carries distinct environmental and safety concerns (see Technical Appendix A2 for more information). The IMO's International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF) and International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC)[125] apply to all gaseous and low flashpoint fuels. The IGF has detailed provisions for natural gas in liquid or compressed form (LNG, CNG), with regulations for methanol and low-flashpoint diesel fuels under development. Ships installing other low-flashpoint fuel systems are required to demonstrate compliance with the IGF Code. Neither hydrogen nor ammonia use, or storage are yet covered by the IGF, although rules are under development and are expected to feature in its next amendment.[126,127]

- **Hydrogen** is highly flammable and must be stored either under pressure (800 bar), or at -253°C in cryogenic tanks. Both are potentially dangerous: pressurised gas can explode when heated, and cryogenic storage can cause burns or injuries. Hydrogen is not-toxic, however, and spills of liquified or compressed hydrogen are not thought to have serious environmental consequences. Regulation typically limits the distribution of hydrogen on land[128], and the proportion of hydrogen that can be deployed in natural gas pipeline systems. There are published guidelines[129] on the use of cryogenic tanks (also used for LNG), but knowledge and legal gaps remain in hydrogen fuel safety standards, especially measures to reduce the severity and likelihood of fires and explosions[130].

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[122] See Appendix for a more detailed summary of Hazard Statements from the UN Globally Harmonised System of Classification and Labelling of Chemicals (GHS) for a range of potential shipping fuels.

[123] ITOPF (2020) *Oil Tanker Spill Statistics 2019.* ITOPF, London. https://www.itopf.org/fileadmin/data/Documents/Company_Lit/Oil_Spill_Stats_brochure_2020_for_web.pdf

[124] Häkkinen, J., & Posti, A. (2015). "Port accidents involving hazardous substances based on FACTS database analysis." In: Proceedings of the 38th AMOP Technical Seminar on Environmental Contamination and Response.

[125] For further information on the IMO IGF Code, see https://www.imo.org/en/OurWork/Safety/Pages/IGF-Code.aspx.

[126] ETH Zürich, Amplifier (2019): "Towards net-zero. Innovating for a carbon-free future of shipping in the North and Baltic sea". p.15.

[127] DNV.GL (2019) "Energy Transition Outlook 2019".

[128] For example, international regulation (ADR) forbids road transport in certain tunnels.

[129] From the EIGA, the ISO, the IMO and CEN.

[130] For example, adequate ventilation, explosion venting and suppression, isolation, containment, blast walls and sensing and means to relieve pressure in closed systems will need to be installed. For further detail on hydrogen safety issues, see Pritchard, D.K., Royle, M. and Willoughby, D. (2009) "Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version". Health and Safety Executive. https://www.hse.gov.uk/research/rrpdf/rr715.pdf. For further detail on safety issues in using ammonia as a shipping fuel, see De Vries (2019). "Safe and effective application of ammonia as a marine fuel".

- **Ammonia** can be stored at -33°C and is less flammable than conventional oils, but is acutely toxic and corrosive, making it a high-risk chemical to transport.[131] It can severely damage skin, eyes and lungs and exposure for 10 mins at 2,700 ppm can be lethal. A spill would have severe environmental consequences, killing most aquatic organisms in close proximity, with long lasting effects including eutrophication.[132] Although regulatory infrastructure for safe transportation, handling and storage of ammonia exists, including exposure limits and protective equipment requirements for those handling it, it cannot currently be used as marine fuel under the IGC code. Limiting exposure to the environment and handlers would require ultra-safe designs of tanks, continuous ventilation systems, and flares to burn leakages[133].
- **Methanol** is mildly corrosive, and toxic at high concentrations. However, a methanol fuel spill would have less environmental impact than ammonia[134], and it is not classified as a marine pollutant by the IMO, meaning it can be carried in tanks along the length of the hull, unlike conventional fuels[135,136,137,138]. The flashpoint (minimum ignition temperature) falls below the minimum for marine fuels in the IMO Safety of Life at Sea Convention (SOLAS), meaning risk assessment or evaluation must be carried out for each use of methanol, demonstrating fire safety equivalent to conventional marine fuels.
- **Methane** is similar to LNG (as its largest chemical component) and poses similar hazards when cryogenically stored.[139] Methane is not toxic but leakages (fugitive emissions, also known as ‘methane slip’) into the atmosphere, including from upstream processes, can substantially reduce its climate benefits. The global warming potential of methane is 28 times higher than CO_2 on a 100-year basis or 84 times higher on a 20 year basis[140].

The cost of transport and insurance of different fuels is a partial proxy for the implied expense and risk associated with doing so and reflects the relative challenges associated with each potential fuel.[141] The differences in costs for different fuels as a percentage of their

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[131] Ammonia ranks 7th in the IMO list of top 20 chemicals likely to pose the highest risk of being involved in an HNS incident. See ITOPF (2012). *TIP 17: Response To Marine Chemical Incidents.* ITOPF Technical Information Paper, 17. https://www.itopf.org/knowledge-resources/documents-guides/technical-information-papers/; Karakavuz, A., Tokgoz, B.E., Zaloom, V., Marquez, A., 2020. "Risk assessment of commonly transported chemicals in the Port of Houston," International Journal of Critical Infrastructures, Inderscience Enterprises Ltd, vol. 16(1), pages 38-52.

[132] Ash and Scarborough (2019) “Sailing on Solar”.

[133] De Vries (2019). “Safe and effective application of ammonia as a marine fuel”.

[134] Methanol is dangerous to humans, but humans are uniquely sensitive to methanol poisoning.

[135] Brynolf, S. (2014). “Environmental Assessment of Present and Future Marine Fuels.” Chalmers University of Technology. https://core.ac.uk/reader/198036870

[136] IRENA (2019) *Hydrogen: A Renewable Energy Perspective.* International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf

[137] ITOPF (2012). TIP 17: Response To Marine Chemical Incident

[138] Svanberg et al (2018) “Renewable methanol as a fuel for the shipping industry”.

[139] DNV.GL. (2018) “Assessment of selected alternative fuels and technologies”.

[140] The official GWP value for methane has changed between successive iterations of the IPCC Assessment Reports, with AR4 reporting 25 and AR6 reporting 28. https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf

[141] The OECD data on CIF-FOB (Cost, Insurance and Freight – Free on Board) ratios are an indirect measure of transportation costs expressed as a percentage of the merchandise trade flow that have been estimated by an economic

value (Figure 7) indicates that ammonia, hydrogen and liquified gas products stand out at a clear disadvantage relative to conventional oil products.

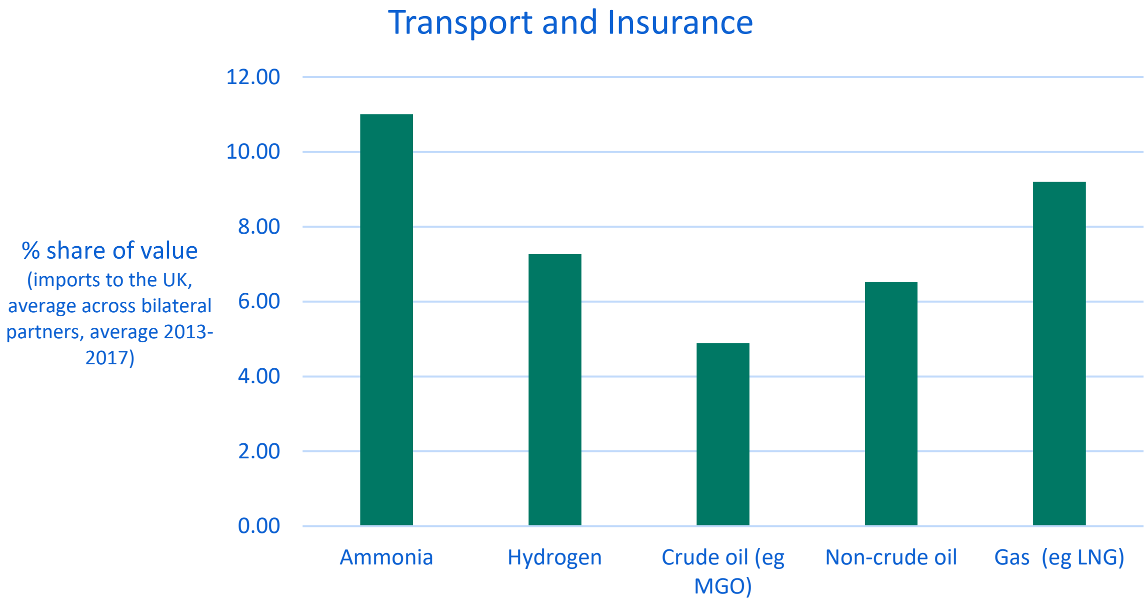

Figure 7: Transport and insurance costs for selected fuels as % of value. imports to the UK, average across bilateral trading partners, average 2013-17. Source: OECD Database. Measure: Cost, Insurance and Freight - Free on Board (CIF-FOB).

Considering these environmental and safety concerns, supporting regulation (in IGF/IGC Codes and elsewhere) will be necessary to properly manage the risks and liabilities associated with the use of net-zero-carbon fuels. Regulation and legislation for the use of these fuels elsewhere in the supply chain largely already exists, but guidelines specific to their use as marine fuel will provide essential clarity to operators. The safety of crews is also a top priority for operators. The shipping industry has substantial experience in moving dangerous and toxic products, and with the correct training, regulation, and buy in, concern for crew safety can likely be sufficiently alleviated.

4.4 Regulatory support for overcoming barriers to adoption

While each net-zero-carbon fuel option carries its own technological and safety-related difficulties, common to all these options is the cost of the fuel as a key barrier to adoption. Regulatory or market-based support for net-zero shipping should, therefore, seek to address this issue if it is to encourage private capital to finance scale-up and mass adoption. As Figure 4 demonstrates, green hydrogen, ammonia, and synfuels are all significantly more expensive than conventional shipping fuels on a fuel-only basis. Technological progress, electricity cost declines and carbon price changes are expected to reduce and eventually

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gravity model (see Miao, G. & Fortanier, F. (2017) “Estimating Transport and Insurance Costs of International Trade”. OECD Statistics Working Papers 2017/4, OECD Publishing. DOI: 10.1787/8267bb0f-en). Average CIF-FOB for bilateral trade with the UK is shown, as an indication of the relative risks.

eliminate this cost premium[142], but in the short term, high investment risks (including policy-, price- and market risk) present major roadblocks to would-be investors in the sector.

Policies for promoting net-zero shipping should therefore both address the cost gap, and, where appropriate, the risks facing investors. Private finance far exceeds government funding, so it is key that such a policy incentivises private investment. A successful policy framework should also minimise policy risks by providing a stable, predictable incentive package that is unlikely to be affected by changes of governments. It should address other risks within government control (such as decarbonisation targets or CO_2 prices) by issuing positive relative price signals for green fuels and supporting the establishment and expansion of a core market for these fuels. These goals can be achieved without undermining competition, and well-designed policy can gradually move towards competitive markets for net-zero-carbon fuels without causing undue disruption to first-mover suppliers and users. As with other green technology sectors, technology and project development risks remain best handled by private sector developers and investors.

Policy support for net-zero shipping is likely to take a number of forms, expressed as a range of instruments and regulations including the direct provision of early-stage R&D and Capex support as subsidies or tax credits for developers, capital providers, and early adopters in the shipping industry including owners and operators. These and other policies may aid developers and investors in recovering of capital costs, developing storage and transport infrastructure, and compensate for market risks and uncertainty in the early stages of sector development. The aim of this report is to investigate the viability of employing a specific policy instrument, contracts for difference (CfD). The remainder of this report will focus on developing such a policy instrument for the decarbonisation of shipping.

4.5. Contracts for difference in net-zero shipping

The main purpose of a CfD, like any subsidy mechanism, is to create incentives to close the cost gap between an old technology and a new one. Unlike other support mechanisms, CfDs can in principle achieve this objective without unduly distorting the market and do so at limited cost to government. A CfD mitigates the market risks faced by suppliers of a new, high-cost commodity by paying the supplier the difference between a predetermined reference price reflecting the old technology (in this case, the cost of MGO shipping fuel) and a ‘strike price’ set at the value required for the new technology to be viable. The strike price can be determined either administratively or through a competitive auction in which bidders submit prices and the lowest bid(s) is awarded the contract, subject to meeting specified conditions. When the reference price is lower than the strike price, the supplier is paid the difference. This ensures that the supplier receives a guaranteed minimum price for the duration of the CfD. In most CfD mechanisms, if the reference price exceeds the strike price, the supplier repays the subsidy. The contracting parties are typically a private developer/investor and a government, or government-backed, counterparty responsible for making and receiving payments.[143] The private party to a CfD would normally be the supplier

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[142] Ives, M. C. et al. (2021) *A new perspective on decarbonising the global energy system.* Oxford University Smith School of Enterprise and the Environment. https://www.energychallenge.info/report/

[143] In the UK’s case, the counterparty is a government-owned independent body, the Low Carbon Contracts Company (LCCC). The LCCC administers the establishment, auctioning, and settlement of CfD schemes.

of the fuel, infrastructure or and/or service being subsidised. CfD can be combined with other policy measures, including measures to help developers and investors recover fixed (capital) costs, and carbon pricing regimes.

CfDs have been used successfully to promote investment and accelerate learning rates for renewable energy.[144] In the UK, the Contracts-for-Difference scheme for supporting low-carbon electricity generation, implemented as part of wider electricity market reforms, is generally viewed as a success. It covers a range of low-carbon technologies and started in 2014 with an ’administered’ first round offering relatively generous strike prices for different technologies. Uptake was high and considerable criticism was focussed on the generous nature of the scheme to suppliers. However, later rounds moved to a reverse auction process (in which suppliers bid for support providing the lowest strike price they believed they could operate under) which saw strike prices drop considerably. Nonetheless, the cost of the scheme remained high, since producers supplied more electricity than expected (and were paid on the basis of electricity supplied, not for capacity built), and the reference price fell with wholesale electricity prices, increasing the size of the ‘difference’ being covered. Despite these potential inefficiencies, support for the scheme continued as industry lobbied for stability, and the success of the scheme in delivering low-carbon electricity and lowering costs of technologies became clearer [145]. For offshore wind in particular, the scheme has been credited with success in attracting significant private investment into the sector and contributing to a dramatic decline in levelized costs, while also hedging market risks to investors at an appropriately low cost to government compared to other financial tools such as direct subsidies and feed-in-tariffs.

Despite this positive experience, it is important to keep in mind the dependencies and potential adverse impacts of CfD schemes. For the UK energy market, its success was heavily dependent on the policy landscape that proceeded it, namely the Renewables Obligation (RO). The RO placed an obligation on electricity suppliers to source an increasing proportion of their electricity from renewable sources. This came into effect in 2002 (for England, Wales, and Scotland, and 2005 for Northern Ireland) and meant the CfD scheme had an emerging renewables industry at its start. Had the scheme started with a less mature industry it is far from certain it would have delivered as successfully. This points to a wider issue around the potential impacts on competitiveness of CfD schemes. In a reverse auction mode, incumbents and larger companies will have a clear economies-of-scale advantage allowing them to bid with lower strike prices, meaning the scheme could reinforce or raise barriers to new entrants in an industry. Uncertainty on costs can also be an issue depending on how a scheme is designed. If the reference price is variable, and is lower than expected on average, the scheme will be more expensive to the government; if suppliers are able to supply more than expected, the costs can rise too.

Translating the CfD concept from renewable energy projects to net-zero shipping requires careful consideration of a number of complicating factors, including the potential for regulatory leakage to other jurisdictions, the need to develop substantial supply chain

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[144] Grubb, M. and Newbery, D. (2018). "UK Electricity Market Reform and the Energy Transition: Emerging Lessons". *The Energy Journal, International Association for Energy Economics* 0(6).
[145] *Ibid.*

infrastructure, and perhaps most importantly, the lack of a stable transport market for most of the net-zero-carbon fuels. This was a point made quite clear by some interviewees who expressed concerns that the shipping industry was too complex for a CfD to succeed. Shipping industry stakeholders interviewed expressed an aversion to anything that might disrupt the “level-playing-field” as it had with a fluid, market constrained product like electricity.

To function optimally, a CfD should be developed around a reference price that is well-established, as liquid as possible, and sufficiently well-understood for government and the private sector to develop reasonable estimates of upside and downside risks associated with entering a CfD contract. For renewable applications, this is usually the wholesale price of electricity or a variant thereof. For shipping, the design of a reference price depends on what exactly the CfD is subsidising.

Section 5 summarises the views of stakeholders across several different groups on the viability and design features of a hypothetical CfD for net-zero shipping. Section 6 combines these findings with independent research to propose workable designs for a net-zero-carbon shipping CfD. Template legal documents for each CfD option are outlined in Section 7.

5. Understanding stakeholder views on CfDs for zero-emissions shipping

A clear aim for this report was for the recommendations to be built on the experience, views, and concerns of industry stakeholders. Accordingly, we conducted almost forty semi-structured online interviews with stakeholders from the shipping industry and industry bodies, government, regulators, energy providers, academics, non-governmental organisations, and academia. All interviews were conducted under Chatham House rules, such that any views and statements are associated only with the group to which the respondent belongs. These stakeholder groups are summarised in Table 1.

Table 1: Interview Subjects by Stakeholder Group

Group	Code	Number	Description
Shipping & Energy	Ship	8	Company representatives from the shipping and energy industry – those most likely to be the first party in a contract-for-difference agreement.
Industry Bodies	Ind	5	Shipping industry representative institutions and regulatory bodies, such as the International Maritime Organisation and the International Chamber of Shipping
Government	Gov	7	Members of government, primarily civil servants in the Ministries and agencies with responsibility for transport, energy, and the environment.
Financial Institutions	Fin	5	Financial industry representatives with expertise in investment, funding, and monitoring of the shipping industry.
Research Institutions & NGOs	Res	11	Representatives of academic institutions, think tanks, and international bodies that provide research and analysis on the shipping industry. Non-governmental organisations with interests in the decarbonisation of shipping.

During the exploratory semi-structured interviews with each stakeholder, a range of themes addressed within this report were discussed, with notes on the views expressed by respondents transcribed to computer files by two or more interviewers. Table 2 provides a summary of the general sentiment (either positive or negative) towards various components within each theme. The percentages shown are not intended to be taken as a precise indicator of the sentiment of each stakeholder group as a whole but rather as merely indicative of potential contrast in views between groups. The themes discussed are necessarily limited, and not all themes were discussed in each interview, but the sentiment analysis provides a guide to the popularity of certain features of shipping decarbonisation pathways among the groups represented. Each theme is discussed below, along with broader insights drawn from the interviews as a whole. In combination with the research summarised in Section 2-5, these insights and sentiments provide the basis for the design considerations and CfD draft documents presented in Sections 7 and 8.

Table 2: Summary of sentiment (positive or negative) towards major themes in decarbonisation pathways of the shipping industry and particulars of shipping-related CfDs. The first column provides the themes and key choices. The second and third columns provide the number of respondents that expressed a positive or negative opinion regarding these choices. The remaining columns provide this breakdown by percentage of respondents expressing a positive or negative sentiment within each stakeholder group (group codes match those shown in Table 3).

	positive	**negative**	**positive**					**negative**				
	All	**All**	**Ship**	**Ind**	**Gov**	**Fin**	**Res**	**Ship**	**Ind**	**Gov**	**Fin**	**Res**
Fuel Preference												
Ammonia	17	1	63%	20%	43%	60%	45%	13%				
Hydrogen	4	4				20%	27%	25%				18%
SynFuels	5	1	13%	20%		40%	9%			14%		
Nuclear	1	0					9%					
Biofuels	2	1	13%		14%				20%			
Interim Solutions												
Dual Engine	6	0		40%	14%	40%	9%					
Grey/Blue Hydrogen	5	3	13%	20%	14%	20%	9%					27%
LNG	3	1	13%				18%	13%				
eFuels	2	0	13%	20%								
Policy Instruments												
CfDs	15	3	38%	40%	71%		45%	13%			20%	9%
Carbon Tax	7	3	13%	40%	14%	40%	9%	13%		14%		9%
FITs/Ros/Innovation Grants	2	0	13%			20%						
Emissions Standards	4	1	25%	20%			9%	13%				
Bilateral agreements	2	1					18%	13%				
Type of CfD												
Fuel Only	18	0	75%	60%	71%	20%	27%					
TCO	3	3		20%			18%	25%			20%	
Route specific	9	0	25%	40%	14%	20%	27%					
Spatial coverage												
Global	8	1			57%	40%	18%	13%				
Regional	15	3	13%	100%	43%		55%	13%			20%	9%
Start with Specific Segment?												
All	7	2		20%	14%	60%	18%	13%				9%
Container	9	0	13%	40%	14%	60%	18%					
Tramp	0	1										9%
Bulk	1	0		20%								
Ferries	2	0	13%	20%								
Cruise	4	0	13%	20%	14%		9%					
Administering Body												
IMO	5	8	25%		14%	40%	18%	38%	40%	29%		9%
EU / EC	15	3	25%	40%	57%		64%	13%		14%	40%	9%
Cross subsidising												
Agriculture	1	3				20%				29%	20%	
Power/Energy	3	2	25%			20%			20%		20%	
Other Transport	1	0	13%									

5.1 Fuel preferences or technology

	positive	negative	positive					negative				
	All	All	Ship	Ind	Gov	Fin	Res	Ship	Ind	Gov	Fin	Res
Fuel Preference												
Ammonia	17	1	63%	20%	43%	60%	45%	13%				
Hydrogen	4	4				20%	27%	25%				18%
Synfuels	5	1	13%	20%		40%	9%			14%		
Nuclear	1	0					9%					
Biofuels	2	1	13%		14%				20%			

In the words of one financial institution respondent the question of fuel technology would not be answered by the shipping industry but by fuel producers - “the ship owner will make decisions on what ship to build based on the fuels available, and not take a risk on a new fuel if they don’t know what the fuel of the future will be”. However, most respondents did have an opinion on which technologies were most likely to succeed. Hydrogen, although easiest to produce due to the smaller number of steps, was considered by many to be problematic due to the difficulty and expense of storage and transport. The vast majority favoured green ammonia as the net-zero-carbon fuel of choice, despite the safety concerns associated with handling it. As one energy supplier stated, “the hydrogen future we see is actually an ammonia future”. Few respondents mentioned synfuels, and those who did mostly saw them as an interim measure allowing existing ships to run on green fuels with few modifications. Very few saw nuclear as an option, except potentially as a source of clean energy for green ammonia.

5.2 Interim solutions

	positive	negative	positive					negative				
	All	All	SE	IB	GR	FI	RI	SE	IB	GR	FI	RI
Interim Solutions												
Dual Engine	6	0		40%	14%	40%	9%					
Grey/Blue Hydrogen	5	3	13%	20%	14%	20%	9%					27%
LNG	3	1	13%				18%	13%				
eFuels	2	0	13%	20%								

Most interviewees took the view that interim fuels or technologies were likely to be needed to bridge the gap between the status quo and genuine net-zero shipping. Among industry bodies, engines capable of running on multiple fuels were the preferred option, reflecting uncertainty in future regulation and increasing the ability to continue running on MGO or its equivalents except under jurisdictions with stricter requirements.

Significantly, given the majority saw hydrogen-based fuels as the most likely fuel in the longer term, both industry bodies and financial institutions favoured initial flexibility in the production of hydrogen i.e., from fossil fuels, with (blue) or without CCS (grey) to support more rapid development and uptake of hydrogen or ammonia-fuelled engines and maximise fuel supply. As one finance representative stated, the “costs of new infrastructure were too high for ship owners and ports” for anything but a gradual phase-in of new fuels. Although one researcher felt that only “a few design changes to ships could make a big difference to prepare for hydrogen or ammonia”. The higher committed upstream emissions from blue or grey hydrogen interim solutions also drew opposition from some research institutions, who along with some financial institutions, preferred an interim path through LNG to reduce the use of more polluting fuels prior to an inevitable switch to green hydrogen-based fuels (although this wisdom of this path, particularly for firms and countries providing the supporting infrastructure, is contested by the World Bank[146]).

5.3 Policy instruments

	positive	negative	positive					negative				
	All	All	SE	IB	GR	FI	RI	SE	IB	GR	FI	RI
Policy Instruments												
CfDs	15	3	38%	40%	71%		45%	13%			20%	9%
Carbon Tax	7	3	13%	40%	14%	40%	9%	13%		14%		9%
FITs/Ros/Innovation Grants	2	0	13%			20%						
Emissions Standards	4	1	25%	20%			9%	13%				
Bilateral agreements	2	1					18%	13%				

Most respondents, particularly public sector bodies and NGOs, believed CfDs were a viable policy instrument for incentivising net-zero shipping. Most expressed a preference for CfDs for green fuels, although only a small minority had direct experience with them. A fuel provider with CfD experience who favoured the use of CfDs cautioned their use with auctions at very early stages of technology development as they could discourage competition, with new players likely to have difficulty competing without existing infrastructure, experience, and established buyers. This has also been a concern for renewable CfDs[147], addressed by gradually shifting from administrative to competitive strike price discovery. Other supporting instruments that are accessible to a wider pool of players and that can address other parts of the supply chain, such as innovation grants for capital expenditure, carbon pricing, emission standards, and feed-in tariffs, can also help the new technologies to develop. While their absence does not rule out the use of CfDs, complementary instruments in the initial phases can help to build up the number of viable players before competitive CfD auctions can function properly.

