Centre for Science and Policy

Policy Workshop

Maritime Decarbonisation

Summary report of the discussion held on 19 September 2023

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Table of Contents

Introduction

In September 2023, the Centre for Science and Policy (CSaP), University of Cambridge, organised a Policy Workshop in partnership with the Department for Transport (DfT). The workshop addressed the overarching theme of maritime decarbonisation.

Purpose of the Workshop

The DfT is continuing to develop an ambitious policy programme to accelerate maritime decarbonisation, and future fuels will be pivotal to this work. The purpose of the Policy Workshop is to help the DfT increase their evidence base by providing academic insights.

Desired outcomes include:

- To collect feedback and recommendations regarding the landscape of future fuels for the maritime sector.
- To identify potential next steps for the Department, such as policies or interventions to explore further.

Outline of the report

This report captures discussions from the Policy Workshop held on 19 September 2023. The report begins by outlining the context around maritime decarbonisation before moving on to some of the associated policy challenges. Following this, it discusses some alternative fuels that could support maritime decarbonisation, before outlining the discussion that resulted from modelling the impacts of some fuels.

Context

Domestic and International Frameworks for Decarbonisation

The DfT participants opened the Policy Workshop by providing a general summary on the state of the sector when it comes to decarbonisation and the UK Government's approach to this process. A key theme was the complexity that underpins the sector, something heightened by the heterogenous nature of the sector itself. The maritime sector encompasses a vast array of different types of vessels and a range of different operations. Concurrently, there is also a greater choice when it comes to technologies that could fuel decarbonisation.

Participants agreed that the sector as a whole recognised that steps need to be taken to achieve decarbonisation, but the challenge is *how*—what technologies should various sub-sectors prioritise? This concern is accentuated by the stakes. Many vessels have an extremely long asset-life and could be in service for decades: the vessels bought today could be in use by 2050. As such, key stakeholders are reluctant to transition for fear of stranded assets if port infrastructure does not support a particular fuel type are there is a strong desire to avoid added costs in the future (retrofits etc.). The challenge and complexity of maritime decarbonisation is further complicated by uncertainty on where to go next.

The release of the Clean Maritime Plan (2019) by the DfT set out a vision on how to decarbonise the sector. The plan reflects general agreement on a transition within the sector to net zero emissions. The subsequent Transport Decarbonisation Plan (2021) focused on decarbonisation across the whole transport system. This comprises some actions for maritime including:

- consulting on the steps to support the uptake of shore power (the provision of shoreside electric power to ships at berth) in the UK;
- plotting a course to net zero for the domestic maritime sector (with indicative targets from 2030);
- considering a programme of research and development.

In 2022, the Government launched UK SHORE, which provided £206m to accelerate research into the development of clean maritime technologies. Participants noted that the DfT had focused on ‘carrot’ initiatives (UK SHORE etc.), but it had not yet brandished the stick. Potential mechanisms could include a fuel standard in the UK. While this would provide a strong incentive to invest it will not necessarily drive investors towards one technology.

It was mentioned that the DfT hopes to produce a refresh of the Clean Maritime Plan as soon as possible, to outline the path to achieve net zero emissions by 2050. The DfT participants were interested in interim goals for the domestic sector that could be set along the way to 2050 and potential policy and/or regulatory interventions to support the sector on its journey. Given widespread uncertainty, the sector is looking to the Government to set guidance and to provide regulatory signals. However, it was noted that the Government is technology neutral, which creates another set of policy challenges.

The DfT are interested in creating greater certainty for investors while recognising that there will be choices to be made. To support this, participants from the DfT were particularly interested in information on barriers to net zero, particularly in relation to fuels and how to design a fuel standard to avoid uptake of transition fuels. Moreover, apart from technology readiness, questions around fuel supply looms large. While some operators may be able to produce fuel for their activities, not every provider or ship builder will be able to follow suit.

In July 2023, International Maritime Organization (IMO) adopted a revised Strategy on Reduction of Greenhouse Gas Emissions (GHG) from Ships for international shipping. 175-member states came to an agreement on a 2050 target with indicative transition points:

- Reduction of GHG emissions by 20% (from a 2008 baseline), striving for 30%, by 2030;
- Reduction of GHG emissions by 70%, striving for 80%, by 2040;
- Meet net-zero emissions targets “by or around” 2050.

IMO has developed the Carbon Intensity Indicator (CII), which will impact vessels above 5,000 gross tonnage and trading internationally. This means that domestic vessels which undertake voyages between UK ports will not be covered. It was explained that the IMO operates a data collection system where each vessel with an IMO number reports its annual fuel consumption and it was noted that GHG costs could be implemented on this basis. The forecast growth in global trade and the global shipping fleet means that reductions required of individual ships are much greater than the overall greenhouse gas emission targets. The UCL Energy Institute released a report on IMO's Greenhouse Gasses Strategy in September 2023 which estimates that cuts of 86–91% to GHG emissions will be required by 2040. This is within 16 years and participants noted that the clarity of these numbers is useful and helps frame the challenge.

