REDUCING THE MARITIME SECTOR'S CONTRIBUTION TO CLIMATE CHANGE AND AIR POLLUTION

Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs

A Report for the Department for Transport

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The shipping industry is critical for the UK's trade in goods. Around 95% of British imports and exports in goods are moved by sea, including 25% of the UK's energy supply and almost half of the country's food supplies (DfT, 2019). The UK port sector is the second largest in the European Union, handling around 5% of the world's total maritime freight traffic at some point in its journey (DfT, 2019).

To undertake this scale of activity, ships require a substantial volume of fuel. The current reliance on fossil fuels, however, has consequences for the environment and health due to the associated emissions. These include greenhouse gases (GHGs), which contribute to climate change, as well as emissions to the air of pollutants such as nitrogen oxides (NO_x), sulphur dioxide (SO_2), particulate matter ($PM_{2.5}$ & PM_{10}), volatile organic compounds (VOCs) and ammonia (NH_3). For example, in 2016, domestic shipping alone (ships that start and end their journey at UK ports, including overseas territories and Crown dependencies) accounted for 11% of the UK's total domestic NO_x emissions, 2% of primary $PM_{2.5}$ and 7% of SO_2 (DfT, 2019).

The need to address these emissions has been apparent for some time and, in 2018, the International Maritime Organization (IMO) adopted an initial strategy to reduce GHG emissions from shipping with an ambition to reduce the absolute GHG emissions from international shipping by at least 50% by 2050 (relative to 2008 levels).[1] The IMO also regulates emissions to the air of pollutants from shipping through the International Convention for the Prevention of Pollution from Ships (MARPOL). The main international limits to pollutant emissions from shipping relevant to the UK are through the North Sea emissions control area (ECA), in which a sulphur cap of 0.1% was introduced in 2015 (a ten-fold reduction from the 1% limit introduced in 2010), and the agreement in 2008 by IMO member states to a 0.5% sulphur limit for global shipping outside ECAs from 2020.[2]

The results of the analysis in this report indicate that some progress will be made in reducing the UK's international and domestic shipping emissions under a business as usual (BAU) case, i.e. under current policies and regulations. This is because a combination of efficiency improvements are likely to be implemented, some driven by existing regulation and some by market forces, which will reduce emissions per tonne-km[3] between now and 2050. For example, the air pollutant international regulations mentioned above were introduced in 1997, covering both SO_2 and NO_x emissions from ships. Revisions with increased ambition entered into force in 2010 and apply to all ships. Also, as newer generation ships enter the fleet, they are manufactured to perform with greater fuel efficiency than the generations

[1] See http://www.imo.org/en/OurWork/Documents/Resolution%20MEPC.304(72)%20on%20Initial%20IMO%20Strategy%20on%20reduction%20of%20GHG%20emissions%20from%20ships.pdf

[2] The 2020 date was subject to a review led by the IMO on fuel availability and was confirmed in 2016.

[3] Tonne-km is a unit used to describe transport work and quantified the movement of 1 tonne of freight a distance of 1 km.

they replace. This is partly driven by an internationally agreed regulatory requirement introduced in 2013 which sets a minimum energy efficiency level for different ships[4] and guidelines agreed in 2016. Market forces (e.g. high fuel prices due to high oil prices) can also provide an incentive for improvements in the efficiency of new ships. As a result of this fleet evolution, average fleet efficiency will improve as older less efficient ships are retired and replaced.

However, although these are vital steps towards reducing shipping emissions, they are not likely to go far enough to achieve the IMO's ambition to reduce GHG emissions from international shipping by at least 50% relative to 2008 levels by 2050 or the UK's ambition for zero emission shipping, as stated by government in *Maritime 2050: Navigating the Future* (DfT, 2019).

This report therefore assesses the most cost-effective ways to further reduce emissions from UK shipping beyond what is expected under BAU. It is one part of several strands of work that follow from *Maritime 2050: Navigating the Future* (DfT, 2019) and supports the development of the UK's Clean Maritime Plan. Other strands of work analyse in more detail the barriers to implementing the measures considered in this report (Frontier Economics et al. 2019a), the economic opportunities to the UK from a shift to zero emission shipping (Frontier Economics, E4tech and UMAS, 2019) and the policy levers that could be used to support deployment of these measures where needed (Frontier Economics, UMAS and E4tech, 2019).