Another concern identified with the use of CfDs was in allocating limited fuel supplies among demand from several players: fuel providers, logistics, shippers, ports; and in managing technology risks, particularly for financial institutions. For green hydrogen-based fuels in particular, interviewees noted that production costs are sensitive to fluctuations in the price of electricity and this potential volatility would need to be carefully considered.

Respondents from across all groups saw a carbon price or tax as inevitable but expressed concern over getting the price level right. Consistent with ongoing developments within the IMO and the slow pace of change, several expressed concern that protracted debate on appropriate price levels (such as the US$2/tonne fuel levy currently being considered) would delay the required action and associated investment. A number of respondents saw CfDs as a viable solution to current (and future) lack of progress. Most saw CfDs and carbon pricing as complementary.

Some respondents suggested CfDs could begin as bilateral agreements between countries, ports, or other jurisdictions, smaller trade regions, or major trade routes, to test their viability

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[146] Englert et al (2021b). The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping.

[147] Peñasco, C., Anadón, L. D. & Verdolini, E. (2021) “Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments.” Nature Climate Change 11:257–265.

and iron out potential problems before moving to encompass larger, more complex trade route patterns. One respondent suggested starting with routes in which fuel prices were higher, to reduce the cost of funding a CfD.

5.4 Types of CfD: from fuel-only to Total Cost of Ownership

	positive	negative	positive					negative				
	All	**All**	**SE**	**IB**	**GR**	**FI**	**RI**	**SE**	**IB**	**GR**	**FI**	**RI**
Type of CfD												
Fuel Only	18	0	75%	60%	71%	20%	27%					
TCO	3	3		20%			18%	25%			20%	
Route specific	9	0	25%	40%	14%	20%	27%					

Among interviewees who saw CfDs as an option, almost all envisaged a fuel-only CfD as the best, or the only viable, CfD solution. “Keep it simple” was a sentiment repeated by a number of interviewees, that such a policy should be enough to incentivise ‘first movers’ to begin the transition. Very few respondents saw the advantage of a CfD covering cost elements other than fuel due to the limited additional cost coverage (fuel costs make up the majority of operating costs) and significantly greater complexity, although one industry expert was sceptical about whether the industry could be impartial on this question given commercial shipping overwhelmingly uses liquid fuels.

A TCO option was seen as potentially better for competition and for making progress on non-fuel components of the industry. One industry body respondent felt the TCO option was problematic as many shipyards already received significant local government support – so the playing field was already not level. If some were positive on the TCO option there was usually a caveat on the size of ships, or the segments, with prolonged contracts necessary to ensure repayments could be finalised.

5.5 Geographical coverage

	positive	negative	positive					negative				
	All	**All**	**SE**	**IB**	**GR**	**FI**	**RI**	**SE**	**IB**	**GR**	**FI**	**RI**
Spatial coverage												
Global	8	1			57%	40%	18%	13%				
Regional	15	3	13%	100%	43%		55%	13%			20%	9%

Respondents within government bodies appeared to be the most disposed to starting with a global solution, although this was less than half of this group and their views were not shared by the other groups. Most felt that starting with a single, commonly managed region as a pilot was the approach that was most likely to succeed. One government body considered the domestic benefits of a CfD for incentivising the development of competitive industries required for net-zero shipping to be sufficiently high to justify its use in subsidising companies domiciled outside the region it covers.

5.6 Sectoral coverage

	positive	negative	positive					negative				
	All	All	SE	IB	GR	FI	RI	SE	IB	GR	FI	RI
Start with Specific Segment?												
All	7	2		20%	14%	60%	18%	13%				9%
Container	9	0	13%	40%	14%	60%	18%					
Tramp	0	1										9%
Bulk	1	0		20%								
Ferries	2	0	13%	20%								
Cruise	4	0	13%	20%	14%		9%					

Most interviewees thought a CfD that could apply to all shipping segments equally was the optimal approach to avoid creating an ‘unlevel playing field’. Most also saw a fuel-only CfD as a means of achieving this. Having said that, many expressed an opinion on which segments were most suitable for pilot CfD programmes. One sentiment was that it made most sense to start with those segments for which fuel costs were the largest. The container and cruise segments were identified as forerunners due to the relative predictability and stability of routes and prices.

5.7 Administering bodies

	positive	negative	positive					negative				
	All	All	SE	IB	GR	FI	RI	SE	IB	GR	FI	RI
Administering Body												
IMO	5	8	25%		14%	40%	18%	38%	40%	29%		9%
EU/EC	15	3	25%	40%	57%		64%	13%		14%	40%	9%

Very few saw the IMO as the most likely party to move quickly on introducing a CfD, mostly due to institutional constraints and the slow pace of change and low ambition of its policies. However, many also believed that if CfDs were shown to be successful by other national or regional bodies, then ultimately the IMO would need to take on this role to ensure the principles of creating a level playing field. The general sentiment was to “start with EU and move to IMO”. However, at least one NGO interviewee expressed concern with the politics of the IMO and whether starting with the EU would hinder or help its adoption on a global basis, including by the IMO. To counter a government representative felt that the "EU would be open to paying other countries to help decarbonise shipping as long as they would be using EU ports, even if they refuel elsewhere".

5.8 Concerns with Cross-subsidisation

	positive	negative	positive					negative				
	All	All	SE	IB	GR	FI	RI	SE	IB	GR	FI	RI
Cross subsidising												
Agriculture	1	3				20%				29%	20%	
Power/Energy	3	2	25%			20%			20%		20%	
Other Transport	1	0	13%									

The risk of shipping CfDs cross subsidising other industries (directly or through learning rates) by enabling green hydrogen or ammonia to be sold for industrial, road transport, or agricultural applications, was discussed with a number of interviewees. Combining the shipping and energy industry interviewees is misleading for this question as the two groups were divided in their opinions. From the perspective of the fuel suppliers having other markets to sell their green fuel product into was a positive, affording them greater certainty of demand and greater likelihood of committing to the fuel production. However, the “shipping industry is keen to have any fund reinvested into the sector”. It was therefore seen by some shipping industry and financial institution representatives as problematic for funding taken from the shipping industry to enable net-zero shipping being inadvertently used to subsidise other industries.

6. Designing CfDs for zero-emissions shipping

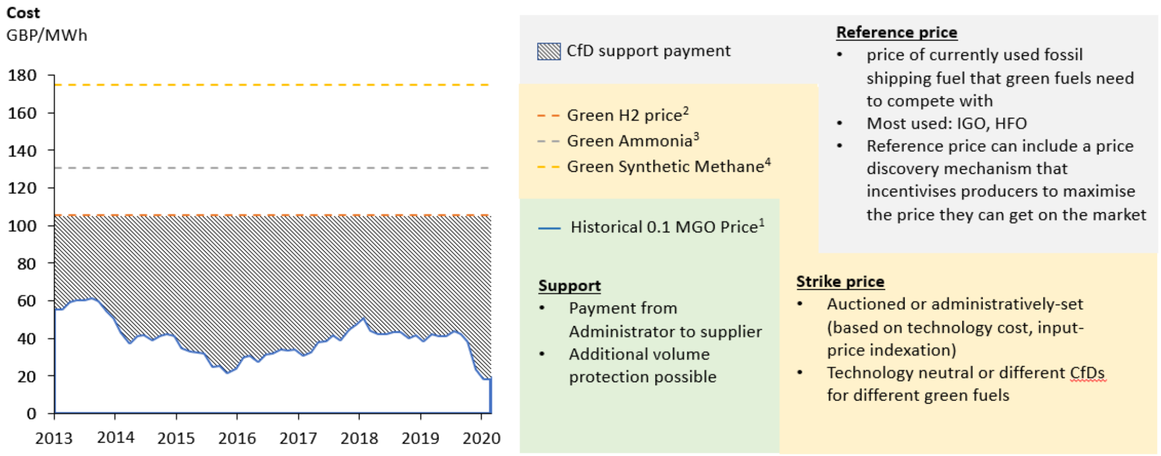
In the preceding sections, a summary of technology options and barriers to their adoption has been laid out, along with opinions on the best way to apply CfDs to net-zero shipping. This section discusses the amalgamation of this information into the design features we believe to best navigate the many issues and opinions to frame viable CfDs for shipping.

6.1 Design options: fuel-only and TCO

There are two primary variants of design options for a shipping CfD, each with a different reference price structure, ranging from covering only the incremental costs associated with the production green fuels, to covering all incremental total ownership costs associated with building and operating a net-zero capable vessel, as compared to a standard MGO-fuelled vessel.

- **Fuel-only CfD** for the supply of net-zero-carbon fuels, for use in a deep-sea ship, in which case the reference price is the market price of MGO. Bidders are required to prove that the net-zero-carbon fuel has been supplied and used for propulsion on a qualifying ship in order to receive CfD funds. In principle, bidders could aim to secure a strike price that allows them to recover costs beyond fuel, but this would depend on how competitive the bidding market is, and whether guaranteeing a price for green fuel would be sufficient to motivate the development of vessels able to use them. The scheme administrator could explicitly rule out non-fuel-related costs, or permit them, depending on the budget available for funding the CfD and the amount of uncertainty over costs (and associated risk) that the administrator is willing to accept. The identity of the counterparty in a fuel-only CfD could take at least two forms. The first restricts bidding to fuel suppliers, conditional on securing an offtake agreement for the fuel supplied to ensure it is used on board a ship. This has the advantage of not requiring shipping companies to participate directly in the CfD, but simply to be the offtaker for fuel suppliers that do participate. The second allows any firm to bid, conditional on proving that qualifying net-zero-carbon fuel has been used on a qualifying vessel. While both options are viable, the second is chosen here since it offers greater flexibility and scope for application at IMO level (see Appendix A.3 for a detailed comparison).
- **TCO CfD** for the total cost of ownership (TCO) of a ship running on net-zero-carbon fuel, in which the reference price is the TCO of an MGO-fuelled ship. Bidders can be any company but must provide proof of delivery and operation of a net-zero-carbon fuel-capable vessel to receive CfD funds. Bidders may operate the ship themselves, or subcontract operation to a third party.

Figure 8 provides a stylised example of a fuel-only CfD. The shaded area represents the cost to government of meeting the difference between the reference price (MGO in this case) on an energy basis, and the strike price for a green fuel. In this representation, the strike price happens to reflect the cost of producing green hydrogen, but this could equally reflect the cost of producing other fuels. A TCO version would look much the same, except with a more complicated (and likely less variable) reference price.



Reference price

- price of currently used fossil shipping fuel that green fuels need to compete with
- Most used: IGO, HFO
- Reference price can include a price discovery mechanism that incentivises producers to maximise the price they can get on the market

Support

- Payment from Administrator to supplier
- Additional volume protection possible

Strike price

- Auctioned or administratively-set (based on technology cost, input-price indexation)
- Technology neutral or different CfDs for different green fuels

1. DNV.GL. Assuming 1 USD = 0.79 GBP = 0.79, and 1 mmBTU = 0.2931 MWh. Average of: IEA (2019) The Future of Hydrogen; Agora Energiewende (2018) The Future Cost of Electricity-Based Synthetic Fuels; and Gorre et al (2018) Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants in dynamic operation. Applied Energy 257.
2. Average of IEA (2019); Ash and Scarborough (2019) Sailing on Solar. EDF and Ricardo; and Nayak-Luke & Bañares-Alcántara (2020) Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production. Energy & Environmental Science 13.
3. Average of Van Hulst (2019) The clean hydrogen future has already begun; BNEF (2020) Hydrogen Economy Outlook; and IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal.

Figure 8: A stylised example of what a fuel-only CfD for net-zero shipping would have looked like between the years of 2013 to 2020 with a reference price based on the historic price of MGO and a strike price equal to the price for green hydrogen.

Each of these options has benefits and drawbacks (see Table 3). As confirmed repeatedly in interviews, fuel costs represent the majority component of TCO and the lion's share of operating costs for ships. Moreover, the high cost of net-zero-carbon fuels is a major barrier to both the financing and construction of ships able to use the fuel, and to their deployment in these ships. There are clear limitations to a restrictive fuel-only contract in that it would not necessarily extend to the incremental costs associated with running a ship on a net-zero-carbon fuel, nor would it allow for non-liquid-fuel ship designs. A less restrictive contract, in which bidders are permitted to submit strike price bids on the basis of both fuel and non-fuel costs, would loosen some of these limitations and allow a fuel-only CfD to capture some of the advantages of a TCO version.

On the other hand, while a TCO-based contract is more comprehensive and would allow 'no-fuel' solutions, such as nuclear ships, and for the recovery of non-fuel-related infrastructure costs in a manner cost-efficient to government. It would be more complex to benchmark and administer, and the mechanism for setting and tracking reference prices would be harder to establish and justify. The potential risk for the administering body would be greater with a TCO-based contract due to the larger range of costs considered. The components of a TCO CfD would explicitly include incremental fuel costs, but also retrofitting costs (where applicable) for engines and fuel tanks, bunkering costs, transport and delivery costs, and additional crew and safety requirements. These incremental costs would vary by ship type and size. In practice, establishing a reasonable reference price for each of these components is fraught with subjectivity and complexity. Even where some components (such as operating costs) can make use of proxy indexes, such as the Baltic Dry Index for dry bulk, and freight charter indexes for container ships, these would still vary by segment. Developing separate CfDs for different ship types would be necessary to reflect the very different business models and cost structures in each segment and to ensure CfD funds. Although ideal in principle, a fully comprehensive TCO CfD may not be workable in practice.

Table 3. Comparison of fuel-only and TCO variants of a net-zero shipping CfD.

CfD	Advantages	Disadvantages
Fuel-only	• **Transparent and straight-forward** contract structure requiring supply of net-zero-carbon fuel and offtake agreement for its use in a ship. • **Agnostic on who the bidders are: Allows, but does not require, direct participation** of ship operator in bid. In principle, any firm can participate if they can prove the fuel is used. • **Addresses gap in funding landscape** by targeting operating costs, where most existing funding targets capital expenditure (e.g., EU Innovation Fund) • Allows the entity offering the CfD to simultaneously support the development of green fuel industries and directly mitigate international shipping carbon emissions • Clear, liquid reference price (MGO) • Single contract can be accessible by a range of ship types and routes • **Retains level playing field,** helping build support from across the shipping industry • **Aligned with industrial strategies of potential funders** (e.g., UK, EU) with existing expertise in renewable energy CfDs • **Lower risk of failure** due to insufficient participation • **Lower risk of cost overruns** for government	• **Not fully technology-neutral:** subsidises fuels based on cost of production, rather than contribution to TCO. Favours fuels in which incremental costs are biased towards production rather than storage, such as synfuels (see • Figure 6) • **Excludes, in practice, capital-intensive technologies** capable of reducing fuel costs (e.g., nuclear)[148] • **May incentivise incrementalism** by not requiring the construction of dedicated net-zero-capable ships and (if permitted under the CfD) allowing the blending of conventional and net-zero-carbon fuels • Does not prevent reversion to standard fuels where engines are dual-fuel capable • **Requires robust certification processes** to reliably exclude fuels produced from non-renewable sources (e.g., blue hydrogen)

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[148] A fuel-only CfD would be simplest to administer if offered for liquid fuels only but can be adapted to include non-liquid fuels like batteries, fuel cells, or nuclear fuels, by requiring that the fuel be purchased by a ship operator. These options, particularly nuclear, are likely to have significantly higher capital cost, but may see lower operating costs, allowing them to bid into a fuel-only CfD competitively if capital expenditures are subsidised separately.

TCO	- Technology neutral - Subsidises all incremental costs - CapEx and OpEx costs - **Incentivises innovation** and avoids picking winners - **Incentivises capital stock turnover**. CfD less likely to be used to keep older, inefficient ships afloat - **Lower risk of reversion to MGO**. New-build ship financing generally conditional on contracts with operators being in place	- **Difficult to identify transparent, liquid reference price.** Requires considering multiple variable CapEx and OpEx inputs - **Requires setting different reference prices** for each ship types and sizes, and for new builds vs retrofits, diluting competition and increasing complexity - **Multiple beneficiaries of CfD payments** where ship owner and operator are different entities (although CfD need only include ship owner) - **Advantages larger firms** more than a fuel-only CfD due to higher risk of bidding on TCO and capital requirements for new build ships - **Bidders would have to estimate multiple costs** in industries they are not familiar with (e.g., fuel storage, bunkering) and engage with multiple entities in order to bid for CfD - Moderate to high chance of insufficient bids and/or failure due to complexity

A third option that combines some of the fuel-only simplicity with the technology neutrality benefits of TCO is a hybrid mechanism with separate contracts for CapEx (a direct subsidy or regulated return mechanism allowing for recovery of fixed costs) and OpEx (a fuel-only CfD)) components, and with the reference price being the cost of building and operating an MGO-fuelled ship, respectively; or an OpEx (fuel-only) CfD with a completely separate competitive subsidy allocation mechanism for CapEx. Under this structure, different entities may bid for the CapEx and OpEx components, which may be helpful in the (fairly common) case where the ship owner and operator are different companies. In addition, a CapEx + OpEx CfD may help high fixed-cost, lower operating-cost fuel options, like fuel cells and nuclear reactors, to bid more competitively.

However, a CapEx + OpEx CfD would also retain many of the inherent difficulties of a TCO CfD, still requiring dedicated reference prices for different ship types and sizes, with the attendant issues of increasing transaction costs and diluting competition within each price 'bucket'. There are also reasons why technology neutrality may not be desirable, where committing to two or three different sets of supporting infrastructure ultimately raises overall costs and limits the pace and direction of technological progress (see Box 1).

The optimal solution may be a fuel-only CfD complemented by sufficient CapEx support. This would incentivise coordination between the – often different – entities responsible for commissioning and operating ships, respectively, helping the incremental CapEx spend on net-zero-carbon fuel capable ships to be at least partly recovered through long-term operation contracts. As one interviewee noted, “If you are looking for impact, then you should do [the CfD] on fuel-only". This is consistent with the majority of respondents.

In a nascent market with few producers of net-zero-carbon fuels and ships, fully competitive auctions may not be appropriate for initial price discovery. Unsuccessful bidders depending on the CfD to finance a pilot project may find themselves with no market to sell to, risking potential insolvency. An initial strike price, set administratively based on relatively generous cost estimates, may entail higher costs to government and higher private profits in the short-term, but reduces the risk of unintentionally punishing early movers. As technology improves and competition intensifies, the use of auctions becomes more appropriate in encouraging competition, favouring lower-cost producers, and enabling price discovery over successive rounds. A well-designed CfD would also incentivise producers to maximise the market price they can obtain and reduce the cost to government (the difference between the CfD strike price and market price) over time. The reference price can be indexed to relevant variables (which may include input prices (MGO fuel), adjustments for volatility (e.g., moving averages) and inflation).

Box 1: Technology neutrality and green shipping: carbon and non-carbon-based fuels

A technology-neutral demand-side policy for green shipping is difficult to design, and it may also not be desirable. For long-distance shipping, the competition is essentially between carbon-based and non-carbon synthetic fuels. The very different infrastructure requirements for each system and the high costs associated with the transition from fossil fuels make it unlikely – and costly – for both to exist simultaneously.

The figure below (adapted from ETH Zurich) illustrates this point. Carbon-based fuels power ships with methane (CH_4) molecules, releasing CO_2 which is then recaptured and used to synthesise more methane. By contrast, a hydrogen economy uses electricity (for batteries, green hydrogen and then ammonia) and CH_4 (blue hydrogen and then ammonia) as inputs to power ships. A fleet operating on a mixture of both would imply higher investment costs associated with two sets of supporting infrastructure.

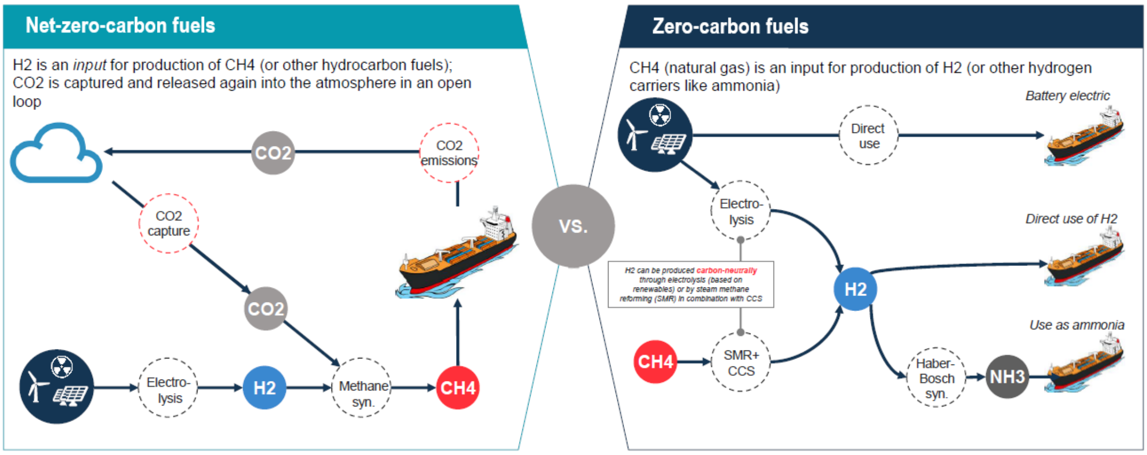

Figure B1.1: Carbon-based vs non-carbon-based fuels. Note that production of hydrogen-based fuels from methane will likely require offsets on top of Carbon Capture and Storage (CCS) to ensure carbon neutrality. Adapted from ETH Zurich (2019) Towards net zero – comparison of zero-carbon

Technology neutrality between carbon- and non-carbon-based fuels is likely to raise costs and slow the growth of both. This suggests that a choice should be made between carbon- and non-carbon-based fuels, rather than committing public resources to both. Neutrality between hydrogen and ammonia is more justifiable, although ammonia is more likely to be the ultimate winner for practical reasons and appears to be the only viable option for long-distance, deep-sea ships. Both technologies are at an early stage and there are considerable unknowns over future cost trends. Ammonia-powered shipping is not fundamentally different to MGO, save for higher input fuel costs and greater space requirements. The costs of hydrogen shipping are driven by the infrastructure cost of fuel cells and storage tanks. Since these are both expected to decline significantly, and maintenance costs are lower than for combustion engines, technology neutrality is still appropriate between hydrogen and ammonia propulsion.

6.2 “Net-zero-carbon-emissions”

Decarbonization is often used as a term for reducing all greenhouse gas emissions but with a focus on the main greenhouse gas carbon-dioxide. Carbon-dioxide is responsible for 82% of the increase in warming over the past decade across all economic sectors[149], with virtually all international shipping emissions coming from carbon dioxide[150]. For the development of the CfD Heads of Agreement we therefore focused on achieving “net-zero-carbon-emissions” for international shipping to avoid the complications associated with including other greenhouse gases in our analysis. This is a practical choice, rather than a suggestion that the other greenhouse gases that can be emitted over the life cycle of fuels should not be included. Not accounting for upstream emissions of methane, for example, may give natural gas-derived fuels an artificial advantage over those derived from renewable electricity. The implications of this simplification will need to be tested before a CfD scheme is implemented in full.

6.3 Interim solutions

It is beyond the scope of this report to test the cost effectiveness of all the many routes to zero-emissions shipping that might be generated through the CfD instruments that are the subject of this report, in combination with the many other policy instruments and technological developments that might come into play over the next few decades. We were advised by industry stakeholders that an interim solution in which clean shipping mixes with non-clean shipping within segments, routes, and companies is inevitable. However, given the IMO timeline for decarbonisation (2030-2050) and those commercial ships typically have a multi-decadal lifespan, the ships being constructed today will have to comply with IMO targets at some point during their service.

Some transition plans currently consider short-term solutions, such as increased usage of liquified natural gas (LNG), however it is likely that decarbonising shipping using LNG could lead to stranded assets and investment in infrastructure unsuitable for carrying net-zero-carbon fuels.[151] Carbon-based green synfuels, although currently expensive, offer a viable decarbonisation pathway. At present, orders are starting to be placed for new dual-fuel ships capable of running on synfuels and ammonia/hydrogen, although in some cases retrofits of the engine and fuel storage on existing ships to allow for use of alternative fuels might be the cheaper option. Ammonia also offers a flexible pathway that could start with grey ammonia (produced from steam reforming of fossil fuels), to cleaner blue ammonia (with added CCS), and end with zero-carbon green ammonia (produced from air, water, and renewable energy).