The IMO and its member states will be bringing forward proposals on how to meet its targets to come to an agreement on a basket of measures that will support the transition to net zero for international shipping. These include the introduction of a fuel standard and wider questions around implementation (should this be a common standard for all ships or should some be able to exceed the standard and trade over compliance to other ships?). The IMO aims to have measures enforced later in the decade (around 2027). In the UK, there is a need for some primary legislation in certain cases with some initiatives expected to emerge in the early 2030s. From the UK perspective, it is important to align measures to IMO actions so that, for instance, international shippers that carry out activities in UK waters are not disproportionately impacted for their emissions.

Policy Challenges

Maritime decarbonisation carries a series of acute policy challenges. The preceding discussion has already highlighted the intersection of international and domestic frameworks and considerations for achieving net zero as well as the overall complexity of the sector.

Technology

As noted, the Government is technology neutral in terms of how net zero emissions are achieved. However, the DfT is trying to set up a workable framework that will facilitate this transition and this requires knowledge of the plethora of technology options that are on the table. Participants drew comparisons with aviation, which, like shipping, has a strong international element. It was noted that policy interventions have an important role in pushing industries over the hump to transition, however, in a sector like aviation, policy needed to be in a steady state because burning existing fuels (such as JetA) will always be cheaper and as such, policy needs to operate in the long-term. It was asked if shipping will be similar to aviation or whether it will be more similar to electric cars where costs come down after the period of transition? In other words, do policy interventions need to drive a steady state condition? One participant made a comparison between the move from wind to steam: this shift was driven by a commercial/operational need. In terms of the current transition, this is driven by a societal need, and, as such, without signals to change from the Government, many will continue with the status quo.

Participants clarified that it does not need to be a choice of one technology; it is widely accepted that there will be a matrix of different vessels and technologies and that different sub-sectors will have some choice as operations may be more applicable to more than one technology. As one participant put it, not every technology will be pertinent for every type of investment: the situation and the solutions will be very different for a workboat that is taking workers to an offshore wind farm than it will be for a container ship travelling from the UK to China and back. A DfT participant clarified that they are thinking at a high level about the entire suite of technologies and fuels (given their remit), but not every option will be under consideration by different operators. Indeed, participants discussed different motivations for change amongst actors. While there is widespread acknowledgement that a transition towards net zero emissions is necessary, not all vessels and operators will be motivated by the regulatory push from the likes of the IMO. One participant explained that with smaller operations that fall outside the IMO’s remit, such as the aforementioned workboat servicing the offshore windfarm, motivation for change was driven by clients who were concerned with their Scope One, Two and Three emissions. These kinds of crew transfer vessels are typically 24–26 meters and Service Operation Vessels (SOVs), which are larger 60–80-meter vessels, could also be classed within this. Some of these private sector companies have set targets for net zero by 2025 across their whole operation, ships included.

Ports

Another major problem arises around ports. As one participant pointed out, there is no standard definition for what constitutes a port. Much like the vessels themselves, the purpose and scale of operations at different ports varies. As it stands, ports bunker one type of fuel, but in the future some ports will have to make choices about bunkering various different options to supply a diversified fleet. Participants noted that as it stands, ports are not fuel suppliers, but this may need to change in the future. There are major infrastructure questions that relate to ports. For instance, developments in electric and hybrid shipping requires that ports are plugged into the electricity grid. One participant reported that the American Bureau of Shipping are considering a situation where different ports provide different supply lines for different types of fuel and it was noted that some UK ports have expressed an interest in becoming hubs for green hydrogen. The key policy challenge is how does this come together from an infrastructure supply-side in a way that enables ports to meet new demands and to help facilitate the greenhouse gas reductions that need to be achieved by the sector. The activity of ports goes beyond the facilitation of shipping and the port ecosystem encompasses a range of other companies and activities on land owned by the ports.

One participant stated that policies should be driven by coherent objectives. They asked whether the UK's ports wanted to be like Singapore, a harbour that is friendly for all ships, or to be more like China, which does everything (building, operations etc.). The DfT participants clarified that ports are primarily private sector and the Government does not want to be overtly interventionist. Ports were a recurrent theme of the discussion, and in response to the multitude of challenges faced by ports, it was noted that UK ports will have very different models for their futures.

Economic Growth

While the primary aim is decarbonising the sector, it was noted that a close second was regional and national economic growth. There was broad agreement that there is both appetite and opportunity for the UK to seize the upsides of decarbonisation. Participants pointed out that the UK is well placed to capitalise on some aspects of the transition — such as areas related to Intellectual Property — but it may be less well placed on the construction side. Participants noted that it was important to understand more broadly where the UK is best placed to take economic advantage of the transition and how to incentivise development in these areas while accepting that the UK cannot do everything.