Options for achieving zero emission shipping

Emission reduction options for shipping include: technologies, operational changes or behavioural changes that increase energy efficiency; options that are able to capture or treat exhaust emissions of GHGs or air pollutants; and alternative fuels or energy sources (including renewables such as wind and solar) and related machinery. Analysis of the cost-effectiveness of abatement options undertaken for this report suggests that:

- Substantial GHG emissions reductions could be achieved while also reducing the overall operating costs of the ship (i.e. at negative cost-effectiveness). These are typically options which improve energy efficiency. However, there are barriers that would need to be overcome for the uptake of these options to increase in practice.
- The cost-effectiveness of abatement options varies substantially across ship types, reflecting the diversity of ships in operation. Common across all ship categories is the finding that a shift to low or zero emission fuels is needed for material emission reductions to be realised of the scale required to achieve the IMO or UK government's ambitions for zero emission shipping.

The cost-effectiveness analysis in this report reveals that there are many options available for reducing shipping emissions (both GHGs and emissions to the air of

[4] This is via the Energy Efficiency Design Index (EEDI). This is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in a specific ship design to the industry, as long as the required energy efficiency level is attained. See http://www.imo.org/en/ourwork/environment/pollutionprevention/airpollution/pages/technical-and-operational-measures.aspx

pollutants) and the cost-effectiveness of each varies depending on several factors: the type of ship under consideration; prevailing fuel prices; and the UK and international policy environment. Scenario analysis has therefore been undertaken which explores different UK and international policy stringency in relation to emissions as well as different fuel prices and the availability of alternative fuels.

It should be noted that in order to assess the impact air pollutants from shipping on air quality, a damage cost approach has been used. This is aligned with the Defra 2018 guidance which applies a single value of damage cost per tonne emitted of each type of pollutant from different categories of ships. This approach only includes emissions within a given proximity of the UK.

A more comprehensive analysis using detailed modelling consistent with an impact pathway approach could be carried out and may produce different results. However, in the time available for this study, a pragmatic and proportionate approach using damage costs has been applied in this analysis. The limitations of this are important to note and results are to be considered indicative. Policy findings related to impacts of air pollution emissions, and the cost-effectiveness of shipping air pollution abatement should be viewed in light of the damage cost approach used[5].

Some important policy insights arise from this analysis:

- Operational emissions from UK shipping (domestic and international) of GHGs could be reduced to close to zero by 2050, along with a reduction to close to zero SO_2 and a substantial reduction in primary particulate matter (PM) emissions under a scenario in which the government's central carbon values per tonne are applied to increase the cost of fossil fuel used by shipping so that it better reflects its climate change impacts and there is no biofuel supply for the sector.
- NO_x emissions from UK shipping are not significantly reduced but remain close to current levels under all scenarios explored in this report. NO_x emissions are expected to rise under BAU as the growth in shipping traffic outweighs any reductions made through the current regulations. Furthermore, the most cost-effective fuel and machinery combinations that achieve zero emission shipping do not reduce NO_x emissions below current levels because these combinations still heavily rely on internal combustion machinery which, due to the temperatures of combustion, continue to produce NO_x emissions even when used with alternatives to fossil fuels. Therefore, this implies that further NO_x emission reductions would require additional regulation.
- The costs of reducing UK domestic shipping emissions are lower than the costs of reducing UK international shipping emissions: the UK domestic fleet's GHG emissions are reduced by nearly 100% by 2050 at the same carbon value per tonne as is needed to achieve a 50% absolute reduction in the global fleet's GHG emissions (the minimum requirement of the IMO's Initial Strategy (IMO 2018)).
- There are similar transition pathways for achieving zero emission shipping for both the UK domestic shipping and UK international shipping fleets, except for

[5] The Technical Annexes provide more detail.

a small subsector of the UK domestic shipping fleet (and a very small subsector of the UK international shipping fleet). For these fleets (a subset of the short-range passenger ferries (Ferry-RoPax) and short-sea freight ships (Ro-Ro)), a shift towards battery electrification (as opposed to the use of a liquid fuel) is likely.