All the interim pathways described above are compatible with the CfDs developed for this report which have been designed to be as solution and technology neutral as possible, including the use of a TCO CfD that might enable the co-evolution of infrastructure with clean energy. However, the use of a strict definition for zero-emissions shipping in the CfDs

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[149] World Meteorological Organization (2019), “Greenhouse Gas Bulletin”, No. 15, 25 November 2019, https://library.wmo.int/doc_num.php?explnum_id=10100

[150] Although methane leakage has been growing in recent years with the increase of LNG-powered vessel https://www.professionalmariner.com/imo-emissions-report-raises-new-concerns-about-methane-slip/

[151] Englert et al (2021b). The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping.

will mean that not all the pathways described above will be incentivised as well by this policy instruments. This is unavoidable as the strict zero-emissions requirements are necessary to align the two CfDs to enable them to be used concurrently, and ultimately this initiative is aligned with the end goal of achieving zero-emissions shipping, for which net-zero-carbon is an implicit requirement.

6.4 Design parameters: shipping CfDs in practice

Who would administer the CfD?

As discussed above, the IMO is unlikely to adopt a CfD mechanism in the short term, given both the institutional constraints of the organisation, and the novelty of CfDs to the shipping industry. While the IMO could, and indeed should, ultimately become the body to administer a global CfD mechanism if uptake is to expand to the extent required, initial applications are more likely to succeed in jurisdictions and regions where sufficient political will and institutional capacity already exists to craft, fund, and reliably implement the mechanism. However, the IMO could benefit from taking the initiative on trialling CfD-like mechanisms with funding from industry. Price inelasticity of demand for shipping (due to limited price-competitive rivals and transport costs being a small proportion of value of traded goods) may allow innovators in the industry to recover some of the costs of proposed levies on fuel through CfD support. The remaining costs could be passed on to consumers without significantly affecting demand. International shipping makes use of a relatively small number of high-volume routes linking key ports. The world's largest port by container volume is Shanghai, with most of the remaining top 10 predominantly in China, and other Asian ports in the top 20 in Singapore, South Korea, Dubai, Malaysia, and Thailand.[152] These ports serve largely as the origin, or transit points, for goods being transported. Most container shipping flows to destinations in Western and Southern Europe (Rotterdam, Antwerp, Hamburg, Bremen, Algeciras, Piraeus), and the United States (Los Angeles, Long Beach, New York).

The European Union (EU) and United Kingdom have clear, well-established climate policy trajectories. The ambition of decarbonisation policies not only in the United States following the change in administration, but also in China, Japan, and South Korea, has risen substantially in recent months. In principle, any of these jurisdictions could pilot the implementation of a shipping CfD. In practice, the EU is likely best placed to do so, partly due to its prominence as a shipping destination and its access to fiscal resources for funding the mechanism (including by recycling potential ETS revenues from shipping), and partly because the political will for taking active steps to decarbonise shipping, and the technical expertise for administering a CfD, are already present.

A combined IMO-governmental financing approach supported by a fuel levy or carbon price may also be workable.

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[152] Authors' calculations, based on World Shipping Council (2021) *Top 50 World Container Ports* (http://www.worldshipping.org/about-the-industry/global-trade/top-50-world-container-ports); and UNCTAD (2020) UNCTADStat Database .

Which companies would be eligible?

A political challenge that all non-IMO CfDs encounter is whether the companies that interact with a given jurisdiction but are not domiciled within it are eligible for CfD funding (either directly or as beneficiaries of funding paid to intermediaries such as fuel suppliers). Restricting the CfD to ‘domestic’ firms would likely diminish its scope considerably and risk distorting the international playing field, strengthening potential industry opposition. Whether funding external companies is worthwhile would depend on whether the costs (financial and political) of doing so outweigh the strategic benefits accruing to the funding jurisdiction of developing zero-emissions technologies and supply chains for shipping to exceed the costs.

Which routes would be eligible?

A third consideration is which routes would be eligible. Container and cruise shipping segments tend to operate along a relatively stable set of routes, meaning that in these segments, a CfD could be limited to funding operations along these routes. However, since bunker prices change constantly, and shipping operates in a competitive landscape, in the absence of good reasons to the contrary it may be preferable not to constrain the CfD to specific routes. In tramp shipping and bulk shipping segments, in which routes are more sensitive to commodity prices and can change frequently, a route-specific approach would be less suitable.

A national or regional entity may not be willing to fund shipping activity lying entirely outside their jurisdiction, particularly where the shipping company is also not domiciled within it. Restricting CfD funding to routes exclusively within territorial waters would likely prove too restrictive and would be of limited relevance to long-distance international shipping, the target of this report. An appropriate balance between the two might make eligible all routes that include a stop at a port within the jurisdiction funding the mechanism.

Which technologies and costs would be eligible?

Although the strong preference from stakeholders was for a fuel-only CfD we have endeavoured to develop the design elements for both fuel-only and TCO CfDs, with the legal blueprints for both provided in Section 7. In the fuel-only case, the cost of fuel would be eligible for the CfD, which would pay out the difference between a reference price (tied to a standard shipping fuel, with MGO the most likely) and a strike price determined administratively or through competitive auction. For a TCO CfD, all incremental costs associated with both building and operating the zero-emissions ship would be eligible, including fuel, additional staff, engines, fuel tanks, and so on. In this case, the reference price would be based on benchmark costs for all these elements, in addition to a reference price on fuel.

How would the reference price be determined?

For a fuel-only CfD, the most obvious choice of reference price is MGO. Since ships can refuel only in specific places and MGO is a specific oil product, there is no single analogy to international benchmarks (e.g., Brent crude). To determine a reference price, an average of MGO bunker prices across a number of ports (within or outside the implementing jurisdictions) could be used. To reduce volatility and uncertainty for both parties, a moving average over a period of time (e.g., two weeks) and/or a floor and ceiling on the reference price could be used.

For a TCO CfD, the reference price would be more difficult to determine. Benchmark prices for each component of TCO would need to be estimated, based on the cost of each component for a standard MGO-fuelled ship (e.g., fuel tanks, engine, staff) in addition to fuel. However, since both fixed and variable costs vary by ship type and size, separate benchmark estimates would be needed for different-sized ships in each segment.

How would the strike price be determined?

The fuel-only CfD would fund the use, on a ship, of a predetermined amount of net-zero-carbon shipping fuel. Depending on the circumstances, it could be organised such that a single entity could receive a 100% allocation, or caps could be set on maximum allocation per supplier to ensure a minimum number of potential suppliers receive an allocation (unless there is insufficient interest).

As discussed above, in the early stages of net-zero technology development and the initial rounds of CfD allocations, the strike price may be set administratively to avoid the risk of bankrupting bidding firms that do not receive an allocation or otherwise damaging the prospects of emerging players. As the market for fuel supply (or supply of zero-emissions ships) becomes more competitive, setting the strike price through a competitive reverse auction would be more appropriate, with the resulting strike price being the market-clearing price at which 100% allocation is reached. All participants would be paid based on this clearing price.

From the perspective of potential bidders, estimating fuel production and supply costs would be relatively straightforward. For a TCO-based CfD, a much broader range of costs would have to be estimated, with correspondingly greater uncertainty. This may raise barriers to the participation of potential bidders. It would also be more difficult for the administrator to determine when the market is sufficiently mature/competitive for competitive auctions to be appropriate.

Which technologies would be (in)eligible?

At this juncture, the long-term fuel source for shipping is not certain. However, both independent research and stakeholder engagement suggest it is very likely to be hydrogen-derived, either for internal combustion or as fuel cells. Synthetic fuels, such as e-methanol and e-methane, require green hydrogen as an input. A fuel-only CfD could designate as eligible any fuel produced from green hydrogen that also meets net-zero-carbon emissions criteria. This could, as an interim measure where sufficient green hydrogen supplies cannot be quickly brought to market, be expanded to include nuclear-derived electricity and blue hydrogen (using fossil fuels with CCS), at least in the short term. In the case of blue hydrogen, the benefits of greater short-term supplies in the short term should be carefully judged against the risks of greater committed emissions and potential stranded asset risks in the medium- and long-term.

How would cross-subsidisation be avoided?

Consider a fuel-only CfD for green hydrogen-based fuels, in which any firm able to meet the fuel use requirement is eligible: from shipping companies to upstream fuel suppliers. If the shipping industry ultimately funds the CfD (through carbon pricing or other measures), it would probably also be helping to meet R&D and infrastructure costs and contributing to lower financing costs for fuel production through, e.g., offtaker agreements, that will help the industry develop and benefit other users of net-zero-carbon fuels, such as agriculture, transport, and heavy industry.

Some positive externalities accruing to other industries are unavoidable – and likely very desirable for policymakers looking to scale hydrogen-related industries. To prevent bidders from using CfD funds to scale up production and selling to higher-value markets, the fuel-only CfD would require clear proof that fuel is actually used in a qualifying ship in order for the corresponding CfD payment to be made, to prevent price arbitrage behaviour.

Who are the parties?

In general terms, the first party to a CfD is an entity able to administer the settlement of CfD payments. In the UK’s case, a dedicated entity, the Low Carbon Contracts Company (LCCC) exists for this purpose. If a CfD mechanism were to reach the IMO, a new organisation would likely need to be established, although if the proposed fuel levy is implemented (requiring a means of collecting revenues and reallocating them to R&D projects), a CfD settlement mechanism could make use of this infrastructure.

In the fuel-only case, counterparties’ participation would be conditional on being able to prove that the fuel is used on a qualifying ship. The CfD administrator may elect to prioritise bids that have a credible set of provisional agreements in place to ensure this occurs. In the TCO case, the counterparty would most likely be a shipping firm, a financial institution/broker, or a dedicated company willing to take responsibility for delivering and operating a ship capable of using net-zero-carbon fuel.

How are obligations enforced?

In the event that the counterparty to a CfD is unable to meet its obligations (to supply fuel, to supply a ship, and/or to operate a ship), the administrator may choose to cancel the CfD contract and offer it to the next available bidder, in ascending order by bid price if allocated competitively. This wastes time and resources, however. To avoid the situation from arising in the first place, it may also be helpful to include deterrent measures such as a ‘performance bond’ in the design of the CfD. This would require the bidder to lodge a payment with the administrator that would be incrementally forfeit in the case of delay, under-delivery, or non-delivery of the CfD requirements.

Given that a CfD for shipping is likely to ultimately be applicable to parties operating in many jurisdictions, a legal framework must be agreed in advance that can work across them. In international commercial agreements covering multiple jurisdictions, it is standard practice to state that a contract is bound by the law of a specific country with which international parties are typically very familiar (e.g., English Law or Irish Law for the EU).

6.5 Summary of parameters for zero-emissions shipping CfDs

In the following section, draft Heads of Terms (HoT) agreements for fuel-only and TCO CfDs are presented. A CfD has many variables, and the ultimate configuration will depend on the circumstances, including who the parties are, the position of industry, the stage of development of zero-emissions technologies, and so on. In the two HoT blueprints presented below, the following assumptions are used, based on the preceding discussion:

1. The CfD is **administered by the European Union** (EU). This may easily be adapted to other national or regional bodies, or the IMO. All references to the EU below are placeholders that can be substituted as needed.
2. **Any shipping route is eligible** for the CfD, provided that it includes a port within the EU.
3. The **obligations** to which the CfD counterparty agrees are:
    a. (for fuel-only) To prove the use of a specified amount of hydrogen-derived, net-zero-carbon shipping fuel for each year the CfD is active, and to submit a performance bond to be returned on successful execution of these obligations.
    b. (for TCO) To deliver a fully seaworthy (i.e., registered, and certified) vessel capable of running on net-zero-carbon fuel, including nuclear fuel or sail-based technology, by a specified date, and to operate it using such fuels for a minimum number of tonne-kilometres for each year the CfD is active, and to submit a performance bond to be returned on successful execution of these obligations.
4. The **penalties** for non-delivery are to forfeit of a proportion of the performance bond:
    a. (for fuel-only) for each unit of fuel use below the annual requirement.
    b. (for TCO) for each tonne-kilometre travelled below the annual requirement.
5. The **reference price** for each day in which the contract is operational, is determined as follows:
    a. (for fuel-only) the two-week rolling average of MGO bunker fuel prices in the largest 5 EU bunkering ports, with a ceiling and floor based on the 5-year maximum and minimum price.
    b. (for TCO) a benchmark total cost of ownership calculation including all capital and operating costs, including fuel, associated with an MGO ship, with different benchmarks for each ship type and size.

7. Legal & technical draft CfDs

In this section, Heads of Agreement for a fuel-only and TCO CfD, developed by international law firm Pinsent Masons, are presented. These documents are not the CfDs themselves: they are more concise legal documents that can be used to define the terms of an agreement in principle between parties and counterparties, laying out in sufficient detail how the CfD would work and under what terms it would operate. In this case, the Heads of Agreement are set to expire a year after signature or upon entry into a full CfD, whichever comes first.

7.1 Fuel-only Contract for Difference

HEADS OF AGREEMENT

This heads of agreement is made on the date of the last signature below.

BETWEEN

[Bidding Entity X][153] (**First Party**)

- AND -

[Directorate-General for Climate Action, European Commission] (**Second Party**),

(each a **Party** and together the **Parties**)

Background

A. The First Party and the Second Party are interested in entering into the Proposed Agreement to support (i) the use by the First Party of Net-Zero Carbon Shipping Fuel in its vessels, or (ii) where the First Party is a fuel supplier, the use by the First Party's customers of Net-Zero Carbon Shipping Fuel in their vessels.

B. This heads of agreement sets out, at a high level, the key terms and conditions of the Proposed Agreement.

1 Definitions

1.1 For the purposes of this heads of agreement:

"Affiliate" means in relation to the Second Party, another person, firm, company, corporation, government, state or agency of a state, or any association, trust or partnership (whether or not having separate legal personality) that controls, is controlled by, or is under common control with the Second Party;

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[153] The bidding entity may be a ship operator or another entity involved in the ownership or operation of ships, or supply of fuel to ships, which can demonstrate the use of Net-Zero Carbon Shipping Fuel in such vessels (which are not already supported by a CfD from the Second Party).

"**Business Day**" means a day on which banks are open for business in [●] (excluding Saturdays, Sundays and public holidays);

"**Ceiling Price**" means the highest two-week average price for [marine gas oil (MGO)] trading at the 5 largest bunkering ports [in the European Union] in the five (5) years immediately preceding the date on which the Reference Price is calculated, adjusted on the date on which the Reference Price is calculated (each such date, the **Indexation Date**) in accordance with the following formula:

$$Ceiling\ Price = CP_{base} \times INF$$

Where:

CP_{base} is the highest two week average price for [marine gas oil (MGO)] trading at the 5 largest bunkering ports [in the European Union] in the five (5) years immediately preceding the date on which the Reference Price is calculated; and

INF is calculated in accordance with the following formula:

$$INF = \frac{HICP_t}{HICP_b}$$

Where:

$HICP_t$ means the Harmonised Index of Consumer Prices for the month immediately prior to the month in which the Indexation Date falls; and

$HICP_b$ means the Harmonised Index of Consumer Prices for [for the first month of the year preceding the Indexation Date];

“CfD Reverse Auction” means a reverse auction process run by or on behalf of the Second Party in accordance with rules determined by the Second Party, pursuant to which eligible users of Net-Zero Carbon Shipping Fuel may bid to receive pricing support with respect to the use of Net-Zero Carbon Shipping Fuel, pursuant to an agreement such as the Proposed Agreement;

"**Change in Law**" means the coming into effect of any law after the date of the Proposed Agreement, and/or the modification, repeal or replacement of any law after the date of the Proposed Agreement, and/or in the case of a judgment of a competent authority any binding change in the interpretation or application of any law after the date of the Proposed Agreement by a competent authority;

"**Difference Amount**" has the meaning ascribed to it in paragraph 3.2.

"**Dispute Notice**" has the meaning ascribed to it in paragraph 6.2.

"**EMIR**" means the European Regulation on OTC Derivatives, Central Counterparties and Trade Repositories (Regulation 648/2012);

"**Expert**" has the meaning ascribed to it in paragraph 6.3;

"**Floor Price**" means the lowest two week average price for [marine gas oil (MGO)] trading at the 5 largest bunkering ports [in the European Union] in the five (5) years immediately preceding the date on which the Reference Price is calculated, adjusted on the date on which the Reference Price is calculated (each such date, the **Indexation Date**) in accordance with the following formula:

$$Floor\ Price = FP_{base} \times INF$$

Where:

FP_{base} is the lowest two week average price for [marine gas oil (MGO)] trading at the 5 largest bunkering ports [in the European Union] in the five (5) years immediately preceding the date on which the Reference Price is calculated; and

INF is calculated in accordance with the following formula:

$$INF = \frac{HICP_t}{HICP_b}$$

Where:

$HICP_t$ means the Harmonised Index of Consumer Prices for the month immediately prior to the month in which the Indexation Date falls; and

$HICP_b$ means the Harmonised Index of Consumer Prices for [for the first month of the year preceding the Indexation Date];

"**Force Majeure**" means, in respect of a Party, any event outside the reasonable control of that Party affecting its ability to perform any of its obligations under the Proposed Agreement and which could not have been prevented or avoided by a reasonable and prudent operator, including acts of war, natural disaster, national strikes or other industrial action, threat of war, terrorist act, blockade, revolution, riot, insurrection, civil commotion, public demonstration, sabotage, lightning, fire, storm, flood, earthquake, or acts or omissions of competent authorities otherwise than in accordance with laws and/or directives (except that lack of funds or strikes only of a Party's own employees and/or those of its contractors shall not constitute Force Majeure);

"**Guarantees of Origin**" shall have the meaning given to the term in Directive 2009/28/EC;

"Net-Zero Carbon Shipping Fuel" means (i) hydrogen or hydrogen derivatives, such as methanol and ammonia, produced from renewable energy; (ii) nuclear energy or (iii) fuel which is produced with complete carbon capture and storage of any Scope 1 & 2 CO2 emissions and which complies with PAS 2060. The First Party must ensure the fuel supplied meets any certification requirements set by the Second Party (e.g., Guarantees of Origin), or be subject to forfeiture of Performance Security provided pursuant to paragraph 4.2.3;

"Performance Security" means a cash payment made by the First Party that is equal to [€X]/metric tonne of Net-Zero Carbon Shipping Fuel the First Party commits to utilise in paragraph 3.1;

"Proposed Agreement" means an agreement, the form of which will be provided to the First Party if the Second Party notifies it that it has been successful in its bid into a CfD Reverse Auction, with a term scheduled not to exceed [x] years, pursuant to which the Second Party agrees to pay the Difference Amount to the First Party where the circumstances described in paragraph 3.2 arise;

"Reference Price" means a two week moving average price for [marine gas oil (MGO)] trading at the 5 largest bunkering ports [in the European Union] on the day the Net-Zero Carbon Shipping Fuel is purchased by the First Party, provided that where this value is below the Floor Price, the Reference Price shall equal the Floor Price and where this value exceeds the Ceiling Price, the Reference price shall equal the Ceiling Price;

“Specified Purpose” means use of the Net-Zero Carbon Shipping Fuel in a ship traveling on an international shipping route that includes any port in [the European Union];

"**Start Date**" means the next Business Day to occur after the day on which the Second Party notifies the First Party pursuant to the Proposed Agreement that the Second Party considers that each of the conditions precedent to the effectiveness of the Proposed Agreement (as such conditions precedent are set out in the Proposed Agreement) have been satisfied or waived in writing by the Second Party;

“Strike Price” means the price either (i) administratively-set by the Second Party, or (ii) the price bid by the First Party in response to reverse auction held on [DD/MM/YYYY]. The Strike Price shall be adjusted on each anniversary of the Start Date during the Term (each such date, the **Indexation Date**) to an amount calculated in accordance with the following formula:

$$Strike\ Price = SP_{base} \times INF$$

Where:

SP_{base} means the Strike Price as at the Start Date; and

INF is calculated in accordance with the following formula:

$$INF = \frac{HICP_t}{HICP_b}$$

Where:

$HICP_t$ means the Harmonised Index of Consumer Prices for the month immediately prior to the month in which the Indexation Date falls; and

$HICP_b$ means the Harmonised Index of Consumer Prices for [insert date]; and

"**Term**" means the period commencing on the Start Date and continuing until the day prior to the [tenth (10th)] anniversary of the Start Date, subject to earlier termination of the Proposed Agreement in accordance with its terms.

2 Status of heads of agreement[154]

2.1 This heads of agreement is not exhaustive and is expressly ‘subject to contract’ until a final written agreement has been entered into. Except with respect to paragraph 7 and otherwise where specifically stated, the terms of this heads of agreement are not intended to be legally binding between the Parties.

3 Basis of the Proposed Agreement

3.1 Under the Proposed Agreement, the First Party’s primary obligation will be to utilise (or, where the First Party is a fuel supplier, procure the utilisation by its customers of) [xxx] metric tonnes of Net-Zero Carbon Shipping Fuel annually between [DD/MM/YYYY] and [DD/MM/YYYY] for the purposes of ship propulsion in its vessels (or, where the First Party is a fuel supplier, the vessels of its customers) on international routes including European ports, in compliance with the Specified Purpose and provide the Second Party with evidence which is acceptable to the Second Party that it has done so . For the avoidance of doubt, where the First Party is a fuel supplier, no Difference Amount will be payable where the customer(s) whose vessels the First Party relies on to satisfy its obligations under this paragraph 3.1 also benefit from an agreement with the Second Party pursuant to which the Second Party agrees to pay such customer(s) a difference amount calculated as the difference between the Reference Price and a strike price awarded to such customer(s) following the CfD Reverse Auction.

3.2 Under the Proposed Agreement, the Second Party’s primary obligation will be to pay the First Party the difference between the Reference Price and the Strike

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[154] Depending on the governing law, local law advice on the status of these heads of agreement and in particular, the extent to which it is possible to agree that certain provisions are not legally binding, may need to be taken.

Price, where the Strike Price exceeds the Reference Price (the **Difference Amount**). Settlement will be as follows:

3.2.1 the First Party will provide the Second Party with a statement detailing the date and quantity of Net-Zero Carbon Shipping Fuel by the First Party (or the First Party's customers, where the First Party is a fuel supplier) for use in ship propulsion in the previous calendar quarter;

3.2.2 the Second Party shall, within [ten (10)] Business Days, provide the First Party with details of the cumulative Difference Amount due to the First Party based on the information provided by the First Party pursuant to paragraph 3.2.1, together with details of the applicable Reference Price used for the purposes of calculating the Difference Amount;

3.2.3 the Second Party shall, unless the First Party has indicated in writing that it disagrees with the calculation of the cumulative Difference Amount set out in the notice referred to in paragraph 3.2.2, pay the First Party the cumulative Difference Amount within thirty (30) days of the date of the notice issued by the Second Party to the First Party pursuant to paragraph 3.2.2; and

3.2.4 late payment interest will be payable on any payments made by the Second Party after the due date indicated in paragraph 3.2.3.

4 Conditions precedent

4.1 To participate in the CfD Reverse Auction (if applicable), the First Party must:

4.1.1 comply with any CfD Reverse Auction rules determined by the Second Party and notified to the First Party in advance of any CfD Reverse Auction; and

4.1.2 not (at the time the CfD Reverse Auction is held) appear on the last published consolidated list of asset freeze targets designated by any of the United Nations, European Union and [*insert any other relevant bodies / jurisdictions*] under legislation relating to current financial sanctions regimes (or, in the event that any such list ceases to be published, an equivalent list produced by the [●] government in respect of the same).

4.2 If the First Party is successful in a CfD Reverse Auction, it will be invited to enter into a Proposed Agreement, the Start Date under which will commence upon the satisfaction by the First Party (or waiver in writing by the Second Party) of certain conditions precedent, which will include:

4.2.1 provision to the Second Party of a legal opinion addressed to the Second Party, in form and content satisfactory to the Second Party (acting reasonably), from the legal advisers to the First Party confirming that the First Party: (i) is duly formed and validly existing under the laws of the jurisdiction of formation; and (ii) has the power to enter into and perform, and has taken all necessary action to authorise its entry into and performance of, the Proposed Agreement;

4.2.2 provision to the Second Party of evidence, in form and content satisfactory to the Second Party, acting reasonably, of compliance by the First Party with “know your customer” or similar identification procedures or checks under all applicable laws and regulations pursuant to the transactions contemplated by the Proposed Agreement; and

4.2.3 provision of Performance Security to the Second Party. The First Party will forfeit an amount equal to [€X]/metric tonne of Net-Zero Carbon Shipping Fuel it fails to utilise (or procure the utilisation of, where the First Party is a fuel supplier) in accordance with paragraph 3.1. Any undrawn Performance Security which is held by the Second Party shall be returned to the First Party upon expiry or early termination of the Proposed Agreement.