Alternative Fuels for Maritime Decarbonisation

While maritime decarbonisation is often framed as a policy challenge, another participant emphasised that it was in fact an engine challenge, noting that engines are often not as equipped as is taken for granted. The range of 'alternative' fuels, technologies, and practices include: Carbon Capture and Storage (CCS); biodiesel; hydrogen; ammonia; methanol; electricity; travelling less frequently; fuel economy measures (slow steaming; air reduction bubbles etc.).

Trade-Offs

A participant presented research that considers conventional ways of producing various fuels and identifying how much energy is required for their production. Figure 1 below presents a visual comparison of alternative fuels for shipping.[1]

Heavy Fuel Oil (HFO) provides a base reference case to compare with 'blue' alternative fuels (that is fuels produced from natural gas) and 'green' fuels (produced from solar energy and biomass). Figure 1 also includes results where Carbon Capture and Storage (CCS) technology is utilised for HFO, Liquefied Natural Gas (LNG), and Blue Methanol (BLUE MEOH). Figure 1 illustrates that alternatives to HFO have major trade-offs in terms of the stated performance criteria. For instance, leaving aside the electric ship which has higher efficiencies in the technology, all other options require a greater level of Relative WTW (Well-to-Wake) Energy than HFO. However, the efficacy of the electric ship for shipping is limited by the energy density of the battery (as indicated by the high Relative Volume). The size of batteries

[1] L. Li Chin, B. Featrice Foscoli, E. Mastorakos, and S. Evans, 'A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost', *Energies* 14 (2021) [https://doi.org/10.3390/en14248502].

(Relative Volume) has a knock-on effect on the amount of cargo a ship can hold. Moreover, a bigger problem that presents itself is the supply of electricity: this requires considerable amounts of electricity available at every port and it takes time to charge.

Participants highlighted the difficulties that these trade-offs present for different stakeholders and noted that some could by priced out of the discussion. One participant, reflecting on discussions with stakeholders, explained that when it became clear that the baseline performance (represented by HFO), will not hold, it will prompt a greater shift in thinking that will inform the kinds of trade-offs the sector is willing to make.

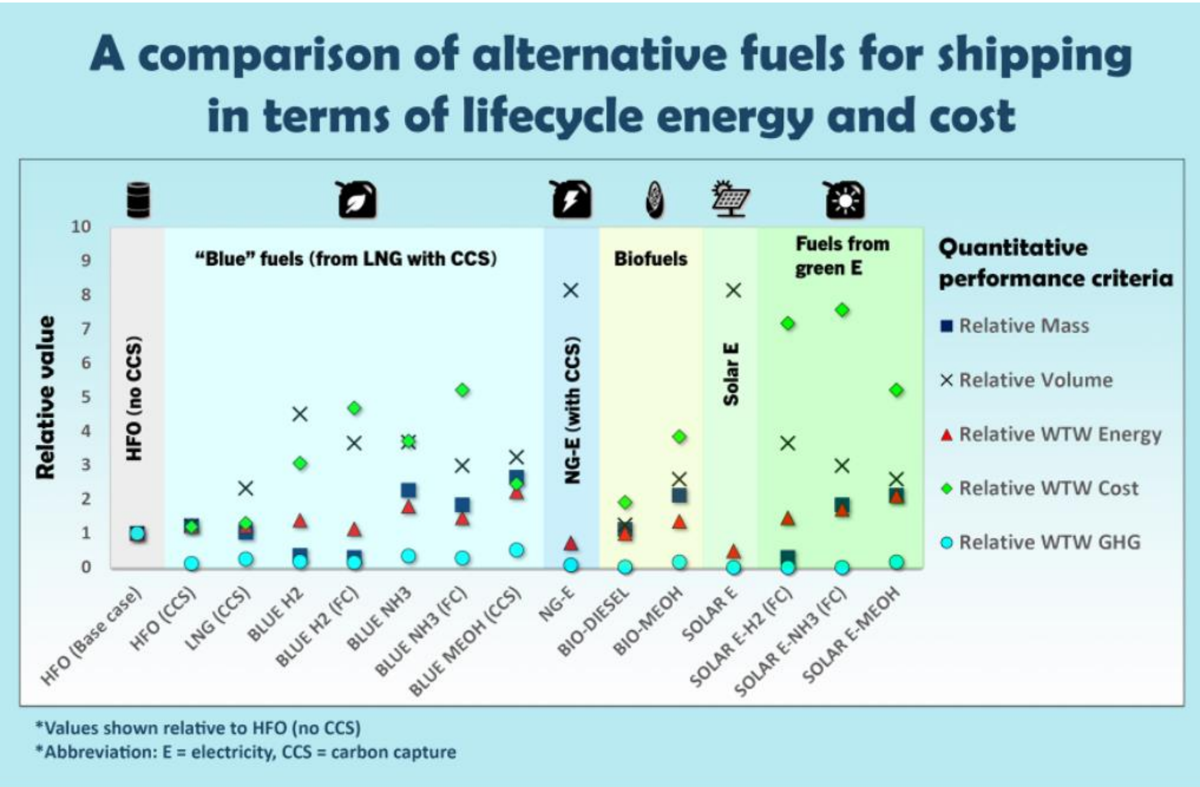

Figure 1: A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost: L. Li Chin, B. Featrice Foscoli, E. Mastorakos, and S. Evans, 'A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost', *Energies* 14 (2021) [https://doi.org/10.3390/en14248502]. See Table of Abbreviations below (p. 22).