- Alternative low emission fuels will be essential to achieve the ambitions for zero emission shipping, particularly beyond 2030. There are a number of fuels that could be used: for the purposes of this analysis, ammonia, methanol and hydrogen are considered and are included in the modelling in combination with a variety of compatible machinery options (for example, internal combustion machinery and fuel cells). The analysis suggests that:
  - under the fuel price assumptions used in this analysis, ammonia and methanol are the preferred options over hydrogen for most of the fleet because of the higher costs of onboard storage for hydrogen (including that it takes up space that lowers the commercial returns from the ship); and
  - under the assumptions of the modelled scenarios, ammonia is generally preferred over methanol for the majority of ship types and sizes,[6] though an adverse side-effect of this is the scale of associated NO_x emissions that would need to be addressed.
- There is, however, substantial uncertainty around both the costs and efficiency of low emission fuels in both the near and long terms. This is important to recognise as even small changes in the costs and efficiency of the low emission fuels could change the commercial incentives to shift towards any of these three options – hydrogen, ammonia and methanol. This points to facilitating the flexibility to keep open multiple options for alternative low emission fuels until there is greater clarity over the potential pace of technology development and cost reduction and the magnitude of potential changes in the costs if using these fuels in the maritime sector.
- The sustainable production of the fuels in sufficient quantity is a significant challenge, the consideration of which is outside the scope of this analysis. Using hydrogen, ammonia or methanol would require a source of low carbon hydrogen, either through steam methane reforming (SMR) with carbon capture and storage (CCS) or by electrolysis using renewable power.
- The preferred engine for use with the low emission fuels considered remains the internal combustion engine (ICE), under the assumptions used about the capital costs relative to alternatives (they are assumed to be lower cost than

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6 The assumption used in this study is that the NO_x emissions from the combustion of ammonia would be equivalent to the Tier III limits. This is based on the assumption that while without any management, the NO_x emissions from ammonia combustion are expected to be higher than this limit, that this limit would still apply for new fuels such as ammonia, and so management solutions (e.g. selective catalytic reduction (SCR)) would be applied (and so we therefore assume in this work that they would be applied). Further reduction below the Tier III limit is technically possible but not assumed to be achieved without the motivation of regulation. It should be noted that there is some uncertainty about the impact on NO_x emissions from the use of ammonia in internal combustion machinery. Exhaust technology should be able to assist with the control of NO_x (and we assume in this work that it does) but further research, development and demonstration (RD&D) is needed to establish this in detail (e.g. performance consequences, costs, emissions consequences). There could also be a risk of ammonia emissions (e.g. through slip). And there could be other non-modelled risks (fuel spill/pollution/safety) that could be material to ammonia's viability. As the costs of pathways that do not use ammonia generally appear to be higher, it is worth progressing RD&D on ammonia and for other potential synthetic fuels in parallel.

the alternatives, e.g. fuel cells). This reliance on ICE could support a simpler transition for the sector given the existing knowledge and experience with this technology and its prevalence in the fleets.

The analysis in this report covers various dates by which the zero emission shipping ambition is to be achieved, and shows how impacts on emissions and costs differ under alternative assumptions about the costs and availability of different low emission fuels. These scenarios do not reflect government policy but are intended to illustrate how the costs of achieving those ambitions could differ under alternative assumptions. It is recommended that further scenarios, which consider different assumptions on the costs and availability of low emission fuels, are explored. This would provide deeper insights into the most cost-effective transition pathways when shifting to zero emission shipping, paying attention to the potential machinery options to accompany low emission fuels.

The analysis in this report has shown that a range of abatement technologies can be cost-effective. Recognising the diversity of the shipping sector, a package of complementary abatement options are likely to be needed to achieve zero emission shipping, key among which is a necessary shift to low or zero emission fuels.

1 THE CASE FOR ACTION

1.1 Context

The shipping industry is critical for the UK's trade in goods. Around 95% of British imports and exports in goods are moved by sea, including 25% of the UK's energy supply and almost half of the country's food supplies (DfT, 2019). The UK port sector is the second largest in the European Union, handling around 5% of the world's total maritime freight traffic at some point in its journey (DfT, 2019).

To undertake this scale of activity, ships require a substantial volume of fuel. The current reliance on fossil fuels, however, has consequences for the environment and health due to the associated emissions. These include nitrogen oxides (NO_x), sulphur dioxide (SO_2), particulate matter ($PM_{2.5}$ & PM_{10}), volatile organic compounds (VOCs) and ammonia (NH_3). For example, in 2016, domestic shipping alone (ships that start and end their journey at UK ports, including overseas territories and Crown dependencies) accounted for 11% of the UK's total domestic NO_x emissions, 2% of primary $PM_{2.5}$ and 7% of SO_2 (DfT, 2019).