5 Rights and remedies

5.1 Each Party agrees that damages alone would not be an adequate remedy for any beach of a legally binding obligation of this heads of agreement by the other Party. In such an event, the non-defaulting Party shall be entitled to the remedies of an injunction, specific performance or other equitable relief (or any equivalent reliefs which may be available) in addition to any other remedy including damages for any threatened or actual breach of any legally binding obligation of this heads of agreement.

5.2 This heads of agreement is for the benefit of the parties to it and is not intended to benefit, or be enforceable by, anyone else.

6 Governing law and jurisdiction

6.1 This heads of agreement shall be governed by the laws of [XXX].

6.2 If any dispute of a technical or financial nature arises between the Parties under this heads of agreement or the Proposed Agreement, either Party may issue a notice of such dispute to the other Party (**Dispute Notice**). If such dispute has not been resolved within twenty (20) Business Days of issue of the Dispute Notice between such Parties' representatives with day-to-day responsibility for the administration of the heads of agreement or Proposed Agreement (as applicable), it shall first be referred to the senior executive of each such Party who shall be supplied with all information which the Parties consider pertinent and shall endeavour to resolve the dispute within ten (10) Business Days of the referral of the dispute to them. This paragraph 6.2 and any discussion between senior executives which takes place pursuant to it shall be without prejudice to any right or remedy which any such Party may ultimately have, should the matter in dispute fail to be resolved by such discussions. If any such dispute is not resolved within ten (10) Business Days of its referral to the senior executives of the Parties, either Party may refer such dispute to an expert in accordance with paragraph 6.3 below. Disputes which are not of a technical or financial nature shall be determined by the courts in accordance with paragraph 6.8 below.

6.3 Any dispute which is of a technical or financial nature and is not resolved pursuant to paragraph 6.2 above or is otherwise provided in this heads of agreement or the Proposed Agreement to be subject to determination in accordance with paragraph 6.2 shall be determined by an expert with appropriate professional qualifications, independent of the Parties and with no interest in the dispute (an **Expert**) in accordance with this paragraph 6.3.

6.4 In the event that the Parties are unable to agree whether a dispute is of a technical or financial nature or not then the matter shall be referred to [●] for determination of that question.

6.5 Either Party may initiate the reference of a dispute described in paragraph 6.3 to an Expert by proposing to the other Party the appointment of a named individual as the Expert.

6.6 The Expert shall be selected by agreement between the Parties or, if they have not agreed within fourteen (14) days after the date of the request to refer by one of the Parties, by [●] on the application of either Party. The Parties shall use reasonable endeavours to procure that the Expert shall accept his appointment within five (5) days of selection. If the Expert has accepted appointment but is unable to complete the reference due to severe ill health, death or resignation or for other insuperable objectively justifiable reason, another Expert shall be appointed by the Parties, or if they have not agreed on the appointment within fourteen (14) days after the request to do so by one of the Parties, by the [●] on the application of either Party.

6.7 The Expert shall act as an expert and not as an arbitrator. The Parties shall each have the right to make representations to the Expert. There will be no formal hearing (unless the Expert otherwise determines) and the Expert shall regulate the procedure as he sees fit. The Expert shall have the power to open up, review, and revise any certificate, opinion, requisition or notice and to determine all matters in dispute. The Expert shall reach a decision within 28 days of their appointment or such longer period as is agreed by the Parties after the dispute has been referred to the Expert. Save in the case of fraud or manifest error, the decision of the Expert shall be final and binding on the Parties and can include orders that one or both of the Parties are to pay his costs, stating the proportion, and that one Party is to pay the other Party’s costs. The Expert may take such advice and assistance from professional advisers or other third parties as he reasonably considers appropriate to enable him to reach a determination of the dispute, and the costs of such advice and assistance shall be included within the Expert's costs for the purposes of the immediately preceding sentence.

6.8 Subject to paragraphs 6.2 – 6.7 above, the courts of [●] shall have exclusive jurisdiction to settle any dispute. The Parties agree that the courts of [●] are the most appropriate and convenient courts to settle disputes, and accordingly no Party will argue to the contrary.

6.9 Subject to paragraphs 6.2 – 6.7 above, nothing in this heads of agreement or the Proposed Agreement shall in any way restrict any Party's right to refer a dispute to such courts.

7 Confidentiality

7.1 This paragraph 7 is legally binding.

7.2 Each Party undertakes that it shall not for a period of three (3) years after the date of this heads of agreement disclose to any person any confidential information concerning the business, affairs, customers, clients or suppliers of the other party or of any member of the group of companies to which the other party belongs, except as permitted by paragraph 7.3.

7.3 Each party may disclose the other party's confidential information:

7.3.1 to its employees, officers, representatives or advisers who need to know such information for the purposes of the negotiation of the Proposed Agreement. Each Party shall ensure that its employees, officers, representatives or advisers to whom it discloses the other Party's confidential information comply with this paragraph 7; and

7.3.2 as may be required by law, a court of competent jurisdiction or any governmental or regulatory authority.

7.4 No Party shall use the other Party's confidential information for any purpose other than the negotiation of the Proposed Agreement.

8 EMIR Reporting

8.1 The Proposed Agreement will contain appropriate provisions dealing with compliance with applicable obligations to report details of contracts that are concluded, modified or terminated in accordance with Article 9 of EMIR.

9 Costs

9.1 Each Party shall pay its own costs incurred in connection with negotiation of this heads of agreement and any Proposed Agreement or other documents contemplated by it.

10 Entire Agreement and Counterparts

10.1 This heads of agreement constitutes the complete agreement of the Parties pertaining to the respective subject matter and supersedes the Parties' prior related agreements, understandings and discussions.

10.2 This heads of agreement may be executed electronically and in counterparts, each of which (including signature pages) is an original, but all of which together is one and the same instrument.

11 Term and Termination

11.1 This heads of agreement shall terminate automatically upon the earlier of (i) the First Party entering into a Proposed Agreement or (ii) the Second Party notifying the First Party in writing that one or more third parties have entered into agreements with it following the conclusion of a CfD Reverse Auction pursuant to which the Second Party agrees to pay such third party(ies) a difference amount calculated as the difference between the Reference Price and a strike price awarded to such party(ies) following the CfD Reverse Auction.

11.2 The Proposed Agreement shall commence on the date of the Proposed Agreement and, subject to the provisions for earlier termination set out in the Proposed Agreement, shall continue in full force and effect until the end of the Term.

11.3 This heads of agreement and any Proposed Agreement shall automatically terminate upon the insolvency of either Party.

11.4 The Second Party shall be entitled (but not obligated) to terminate the Proposed Agreement if:

11.4.1 the First Party fails to maintain the required Performance Security in place or the full amount of Performance Security has been drawn down by the Second Party in accordance with the terms of the Proposed Agreement;

11.4.2 the First Party fails to satisfy the conditions precedent thereunder by any long-stop date for their satisfaction set out in the Proposed Agreement (unless the Second Party has waived such conditions precedent); or

11.4.3 the First Party defaults in the performance of any of its other material obligations under the Proposed Agreement and such default is either not capable of remedy or if capable of remedy, remains un-remedied after thirty (30) days from the date of notice from the Second Party requiring such default to be remedied.

11.5 The First Party shall be entitled to terminate the Proposed Agreement if:

11.5.1 the Second Party fails to pay any amount due under the Proposed Agreement on the due date for payment and the same is not remedied within twenty (20) days of the First Party giving the Second Party notice of the default; or

11.5.2 the Second Party defaults in the performance of any of its other material obligations under the Proposed Agreement and such default is either not capable of remedy or if capable of remedy, remains un-remedied after thirty (30) days from the date of notice from the First Party requiring such default to be remedied.

12 Force Majeure

12.1 Subject to paragraph 12.2, neither Party shall be in breach of the Proposed Agreement, or otherwise liable to the other, by reason of any delay in performance or non-performance of any of its obligations under the Proposed Agreement to the extent such delay or non-performance is caused by Force Majeure.

12.2 A Party may only rely upon paragraph 12.1 to the extent that it:

12.2.1 notifies the other Party of the matters constituting Force Majeure as soon as reasonably practicable following its occurrence;

12.2.2 keeps the other Party fully informed as to the matters relating to the Force Majeure; and

12.2.3 uses its reasonable endeavours to minimise the effects of the Force Majeure on the performance of its obligations under the Proposed Agreement.

12.3 The Party not affected by the Force Majeure may terminate the Proposed Agreement at any time while the Force Majeure is continuing by written notice to the Party affected by the Force Majeure if the Force Majeure prevents the affected Party from fulfilling its material obligations under the Proposed Agreement for a continuous period exceeding [twelve (12)] months.

13 Change in Law

13.1 The Proposed Agreement will contain provisions which provide that if a Party reasonably considers that there has been a Change in Law which materially affects the subject matter, the operation, or the interpretation of the Proposed Agreement (including situations in which the provisions of the Proposed Agreement become inconsistent with any applicable law), that Party shall be entitled to serve notice on the other requiring the Parties to meet and seek to negotiate in good faith (both acting reasonably) such amendments to the Proposed Agreement as are necessary to achieve (in so far as possible) the same overall balance of benefits, rights, obligations, costs, liabilities and risks as applied immediately prior to the relevant Change in Law.

13.2 If the Parties fail to reach agreement within thirty (30) days of the first meeting referred to in paragraph 13.1, either Party may refer the matter to an Expert (acting as expert not as arbitrator) to determine such amendments as are necessary to achieve (in so far as possible) the same overall balance of benefits, rights, obligations, costs, liabilities and risks as applied immediately prior to the relevant Change in Law.

13.3 Neither Party will be liable to the other Party for a failure to perform any obligation under the Proposed Agreement which has become prohibited or impossible to perform by reason of a Change in Law.

14 Representations, Warranties and Covenants

14.1 The Proposed Agreement will contain standard representations and warranties, made by each Party, covering (*inter alia*) the following: (i) due organisation and valid existence; (ii) powers to execute the Proposed Agreement and perform the Party's obligations thereunder; (iii) non-violation of law or constitutional documents by entering into or performing obligations under the Proposed Agreement; (iv) confirmation that obligations under the Proposed Agreement constitute legal, valid and binding obligations; (v) no litigation and (vi) no events of default or potential events of default have occurred at the date of the Proposed Agreement.

14.2 The Proposed Agreement will contain covenants binding on the First Party, covering (*inter alia*) the following: (i) compliance with applicable law; (ii) provision of information to the Second Party where reasonably required by the Second Party in connection with the subject matter of the Proposed Agreement; (iii) evidence in form and substance satisfactory to the Second Party (acting reasonably) that the First Party has actually utilised or supplied (as applicable) the Net-Zero Carbon Shipping Fuel in respect of which it claims any Difference Amount for ship propulsion; (iv) maintenance of appropriate insurance in respect of the use of Net-Zero Carbon Shipping Fuel during the term of the Proposed Agreement and (v) [●].

15 Transferability

15.1 Neither Party may assign or novate its rights under this heads of agreement or the Proposed Agreement without the prior written consent of the other Party (not to be unreasonably withheld or delayed), except that the Second Party may transfer, assign or novate all or any of its rights or obligations under this heads of agreement or the Proposed Agreement to an Affiliate.

16 IP Rights

16.1 The Proposed Agreement will contain provisions pursuant to which each Party reserves any IP Rights developed by or on behalf of it prior to or during the term of the Proposed Agreement. Provision for non-exclusive, royalty-free, non-transferable licences to be issued by each Party to the other if required during the term of the Proposed Agreement will be included in the Proposed Agreement.

17 Direct Agreement

17.1 Upon written request from the First Party, the Second Party agrees to enter into negotiations in respect of a direct agreement in respect of the Proposed Agreement, with or for the benefit of any lender providing financing or refinancing to the First Party in connection with the use or supply (as applicable) of Net-Zero Carbon Shipping Fuel, such direct agreement to be on terms acceptable to the Second Party (acting reasonably).

18 Commencement and signature

The Parties have signed this heads of agreement on the dates(s) below:

Agreed by (First Party):	Agreed by (Second Party):
Signature	Signature
Print Name	Print Name
Date	Date

7.2 Total Cost of Ownership Contract for Difference

HEADS OF AGREEMENT

This heads of agreement is made on the date of the last signature below.

BETWEEN

[Bidding Entity X][155] (**First Party**)

- AND -

[Directorate-General for Climate Action, European Commission] (**Second Party**),

(each a **Party** and together the **Parties**)

SUBJECT TO CONTRACT

Background

C. The First Party and the Second Party are interested in entering into the Proposed Agreement to support the First Party's supply and operation of a **Zero-emissions Deep Sea Shipping Vessel**, as defined below.

D. This heads of agreement sets out at a high level, the key terms and conditions of the Proposed Agreement.

1 Definitions

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[155] The bidding entity may be a ship operator or another entity involved in the ownership or operation of ships, which can supply and operate a Zero-emissions Deep Sea Shipping Vessel, and use Net-Zero Carbon Shipping Fuel in the vessel (which is not already supported by a CfD from the Second Party).

1.1 For the purposes of this heads of agreement:

"Affiliate" means in relation to the Second Party, another person, firm, company, corporation, government, state or agency of a state, or any association, trust or partnership (whether or not having separate legal personality) that controls, is controlled by, or is under common control with the Second Party;

"**Business Day**" means a day on which banks are open for business in [●] (excluding Saturdays, Sundays and public holidays);

"**Ceiling Price**" means the highest two-week average price for [marine gas oil (MGO)] trading at the 5 largest bunkering ports [in the European Union] in the five (5) years immediately preceding the date on which the Reference Price is calculated, adjusted on the date on which the Reference Price is calculated (each such date, the **Indexation Date**) in accordance with the following formula:

$$Ceiling\ Price = CP_{base} \times INF$$

Where:

CP_{base} is the highest two-week average price for [marine gas oil (MGO)] trading at the 5 largest bunkering ports [in the European Union] in the five (5) years immediately preceding the date on which the Reference Price is calculated; and

INF is calculated in accordance with the following formula:

$$INF = \frac{HICP_t}{HICP_b}$$

Where:

$HICP_t$ means the Harmonised Index of Consumer Prices for the month immediately prior to the month in which the Indexation Date falls; and

$HICP_b$ means the Harmonised Index of Consumer Prices for [for the first month of the year preceding the Indexation Date];

“CfD Reverse Auction” means a reverse auction process run by or on behalf of the Second Party in accordance with rules determined by the Second Party, pursuant to which eligible suppliers and operators of the Vessel may bid to receive pricing support with respect to the supply and operation of the Vessel, pursuant to an agreement such as the Proposed Agreement;

"**Change in Law**" means the coming into effect of any law after the date of the Proposed Agreement, and/or the modification, repeal or replacement of any law after the date of the Proposed Agreement, and/or in the case of a judgment of a competent authority any binding change in the interpretation or application of any law after the date of the Proposed Agreement by a competent authority;

"**Difference Amount**" has the meaning ascribed to it in paragraph 3.2.

"**Dispute Notice**" has the meaning ascribed to it in paragraph 6.2.

"**EMIR**" means the European Regulation on OTC Derivatives, Central Counterparties and Trade Repositories (Regulation 648/2012);

"**Expert**" has the meaning ascribed to it in paragraph 6.3.

"**Floor Price**" means the lowest two week average price for [marine gas oil (MGO)] trading at the 5 largest bunkering ports [in the European Union] in the five (5) years immediately preceding the date on which the Reference Price is calculated, adjusted on the date on which the Reference Price is calculated (each such date, the **Indexation Date**) in accordance with the following formula:

$$Floor\ Price = FP_{base} \times INF$$

Where:

FP_{base} is the lowest two week average price for [marine gas oil (MGO)] trading at the 5 largest bunkering ports [in the European Union] in the five (5) years immediately preceding the date on which the Reference Price is calculated; and

INF is calculated in accordance with the following formula:

$$INF = \frac{HICP_t}{HICP_b}$$

Where:

$HICP_t$ means the Harmonised Index of Consumer Prices for the month immediately prior to the month in which the Indexation Date falls; and

$HICP_b$ means the Harmonised Index of Consumer Prices for [for the first month of the year preceding the Indexation Date];

"**Force Majeure**" means, in respect of a Party, any event outside the reasonable control of that Party affecting its ability to perform any of its obligations under the Proposed Agreement and which could not have been prevented or avoided by a reasonable and prudent operator, including acts of war, natural disaster, national strikes or other industrial action, threat of war, terrorist act, blockade, revolution, riot, insurrection, civil commotion, public demonstration, sabotage, lightning, fire, storm, flood, earthquake, or acts or omissions of competent authorities otherwise than in accordance with laws and/or directives (except that lack of funds or strikes only of a Party's own employees and/or those of its contractors shall not constitute Force Majeure);

"**Guarantees of Origin**" shall have the meaning given to the term in Directive 2009/28/EC;

"Gross Tonnage" means the gross tonnage (GT) of the ship as defined in Regulation 3 of Annex 1 of *The International Convention on Tonnage Measurement of Ships*, using the following formula:

$$GT = V \times K$$

Where V is the ship's total volume in cubic metres, and

$$K = 0.2 + 0.02 \times \log_{10} V$$

"Net-Zero Carbon Shipping Fuel" means (i) hydrogen or hydrogen derivatives, such as methanol and ammonia, produced from renewable energy; (ii) nuclear energy or (iii) fuel which is produced with complete carbon capture and storage of any Scope 1 & 2 CO2 emissions and which complies with PAS 2060. The First Party must ensure the fuel supplied meets any certification requirements set by the Second Party (e.g., Guarantees of Origin), or be subject to forfeiture of Performance Security provided pursuant to paragraph 4.2.4.

“Performance Security” means a cash payment made by the First Party that is equal to [€X]/Tonne-kilometres (“tkm”) of freight transport that the First Party commits to supply in 3.1;

“Proposed Agreement” means an agreement, the form of which will be provided to the First Party if the Second Party notifies it that it has been successful in its bid into a CfD Reverse Auction, with a term scheduled not to exceed [x] years, pursuant to which the Second Party agrees to pay the Difference Amount to the First Party where the circumstances described in paragraph 3.2 arise;

“Reference Price” means the Benchmark Total Cost of Ownership as defined by the Schedule in Appendix 2 and is defined in EUR/Tonne-kilometres travelled;

“Specified Purpose” means use of a Vessel subject to the conditions in 2.1.1 and 2.1.2 on international shipping routes that include any port in [the European Union];

"**Start Date**" means the next Business Day to occur after the day on which the Second Party notifies the First Party pursuant to the Proposed Agreement that the Second Party considers that each of the conditions precedent to the effectiveness of the Proposed Agreement as such conditions precedent are set out in the Proposed Agreement have been satisfied or waived in writing by the Second Party;

“Strike Price” means the price either (i) administratively-set by the Second Party, or (ii) the price bid by the First Party in response to reverse auction held on [DD/MM/YYYY]. The Strike Price shall be adjusted on each anniversary of the Start Date during the Term (each such date, the **Indexation Date**) to an amount calculated in accordance with the following formula:

$$Strike\ Price = SP_{base} \times INF$$

Where:

SP_{base} means the Strike Price as at the Start Date; and

INF is calculated in accordance with the following formula:

$$Strike\ Price = \frac{HICP_t}{HICP_b}$$

Where:

$HICP_t$ means the Harmonised Index of Consumer Prices for the month immediately prior to the month in which the Indexation Date falls

$HICP_b$ means the Harmonised Index of Consumer Prices for [insert date];

"**Term**" means the period commencing on the Start Date and continuing until the day prior to the [tenth (10th)] anniversary of the Start Date, subject to earlier termination of the Proposed Agreement in accordance with its terms;

“Tonne-kilometres” (“tkm”) means the actual distance travelled by the Zero-emissions Deep Sea Shipping Vessel, multiplied by the weight of its cargo in tons for each kilometre travelled; and

“Zero-emissions Deep Sea Shipping Vessel” means a shipping vessel meeting the following requirements: 1. ‘Zero-emissions’ means that zero carbon dioxide emissions are emitted in the generation or use of the energy that powers the ship’s propulsion. The same requirement does not apply to ship construction (if applicable), onboard power consumption or ignition. The First Party is not permitted to purchase carbon offsets, i.e. the propulsion source must itself produce zero carbon dioxide emissions. This is not limited to liquid fuels. 2. ‘Deep Sea Shipping Vessel’ means that the vessel being supported under the Proposed Agreement must be registered for international travel with the International Maritime Organisation (IMO) and be certified according to international maritime, safety, quality and environmental standards as required by the IMO and national regulation such that it can legally operate along its intended operational routes.

2 Status of heads of agreement[156]

2.1 This heads of agreement is not exhaustive and is expressly ‘subject to contract’ until a final written agreement has been entered into. Except with respect to paragraph 7 and otherwise where specifically stated, the terms of this heads of agreement are not intended to be legally binding between the Parties.

3 Basis of the Proposed Agreement

3.1 Under the Proposed Agreement, the First Party’s primary obligations will be:

3.1.1 to complete full registration and certification of a Zero-emissions Deep Sea Shipping Vessel by [DD/MM/YYYY]; and

3.1.2 to operate, either directly or through a third party, said Zero-emissions Deep Sea Shipping Vessel (“Vessel”) for a minimum of [XXX] tkm annually between [DD/MM/YYYY] and [DD/MM/YYYY] on international routes including European ports, in compliance with the Specified Purpose.

3.2 Under the Proposed Agreement, the Second Party’s primary obligation will be to pay the First Party the difference between the Reference Price and the Strike Price, where the Strike Price exceeds the Reference Price (the "**Difference Amount**”). Settlement will be as follows:

3.2.1 the First Party will provide the Second Party with a statement detailing the dates and quantities of tkm travelled by the Vessel in the previous calendar quarter;

3.2.2 the Second Party shall, within [ten (10)] Business Days, provide the First Party with details of the cumulative Difference Amount due to the First Party based on the information provided by the First Party pursuant to paragraph 3.2.1, together with details of the applicable

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[156] Depending on the governing law, local law advice on the status of these heads of agreement and in particular, the extent to which it is possible to agree that certain provisions are not legally binding, may need to be taken.

Reference Price used for the purposes of calculating the Difference Amount;

3.2.3 the Second Party shall, unless the First Party has indicated in writing that it disagrees with the calculation of the cumulative Difference Amount set out in the notice referred to in paragraph 3.2.2, pay the First Party the cumulative Difference Amount within thirty (30) days of the date of the notice issued by the Second Party to the First Party pursuant to paragraph 3.2.2; and

3.2.4 late payment interest will be payable on any payments made by the Second Party after the due date indicated in paragraph 3.2.3.

4 Conditions precedent

4.1 To participate in the CfD Reverse Auction (if applicable), the First Party must:

4.1.1 comply with any CfD Reverse Auction rules determined by the Second Party and notified to the First Party in advance of any CfD Reverse Auction; and

4.1.2 not (at the time the CfD Reverse Auction is held) appear on the last published consolidated list of asset freeze targets designated by any of the United Nations, European Union and [*insert any other relevant bodies / jurisdictions*] under legislation relating to current financial sanctions regimes (or, in the event that any such list ceases to be published, an equivalent list produced by the [●] government in respect of the same).

4.2 If the First Party is successful in a CfD Reverse Auction, it will be invited to enter into a Proposed Agreement, the Start Date under which will commence upon the satisfaction by the First Party (or waiver in writing by the Second Party) of certain conditions precedent, which will include:

4.2.1 provision to the Second Party of a legal opinion addressed to the Second Party, in form and content satisfactory to the Second Party (acting reasonably), from the legal advisers to the First Party confirming that the First Party: (i) is duly formed and validly existing under the laws of the jurisdiction of formation; and (ii) has the power to enter into and perform, and has taken all necessary action to authorise its entry into and performance of, the Proposed Agreement;

4.2.2 provision to the Second Party of evidence, in form and content satisfactory to the Second Party, acting reasonably, of compliance by the First Party with “know your customer” or similar identification procedures or checks under all applicable laws and regulations pursuant to the transactions contemplated by the Proposed Agreement; and

4.2.3 entry into an agreement for the operation of the Zero-emissions Deep Sea Shipping Vessel referred to in paragraph 3.1 for the Specified Purpose and provision of a copy of same to the Second Party, where the counterparty to the agreement can be either the Second Party itself or a third party;

4.2.4 provision of Performance Security to the Second Party. The First Party will forfeit an amount equal to [€X]/tkm that the vessel fails to travel below the annual minimum specified in paragraph 3.1.2. Any undrawn Performance Security which is held by the Second Party shall be returned to the First Party upon expiry or early termination of the Proposed Agreement.

5 Rights and remedies

5.1 Each Party agrees that damages alone would not be an adequate remedy for any beach of a legally binding obligation of this heads of agreement by the other Party. In such an event, the non-defaulting Party shall be entitled to the remedies of an injunction, specific performance or other equitable relief (or any equivalent reliefs which may be available) in addition to any other remedy including damages for any threatened or actual breach of any legally binding obligation of this heads of agreement.

5.2 This heads of agreement is for the benefit of the parties to it and is not intended to benefit, or be enforceable by, anyone else.