Participants also pointed to other variables, such as the speed of the ship. 'Slow steaming' (the deliberate reduction of the speed of cargo ships to cut down fuel consumption and carbon emissions) could facilitate maintenance of cargo levels if ships go slower. However, it was acknowledged that this does not mitigate the economic impact and could require a larger fleet to maintain capacity.

Costs Associated with Maritime Decarbonisation

In most cases, alternative fuels require greater Relative WTW Energy and/or Relative Volume. It is also the case that they incur greater costs. Figure 2 highlights the relative CapEx (Capital Expenditure) and OpEx (Operational Expenditure) costs associated with alternative fuels. While it may be expected that some costs will decrease as technology develops, Figure 2 represents the relative Well-to-Wake costs costs in 2020 with HFO (Base Case) as 1 unit.

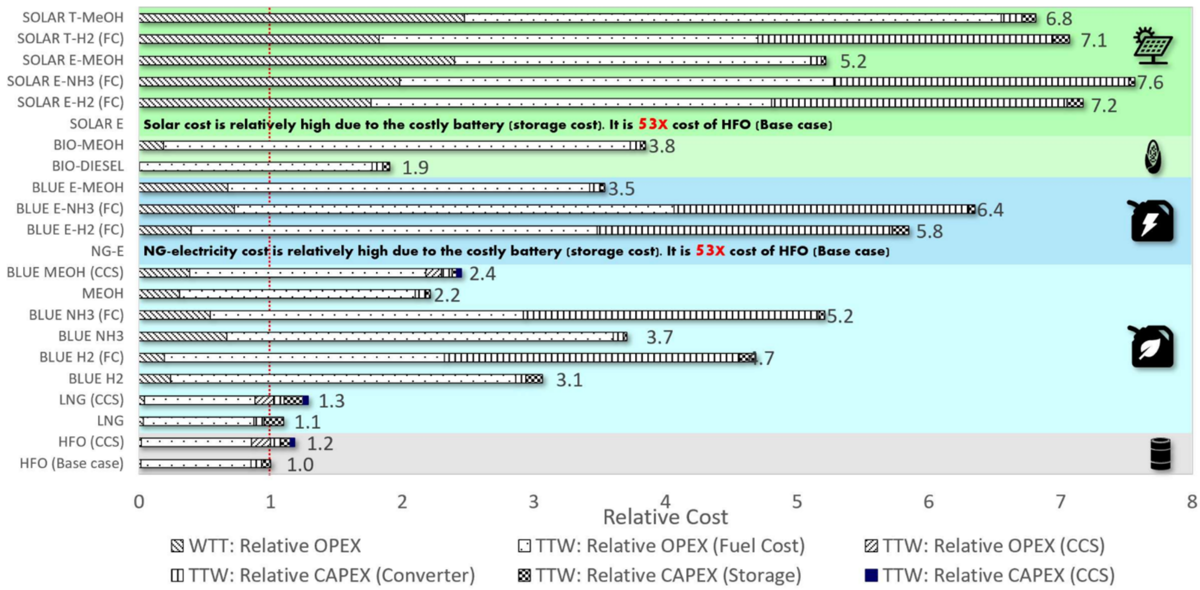

Figure 2: Relative Well-to-Wake Costs of Different Fuels: L. Li Chin, B. Featrice Foscoli, E. Mastorakos, and S. Evans, 'A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost', *Energies* 14 (2021) [https://doi.org/10.3390/en14248502]. See Table of Abbreviations below (p. 22).

Technology Readiness Levels (TRL) for Different Fuels and Demand

Participants emphasised that it is also important to understand the Technology Readiness Levels (TRL) for the various technologies. This is not always clear, and the industry is often in disagreement about the readiness levels. It was noted that the definition of TRL should include health and safety (especially for technologies like ammonia), knowledge base of personnel, and the (re)training infrastructure.

It is also important to think about non-CO_2 emissions. For instance, ammonia emits N_20 which has a much greater greenhouse gas potential than CO_2 meaning that small emissions can make a big impact. Ammonia slip is highly toxic and arguments around the comparative toxicity of biodiesel soot to fossil fuel soot must also be taken into account.

As noted above, in relation to ports, supply lines are also a key factor. Participants sketched out a scenario where different ports could act as supply points for different fuels and where fuel choices are conditioned by individual journey types (i.e. short, medium, and long journeys) or by regional contexts. Further, to inform choices about technology uptake and development, it is important to model how much shipping is to be envisaged in 2050. While a decline in trade of commodities like oil and coal may be expected, there will be increased transport of renewable energy from one location to another. This increased trade in renewable energy brings up further questions about the vectors for transmitting these fuels.