Reducing emissions from ships is a major challenge because ship owners and operators face few incentives to do so on their own and experience several barriers that can hinder the uptake of actions, technologies or fuels that could lower emissions. A major barrier to reducing emissions is that the price of fuel does not reflect the damage it imposes on the environment and society when it is used. Therefore, although shipowners' and operators' decisions account for the cost of fuel they face, they have no incentive to take into account the cost to society of emissions of greenhouse gases (GHGs) and air pollutants.

Other barriers also exist that further hinder emission reduction action,[7] for example the so-called 'split incentives' such that ship owners, who would need to make the relevant capital investment in technologies or alternative fuel investments to reduce emissions, often do not benefit, at least directly. Such benefits would often flow to charters through lower fuel costs or to wider society from lower harmful emissions.

Some progress will be made to reduce emissions from shipping. In a competitive global market, ship owners and operators have strong incentives to operate efficiently, which can reduce emissions where they take action to reduce their fuel use and hence fuel costs. In addition, emissions will be addressed through air pollutant international regulations introduced in 1997 and revisions with increased ambition, which entered into force in 2010 and apply to all ships. Plus, as newer generation ships enter the fleet, they are manufactured to perform with greater fuel efficiency, hence average fleet efficiency will improve as older less efficient ships are retired and replaced.

Although these are vital steps towards reducing emissions, they are not likely to go far enough to achieve the IMO's ambition to reduce GHG emissions from

[7] These are discussed in Frontier Economics, UMAS, E4tech and CE Delft (2019) *Reducing the UK Maritime Sector's Contribution to Climate Change and Air Pollution: Identification of Market Failures and other Barriers to the Commercial Deployment of Emission Reduction Options*.

international shipping by at least 50% relative to 2008 levels by 2050 or the *Maritime 2050: Navigating the Future* (DfT, 2019) zero emission shipping ambition.

This report therefore presents analysis of the scale of the challenge in reducing UK shipping emissions in terms of a business as usual (BAU) situation in which current policies only are continued. It then explores the relative cost-effectiveness of a range of different options for reducing emissions from both UK domestic and UK international shipping. Then, in order to consider how long-term ambitions for zero emission shipping could be achieved, ten illustrative scenarios are considered to show what the impacts on emissions and costs could be under different assumptions about future policy and fuel availability and prices.

This analysis is one part of several strands of work that follow from *Maritime 2050: Navigating the Future* (DfT, 2019) and support the development of a Clean Maritime Plan. Other strands of work consider in more detail the barriers to implementing the measures suggested in this report;[8] the economic and commercial opportunities to the UK from a shift to lower emission shipping in terms of the various technologies, services and fuels that are likely to need to be developed and the associated supply chains;[9] and the targets and policy levers that could be used to support deployment of these measures where needed.[10]

1.2 Challenge

Understanding which technologies, behavioural changes or fuels are likely to be the most cost-effective in reducing emissions is complex. The most effective approach to reduce shipping emissions is likely to differ based on the type, size and age of ship – and these vary substantially across the fleet. Furthermore, the cost of the technologies will vary, in part, depending on the scale of the market for those technologies and the time period over which they are developed (if economies of scale are achievable, costs may decline over time as markets grow) and when they are deployed. In addition, a key challenge facing the industry is that to achieve zero emission shipping, determined action is likely to be needed over many decades. This is because, with the life of a vessel often around 25-30 years (or longer) and many markets for low emission technologies still in their infancy, this requires co-ordinated action involving multiple parties such as the shipping industry, the government, technology and fuels industries, international shipping representatives and others all coming together to achieve the shared objective over a sustained period.