6 Governing law and jurisdiction

6.1 This heads of agreement shall be governed by the laws of [XXX].

6.2 If any dispute of a technical or financial nature arises between the Parties under this heads of agreement or the Proposed Agreement, either Party may issue a notice of such dispute to the other Party (Dispute Notice) and if such dispute has not been resolved within twenty (20) Business Days of issue of the Dispute Notice between such Parties' representatives with day-to-day responsibility for the administration of the heads of agreement or Proposed Agreement (as applicable), it shall first be referred to the senior executive of each such Party who shall be supplied with all information which the Parties consider pertinent and shall endeavour to resolve the dispute within ten (10) Business Days of the referral of the dispute to them. This paragraph 6.2 and any discussion between senior executives which takes place pursuant to it shall be without prejudice to any right or remedy which any such Party may ultimately have, should the matter in dispute fail to be resolved by such discussions. If any such dispute is not resolved within ten (10) Business Days of its referral to the senior executives of the Parties, either Party may refer such dispute to an expert in accordance with paragraph 6.3 below. Disputes which are not of a technical or financial nature shall be determined by the courts in accordance with paragraph 6.8 below.

6.3 Any dispute which is of a technical or financial nature and is not resolved pursuant to paragraph 6.2 above or is otherwise provided in this heads of agreement or the Proposed Agreement to be subject to determination in accordance with paragraph 6.2 shall be determined by an expert with appropriate professional qualifications, independent of the Parties and with no interest in the dispute (an Expert) in accordance with this paragraph 6.3.

6.4 In the event that the Parties are unable to agree whether a dispute is of a technical or financial nature or not then the matter shall be referred to [●] for determination of that question.

6.5 Either Party may initiate the reference of a dispute described in paragraph 6.3 to an Expert by proposing to the other Party the appointment of a named individual as the Expert.

6.6 The Expert shall be selected by agreement between the Parties or, if they have not agreed within fourteen (14) days after the date of the request to refer by one of the Parties, by [●] on the application of either Party. The Parties shall use reasonable endeavours to procure that the Expert shall accept his appointment within five (5) days of selection. If the Expert has accepted appointment but is unable to complete the reference due to severe ill health, death or resignation or for other insuperable objectively justifiable reason, another Expert shall be appointed by the Parties, or if they have not agreed on the appointment within fourteen (14) days after the request to do so by one of the Parties, by the [●] on the application of either Party.

6.7 The Expert shall act as an expert and not as an arbitrator. The Parties shall each have the right to make representations to the Expert. There will be no formal hearing (unless the Expert otherwise determines) and the Expert shall regulate the procedure as he sees fit. The Expert shall have the power to open up, review, and revise any certificate, opinion, requisition or notice and to determine all matters in dispute. The Expert shall reach a decision within 28 days of their appointment or such longer period as is agreed by the Parties after the dispute has been referred to the Expert. Save in the case of fraud or manifest error, the decision of the Expert shall be final and binding on the Parties and can include orders that one or both of the Parties are to pay his costs, stating the proportion, and that one Party is to pay the other Party's costs. The Expert may take such advice and assistance from professional advisers or other third parties as he reasonably considers appropriate to enable him to reach a determination of the dispute, and the costs of such advice and assistance shall be included within the Expert's costs for the purposes of the immediately preceding sentence.

6.8 Subject to paragraphs 6.2 – 6.7 above, the courts of [●] shall have exclusive jurisdiction to settle any dispute. The Parties agree that the courts of [●] are the most appropriate and convenient courts to settle disputes, and accordingly no Party will argue to the contrary.

6.9 Subject to paragraphs 6.2 – 6.7 above, nothing in this heads of agreement or the Proposed Agreement shall in any way restrict any Party's right to refer a dispute to such courts.

7 Confidentiality

7.1 This paragraph 7 is legally binding.

7.2 Each Party undertakes that it shall not for a period of three (3) years after the date of this heads of agreement disclose to any person any confidential information concerning the business, affairs, customers, clients or suppliers of the other party or of any member of the group of companies to which the other party belongs, except as permitted by paragraph 7.3.

7.3 Each party may disclose the other party's confidential information:

7.3.1 to its employees, officers, representatives or advisers who need to know such information for the purposes of the negotiation of the Proposed Agreement. Each Party shall ensure that its employees, officers, representatives or advisers to whom it discloses the other Party's confidential information comply with this paragraph 7; and

7.3.2 as may be required by law, a court of competent jurisdiction or any governmental or regulatory authority.

7.4 No Party shall use the other Party's confidential information for any purpose other than the negotiation of the Proposed Agreement.

8 EMIR Reporting

8.1 The Proposed Agreement will contain appropriate provisions dealing with compliance with applicable obligations to report details of contracts that are concluded, modified or terminated in accordance with Article 9 of EMIR.

9 Costs

9.1 Each Party shall pay its own costs incurred in connection with negotiation of this heads of agreement and any Proposed Agreement or other documents contemplated by it.

10 Entire Agreement and Counterparts

10.1 This heads of agreement constitutes the complete agreement of the Parties pertaining to the respective subject matter and supersedes the Parties' prior related agreements, understandings and discussions.

10.2 This heads of agreement may be executed electronically and in counterparts, each of which (including signature pages) is an original, but all of which together is one and the same instrument.

11 Term and Termination

11.1 This heads of agreement shall terminate automatically upon the earlier of (i) the First Party entering into a Proposed Agreement or (ii) the Second Party notifying the First Party in writing that one or more third parties have entered into agreements with it following the conclusion of a CfD Reverse Auction pursuant to which the Second Party agrees to pay such third party(ies) a difference amount calculated as the difference between the Reference Price and a strike price awarded to such party(ies) following the CfD Reverse Auction.

11.2 The Proposed Agreement shall commence on the date of the Proposed Agreement and, subject to the provisions for earlier termination set out in the Proposed Agreement, shall continue in full force and effect until the end of the Term.

11.3 This heads of agreement and any Proposed Agreement shall automatically terminate upon the insolvency of either Party.

11.4 The Second Party shall be entitled (but not obligated) to terminate the Proposed Agreement if:

11.4.1 the First Party fails to maintain the required Performance Security in place or the full amount of Performance Security has been drawn down by the Second Party in accordance with the terms of the Proposed Agreement;

11.4.2 the First Party fails to satisfy the conditions precedent thereunder by any long-stop date for their satisfaction set out in the Proposed Agreement (unless the Second Party has waived such conditions precedent); or

11.4.3 the First Party defaults in the performance of any of its other material obligations under the Proposed Agreement and such default is either not capable of remedy or if capable of remedy, remains un-remedied after thirty (30) days from the date of notice from the Second Party requiring such default to be remedied.

11.5 The First Party shall be entitled to terminate the Proposed Agreement if:

11.5.1 the Second Party fails to pay any amount due under the Proposed Agreement on the due date for payment and the same is not remedied within twenty (20) days of the First Party giving the Second Party notice of the default; or

11.5.2 the Second Party defaults in the performance of any of its other material obligations under the Proposed Agreement and such default is either not capable of remedy or if capable of remedy, remains un-remedied after thirty (30) days from the date of notice from the First Party requiring such default to be remedied.

12 Force Majeure

12.1 Subject to paragraph 12.2, neither Party shall be in breach of the Proposed Agreement, or otherwise liable to the other, by reason of any delay in performance or non-performance of any of its obligations under the Proposed Agreement to the extent such delay or non-performance is caused by Force Majeure.

12.2 A Party may only rely upon paragraph 12.1 to the extent that it:

12.2.1 notifies the other Party of the matters constituting Force Majeure as soon as reasonably practicable following its occurrence;

12.2.2 keeps the other Party fully informed as to the matters relating to the Force Majeure; and

12.2.3 uses its reasonable endeavours to minimise the effects of the Force Majeure on the performance of its obligations under the Proposed Agreement.

12.3 The Party not affected by the Force Majeure may terminate the Proposed Agreement at any time while the Force Majeure is continuing by written notice to the Party affected by the Force Majeure if the Force Majeure prevents the affected Party from fulfilling its material obligations under the Proposed Agreement for a continuous period exceeding [twelve (12)] months.

13 Change in Law

13.1 The Proposed Agreement will contain provisions which provide that if a Party reasonably considers that there has been a Change in Law which materially affects the subject matter, the operation, or the interpretation of the Proposed Agreement (including situations in which the provisions of the Proposed Agreement become inconsistent with any applicable law), that Party shall be entitled to serve notice on the other requiring the Parties to meet and seek to negotiate in good faith (both acting reasonably) such amendments to the Proposed Agreement as are necessary to achieve (in so far as possible) the same overall balance of benefits, rights, obligations, costs, liabilities and risks as applied immediately prior to the relevant Change in Law.

13.2 If the Parties fail to reach agreement within thirty (30) days of the first meeting referred to in paragraph 13.1, either Party may refer the matter to an Expert (acting as expert not as arbitrator) to determine such amendments as are necessary to achieve (in so far as possible) the same overall balance of benefits, rights, obligations, costs, liabilities and risks as applied immediately prior to the relevant Change in Law.

13.3 Neither Party will be liable to the other Party for a failure to perform any obligation under the Proposed Agreement which has become prohibited or impossible to perform by reason of a Change in Law.

14 Representations, Warranties and Covenants

14.1 The Proposed Agreement will contain standard representations and warranties, made by each Party, covering (*inter alia*) the following: (i) due organisation and valid existence; (ii) powers to execute the Proposed Agreement and perform the Party's obligations thereunder; (iii) non-violation of law or constitutional documents by entering into or performing obligations under the Proposed Agreement; (iv) confirmation that obligations under the Proposed Agreement constitute legal, valid and binding obligations; (v) no litigation and (vi) no events of default or potential events of default have occurred at the date of the Proposed Agreement.

14.2 The Proposed Agreement will contain covenants binding on the First Party, covering (*inter alia*) the following: (i) compliance with applicable law; (ii) provision of information to the Second Party where reasonably required by the Second Party in connection with the subject matter of the Proposed Agreement, including but not limited to the information specified in Appendix 1; (iii) provision of copies of any offtake agreements for supply of Zero-CO2 Shipping Fuel in respect of which the First Party claims any Difference Amount under the Proposed Agreement, together with evidence in form and substance satisfactory to the Second Party (acting reasonably) that the First Party has actually supplied the Zero-CO2 Shipping Fuel in respect of which it claims any Difference Amount to an international shipping operator for use in ship propulsion; (iv) maintenance of appropriate insurance in respect of the sourcing and supply of Zero-CO_2 Shipping Fuel during the term of the Proposed Agreement and (v) [●].

15 Transferability

15.1 Neither Party may assign or novate its rights under this heads of agreement or the Proposed Agreement without the prior written consent of the other Party (not to be unreasonably withheld or delayed), except that the Second Party may transfer, assign or novate all or any of its rights or obligations under this heads of agreement or the Proposed Agreement to an Affiliate.

16 IP Rights

16.1 The Proposed Agreement will contain provisions pursuant to which each Party reserves any IP Rights developed by or on behalf of it prior to or during the term of the Proposed Agreement. Provision for non-exclusive, royalty-free, non-transferable licences to be issued by each Party to the other if required during the term of the Proposed Agreement will be included in the Proposed Agreement.

17 Direct Agreement

17.1 Upon written request from the First Party, the Second Party agrees to enter into negotiations in respect of a direct agreement in respect of the Proposed Agreement, with or for the benefit of any lender providing financing or refinancing to the First Party in connection with Zero-CO_2 Shipping Fuel, such direct agreement to be on terms acceptable to the Second Party (acting reasonably).

18 Commencement and signature

The Parties have signed this heads of agreement on the dates(s) below:

Agreed by (First Party):	Agreed by (Second Party):
Signature	Signature
Print Name	Print Name
Date	Date

Appendix 1

Information to be provided by the First Party to the Second Party pursuant to the Proposed Agreement

The forms and documents that the Second Party may demand from the first party are listed in the ‘Convention on Facilitation of International Maritime Traffic, 1965’ (FAL), Standard 2.1.

The documents include:

- IMO General Declaration (FAL form 1)
- Cargo Declaration (FAL form 2)
- Ship’s Stores Declaration (FAL form 3)
- Crew’s Effects Declaration (FAL form 4)
- Crew List (FAL form 5)
- Passenger List (FAL form 6)
- Dangerous Goods (FAL form 7)

In addition to FAL the following declarations entered into force 1 January 2018 and include relevant listed documents:

- Security-related information as required under SOLAS regulation XI-2/9.2.2
- Advanced electronic cargo information for customs risk assessment purposes
- Advanced Notification Form for Waste Delivery to Port Reception Facilities

In addition, under FAL the Second Party may demand two further documents under the Universal Postal Convention and the International Health Regulations.

The Second Party may demand relevant flag State documents listed under FAL.2/Circ.131.

Appendix 2

Schedule for Benchmark Total Cost of Ownership

The ‘Benchmark Total Cost of Ownership’ is a is a measure of the Total Cost of Ownership of a benchmark shipping vessel representative of those predominantly in use today in different vessel categories. Its purpose is to establish a reference cost for such a vessel such that the amount paid by the Second Party to the First Party reflects the cost premium associated with construction, operation and maintenance of a Zero-Emissions Deep Sea Shipping Vessel as compared to the benchmark vessel.

The benchmark is expressed in EUR per Tonne-kilometre travelled, using assumptions that are based on typical operating conditions for a carbon dioxide-emitting ship using the dominant fuel in each category. How a ship is categorised depends on its Gross Tonnage, the Vessel Type and the Build Type (whether it is a New Build, or a Retrofit of an existing vessel).

Benchmark TCO schedule

Container

Gross Tonnage	**Build Type**	**Benchmark TCO (EUR)**	**Lifetime utilisation (tkm)**	**Reference Price (EUR/tkm)**
0-x	New Build			
0-x	Retrofit			
x-y	New Build			
x-y	Retrofit			

Wet Bulk

Gross Tonnage	**Build Type**	**Benchmark TCO (EUR)**	**Lifetime utilisation (tkm)**	**Reference Price (EUR/tkm)**
0-x	New Build			
0-x	Retrofit			
x-y	New Build			
x-y	Retrofit			

Dry Bulk

Gross Tonnage	**Build Type**	**Benchmark TCO (EUR)**	**Lifetime utilisation (tkm)**	**Reference Price (EUR/tkm)**
0-x	New Build			
0-x	Retrofit			
x-y	New Build			
x-y	Retrofit			

Cruise

Gross Tonnage	**Build Type**	**Benchmark TCO (EUR)**	**Lifetime utilisation (tkm)**	**Reference Price (EUR/tkm)**
0-x	New Build			
0-x	Retrofit			
x-y	New Build			
x-y	Retrofit			

Calculations for TCO schedule

The TCO schedule is based on the sum of the total expected costs of construction and operation of a benchmark ship in each category, assuming a given utilisation rate. These costs are calculated differently for each ship size, class, and build type.

CapEx

- New builds: Cost of building an MGO-fuelled ship, for each type. Includes chassis/structure, internal fittings and equipment, engine, fuel tanks, fuel delivery system, transmission, pollution control systems.

$$CapEx_{NB} = \sum(Chassis, Fittings, Engine, Tanks, FuelSystem, Transmission, PollutionCtrl)$$

- Retrofit: Cost of replacing the engine with an MGO-compatible engine and fuel supply system for an existing ship

$$CapEx_{RF} = \sum(Engine, Tanks, FuelSystem)$$

OpEx

- This is the same for new builds and retrofits
- Expected nominal cost of fuel (using the same measure as the fuel CfD; paste relevant paragraphs here) multiplied by the fuel used per kilometre at average load (e.g. for a ship of 100,000 DWT the average load might be 80,000 DWT), multiplied by years in service (e.g. 30)

$$OpEx_{Fuel} = FuelPrice \ \times FuelPerKm_{avg} \times KmPerYear_{avg} \times years$$

- Cost of maintenance, insurance, crew salaries, any cost associated with securing access to bunkering fuel, multiplied by years in service (e.g. 30)

$$OpEx_{Non-fuel} = years \times \sum(Maintenance, Insurance, Crew, Bunkering)$$

TCO

Once the total CapEx and OpEx for a given ship type are calculated, they are added together to arrive at a figure for Total Cost of Ownership.

$$TCO = \sum(CapEx, OpEx_{Fuel}, OpEx_{Non-Fuel})$$

Reference Price

Then, using the same average load (in tonnes) and distance (in kilometres/year) assumptions used to calculate average fuel cost per kilometre, this figure is divided by average tonnage, times the number of kilometres travelled by year, times the number of years in service, to arrive at the Reference Price (in EUR per tkm):

$$RP = \frac{TCO}{Tonnage_{avg} \times KmPerYear_{avg} \times years}$$

Appendix 3

Gross Tonnage

The reference price determination of Gross Tonnage (GT) may be the most effective choice in the majority of cases. The simplistic nature of GT as a volumetric measure of capacity is an effective choice, through limiting in practice for open-top (“hatchless”) vessels such as containerships. In this scenario, Twenty-foot Equivalent Unit (TEU) capacity may be an effective approximation as GT refers to enclosed space. Regardless, GT would be a useful approach to many sectors including bulk carriers (dry/wet), tankers, and LNG/LPG vessels. The relationship between GT and TEU is well correlated[157]. This may simplify the number of measures we would need to employ in the initial version of the CfD proposal:

The usage of FT as a measure for other segments correlates relatively well with ship shove (calculated: length x beam x (D)Depth of (d)draft), with a few notable exceptions. These are primarily cruise vessels where LBd is a stronger overall calculation as determined in Vasudevan, 2010[158]. Therefore, the usage of GT and TEU are both considered effective choices within the reference schedule.

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[157] Abramowski, Cepowski, and Zvolensky, 2018, Determination of regression formulas for key design characteristics of container ships at preliminary design stage, New Trends in Production Engineering, vol 1 issue 1, pp. 247-257 https://sciendo.com/downloadpdf/journals/ntpe/1/1/article-p247.xml

[158] Vasudevan, A., 2010, Tonnage measurement of ships: historical evolution, current issues and proposals for the way forward, World Maritime University https://commons.wmu.se/cgi/viewcontent.cgi?article=1213&context=all_dissertations

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9. Technical Appendix

A.1 Summary of technology options

Table A4 provides a brief summary of the technologies being examined to replace conventional fossil fuels, comparing their technical applicability given variance in volumetric energy density, relative impact on total cost of ownership (TCO), storage properties, safety risks and potential for integration into existing infrastructure.

Table A4. A summary of the pros and cons of some of the technology options available for decarbonising transport

Fuel	Advantages	Disadvantages	Existing Examples/Pilots
Hydrogen	• Cheaper and less electricity-intensive than ammonia and synfuels[159] • No toxic by-products • Does not require co-firing of another fuel (for ignition engines)[160] • Engines commercially available in 3-5 years[161]	• Low energy density (7.5x storage volume of MGO)[162] • Lack of global logistical infrastructure • Liquefication technology and capacity still immature • Expensive to transport (cryogenic) • Low compatibility with existing bunkering infrastructure • Highly flammable	• "Northern Lights" SMR+CCS project • CMB developing mono- and dual-fuel hydrogen engines • Norwegian Electrical Systems fuel cell retrofit, operational by 2023 • EU FLAGSHIPS project to deploy two commercial vessels (France & Norway)
Ammonia	• Usable in ICE engines with minor adaptation, commercially	• Toxic to human and aquatic life, corrosive [168] • Fuel cells commercially available in 5-7+ years[169]	• Equinor/Eidesvik ammonia pilot vessel • MAN/Samsung /Lloyd's Register/MSC joint

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[159] Electricity required to produce enough fuel for one day's sailing of a Panamax container vessel: 1.2 GWh for H2; 1.4 GWh for NH3; 1.6 GWh for biogas source; 1.8 GWh for synthetic methanol. See Ash, Sikora, and Richelle (2019) "Electrofuels for shipping".

[160] *Ibid.*

[161] ETH Zürich and Amplifier (2019) "Towards net-zero – Deep Dive Comparison of Zero Carbon Fuels". https://fe8dce75-4c2a-415b-bfe4-e52bf945c03f.filesusr.com/ugd/0a94a7_0980799ebca344158b897f9040872d36.pdf

[162] Ash, Sikor and Richelle: "Electrofuels for shipping" (EDF, 2019)

[168] "Since ammonia is currently shipped around the world in significant quantities, there are established risk mitigation measures available, but these would need to be formalised into industry regulations and more research undertaken into protocols for use as a fuel before ammonia could be widely adopted." (Ash, Sikora, and Richelle (2019) "Electrofuels for shipping").

[169] ETH Zürich and Amplifier (2019) "Towards net-zero – Deep Dive Comparison of Zero Carbon Fuels".

	available in 3-5 years[163] • More energy dense, less burden on TCO than hydrogen/ammonia[164] [165] • Established global market and logistical infrastructure • Less price uncertainty relative to other fuels (electrolyser technology, electricity prices) • Low SO_2, particulate matter, metal, and polycyclic aromatic hydrocarbon pollution[166] • Less flammable than hydrogen or synfuels. Safe handling expertise already exists[167]	• Requires co-firing with another fuel (compression and spark ignition engines) • Low compatibility with existing bunkering infrastructure • N_2O emissions comparable with current fuels • 4.1x storage volume of MGO[170]	project for ammonia-fuelled tanker (available 2022) • Yara Sluiskil (Netherlands) and Pilbara (Australia) green ammonia plants
Carbon-based synthetic electrofuels (synfuels)	• Synthetic diesel (from electrolysis) works with existing infrastructure • Compatible with existing bunkering infrastructure • No co-firing required in spark ignition engines	• Low efficiency, high cost: requires hydrogen production, CO_2 capture, and e-fuel synthesis[171] • 95% of engines would have to be replaced to use e-methanol • 2.3x storage volume of MGO[172]	• Methanol ship “Stena Germanica” in operation since 2015 (Sweden/Germany) • Green Maritime Methanol consortium selected 9 research and pilot ships in 2019 (Netherlands)

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[163] *Ibid.*

[164] IEA (2019) “Current and future total cost of ownership of fuel/powertrain alternatives in a bulk carrier ship”.

[165] Middlehurst, C. (2020, 30 March). “Ammonia flagged as green shipping fuel of the future”. Financial Times. https://www.ft.com/content/2014e53c-531f-11ea-a1ef-da1721a0541e

[166] Ash and Scarborough (2019) “Sailing on Solar”.

[167] *Ibid.*

[170] Ash, Sikora, and Richelle (2019) “Electrofuels for shipping”.

[171] “Synthetic Diesel would cost approximately twice as much as green hydrogen in terms of energy on a MJ-per-MJ basis”. (Deign, J. (2020, 21 May) “Marine Sector Turns to Ammonia to Decarbonize Shipping”. GreenTech Media. https://www.greentechmedia.com/articles/read/marine-sector-looks-to-ammonia-to-decarbonize-shipping).

[172] Ash, Sikora, and Richelle (2019) “Electrofuels for shipping”.

		• Lifecycle emissions reflect source of CO_2 used in production[173] • Locational flexibility limited by CO_2 source[174,175] • Sensitive to cost projections for direct air capture of CO_2, representing half of TCO under best-case scenario[176] • Large-scale methane synthesis not currently available	
Batteries	• Most efficient use of energy • Battery costs low and still declining. Already cost-effective for short distances[177] • Lower maintenance costs[178]	• Low energy density • Require replacement every 8-12 years[179]	• Soby-Fynshav ferry (Denmark) • Helsingor-Helsingborg ferry (Denmark, Sweden)
Biofuels	• Compatible with existing engines/powertrains[180] • High energy density, low storage volume • High compatibility with existing bunkering infrastructure • No co-firing required in spark ignition engines	• Not scalable due to competition for land use and with other applications	• “CMA CGM White Shark” container vessel, 2019 (France/Netherlands) • Van Oord/Shell marine biofuel pilot (Netherlands)

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[173] To produce methanol with zero-emissions emissions over the lifecycle, CO2 must be removed directly from the air or seawater with green energy”. Hänggi et al (2019) “A review of synthetic fuels for passenger vehicles”.

[174] Pérez-Fortes, M. Schöneberger, J. C., Boulamanti, A. and Tzimas, E. (2016) “Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment”. *Applied Energy* 161:718-732.

[175] Svanberg et al (2018) “Renewable methanol as a fuel for the shipping industry”.

[176] IEA (2019) “Current and future total cost of ownership of fuel/powertrain alternatives in a bulk carrier ship”.

[177] ETH Zürich and Amplifier (2019) “Towards net-zero – Deep Dive Comparison of Zero Carbon Fuels”.