Bringing these concerns together provided an outline of the main advantages, disadvantages, and TRL of different fuel types, as outlined below in Table 1.

Table 1: Prepared by Professor Epaminondas Mastorakos, Hopkinson and Imperial Chemical Industries, Professor of Applied Thermodynamics Department of Engineering, University of Cambridge.[2]

"FUEL"	Comments	Main pros	Main cons	Readiness for widespread use
Reduce fuel consumption	Wind-assist (Floettner, sails); reduce drag (shape, air bubbles); reduce speed	Reasonable cost; retrofit possible	Not all feasible in all routes	Medium/High
Electricity	Battery & electric motor	As green as the electricity	Loss of cargo; long charging times (business model); ports	Low for large ships. Medium/High for harbour craft & short-

[2] Abbreviations: CCS (carbon capture and storage); GT (HFO (heavy fuel oil); ICE (internal combustion engine); GT (gas turbine); PM (particulate matter).

			have to be re-gridded	distance ferries
LNG/HFO + CCS	Pre- or post-combustion CCS; can use ICE or GTs & hybrid architectures	No new infrastructure for fuel; retrofit possible	New CO_2 delivery infrastructure needed	Medium/High
Hydrogen-based synthetic fuels (H_2, NH_3, methanol)	Electricity➔H_2➔NH_3, CH_2OH (plus C from somewhere)	No PM emissions; can be used in ICE	Cost (money, energy); New infrastructure needed; non-CO_2 emissions (H_2 leak, N_2O, formaldehyde)	H_2/NH_3: Low Methanol: Medium/High
Biodiesel	Very similar fuel to HFO	Drop-in, reduced PM.	Fuel degradation; availability	High
Less maritime transport	Less need for fossil fuel trade; more need for renewable energy trade	Direct energy reduction	Unknown effects on overall economy	Low

Participants responded by noting that while the global transport and energy system that currently operates has been optimised over decades around a single fuel, the conditions are in place for a much quicker optimisation process for new fuels. One participant queried if there was a general trajectory for how rapidly stakeholders can expect these fuel sources to be made more efficient. There was general agreement across academic and policy participants that this process will occur more quickly than in the past and that there is a willingness to invest resources. However, there is a strong need for Research and Development. An example of the pace of TRL is developments related to the boil-off of liquid hydrogen (-253°C). Liquid hydrogen has traditionally boiled off at a much quicker rate that it can burn, however, Shell has announced a new thermos type of tank that solves this boil-off problem.

One participant commented on a tension that underlies discussions on new technologies. When researchers and policymakers know the solution and are working on incrementally improving/implementing technology, then the rate at which technology improvement takes place can be identified. However, when, as in the maritime sector, the whole system is being disrupted and the technology being developed changes the solution entirely, then the Government needs to pursue an investment programme that is relatively high risk: this is the space in which new industries are created.

A participant from the DfT noted that the UK SHORE initiative covers all TRL levels. For instance, the Clean Maritime Demonstration Competition supports projects that are mid-tier TRL. They also pointed to funding at the lower end of TRL, noting the establishment, with the Engineering and Physical Sciences Research Council, of the Clean Maritime Research Hub as well as the Transport Research and Innovation Grants (TRIG), designed to help bridge the early stage funding gap in transport innovation. On the high TRL, the DfT offered the Zero Emission Vessels and Infrastructure (ZEVI) competition, which will fund 10 projects until March 2025 that are at, or close to, commercialisation to get them over the valley of death from research to commercialisation.

The focus of the Policy Workshop has been on international and cargo shipping. Participants queried whether similar analyses had been carried out for other sub-sectors. An academic expert pointed out that members of their team were looking specifically at ferries, which present a different context. For instance, the distance to be travelled by a ferry and the timing of its journey(s) can be assessed with relative ease. Another academic expert explained that they were working with stakeholders in Norway who were investing in electric ferries and that battery powered ferries are on the higher end of the TRL spectrum. With smaller vessels, such as catamarans, high-speed battery driven outputs are possible. Participants explained that electrification solutions that are efficient have the potential to impact much of the domestic fleet.

As noted, the major challenge here is the CapEx (batteries for the vessels; adaption of port infrastructure etc.), but once this is overcome the OpEx is manageable. ZEVI (see above) exists as a capital grants policy tool to help overcome the CapEx problem. For fuel orientated solutions the CapEx is relatively low and it is the OpEx that is a problem. It was noted that the UK is less well prepared on this front; one participant cited 300+ non-ammonia pilots, but noted that these are not happening in the UK (rather in countries such as Singapore and Norway that have tackled this as an OpEx problem). One participant argued that the business case for investment only makes sense if there are mechanisms to underwrite the higher operating costs of these vessels when using these fuels. Several participants pointed out that until the Government addresses the OpEx problem it will remain unattractive to develop alternatives other than electrification.