The rest of this report sets out:

- Section 2: Shipping emission abatement options likely to be available by 2031 and 2051, and their take-up under BAU;
- Section 3: Cost-effectiveness of shipping abatement options in 2031 and 2051;

[8] See Frontier Economics, UMAS, E4tech and CE Delft (2019a) *Reducing the UK Maritime Sector's Contribution to Climate Change and Air Pollution: Identification of Market Failures and other Barriers to the Commercial Deployment of Emission Reduction Options.*

[9] See Frontier Economics, E4tech and UMAS (2019) *Reducing the UK Maritime Sector's Contribution to Climate Change and Air Pollution: Economic Opportunities from Low and Zero Emission Shipping*

[10] See Frontier Economics, UMAS and E4tech (2019) *Reducing the UK Maritime Sector's Contribution to Climate Change and Air Pollution: The Potential Role of Targets and Economic Instruments*

- Section 4: Illustrative policy scenarios for reducing UK shipping emissions; and
- Section 5: Policy insights.

The focus of this report is on the years 2031 and 2051. The latter reflects the timeframe of *Maritime 2050: Navigating the Future* (DfT, 2019), which presents the government's vision for the maritime industry over coming decades. It is also a key date for the United Nations Framework Convention on Climate Change Paris Agreement, which is '…a landmark agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future'[11] (UNFCCC, 2015); the UK Climate Change Act 2008; and the International Maritime Organization Initial Strategy which sets out '… a vision to reduce GHG emissions from international shipping and phase them out, as soon as possible in this century'[12] (IMO, 2018). The date of 2031 provides a useful mid-point against which to benchmark progress. The formal modelling results are presented for 2031 and 2051 because of the years that have been modelled,[13] but are essentially equivalent to 2030 and 2050 and are referred to as such in this report.

The report also has a separate Technical Annex that describes aspects of the methodology in more detail.

Finally, the results presented in this report represent an initial set of scenarios. It is recommended that further scenario and sensitivity analysis is undertaken, which would allow particular issues to be investigated in more depth to inform policy making.

[11] See https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement

[12] See http://www.imo.org/en/mediacentre/pressbriefings/pages/06ghginitialstrategy.aspx

[13] The GloTraM modelling used for the majority of the analysis in this report has 2016 as its baseline. It then projects forward in 5-year intervals, meaning that 2031 and 2051 are the closest modelled years to 2030 and 2050 respectively.

2 SHIPPING EMISSION ABATEMENT OPTIONS LIKELY TO BE AVAILABLE BY 2030 AND 2050

2.1 Approach

The options available to reduce or eliminate shipping emissions are summarised in an accompanying paper.[14] The options can be divided into four categories:

1. technologies that can increase energy efficiency;
2. operational or behavioural change that can increase efficiency;
3. technologies specific to the capture/treatment of exhaust emissions (GHG and air pollutant emissions); and
4. alternative fuels and energy sources[15] and related machinery.

Some of these options are likely to be taken up under BAU incentives for ship owners operating within existing and agreed regulatory requirements. To assess what might happen in a BAU scenario[16], a model (GloTraM) is used to simulate the evolution of the global shipping industry under current and committed regulations.

The modelling simulates the profit-maximising decisions of ship owners/operators, including how this might influence their take-up abatement options in each of the four categories above. The simulation starts in a baseline year (2016), with the global and UK fleets as they were specified at that point in time. The model then projects forward in 5-year intervals. So, every five years, selections are made by the model to retrofit technologies, or to change some of the operational characteristics (e.g. ship speeds) of the existing fleet. The model also retires (scraps) the oldest ships and identifies the characteristics (e.g. use of energy efficiency technology, fuels and machinery) of new ships entering the fleet as a function of both the regulation that needs to be met and the commercial competitiveness of these designs.

The model simulates these decisions for each age range of ships (e.g. 0-5-year-old ships, 5-10-year-old ships), across 35 different ship types and sizes. The modelling is underpinned by detailed estimates of the performance and the costs of different abatement options for these individual subsectors. Detailed descriptions of the modelling undertaken can be found in the Technical Annex.

GloTraM is one of the leading global models of shipping. Its outputs have been extensively peer reviewed in academic papers based on its results.

[14] Frontier Economics, UMAS, E4tech and CE Delft (2019) *Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution: Maritime Emission Reduction Options*

[15] This category includes renewables such as wind and solar power.

[16] This BAU scenario is referred to as Scenario A in Figure 1 and Figure 2. Further details on this BAU scenario can be found in Section 2.3 in this report, and in the separate Technical Annex report.

As with all modelling that looks over a long-term period into the future, there are limitations that need to be borne in mind when interpreting results. They include but are not limited to:

- the accuracy with which the model simulates the decision-making behaviour of ship owners and operators;
- the accuracy of the key inputs to the scenarios modelled, e.g. the assumed fuel prices, the costs and performance of the abatement options; and
- the characterisation of UK domestic and international fleets, including the size of these fleets and their technical and operational specifications.