[178] *Ibid.*

[179] *Ibid.*

[180] Ash, Sikor and Richelle: “Electrofuels for shipping” (EDF, 2019)

Nuclear	• For Molten Salt Reactors (MSR) with enriched fuels no refuelling is required for the ship’s 30-year lifetime. • Reduces uncertainty regarding fuel costs	• Few nuclear ships have ever been built for commercial purposes • Enriched fuels for MSR have proliferation issues • Spent reactors must be disposed of eventually	• NS Savannah, 1959

A.2 Detailed analysis of nuclear options

Background & Overview

Nuclear technology is an attractive option to consider for the decarbonization of the shipping sector because of its capability to supply a large, dependable, carbon-free source of energy with relatively low fuel costs. However, despite low, relatively stable fuel costs, there is considerable capital investment required along with higher decommissioning expenses and additional operating costs due to the unique attributes associated with managing a radioactive source material.

Projected Levelized Costs of Electricity (LCOE) from Nuclear Energy

The IEA estimate the average Levelized Costs of Electricity (LCOE) of nuclear power in the United States for new nuclear build in 2040 is expected to be >$100 USD/MWh. In contrast a plant that has been in operation more than 30 years (i.e., had a lifetime extension) has costs closer to $40 USD/MWh. The cost benefits achieved from life extension are even more evident in the European Union where the costs of new nuclear build are expected to be more than $100 USD/MWh. [181]

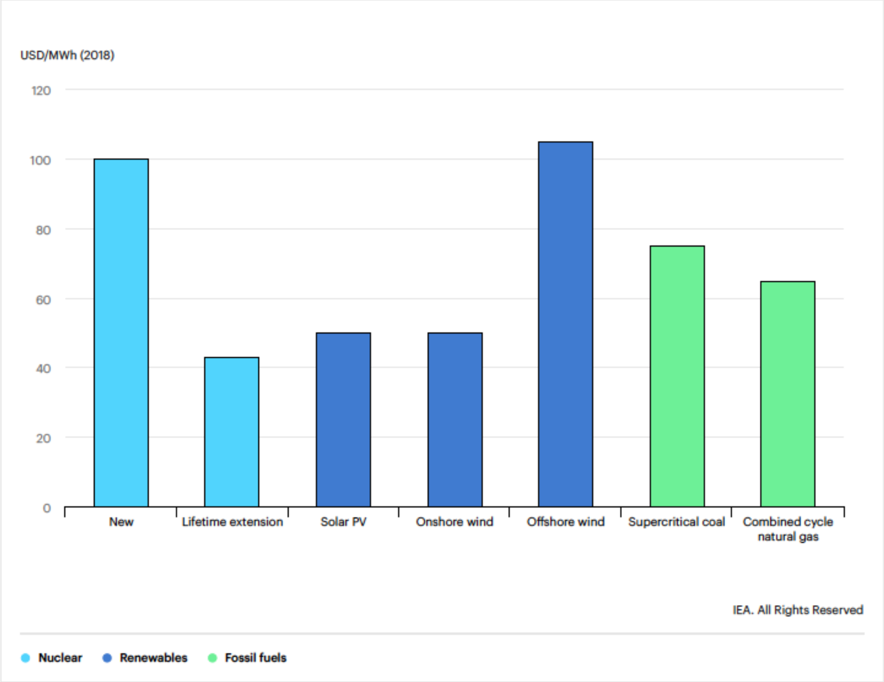

Figure 9: Levelized cost of electricity in the United States in 2040. Source: Sadamori 2020[182]

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[181] Sadamori, K. (2020) "Nuclear Power in a Clean Energy System." In *Annales des Mines-Responsabilite et environnement*, no. 1, pp. 122-126.

[182] *Ibid.*

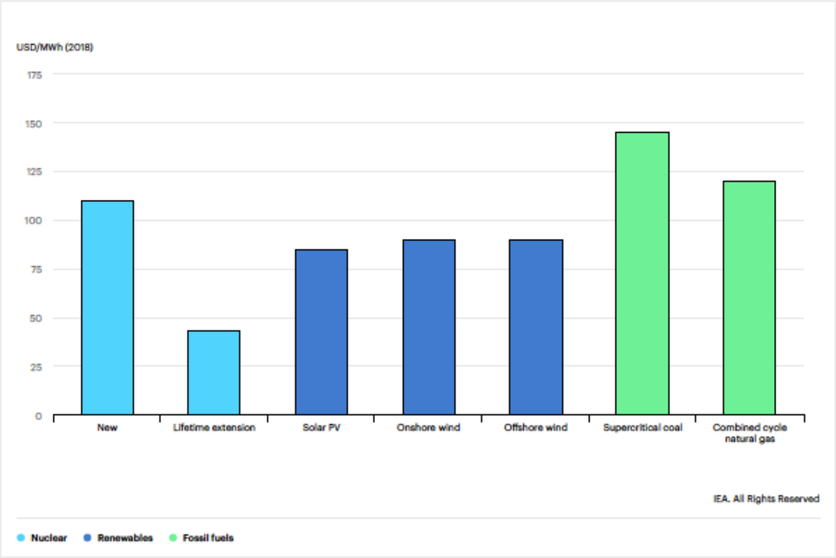

Figure 10: Levelized cost of electricity in the European Union, 2040. Source: Sadamori 2020[183]

This is consistent with similar estimates of LCOE in the US from Lazard's Asset Management group, which show the vast majority of the costs associated with new nuclear build are capital expenditure, whereas only marginal costs exist with existing plant operation. The Lazard LCOE costs of existing nuclear generation range from an estimated $25-$32/MWh.

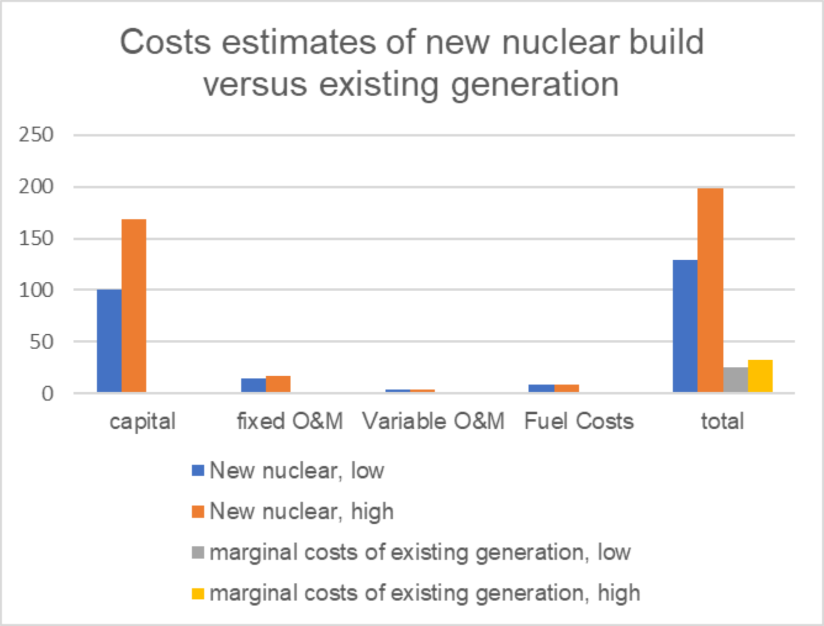

Figure 11. Generated using data from Lazard's Levelized Costs of Energy Analysis Version 14.0 [184]

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[183] *Ibid.*

[184] Lazard (2020) "Lazard's Levelized Cost of Energy Analysis - Version 14.0". https://www.lazard.com/media/451419/lazards-levelized-cost-of-energy-version-140.pdf

Advancements in nuclear capabilities and construction is predicted to reduce costs long-term. OECD countries which have continued to invest in nuclear development are expected to benefit from established supply chains and faster learning rates. As stated by the OECD's Nuclear Energy Agency Outlook (2020), "with several projects near completion that have served to establish industrial capabilities, future projects could take advantage of the experience gained and be more competitive."[185] Based on assumed advancements in learning and cost reductions, the projected overnight costs (i.e. capital costs without interest) of new, large Generation III/III+ nuclear plants from 2025 to 2030 is shown in Figure 12, suggesting a 20% decline from 2020.

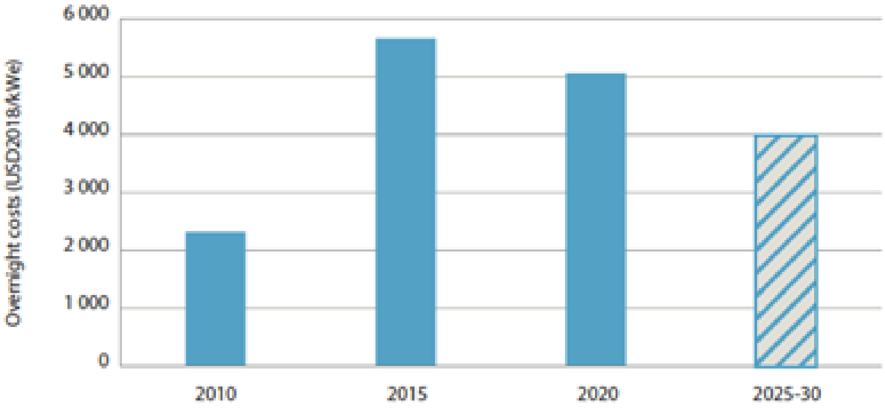

Figure 12:Trend in projected cost of new nuclear in OECD countries. Source IEA, NEA 2020 [186]

Existing and Future Nuclear Technologies

The cost estimates shown in Figure 12 are for large commercial nuclear reactors (i.e., > 300 MWe). As of December 31st, 2019, there were 443 nuclear power reactors in operation around the world. There are an additional 186 reactors permanently shut down. In 2019 there were six new reactors added to the global electricity grid with an average construction time of 118 months (i.e., ~10 years).[187] All reactors that started construction and that were added to the grid in 2019 are of the Pressurized Water Reactor (PWR) type, light-water reactor utilizing a thermal neutron fuel cycle.

Nuclear Reactor technologies have evolved since the first simple demonstration project at Chicago Pile 1 in 1942. Figure 13 shows how the nuclear energy community classifies the different technology advances over time:[188]

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[185] IEA, NEA (2020) Projected Costs of Generating Electricity, https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf

[186] *Ibid.*

[187] Cobb, J. (2020), "Highlights of the World Nuclear Performance Report."

[188] U.S. Department of Energy, Office of Nuclear Energy (n.d.) "Generation IV Nuclear Energy Systems: Program Overview" Department of Energy. http://nuclear.energy.gov/genIV/neGenIV1.html.

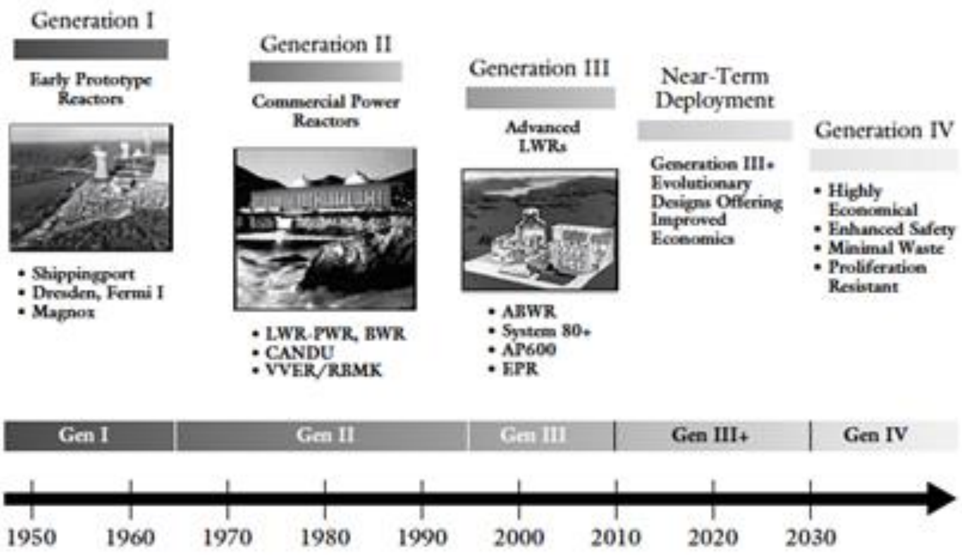

Figure 13: U.S. Department of Energy, Office of Nuclear Energy[189]

While the distinctions between generations are somewhat arbitrary, improvements in reactor technology include better safety and lower overall costs. The majority of reactor technologies in service today are Generation II technologies.[190] New nuclear plants are generally Generation III or Generation III+ technologies. A key feature of Generation III+ is incorporation of passive safety features that do not rely on electricity back-up or operator actions to shut down in the event of an emergency. As with most previous generation systems Generation III reactors use light-water as their moderating source.

Generation IV reactor technologies utilise different materials, such as gas, lead, or salt to provide cooling for sustaining the nuclear reaction. The key aspect of Generation IV reactors is their closed fuel cycle design which makes use of spent fuel and allows for sustainability in reprocessing. The world's first and only generation IV reactor is a Chinese demonstration reactor completed in January 2021. The reactor was produced by China's Chinergy, a consortium between the China Nuclear Engineering Corporation (CNEC) and Tsinghua University's Institute of Nuclear and New Energy Technology.

Small Modular Reactors (SMRs)

SMRs are generally defined as producing power outputs of less than 300 MW(e) per module and can be produced in a factory and transported to site.[191] SMRs are generally Generation IV designs which include advancements in capabilities that may be able to provide a cost

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[189] *Ibid.*

[190] Goldberg, S., and Rosner, R. (2011). "Nuclear reactors: Generation to generation." Cambridge: American Academy of Arts and Sciences.

[191] IAEA (2021) "Small Modular Reactor (SMR) Regulators' Forum". https://www.iaea.org/topics/small-modular-reactors/smr-regulators-forum.

advantage in production. Specifically, due their smaller size and modularity, they can address many of the construction challenges that have occurred in recent nuclear plant construction.[192] While larger (i.e., > 300 MW(e)) nuclear reactors are typically deployed to gain efficiencies in economies of scale, a small modular plant can reportedly make up for these efficiencies in plant design simplification, modularization and factory build, and general harmonization in the licensing and siting process (Figure 14).

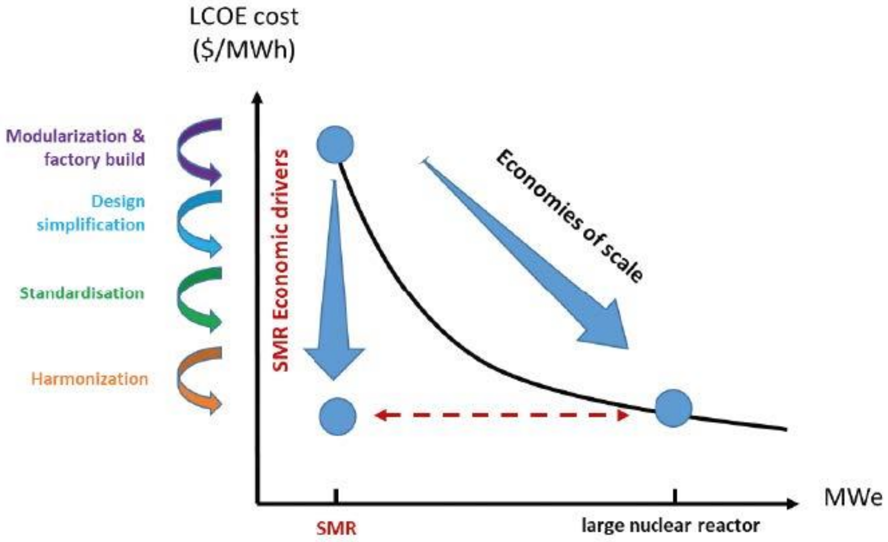

Figure 14: Stylised representation of how advocates of small modular reactors propose to overcome the economies of scale evident in the build of nuclear reactors. Source: Berthelemy et al. 2020[193]

The Chinese Chinergy unit is the first advanced technology small modular reactor (i.e., Generation IV) and was in construction for nearly ten years.[194] Efforts by western countries to develop small modular nuclear have relied on private financing initiatives that have only recently been backed by government initiatives in the US, Canada, and the UK.[195] Further funding hinges on successful demonstration projects. As the NEA states, "completion of first prototypes during the 2020s will therefore be essential in the demonstration of the expected benefits of SMRs."[196]

Globally, there is an estimated 25+ private companies currently developing over 72 different designs of small modular reactors, however no plant has yet to achieve commercial

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[192] Reuters (2021). "Southern Targets Dec Start for New Georgia Vogtle 3 Nuclear Reactor," April 29, 2021. https://www.reuters.com/business/energy/southern-targets-dec-start-new-georgia-vogtle-3-nuclear-reactor-2021-04-29/.

[193] Berthelemy, M., Vaya Soler, A., Bilbao y Leon, S., Middleton, M., Piette, C., Hautojaervi, J., Bard, O. et al. (2020) *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*. OECD NEA--7530.

[194] CNNC (2021) "Hot functional testing of HTR-PM reactors starts" (WNN). http://en.cnnc.com.cn/2021-01/05/c_579757.htm

[195] U.S. Department of Energy (2021) "Advanced Small Modular Reactors (SMRs)." https://www.energy.gov/ne/advanced-small-modular-reactors-smrs

[196] OECD (2020) *Projected Costs of Generating Electricity 2020*.

operation.[197] Different designs are at different levels of technical development and demonstration. The industry has called for increased government and public cooperation to determine a new framework for harmonization of licensing regimes.[198] Since no SMRs are functionally operational, costs are unknown, and all references are based on assumptions about hypothetical development and deployment of SMRs.

SMR Nuclear Propulsion

It is estimated that there over 100 nuclear reactors today in maritime use.[199] Exact figures are not retrievable since the majority of applications is military use. Nuclear maritime propulsion has been in use since 1955 with the American submarine, USS Nautilus, first launched in 1955.[200] In addition to nuclear submarines, other military application of nuclear-powered boats includes above water ships and aircraft carriers. Interest and evaluation of nuclear applications in maritime use grew from the initial USS Nautilus deployment through the early 1970s. Everything from smaller simpler freightliners to large shipping vessels, heavy oil tankers, to high-speed nuclear-powered ocean liners were evaluated and studied.[201] However, initial costs, insurance costs and operating costs were too high to justify the cost and further efforts to study and build ships were abandoned. Furthermore, there is only one demonstration of a nuclear ship in operation for commercial shipping, the USS Savannah which was in commercial operation from August 1965- August 1968. The USS Savannah was decommissioned due to higher operational costs than anticipated. [202] Specifically, it was deemed unviable due to higher operating costs (i.e., up to $2M per year higher in 1970 USD or ~$14M in 2021 USD per year higher than a non-nuclear merchant ship).

As of 2019, four nuclear powered commercial vessels had been constructed, but only one remains active.[203] The ship is owned by the Russian Federation and while initially constructed for commercial shipping, it has primarily been used for government transport of equipment for the establishment of military infrastructure in the arctic[204]. Russian nuclear-

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[197] NEA and IFNEC (2021), Financing of Small Modular Reactors (SMRs) event. Panellists: Diane Cameron, Head of the Division of Nuclear Technology Development and Economics, NEA, Jeff Harper, Vice President, Strategy & Business Development, X-Energy, United States, Kalev Kallemets, CEO, Fermi Energia, Estonia, Erick Ohaga, Director, Nuclear Energy Infrastructure Development, Nuclear Power and Energy Agency, Kenya.

[198] NEA and IFNEC (2021, 18 May) "Small Modular Reactors NEA-IFNEC Nuclear Financing Webinar Series". Presenter: Diane Cameron Head of Nuclear Technology Development and Economics Division OECD Nuclear Energy Agency.

[199] Jenkins, V. and Haskell, C. (2021) "How Can Nuclear Support Shipping's Route to Zero-Carbon?" https://www.lr.org/en-gb/insights/articles/how-can-nuclear-support-shippings-route-to-zero-carbon/.

[200] United States General Accounting Office (2018). *Nuclear-Powered Ships: Accounting for Shipyard Costs and Nuclear Waste Disposal Plans*. North Charleston, SC: Createspace Independent Publishing Platform.

[201] ANS (2021) "Nuclear Merchant Ships: Five Fast Facts." https://www.ans.org/news/article-2010/nuclear-merchant-ships-five-fast-facts/.

[202] Comptroller General of the United States (1970, 26 June). "Report to the Congress: Costs of Operating the Nuclear Merchant Ship Savannah, B-136209". https://www.gao.gov/assets/b-136209.pdf

[203] Balcombe et al (2019) "How to decarbonise international shipping".

[204] Navy Recognition (2017, 20 May) "Focus: Russia beefing up its ice-rated vessel fleet in the Arctic - Part II". Navy Recognition. http://www.navyrecognition.com/index.php/focus-analysis/naval-technology/5223-focus-russia-beefing-up-its-ice-rated-vessel-fleet-in-the-arctic-part-ii.html

powered ships rely on fuel that is 45-90% enriched[205]. By contrast, existing commercial nuclear power reactors (i.e., electricity generation) utilize fuel that is only 3-5% enriched. Newer, advanced small modular reactor designs, like ships, rely on highly enriched fuel[206]. Fuel at higher than 20% enrichment is typically only used in military applications, due to proliferation concerns. There are no civilian facilities currently licensed within the United States to provide greater than 5.5% enriched fuel, and the United Kingdom does not have plans to develop fuel manufacturing for advanced reactor designs until after 2030[207,208]. In the past, nuclear-powered commercial vessels have relied on lower enriched fuels, such as NS Savannah (launched in 1959). They were, however, deemed commercially unviable due to high operating costs over conventional ships (up to US$2 million per year higher in 1970 USD, or ~$14 million in 2021 USD) covering crew, supplies and maintenance and were decommissioned after only a few years of use[209].

Existing nuclear reactor ships are powered through steam generated by the reactor. Although steam propulsion is not particularly sophisticated, including a nuclear reactor in the design of a ship still requires the ship to be built specifically to accommodate a nuclear reactor. This type of energy propulsion would therefore require a contract for difference based on total cost of ownership.

It would also be reasonable to assume that any future use of nuclear power for shipping will utilize new generations of reactor technology (i.e., SMRs). This is because advanced generations of reactors are needed to provide the savings and added security of no refuelling. A typical nuclear power plant requires refuelling every 18-24 months whereas a small modular reactor using higher energy dense fuel will be capable of operating for 30+ years without refuelling.

Advanced nuclear technologies making use of small modular reactors have the capability to provide economies of scale in production and operations that greatly reduce the initial investment and operating costs[210]. The inherent safety features of these technologies also reduce risk and improve prospects for deployment. Globally, there are an estimated 25+ companies currently developing small modular reactors (defined as less than 300 MWe), but no plant has yet entered contracts for commercial operation, and a dominant standard plant design has yet to emerge. In January 2021, Chinergy, a consortium representing China Nuclear Engineering Corporation (CNEC) and Tsinghua University's Institute of Nuclear and New Energy Technology, completed final testing of an advanced small modular reactor in

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[205] Ma, C. and von Hippel, F. (2001) “Ending the production of highly enriched uranium for naval reactors”. *The Nonproliferation Review*, 8:1, 86-101, DOI: 10.1080/10736700108436841.

[206] *Ibid.*

[207] World Nuclear Association (2021) “US Nuclear Fuel Cycle”. World Nuclear Association. https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-fuel-cycle.aspx

[208] HM Government (2013). Nuclear Industrial Strategy: The UK’s Nuclear Future. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/168048/bis-13-627-nuclear-industrial-strategy-the-uks-nuclear-future.pdf

[209] Comptroller General of the United States (1970, 26 June). “Report to the Congress: Costs of Operating the Nuclear Merchant Ship Savannah”.

[210] Energy Information Reform Project (2017). “What will advanced nuclear power plants cost? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development”. https://www.eenews.net/assets/2017/07/25/document_gw_07.pdf

Shandong province. Construction took nearly ten years[211]. Western countries' efforts to develop small modular nuclear reactors have relied on private finance, only recently backed by government initiatives in the US, Canada, and the UK [212]. Funding hinges on successful demonstration projects, which are not expected to reach completion until the late 2020s or early 2030s[213].

When are SMR ships likely to be cost competitive?

Small modular reactors are an attractive new technology to fit the size of reactor needed for a nuclear ship. Nuclear plant costs are typically inclusive of four categories: initial capital costs, operations, and maintenance (O&M), fuels cost and decommissioning costs. The same is expected for nuclear shipping along with the cost of the actual ship itself. Since the cost of the ship is expected to remain reasonably similar to a ship that relies on other sources of fuel[214] we only consider the cost of deployment of the SMR.