One participant returned to the plethora of options available to stakeholders and asked if a filter was applied on solutions that achieve less than ≈90% GHG reduction by 2040, would the same platter of options be available to stakeholders? This approach would rule out CCS and jeopardise the status of other contenders such as biofuels, which may only hit 50–70% GHG reduction. Biofuels also carry a host of supply problems related to feedstocks. The maritime sector is in competition with aviation and agriculture, and any one of these sectors has the capacity to monopolise the store of feedstocks on its own. The overall point was that if discussions factored in the end goal it could provide a guiding principle that directs investment.

A DfT colleague emphasised the importance of acquiring quality evidence and evidence sharing mechanisms on potential options and routes forward, such as independent verified data from pilot projects. Particular areas of interest include:

- infrastructure;
- how much fuel production takes place in the UK versus overseas;
- how fuels are distributed (ports; hub and spoke model).

Participants asked if work was being done to identify the number of vessels/vessel type per sub-sector and noted some potential easy wins (for instance, there are solvable solutions that could support the transition in the workboat sector for offshore platforms and the ferry sector). An academic expert pointed to a report by Maritime Capital published in November 2022 that focuses on UK Domestic Shipping: Mobilising Investment in Net Zero that breaks down the UK fleet into various different groups. One takeaway point from this was that while electrification will not eliminate of the majority of CO_2 emitted via the maritime sector, it is still worth pursuing as it is a technology that is readily available.

Uncertainty and Stranded Assets

The uncertainty around this cluster of policy questions comes to a head around the issue of stranded assets. While many are working on business models that assume there will not be stranded assets, this may be an incorrect assumption. Participants outlined a 'carrot and stick' approach to the stranded assets problem. Stakeholders need to know that if they operate an old vessel in five years' time, it will be dealt with as a stranded asset. However, if adequate measures are not in place, vessel owners that are more comfortable utilising dirtier vessels may be willing to take the risk on the assumption that they will see out their finances.

One participant outlined how modelling suggests that goals can still be met by introducing interventions at different points, but that later interventions can have a marked effect on the retrofit costs. Their point was that, if these interventions happen later, it is still possible to get to 2050, but it will be more expensive, in terms of retrofit costs. This raised a wider question about how to motivate the supply of fuel to the UK. Participants agreed that it was important to identify what production can take place locally and what will have to be imported. If national and international developers start producing, this will help alleviate problems by giving confidence to other actors in the supply chain. Given the international nature of the maritime sector, there were questions about how far UK policy action could actually move the dial, or if the UK would simply respond to developments elsewhere. However, other participants noted that the political space may make action difficult. If action is delayed due to constraints related to the ongoing cost of living crisis, it could have major implications.

Modelling Fuels for Maritime Decarbonisation

While the Policy Workshop focused on maritime decarbonisation, participants emphasised the importance of a whole systems approach. One participant, drawing on expertise acquired from working on decarbonisation of the aviation sector, presented a version of the Resource to Climate Comparison Evaluator (RECCE) for shipping, which models various fuels for shipping based on their climate impact, resource requirement, and associated costs. This model provides insight into four different fuel groups.

1) Long Chain Hydrocarbons
2) Carbon Capture and Storage (CCS)
3) Liquified Natural Gas (LNG) and Methane
4) Zero carbon options

The workshop was brought through an interactive model that displays the climate impacts associated with different fuels against a base case of HFO. The model displayed a range between the minimum and maximum impact and presented the relative level of uncertainty associated with this impact. The model highlighted the impacts on emissions from infrastructure (acknowledging that ship manufacture is quite a big contributor to embodied emissions) as well as gas leaks (for instance, hydrogen and methane leaks which have a substantial GHG effect), and resource requirements (such as the GHG impact from feedstocks). This document will work through the different fuel groups listed above.

Long Chain Hydrocarbons

One important issue raised was resource requirements. If the resource requirements for these fuels are broken down, they all require feedstocks like biomass and some require electricity, and, they all cost something. Relative to HFO, the feedstock requirements for these fuels are very substantial: to conduct global shipping at 2019s demand, the amount of waste oil required would equate 1,200 calories of oil per person per day. As one participant quipped, unless people start eating *a lot* of fish and chips, there is not anything like enough waste oil to provide the oil supplies.

While a biomass liquid process allows a greater range of feedstocks, it would require an amount equivalent to approximately 62% of forestry residues. It was also noted that many of these long chain hydrocarbon processes do not only make diesel, but a range of hydrocarbon products. In response to a question about biomass supply, it was explained that shipping needs around 9 exajoules of energy. The total available biomass that is available in the system notionally to spare is about 80 exajoules: this could produce maybe 16 exajoules of diesel. Thus, half of the world's spare biomass would have to be devoted to shipping.

It was also explained that giving more land over to energy crops is problematic. Land use trends are influenced by increasing population and technological improvements in crop density and unless consumers choose to either factory farm cows or to reduce meat consumption, it is difficult to devote new land to energy crops (unless forests are chopped down elsewhere). In other words, while spare land could be made available, it requires radical changes to diet and/or farming practices.

Alternative Resource Use

Participants had a discussion about the choices for where renewable resources could be funnelled. A scenario was sketched out, for instance, that biomass could be converted into hydrogen rather than into fuels. Grey hydrogen production is of a similar order of shipping fuel consumption (both in the range of 450 gigawatts). Arguably, by focusing on other sectors, a much larger emission saving could be achieved than by putting these renewable resources into shipping. It is not simply that a very large amount of feedstock is needed or that only a limited amount is available, but also that the usage is not necessarily best aligned purely from a carbon perspective. Stakeholders across different sectors need to be careful to avoid a gerrymandering of emissions, where the aim of reducing emissions within one sector ends up creating greater total emissions across the whole.

It was emphasised that academic and policy colleagues need to decide if they are thinking about 'shipping', narrowly defined, or the impact of shipping on itself and other sectors. It was noted that if the global community is to avoid a 1.5 degrees Celsius rise in temperatures, then quick action is necessary and that all sectors must decarbonise eventually. However, something like grey hydrogen is easier and cheaper to decarbonise in terms of dollar per tonne. While there is a certain logic in prioritising dollars per tonne, the counterargument is that this approach does not encourage earlier investment. While grey hydrogen emissions are easier to deal with, there are other things to consider.

Carbon Capture and Storage (CCS)

It was noted that CCS has a mixed reputation and questions on the potential reductions in emissions it can support were at the forefront of the Policy Workshop. While it was argued by some participants that CCS can capture a notable proportion of GHG produced in fuel use, there is still a lot of upstream fuel usage which includes heavy oil infrastructure. It was noted above that cuts of 86–91% to GHG emissions will be required by 2040. Therefore, CCS will still be above the emission levels that will be acceptable by 2040. However, the cost of CCS is relatively low: it may only be 5–6% higher than the cost of HFO on a total cost of ownership basis. It was suggested that CCS may provide a transitional solution. Moreover, if the focus shifted towards renewable diesels, CCS could continue to be useful and it could provide a valuable CO_2 feedstock to be put back into synthesis plants.

It was explained that CCS is taken seriously by ship owners, but there are concerns. For instance, what will be done with the CO_2: there were serious doubts expressed that the receiving end is ready at scale. Moreover, not everywhere in the world has the geological structure conducive to secure carbon storage. Nonetheless, CCS is receiving investment. One major advantage is that it is a retrofit and does not require a change in ship: keep the asset but stick something on at the end. Moreover, as stated, the cost is not exorbitant. Against this, other participants noted that CCS is not achieving the end results that are being sold meaning its bankability is questionable. There was general consensus that CCS is acknowledged as a more politically charged fuel. It is a cost-efficient mechanism, but questions need to be asked about efficacy, storage, infrastructure and payment for storage, and this impacts the choice. One participant compared the product of CCS to nuclear waste: there are long-term implications involved.

Liquefied Natural Gas (LNG) and Methane

It was noted that this fuel group can be converted into synthetic options, but electricity consumption, while lower than something like renewable diesel, is still very substantial. LNG is a transitional fuel and while the CO_2 is about 25% lower, the methane emitted is substantial and the impact of methane slip is pronounced. There are fears that methane slip might negate any GHG emissions benefits during the burning.

On the resources side, the feedstocks required are a lot smaller, but even for something like bio-liquid methane, an equivalent of 130 kilograms of manure, per person, per day would be needed: this is quite a lot. The by-product production from these processes is one reason why it is more attractive on costs than alternatives such as renewable diesels. It is a one-step process to go to synthetic methane or methanol. There are also some hybrid solutions where electricity is added to biomass so that you can reduce the biomass time and the electricity demand compared to a purely synthetic or purely bio route. If the focus is on synthetic methanol or synthetic methane, it was noted that the use of CCS in this context provides a good way of taking carbon out of the ships to feed back into the production processes.

A participant asked if it was possible to mitigate methane slip and, if methane slip was removed as a risk, where this fuel would sit in terms of emissions. It was explained that there is a degree of uncertainty around the methane slip and while work can be done to minimise it, it is impossible to eliminate entirely. However, an advantage, compared to hydrogen and ammonia, is that methane slippage can be measured: methane leakage is visible from space. This creates a strong motivation to monitor methane slippage. It was explained that there are two types of methane slip:

1. during the production process (from the well to the LNG tank on the ship);
2. through the engine as it was burned (some new engines have reduced slippage).

Zero Carbon Options

For zero carbon fuel options, they have little operational grounds for use. There are also risks associated with leakage (it is especially hard to monitor the GHG effect of hydrogen spill). These have significant electricity demands and there is room to include embodied carbon that comes from associated infrastructure such as building electrolysers, wind turbines, solar panels. However, the resources required are very large. It was noted that to run shipping on green hydrogen would require something like 15% of the world grid, and ammonia may require more.