There is no standardized approach to estimating the cost of small modular reactor. The industry developed two standardized methods for consideration of costs, [215] a bottoms-up approach which estimates costs of individual components, or a top-down approach which scales existing known costs of production down to the projected size of a small-modular reactor. However, a systematic literature review of the economics and financing of small modular reactors identified considerable variation in costs and cost estimating techniques. The levelized costs of electricity showed as a wide range of estimated costs, from ~$50/MWh to greater than $100/MWh.[216]

Key assumptions of the lowest cost estimate (i.e., ~$50/MWh) include: a 335 MW plant, 60 years lifetime, 95% capacity, construction time of 5 years, and a discount rate of 5%. This analysis used a "top-down" approach to cost estimating that is generally seen as a less reliable method of estimating the true cost.[217] Additionally, 60 years of plant operation is unlikely as existing plants operate for 30 years and at most, receive an extension to operate for 50 years in total. Furthermore, reactor lifetime without substantial maintenance after 30

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[211] China National Nuclear Corporation (2021, 5 January) "Hot functional testing of HTR-PM reactors starts". CNNC. http://en.cnnc.com.cn/2021-01/05/c_579757.htm

[212] Deign, G. (2021, 4 January) "Nuclear Enters 2021 With Buoyant Global Outlook for Small Modular Reactors". GreenTech Media. https://www.greentechmedia.com/articles/read/nuclear-enters-2021-with-buoyant-global-outlook-for-small-modular-reactors

[213] United States Office of Nuclear Energy (2021) "Advanced Small Modular Reactors (SMRs)". https://www.energy.gov/ne/advanced-small-modular-reactors-smrs

[214] A conceptual design for a SMR ship was made by Hirdaris et al. and due to the size and weight of the SMR, the overall ship length would increase by over 25m along with the length between perpendiculars. Hirdaris, S. E., Y. F. Cheng, P. Shallcross, J. Bonafoux, D. Carlson, and G. Sarris. 2014, "Concept design for a Suezmax tanker powered by a 70 MW small modular reactor." Trans RINA 156: A1.

[215] GenIV International Forum. 2007. "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems@. https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf

[216] Mignacca, B., and Locatelli, G. (2020) "Economics and finance of Small Modular Reactors: A systematic review and research agenda." *Renewable and Sustainable Energy Reviews* 118: 109519.

[217] Locatelli, G, and Mancini, M. (2010) "Small–medium sized nuclear coal and gas power plant: A probabilistic analysis of their financial performances and influence of CO2 cost." *Energy Policy* 38(10): 6360-6374.

years is unlikely in a shipping environment due to salination in operation. Therefore, a more realistic cost estimate is likely closer to the ~$60 USD/MWh.

A 2016 report by commissioned by the UK Department of Energy and Climate Change (DECC) determined that price parity of SMRs with large nuclear reactors could be achieved by manufacturing 10 units/year at 5 gigawatts electrical (GWe) of total deployment.[218] The key to achieving the decrease in LCOE is through higher learning rates. As shown in Figure 15, cost parity could be achieved at 2 GWe if a strong learning rate of 10% is assumed. Without a strong learning rate, the LCOE for the SMR technology could remain above $100/MWh.

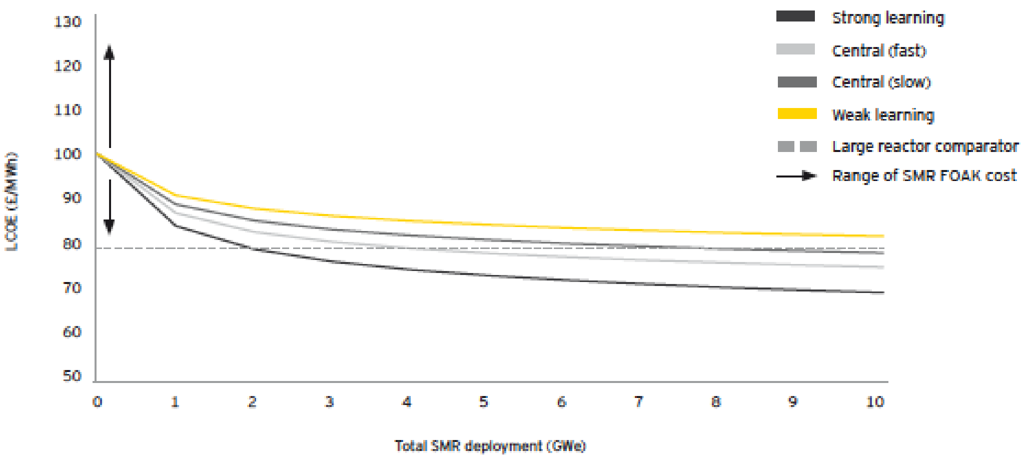

Figure 15: Learning rates expected for SMR technology as a function of reactor deployment. Source: Lewis et al. 2016[219]

Previous estimates of SMR costs (i.e., ~$50/MWh predicted in 2010[220]), do not appear to reflect the actual deployment rates today or the expected future schedule of deployments. If we assume ships containing SMRs could be commissioned in the next few years (only one SMR technology could get close to meeting this target[221]), and given an 8% learning rate, the goal of cost parity rate (i.e., 10 units/ year) is not likely to be achieved until between 2030 and 2040.

Critical to achieving these costs by 2030 is achieving the 8% learning rates. The industry rate prior to the DECC 2016 report was 3% but DECC assumed a rate of 8% following recent successes in Japan and South Korea. It is not unreasonable to assume that with standardization of design and factory modularization such rates could be achieved.

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[218] Lewis, C., R. MacSweeney, M. Kirschel, W. Josten, T. Roulstone, and G. Locatelli. (2016) "Small Modular Reactors: Can Building Nuclear Power Become More Cost-Effective." National Nuclear Laboratory: Cumbria, UK.

[219] Lewis, C., R. MacSweeney, M. Kirschel, W. Josten, T. Roulstone, and G. Locatelli. "Small Modular Reactors: Can Building Nuclear Power Become More Cost-Effective." National Nuclear Laboratory: Cumbria, UK (2016).

[220] Ma, C. Von Hippel, F. (2001). "Ending the production of highly enriched uranium for naval reactors." The Nonproliferation Review 8(1): 86-101.

[221] Subki, Hadid. "Advances in small modular reactor technology developments." (2020).

Nuclear Energy for Zero-emissions shipping fuels

Nuclear energy can also be used to produce clean fuels such as hydrogen, ammonia or synfuels. This could be through existing ports which could provide fuelling stations, or, through the development and deployment of nuclear barges that could provide a stop along shipping routes for refuelling of hydrogen or ammonia fuel.[222] For simplicity, the below analysis refers to land-based nuclear energy to produce hydrogen which is an output of several potential nuclear cycles and can be synthesized to produce synfuels or ammonia using air capture and the Haber Bosch process (Figure 16).

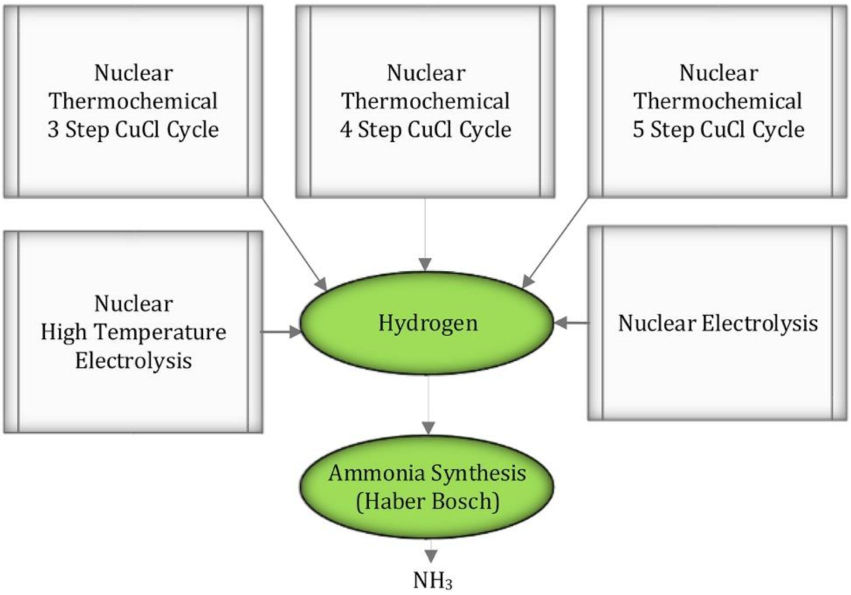

Figure 16: Nuclear to Hydrogen and Ammonia synthesis[223]

The cycles shown in Figure 16 which utilize the Copper Chlorine cycle, require use of Generation IV nuclear plants as the Cu-Cl cycle with is fed with heat and electricity, both of which are produced by a gas-cooled fast nuclear reactor (a Generation IV reactor).[224] The other two options for producing hydrogen outlined by the Nuclear Industry Association include:

1. Cold-water electrolysis using existing operating reactors (i.e., nuclear electrolysis)
2. High temperature reactors (i.e., Advanced modular reactors operating between 600-900°C which could split water into hydrogen and oxygen without electricity) (i.e., nuclear high temperature electrolysis)[225]

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[222] Neimagazine (2021) “Akademik Lomonosov Begins Commercial Operation.” https://www.neimagazine.com/news/newsakademik-lomonosov-begins-commercial-operation-7938482/.

[223] Bicer, Y., and Dincer, I. (2017) "Life cycle assessment of nuclear-based hydrogen and ammonia production options: A comparative evaluation." *International Journal of Hydrogen Energy* 42(33): 21559-21570.

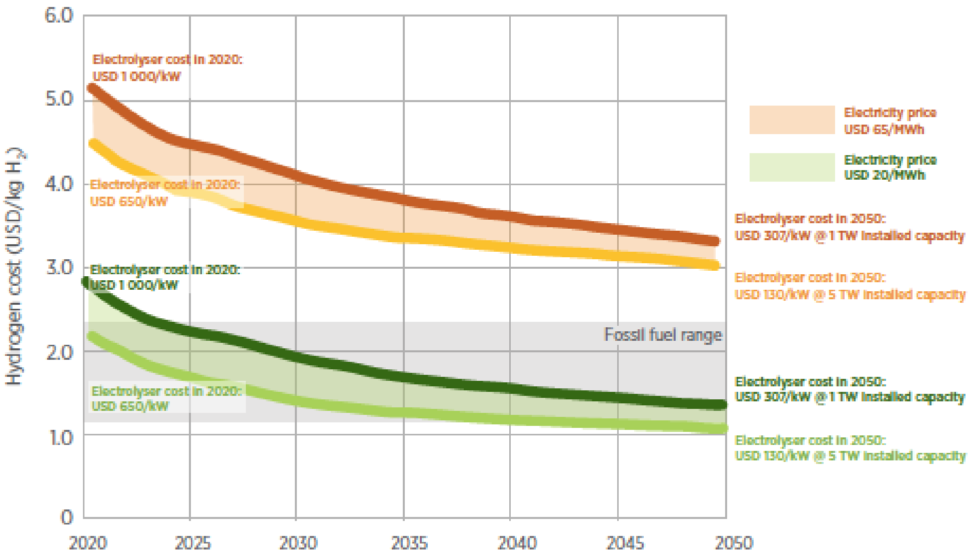
[224] Al-Zareer, M, Dincer, I. and Rosen, M.A. (2020) "Analysis and assessment of the integrated generation IV gas-cooled fast nuclear reactor and copper-chlorine cycle for hydrogen and electricity production." *Energy Conversion and Management* 205: 112387.

[225] NIA (2021) “Hydrogen Roadmap.” https://www.niauk.org/wp-content/uploads/2021/02/Nuclear-Sector-Hydrogen-Roadmap-February-2021.pdf

It is important to note that available hydrogen technologies that are coupled to nuclear power reactors greatly depend on the type of the nuclear power plant itself. Specifically, Option 1, which is conventional electrolysis, requires only electric power.

Option 2 relies upon higher temperature heat and a thermochemical cycle driven by process heat from the nuclear reaction occurring at elevated temperature values not currently available in existing nuclear technology (i.e., option 2 relies on Generation IV reactors, as shown above in Figure 5). Therefore, option 2 reactors are not further considered since nuclear technology development is the same as presented above for SMRs, which do not show cost parity (i.e., conservatively assumed at $70/MWh) until at least 2030. [226]

There are two main cost components that determine the price of hydrogen available: the price of electricity to drive the electrolysis and the electrolyser itself. **Error! Reference source not found.**, from IRENA, shows how the two determine costs projections out to 2050.



Note: Efficiency at nominal capacity is 65%, with a LHV of 51.2 kilowatt hour/kilogramme of hydrogen (kWh/kg H2) in 2020 and 76% (at an LHV of 43.8 kWh/kg H2) in 2050, a discount rate of 8% and a stack lifetime of 80 000 hours. The electrolyser investment cost for 2020 is USD 650-1000/kW. Electrolyser costs reach USD 130-307/kW as a result of 1-5 TW of capacity deployed by 2050.

Figure 16: Cost of Hydrogen as a function of electricity prices and electrolyser prices [227]

As shown in **Error! Reference source not found.**, utilizing nuclear energy to drive hydrogen electrolysis can be cost competitive with fossil fuel-based approaches (i.e., <$2/ kg

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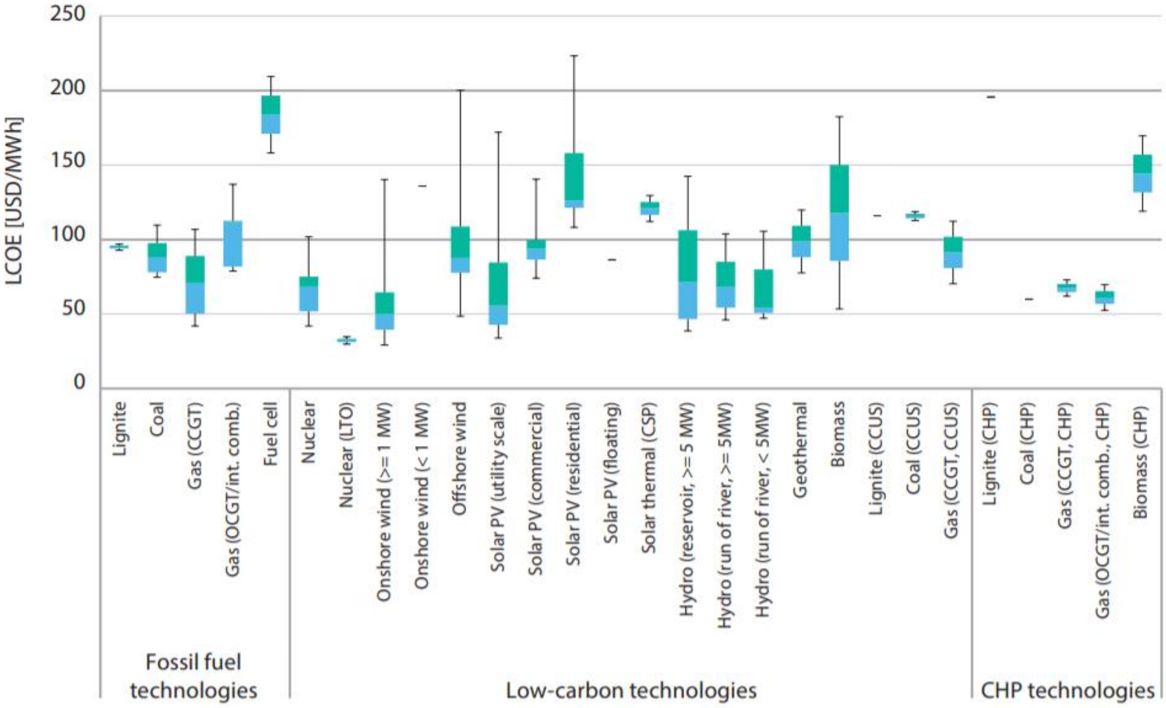
[226] IRENA (2020), Green Hydrogen Cost Reduction, Scaling Up Electrolysers to meet the 1.5°C Climate goals, Accessed June 21, 2021. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

[227] IRENA, 2020, Green Hydrogen Cost Reduction, Scaling Up Electrolysers to meet the 1.5°C Climate goals, Accessed June 21, 2021. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

hydrogen) if: 1) electrolyser costs decrease, as expected[228] and 2) the cost of the electricity is approximately $20/MWh.

The levelized cost of electricity (LCOE) of various technologies is shown in Figure 17. Existing nuclear in LTO (Long Term Operation) is shown to have a global average LCOE value at less than $50 USD/MWh with a 7% discount rate. The technology costs vary by region, with the cost of existing nuclear plant operation lowest in India.



Note: Values at 7% discount rate. Box plots indicate maximum. median and minimum values. The boxes indicate the central 50% of values, i.e. the second and the third quartile.

Figure 17: Current minimum, median and maximum LCOE values at a 7% discount rate. Source: IEA, NEA, 2020[229]

As noted by the IEA and NEA: “while requiring extensive refurbishments and replacement of some key components, *LTO long term operation constitutes currently the least cost option for low-carbon electricity generation* [emphasis added].”[230] While the normal lifetime of an operating plant is 30-years, long-term operation beyond 30 years results in the lowest cost of carbon-free electricity, as shown below with a range from a low of ~$26/MWh for an extended 20 years of operation (i.e., 50 years in total) with a capacity factor of 85% and a

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[228] Cesaro, Z., Ives, M., Nayak-Luke, R., Mason, M. & Bañares-Alcántara, R. (2021) “Ammonia to power: Forecasting the levelized cost of electricity from green ammonia in large-scale power plants.” Applied Energy 282, 116009. https://doi.org/10.1016/j.apenergy.2020.116009

[229] IEA, NEA, 2020 Projected Costs of Generating Electricity, https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf

[230] *Ibid*

discount rate of 3%, to a maximum of ~$48/MWh for 10 years of life extension (i.e., 40 years operation in total) using a discount rate of 10%.

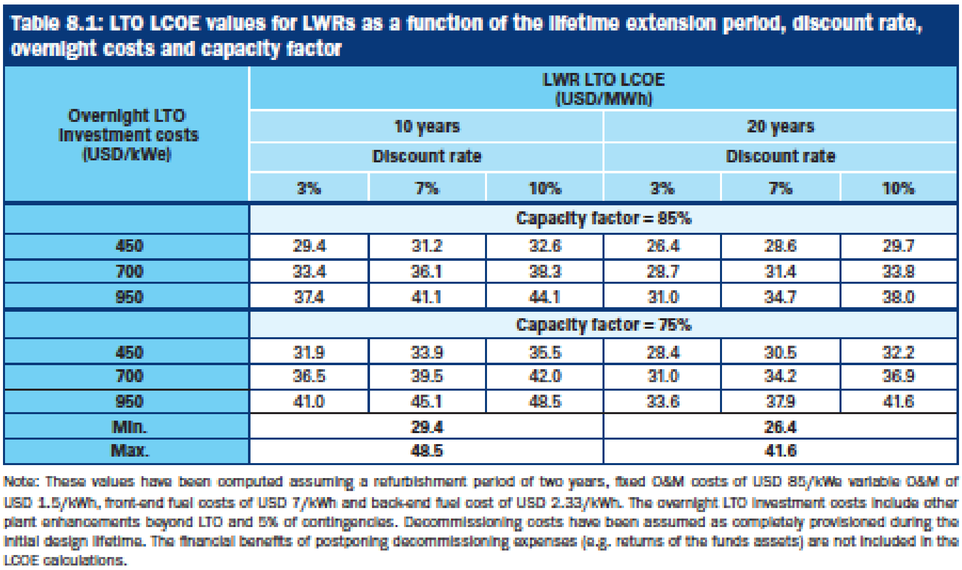

Table 8.1: LTO LCOE values for LWRs as a function of the lifetime extension period, discount rate, overnight costs and capacity factor

Overnight LTO investment costs (USD/kWe)	LWR LTO LCOE (USD/MWh)					
	10 years			20 years		
	Discount rate			Discount rate		
	3%	7%	10%	3%	7%	10%
	Capacity factor = 85%					
450	29.4	31.2	32.6	26.4	28.6	29.7
700	33.4	36.1	38.3	28.7	31.4	33.8
950	37.4	41.1	44.1	31.0	34.7	38.0
	Capacity factor = 75%					
450	31.9	33.9	35.5	28.4	30.5	32.2
700	36.5	39.5	42.0	31.0	34.2	36.9
950	41.0	45.1	48.5	33.6	37.9	41.6
Min.	29.4			26.4		
Max.	48.5			41.6		

Note: These values have been computed assuming a refurbishment period of two years, fixed O&M costs of USD 85/kWe variable O&M of USD 1.5/kWh, front-end fuel costs of USD 7/kWh and back-end fuel cost of USD 2.33/kWh. The overnight LTO investment costs include other plant enhancements beyond LTO and 5% of contingencies. Decommissioning costs have been assumed as completely provisioned during the initial design lifetime. The financial benefits of postponing decommissioning expenses (e.g. returns of the funds assets) are not included in the LCOE calculations.

Figure 18: LCOE for LTO nuclear reactors as a function of lifetime extension period (i.e., 10-20 years) and discount rate. Source: NEA 2020 [231]

The LCOE for LTO nuclear electricity are competitive with alternative clean technologies such as solar PV (i.e., $26/MW), however, it important to note that there are no current commercial projects that link electrolysers to long-term nuclear plants in operation. The US Department of Energy, the UK government and others have been studying this issue for some time and projects exist at the demonstration level. In these scenarios, the link to nuclear power is “indirect” as it is only through an agreement between the electrolyser owner and the nuclear generating company which provide the electricity needed to power the PEM or alkaline electrolyser.

As described by the OECD/NEA, “Hydrogen costs in these scenarios are largely a function of the electricity cost and although various modelling scenarios utilizing “off-peak” power to drive electrolyzers have been considered, no clear business case has emerged.” The study went on to state that “the use of existing nuclear technologies with conventional electrolysis will likely be economically viable only in selected niche markets or forecourt applications.”[232]

Table 5 shows the status of research and development into the use of electrolyser technology with existing, long-term operations nuclear plants. An existing electrolyser (PEM or alkaline) be coupled with an existing, long-term operating reactor in the right geographical location should be able to produce cost competitive hydrogen. However, since a demonstration has not yet been achieved at scale, it is likely that scaled operation is at least 5-10 years away. By 2030, the LCOE of solar power is estimated to be $19.10 suggesting

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[231] *Ibid.*

232 Keuter, Dan. (2010). "Nuclear H2 production–a utility perspective.", Fourth Information Exchange Meeting Oakbrook, Illinois, USA 14-16 April 2009. p289-298 https://read.oecd-ilibrary.org/nuclear-energy/nuclear-production-of-hydrogen_9789264087156-en

even LTO nuclear will have competition.[233] Furthermore, electrolysers coupled with solar energy are already under demonstration with plants expected in operation this year. [234]

Conclusions/Recommendations

The existing nuclear fleet is capable of supplying carbon free electricity. As the second largest source of carbon free energy, plants in operation today offer production cost benefits as compared to other sources of energy. As-is, nuclear plants in advanced economies currently have a reactor fleet that is on average, greater than 35 years old.[235] To work as a consistent source of clean shipping fuel generation the US DOE identified four key conditions:

1. "A consistent, reliable, and low-cost energy is available throughout the life of the project." Only large, long-term operation nuclear plants can produce hydrogen for less than $2/kg.
2. "The capital and operating costs of electrolysis stacks are reduced to around $100/kWe for high-temperature steam electrolysis solid-oxide stacks and less than $86/kWe for polymer-electrolyte membrane stacks."
3. The market for hydrogen in industrial centres is large and can be supplied from a central hydrogen-production plant to reduce application to niche uses and,
4. "Policy and regulatory conditions spur the transition from electricity production to nuclear electricity/hydrogen hybrid operations"[236]

In addition to nuclear as an energy source to produce clean fuels for shipping, newer SMR reactors hold potential as a source of clean ship propulsion that requires no refuelling. However, the technology is not yet commercially ready and not expected to achieve cost parity with large nuclear until at least 2030. In addition, the Maritime regulatory system would likely need to be adjusted to permit the operation and porting of nuclear ships. Improvements in international cooperation and deployment of SMRs could increase the learning rate and thus, reduce the time the technology would take to achieve cost parity. Increased modularization and greater proportion of factory build (i.e., 60%) could reduce the learning rate to 10%, which may slightly reduce the time to achieve cost competitiveness. Unfortunately, the learning rates of nuclear have historically been poor compared to renewables, despite recent improvements witnessed in Japan and South Korea. [237]

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[233] Cesaro, Z., Ives, M., Nayak-Luke, R., Mason, M. & Bañares-Alcántara, R. (2021) "Ammonia to power: Forecasting the levelized cost of electricity from green ammonia in large-scale power plants." Applied Energy 282, 116009. https://doi.org/10.1016/j.apenergy.2020.116009

[234] Largue, Pamela. (2021) "BayWa Advances SinneWetterstof Green Hydrogen Project." PowerEngineeringInt.com. June 14, 2021. https://www.powerengineeringint.com/hydrogen/baywa-advances-sinnewetterstof-green-hydrogen-project/.

[235] Sadamori, Keisuke. 2020. "Nuclear power in a clean energy system." Annales des mines - Responsabilité et environement N°97 (1): 122.

[236] OSTI (2019), "Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest, Light Water Reactor Sustainability Program". INL/EXT-19-55090, https://www.osti.gov/biblio/1559965-evaluation-non-electric-market-options-light-water-reactor-midwest

[237] Samadi, Sascha. "The experience curve theory and its application in the field of electricity generation technologies–A literature review." Renewable and Sustainable Energy Reviews 82 (2018): 2346-2364.