While it was noted that batteries provided an attractive option for shorter range vessels (less than 1,000-kilometre journeys), they were problematic for longer range. Not only is there the very significant charging issue, but there were further issues around the costs of energy, which will be much higher than HFO. Unlike other sectors, direct electrification remains a challenge in the long-run. There are also particular health and safety concerns associated with batteries, especially in relation to fire hazards (although, as was mentioned above, safety issues impact all fuels). One major difference between hydrogen and ammonia is that the latter is much easier to transport between A and B: it does retain energy and can be kept for seasonal storage. One case in favour of ammonia is energy density, while it is not quite as good as fossil fuels, it is not that far away (especially compared to the likes of the battery).

Participants were interested in whether the finite nature of biomass also applied to electricity. It was explained that electrons scale up over time so in the long run electrons will become more available and this is worth thinking about in terms of transitions (what will scale be like in the future?). Electrons are needed to produce green ammonia and green hydrogen and the cost of solar and wind is decreasing fast. A major challenge to capitalising on these fuels comes from ability of the UK to produce the required renewable electricity outputs. Participants pointed to difficulties around the offshore market, as indicated by ARF (Allocation Round 5) of the CfD (Contracts for Difference), a funding mechanism for offshore wind designed to de-risk investment and bring down the costs associated with renewables like offshore wind, which had problems securing investment.

It was also noted, however, that there is room for opportunity here. The placement of offshore wind farms is determined by a series of factors including grid infrastructure. If the aim is to produce electrolytic fuels offshore, then this constraint is removed and this could allow for other marine areas to be opened for the production of electrolytic fuels from renewable sources. There are constraints around producing just electrolytic fuels from renewable sources such as offshore winds, such as funding, but there are also opportunities. Participants pointed to examples where developers are considering projects that are specifically designed to produce just renewable fuels from offshore wind. It was noted that in terms of the market dynamics for renewables there is a place for producing solely electrolytic fuels.

There was disagreement about the UK’s capacity to produce enough electricity to support, for instance, ammonia production. While some participants noted that, ultimately, ammonia production will take place elsewhere (Australia, South America, Africa etc.), another challenged the notion that the UK would not be able to access green electrons that are cheap. They explained that, using artificial intelligence, it was predicted that the North Sea becomes extremely attractive if you do not use all the electrons for a particular process: they argued that what is missing is an integration of processes. If all the electrons are used for a particular process like making ammonia it will be very expensive, but that is not how the chemical industry works. Rather, if integration is achieved, so that some electrons are used to make ammonia and some for other purposes, it becomes economically feasible.

Indeed, it was noted that the UK will not run out of a need for green electrons and protons for a long time. If a strong pipeline is created, it was suggested this could help anchor an uncertain policy environment. One participant called this a ‘no regrets option’. However, this cuts to the heart of how the Government is structured, as renewable electricity production in the UK is the responsibility of the Department for Energy Security and Net Zero. It was noted that how Government works across Departmental boundaries and collaborates will be key to ensuring progress on maritime decarbonisation.

Glossary of terms used in Figures 1 and 2

Table 2: Abbreviations for Figures 1 and 2. See also, Li Chin, B. Featrice Foscoli, E. Mastorakos, and S. Evans, 'A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost', *Energies* 14 (2021), p. 4 [https://doi.org/10.3390/en14248502].

Abbreviations	Marine Fuel Pathways
HFO (Base Case)	Heavy Fuel Oil
HFO (CCS)	Heavy Fuel Oil (Carbon Capture & Storage)
LNG (CCS)	Liquified-Natura-Gas (Carbon Capture & Storage)
BLUE H_2	Blue Hydrogen *[Natural-Gas-Hydrogen]
BLUE H_2 (FC)	*Blue Hydrogen (Fuel Cell) [Natural-Gas-Hydrogen (Fuel Cell)]
BLUE NH_3	Blue Ammonia *[Natural-Gas-Ammonia]
BLUE NH_3 (FC)	Blue Ammonia (Fuel Cell)] *[Natural-Gas-Ammonia (Fuel Cell)]
MeOH	Methanol
BLUE MeOH (CCS)	Blue Methanol (Carbon Capture & Storage) *[Natural-Gas-Methanol (Carbon Capture & Storage)]
NG-E	Natural Gas-Electricity
BLUE E-H_2 (FC)	Blue Electricity-Hydrogen (Fuel Cell) *[Natural-Gas-Electricity-Hydrogen (Fuel Cell)]
BLUE E-NH_3 (FC)	Blue Electricity-Ammonia (Fuel Cell) *[Natural-Gas-Ammonia (Fuel Cell)]
BIO-DIESEL	Biomass-Biodiesel
BIO-MeOH	Biomass-Bio-Methanol
SOLAR E	Solar-Electricity
SOLAR E-H_2 (FC)	Solar-Electricity-Hydrogen (Fuel Cell)
SOLAR E-NH_3 (FC)	Solar-Electricity-Ammonia (Fuel Cell)

SOLAR E-MeOH	Solar-Electricity-Methanol
SOLAR T-H_2 (FC)	Solar-Thermochemical-Hydrogen (Fuel Cell)
SOLAR T-MeOH	Solar-Thermochemical-Methanol