Table 5: Current status of R&D in nuclear-based hydrogen production around the world

Country	**Status**	**More details**	**Reference**
United States	Under development.	Projects in consortium with the DOE are being developed at four U.S. nuclear generators—Energy Harbor, Xcel Energy, Exelon, and Arizona Public Service (APS) to demonstrate hydrogen production at nuclear plant. The utilities will this year embark on a two-year pilot project to demonstrate hydrogen production using a 2-MWe low-temperature electrolysis (LTE) polymer electrolyte membrane (PEM) technology that will be integrated with Energy Harbor's 925-MWe (2,817 MWth) Davis-Besse Nuclear Power Station, a pressurized water reactor (PWR) in Ohio. Hydrogen usage will be for either on-site application or nearby industry uses.	https://www.powermag.com/hydrogen-may-be-a-lifeline-for-nuclear-but-it-wont-be-easy/
France	Under study	A published report says to meet the European objective of installing 6GW of electrolysis for the production of 1m tonnes of renewable hydrogen by 2024 and then 40GW for 10m tonnes by 2030 would represent 400 new nuclear reactors of 1GW each, "which is an unreal prospect, especially at a time when several countries including ours are reducing the share of nuclear power in their energy mix".	https://www.neimagazine.com/news/newsfrench-parliamentary-office-looks-at-hydrogen-8766389
Russia	Under Study	In October 2020, the Government approved an action plan (Roadmap) for hydrogen development until 2024, including hydrogen from nuclear power plants	https://www.bakermckenzie.com/en/insight/publications/2021/02/Russia-taking-a-stand-in-global-hydrogen-race
UK	Under study	EDF-led Hydrogen to Heysham (H2H) consortium completed a feasibility study in 2020 to install an initial 2MW system, comprising a 1MW alkaline and 1MW proton exchange membrane (PEM) electrolyser, capable of producing up to 800kg of hydrogen per day and testing the performance of the two main electrolyser technologies at the Heysham nuclear power plant. In November 2020, Sizewell C issued an Expression of Interest (EoI) seeking partners to develop its hydrogen demonstrator project, which may be powered by Sizewell B. Current steps also include an Innovate UK funded study on transitioning from a diesel to a hydrogen fleet of vehicles at Sizewell.	https://www.rechargenews.com/transition/edf-plans-vast-hydrogen-production-at-uk-nuclear-plants/2-1-763048 and https://www.niauk.org/wp-content/uploads/2021/02/Nuclear-Sector-Hydrogen-Roadmap-February-2021.pdf

A.3 Detailed safety considerations for chemical zero-emissions fuels

Understanding and anticipating the current and future international regulations and associated costs for safety of fuels is important when considering which fuels are viable clean energy alternatives. Each proposed alternative fuel has potential hazards beyond those associated with conventional fuels. *(See 'Hazard Statements' below).* Minimising environmental damage must address emissions (including CO, SOx, NOx, particulate matter, black carbon) but also the possibility of major accidents, spills and leakages of oil and hazardous noxious substance (HNS); while minimising human damage includes mitigating the risk of explosion, fire and health hazards encountered by people handling the fuel. Important for bunker operations and bargemen, including workplace safety and national health and safety regulations. There are potential risks at every stage in the life-cycle of a fuel: production, storage, distribution (by ship, by truck or by pipeline), bunkering and usage, and the most shipped chemicals are the ones most likely to be involved in an incident [238]. Exposure is a common hazard in the industry as many employees work in confined spaces, including bunker barges.

As above, it is useful to compare the alternatives with a conventional fuel that is currently in use. All conventional fuels produce carbon emissions and non-carbon emissions, although MGO is a low-sulphur fuel, which complies with the 0.1% limits permitted within the Sulphur Emissions Control Areas (SECAs). Conventional oil spills threaten seabirds and marine mammals and are toxic to other marine organisms. Mitigating this risk, such as the double hulling of ships (which has been the single biggest cause of reductions of spills) is well established in the breadth of regulatory, technological and procedural mechanisms. By contrast, there is a relative underdevelopment of safety standards for other Hazardous and Noxious Substances (HNS), and even though oil and oil products are transported in larger amounts, transportation of chemicals causes similar numbers of accidents[239].

Hydrogen is a highly flammable gas at atmospheric conditions, that needs cryogenic storage for shipping.

Hydrogen has wide flammability bandwidth of 4% to 74% and must be stored under pressure of ~800 bar or at a very low temperature of -253 degrees in cryogenic tanks. Both require considerable energy, and both carry dangers: gas under pressure can explode when heated, and cryogenic storage may cause cryogenic burns or injuries. Liquefication/cooling has the highest energy requirements and would consume 25-45% of the energy content of H2. Hydrogen can be stored long term in geological salt caverns, of which there are three in the UK[240]. However, hydrogen is non-toxic, and a spill of large liquified or compressed hydrogen is not thought to have serious environmental consequences, other than in circumstances of

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[238] Purnell, K. (2009). "Are HNS Spills More Dangerous Than Oil Spills?" In: Interspill Conference & the 4th IMO R&D Forum. https://www.hnsconvention.org/wp-content/uploads/2018/08/whitepaper.pdf

[239] Häkkinen, J., & Posti, A. (2015). "Port accidents involving hazardous substances based on FACTS database analysis."

[240] IEA (2019). *The Future of Hydrogen: Seizing today's opportunities*. International Energy Agency, Paris. https://www.env.go.jp/earth/g20karuizawa/assets/pdf/The%20future%20of%20Hydrogen.pdf

fire or explosion.[241] Today, compressed gas trailer trucks are most common for hydrogen distribution under 300km[242]. The distance of established hydrogen pipelines globally is quite small at just over 5,000 km including 2,600 km in the US, 1,500 km in the EU and 300-400 km in China. In the UK, the H21 Leeds City Gate project aims to demonstrate the feasibility of delivering blended hydrogen through the gas distribution network. Pipelines carrying pure hydrogen are technically feasible and have operated in the US, Germany, the Netherlands, France, and Belgium for decades[243] (although without a basis for rapid upscaling). The extent to which pipeline systems would need to be adjusted is unclear, but today standards limit the amount of hydrogen that can be deployed in natural gas pipeline systems. Although not currently heavily transported by sea, it is anticipated that initial restrictions regarding storage quantities and locations will be put in place[244]. Hydrogen is non-polluting and produces only water if used in fuel cells, however the life cycle performance depends on production, distribution, and storage, which as discussed have high energy demands.

Hazard Mitigation and Regulation: Additional safety to reduce severity and likelihood of fires and explosions will be needed; including for bunkering and distribution. This would include adequate ventilation, explosion venting and suppression, isolation, containment, blast walls and sensing,[245] and means to relieve pressure in closed systems will need to be installed.

There remain limitations for hydrogen distribution on land (for example, the ADR tank transport is forbidden in certain tunnels.) There are published guidelines from the EIGA, the ISO, the IMO and CEN on the use of cryogenic tanks (because cryogenic storage is used for LNG), but there remain knowledge and legal gaps in the hydrogen safety code: for example, there is uncertainty regarding whether hydrogen in double piping should be recommended, or whether double piping might actually add dangers of captured gas.[246]

Ammonia is a highly toxic, corrosive, colourless gas under atmospheric conditions.

Ammonia is less flammable than conventional oils and can be easily stored at -33.4 degrees and 1 bar, meaning the risk of explosion is low. Although its lower flammability requires a co-firing fuel for ignition in ICEs, only small amounts of the co-firing fuel are required. (In a zero-carbon ship, this could by hydrogen derived from the ammonia or a biofuel - the cracking step is still a challenge and currently under development.)[247] Despite its lower flammability ammonia is classified as acutely toxic and corrosive, which makes it one of the most highest-risk chemicals transported: ammonia ranks 7th in the IMO list of top 20 chemicals likely to

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[241] Liquid organic hydrogen carriers (LOHCs), such as MCH and ammonia, that are reversibly hydrogenated and dehydrogenated can be used to store and transport hydrogen. The IEA recommends that for distances above 150km, shipping hydrogen as ammonia or an LOHC is likely to be more cost effective. However, conversion and reconversion into LOHCs or Ammonia requires 15-40% of energy content. Using ammonia directly as a fuel would avoid this inefficiency.

[242] IEA (2019). The Future of Hydrogen: Seizing today's opportunities.

[243] IRENA (2019) *Hydrogen: A Renewable Energy Perspective.* International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf

[244] NCE Maritime Cleantech. (2019). *Norwegian future value chains for liquid hydrogen*. Norwegian Centres of Expertise. p.84. https://maritimecleantech.no/wp-content/uploads/2016/11/Report-liquid-hydrogen.pdf?fbclid=IwAR3uqivsh0dF3_VBQd8UB_0cgVtnf3XIM1of2xG7Y2WAS07e3OHzoTT-_9Q

[245] Pritchard, D.K., Royle, M. and Willoughby, D. (2009) "Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version".

[246] NCE Maritime Cleantech. (2019). Norwegian future value chains for liquid hydrogen.

[247] IRENA (2019) Hydrogen: A Renewable Energy Perspective.

pose the highest risk of being involved in an HNS incident.[248] [249] (. This will be important in across the entire industry– ship docking companies, bunker corporations, and ports etc will want to ensure this is well handled before they will offer their services to a ship that transports a novel, dangerous product. It is corrosive to skin, eyes and lungs and exposure for 10 mins at 2,700 ppm can be lethal. A spill would have very severe environmental consequences: liquified ammonia would float on the water surface, rapidly dissolving into the water as ammonium hydroxide and at the same time releasing gaseous ammonia, which would kill most aquatic organisms in close proximity, with long lasting effects including a eutrophication process which would reduce availability of oxygen in the water[250] If combustion is not optimised, ammonia can be a source of NOx emissions. If uncombusted ammonia escapes into the atmosphere it can lead to the formation of atmospheric particulate matter and acidification.[251] [252]

Hazard Mitigation and Regulation: Since ammonia is so toxic, storage and handling must limit the likelihood and effect of exposure to humans and the environment. This demands a safe design of the tank to withstand collision (e.g., external frames, level indicators, gas alarms). Fuel lines will need to be routed sufficient distance and located in separate unmanned spaces. To mitigate leakages in an enclosed space, remote shut-off valves, detectors, and either a continuous ventilation system, water spray to dissolve ammonia or a flare to burn a large release would be needed.[253] Although ammonia is currently not permitted to be used as marine fuel by the IGC code, regulatory infrastructure for the safe transportation of ammonia is better developed than for hydrogen. Since ammonia already has industrial uses, safe handling and storage procedures have been developed for its production, storage, and distribution; including exposure limits and protective equipment requirements for those handling it. Selective catalytic reduction equipment will be needed to reduce potential NOx emissions, similarly to vessels complying with Tier III requirements of Emission Control Areas.[254]

Synfuels, such as methanol and methane, are mildly hazardous flammable gases at atmospheric conditions.

They have a similar flammability and associated fire regulations to conventional fuels[255]. Some synfuels, e.g., methanol, are also mildly corrosive. Methanol can be stored easily as it is a liquid at ambient conditions. It is less corrosive than ammonia and can be integrated easily into existing infrastructure. Methane is very similar to LNG (it is the largest component of LNG) and poses the same hazards when stored in cryogenic conditions.[256] Methanol is toxic at high concentrations and water soluble, and its use has been banned in several countries including the US. However, a methanol fuel spill would have lower environmental impact than ammonia because it does not persist in the environment as it biodegrades quickly. Methanol is not classified as a marine pollutant by the IMO, so it can be carried in tanks next to the hull (by comparison, conventional oil fuels must be stored in double bottom

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[248] ITOPF (2012). TIP 17: Response To Marine Chemical Incidents.

[249] Karakavuz, A., Tokgoz, B.E., Zaloom, V., Marquez, A., 2020. "Risk assessment of commonly transported chemicals in the Port of Houston," International Journal of Critical Infrastructures, Inderscience Enterprises Ltd, vol. 16(1), pages 38-52.

[250] Ash and Scarborough (2019) “Sailing on Solar”.

[251] Brynolf (2014). Environmental Assessment of Present and Future Marine Fuels.

[252] IRENA (2019) Hydrogen: A Renewable Energy Perspective.

[253] De Vries (2019) "Safe and effective applications of ammonia as a marine fuel"

[254] Ash and Scarborough (2019) “Sailing on Solar”.

[255] Svanberg et al (2018) “Renewable methanol as a fuel for the shipping industry”.

[256] DNV.GL. (2018) “Assessment of selected alternative fuels and technologies”.

tanks). Nevertheless, it ranks 12th in the IMO's top chemicals likely to pose the highest risk in HNS incidents[257,258,259,260]. Emissions remain a concern: all carbon-based synfuels produce CO2 emissions. Pure synfuels such as methanol contain no sulphur will not produce carbon-based soot and produce NOx emissions 30% lower than diesel oil.[261] Methane poses the additional risk that leakages (fugitive emissions/ 'methane slip') into the atmosphere (including from upstream processes) can substantially reduce or even outweigh its climate benefits given that methane has a global warming potential 28-36 times higher than CO2[262,263].

Hazard Mitigation and Regulation: Some synfuels, including methanol, have a flashpoint below the minimum for marine fuels specified in the IMO safety of Life at Sea Convention SOLAS, meaning risk assessment or evaluation must be carried out for each case demonstrating fire safety equivalent to conventional fuels for marine use. As with ammonia, selective catalytic reduction equipment will be needed to reduce potential NOx emissions, similarly to vessels complying with Tier III requirements of Emission Control Areas.

International Regulation

Regulation relating to the prevention of major incidents involving dangerous substances, health and safety, industrial emissions, environmental impact assessment and pressurised equipment remains a barrier to rapid development, and there is safety regulation which applies for each level of the value chain.[264] However, for each of the fuels discussed, there are gaps in knowledge and/or legal guidelines regarding safe handling of fuel.

For example, relevant regulation includes the IMO's IGF[265] and IGC Codes[266] which together apply to all gaseous and other low flashpoint. The IGF currently has detail provisions for natural gas in liquid or compressed form (LNG, CNG), with regulations for methanol and low-flashpoint diesel fuel under development. Ships installing other low-flashpoint fuel systems need to individually demonstrate that the design is compliant with the IGF Code. Neither hydrogen nor ammonia use and storage are covered by the IGF, although the rules for their use are under development and expected to be included in the next amendment [267,268].

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[257] IRENA (2019) Hydrogen: A Renewable Energy Perspective

[258] Brynolf (2014). Environmental Assessment of Present and Future Marine Fuels.

[259] ITOPF (2012). TIP 17: Response To Marine Chemical Incidents.

[260] Svanberg et al (2018) "Renewable methanol as a fuel for the shipping industry".

[261] Ibid.

[262] DNV.GL. (2018) "Assessment of selected alternative fuels and technologies". pp.1–12.

[263] EASAC (2019). *Decarbonisation of transport: options and challenges*. European Academies' Science Advisory Council. EASAC Policy Report 37. https://easac.eu/fileadmin/PDF_s/reports_statements/Decarbonisation_of_Tansport/EASAC_Decarbonisation_of_Transport_FINAL_March_2019.pdf

[264] For example, Pressure Equipment Directive (PED) and ATEX apply at every level of the Hydrogen value chain. Relevant international regulatory bodies and standards include the EIGA, IMO, CEN/TC, IGC, IMDG, ECE, UNECE ADR, SAE, ISO, SECA and UNCLOS. See NCE Maritime Cleantech. (2019). *Norwegian future value chains for liquid hydrogen.*

[265] IMO IGF Code: The International Code for the Construction and Equipment of Ships Carrying Liquified Gases in Bulk. See http://www.imo.org/en/OurWork/Safety/Cargoes/CargoesInBulk/Pages/IGC-Code.aspx

[266] Ibid.

[267] ETH Zürich and Ampliifer (2019). "Towards net-zero: Funding support and regulatory incentives." https://fe8dce75-4c2a-415b-bfe4-e52bf945c03f.filesusr.com/ugd/0a94a7_2e539772009b429e9c62125c5093f43c.pdf

[268] DNV-GL. (2019). *Comparison of Alternative Marine Fuels*. Report No. 2019-0567.

GHS Hazard Statements

Under the UN Globally Harmonized System of Classification and Labelling of Chemicals (GHS), comprehensive information such as the chemical and proper shipping name, hazard identification, physical and chemical properties, emergency response information, and toxicological and ecological information must be provided[269].

Hazard Statements, part of the Globally Harmonised System of Classification and Labelling of Chemicals, GHS.

									Synfuels			
	Hazard Statement		NH3	LNG	MGO	Diesel	H2 (liquid)	H2 (comp)	Methanol	Methane	HVO	Ethanol
H220	Extremely flammable gas	Flammable		x			x	x		x		
H221	Flammable gas		x						x			
H225	Highly flammable liquid and vapour											x
H226	Flammable liquid and vapour				x	x						
H227	Combustible liquid										x	
H280	Contains gas under pressure - may explode if heated	Press/Temp	x					x				
H281	Contains refrigerated gas may cause cryogenic burn or injury			x			x					
H301	Toxic if swallowed	Health							x			
H304	May be fatal if swallowed and enters airways				x	x					x	
H311	Toxic in contact with skin								x			
H313	May be harmful in contact with skin					x						
H314	Causes severe skin burns and eye damage		x									
H315	Causes skin irritation				x	x						x

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[269] Purnell, K. (2009). "Are HNS Spills More Dangerous Than Oil Spills?"

H319	May cause eye damage/irritation					x						
H320	Causes eye Irritation											x
H331	Toxic if inhaled		x						x			
H332	Harmful if inhaled				x	x						
H335	May cause respiratory inflammation											x
H336	May cause drowsiness or dizziness					x						
H350	May cause cancer					x						
H351	Suspected of causing cancer				x							
H360	May damage fertility or the unborn child											
H361	Suspected of damaging fertility or the unborn child											
H370	Causes damage to organs								x			
H373	may cause damage to organs through prolonged and repeated exposure				x	x						
H401	Toxic to aquatic life	Env										
H410	Very toxic to aquatic life with long lasting effects		x									
H411	Toxic to aquatic life with long lasting effects				x	x						

Quantifying the risks: Insurance and Liability

Insurance costs can be a useful proxy to help identify the implied risks of transporting goods. The OECD data on CIF-FOB (Cost, Insurance and Freight – Free on Board) ratios, an indirect measure of transportation costs that have been estimated by an economic gravity model[270]. In the past, there have been concerns about errors in the use of CIF-FOB for information about cross-commodity variation, but this has become more adapted to this purpose [271]. Figure 19 provides estimates of international transport and insurance costs expressed as a percentage of the merchandise trade flow, as an indication of the relative dangers.

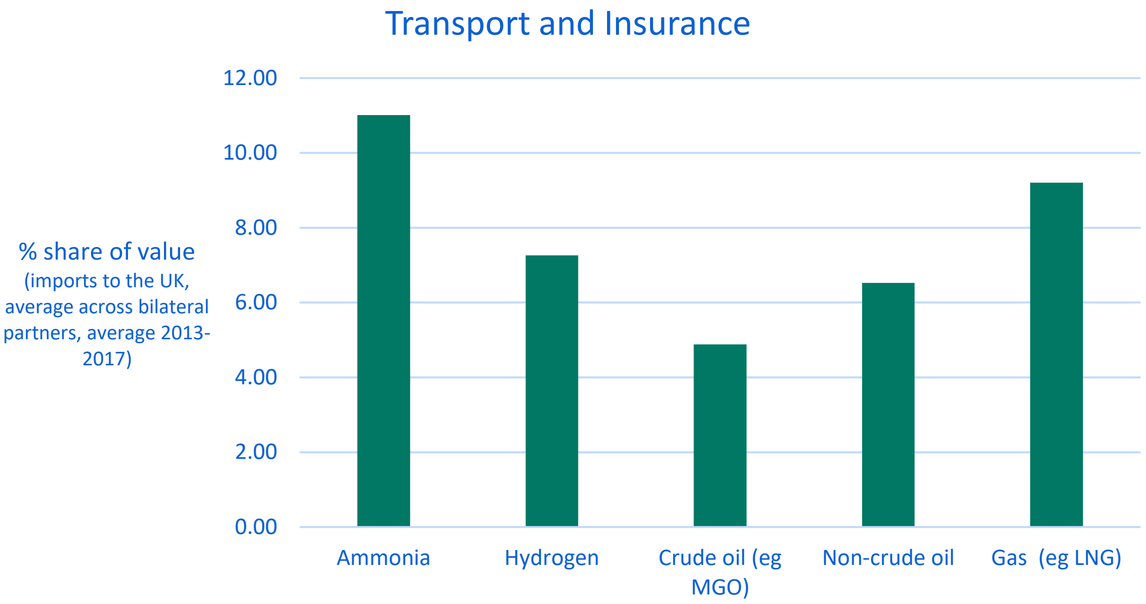

Figure 19: Transport and insurance costs for selected fuels as % of value. imports to the UK, average across bilateral trading partners, average 2013-17. Source: OECD Database. Measure: Cost, Insurance and Freight - Free on Board (CIF-FOB).

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[270] Miao and Fortanier (2017) “Estimating Transport and Insurance Costs of International Trade”.

[271] Hummels, D., and Lugovskyy, V. (2006). Are matched partner trade statistics a usable measure of transportation costs? Review of International Economics, 14(1):69–86. https://doi.org/10.1111/j.1467-9396.2006.00561.x

A.4 Fuel-only CfD counterparties

Restricting the CfD counterparty to net-zero-carbon fuel suppliers

If the CfD is designed such that only fuel suppliers may bid into the CfD, they would simply need to provide proof that qualifying net-zero-carbon fuel has been produced and further that a shipping company has agreed to purchase it through an offtake agreement. The potential advantages of this approach are as follows:

- It is **straightforward to administer**, since the CfD administrator need only deal with the fuel supplier, with the latter responsible for negotiating and securing offtake agreements with shipping companies.
- Fuel suppliers are better placed than shipping companies to estimate fuel production costs and manage associated construction and operation risks, particularly with a 10-15 year horizon. Auctions may therefore be more competitive and see more efficient price discovery.
- There are **clear incentives for suppliers to scale up the production of net-zero-carbon fuels** for other industrial applications. Fuel suppliers may be able to use the CfD funding to increase their production for non-shipping customers, lower financing costs, and realise returns to scale. If so, they have a more direct incentive to participate in the CfD than shipping companies because they can use the subsidy to accelerate their development.

A fuel supplier-focused CfD may be most appropriate for national or regional governments for whom large-scale production of net-zero-carbon fuels is a major component of industrial strategy. Subsidising fuel production can both support the shipping industry by reducing the cost of these fuels, while also investing in the development of immature domestic industries vital to decarbonisation in agriculture, heavy industry, and transport.

Allowing the CfD counterparty to be any entity able to meet qualifying criteria

The CfD could also be designed to allow any firm to participate, as long as they can prove that net-zero-carbon fuel has been used on a ship. This allows for a broader range of potential participants and does not predetermine the contractual arrangements required for the fuel to be supplied. Bidders may be shipping companies, financial institutions leasing ships, or (as in Option 1) fuel suppliers with offtake agreements in place. The potential advantages are as follows:

- This design **simpler to monitor and enforce.** The counterparty must meet only one requirement regardless of what type of institution they are, or how they obtain the fuel: to prove that net-zero-carbon fuel is being used on a ship.
- It favours whichever bidder is in **the best position to coordinate fuel supply chains** and has the capacity and experience necessary to set up contracts with fuel suppliers, offtakers or intermediaries. The CfD design does not determine in advance whether this would be a shipping company, bunkering fuel provider, fuel supplier or other intermediary. This has the additional benefit of broadening the suite of potential bidders and increasing the likelihood that the CfD will attract sufficient interest.
- It **can easily be adapted for international implementation via the IMO.** This may require the restriction of bidding to shipping companies that are IMO members (which

can make their own contractual arrangements via intermediaries as needed), to ensure that CfD funding is being directed to the shipping industry.

- **It is more technology neutral.** Bidders need not specialise in a specific fuel but bid for a mixture of fuels based on the needs of the company (if an individual shipper) or the market (if a fuel supplier or intermediary).

Conclusion

Allowing the counterparty to be any entity meeting the criteria is preferable for the following reasons:

- In the initial application of a shipping CfD, efficient price discovery is less important than ensuring there is sufficient interest from bidders. The risk of paying slightly more than necessary for fuel is outweighed by the risk of the CfD failing to attract qualifying bids and losing credibility as a mechanism. Option 2 allows for a much wider group of potential bidders.
- Option 2 is more technology neutral (allowing multiple fuels to be produced depending on requirements) and allows bidders flexibility in determining the contractual arrangements required to meet the CfD requirements.,
- Option 2 provides a blueprint for implementation at the IMO, which will ultimately be required for wholesale uptake by the shipping industry even if initial applications are restricted to specific national