The level of demand is specified as a fixed modelling input. There is, therefore, no demand response to the prevailing conditions within any scenario. This simplifies the modelling and allows comparability between scenarios on the basis of technical and operational variations.

Given these limitations and recognising uncertainty when considering a long-term period to 2050, further sensitivity analyses beyond what has been feasible to deliver for this study should be carried out to understand whether the central results change under slightly different specifications (e.g. different future fuel prices).

To manage and understand these potential limitations, the Technical Annex includes a section on the quality assurance steps taken and, where possible, validation against appropriate data and published studies.

2.2 Domestic and international shipping emissions

Domestic shipping is generally considered to be straightforward to define – it refers to shipping activity that starts and ends at a UK port, for example, a ferry between two UK ports or a merchant ship carrying goods between two UK ports.

There is, however, no universally adopted definition of the UK's international shipping emissions. Therefore, for the purposes of this study, an approach was required to estimate the UK's international shipping emissions and how much of those emissions are reduced in the scenarios modelled.

Following detailed discussions with DfT, it was decided that an appropriate way to measure the UK's international shipping emissions for the purposes of this study was to use a trade-weighted basis. That is, the emissions were estimated based on the amount of shipping activity that is undertaken for the purposes of UK trade.[17] This recognises the fact that international ships often call at multiple ports (e.g. a ship from China with cargo for the UK will also stop at several other ports to unload cargo) and so not all of a ship's route is determined by UK demand for, or sale of, goods. The justifications for this approach are that it provides a defensible logic for associating responsibility for international shipping emissions with an individual country and that the estimates obtained through this method are broadly

[17] In practice, this means estimating the proportion of shipping activity that serves UK trade exports, or imports, or 50% of both. The specific assumption used in this work is to base this on imports because it is representative of a consumption-based carbon accounting framework commonly used when considering emissions that fall outside of geographical national boundaries.

comparable to those used in earlier studies.[18] The detailed justification for the selection of this approach is provided in the Technical Annex.

This approach differs from alternatives that have been used in some other studies. They include attributing all the emissions to the country of the last port of call (e.g. only counting shipping emissions between the UK and the previous or next stop in a different country) or attributing all the emissions to the country from which the ship purchases its fuel. The approach used in this study may result in slightly higher emissions attributed to the UK than a 'last port of call' approach because the UK is rarely the last port of call. It produces similar estimates to the approach taken by the Committee on Climate Change (CCC) in a 2011 study, which uses an estimate of the miles travelled by ships engaged in UK trade and an estimate of the emissions intensity of those ships.[19] An earlier comparison[20] showed broad similarity between assumptions and data on trade and shipping activity between both the approach used in this report and the CCC's approach.

The choice of how to assign international emissions to the UK is not intended to pre-judge an international agreement or represent the UK government's position on how this should be done. It is solely intended to provide a pragmatic approach for the purpose of undertaking the modelling in this study that is transparent and broadly agrees with other approaches.

2.3 Take-up of options for reducing shipping emissions under BAU

The figures below provide an overview of the take-up of the four categories of options for reducing shipping emissions that has been estimated under the BAU scenario. This forms the baseline against which to compare the additional take-up required to meet long-term emission reduction objectives.

Figure 1 to Figure 3 set out, respectively, the take-up of:

- technologies that can increase energy efficiency, and operational or behavioural change that can increase efficiency;
- alternative fuels and energy sources[21] and related machinery; and
- technologies specific to the capture/treatment of exhaust emissions (GHG and air pollutant emissions).

Figure 1 provides the outcome from detailed modelling of the take-up by UK domestic shipping of technologies that can increase energy efficiency, and operational or behavioural change that can increase efficiency under BAU. All of these options are assumed to have zero or low take-up in 2016. The results are presented for three example ship types, although the model produces outputs for all ship types. The three ship types chosen for presentation are Ferry-RoPax (passenger ferries with the ability to carry road vehicles), container ships and oil tankers. These three ship types represent a range of technical specifications

[18] CCC (2011) *Review of UK Shipping Emissions, supporting analysis*

[19] CCC (2011) *Review of UK Shipping Emissions, supporting analysis*

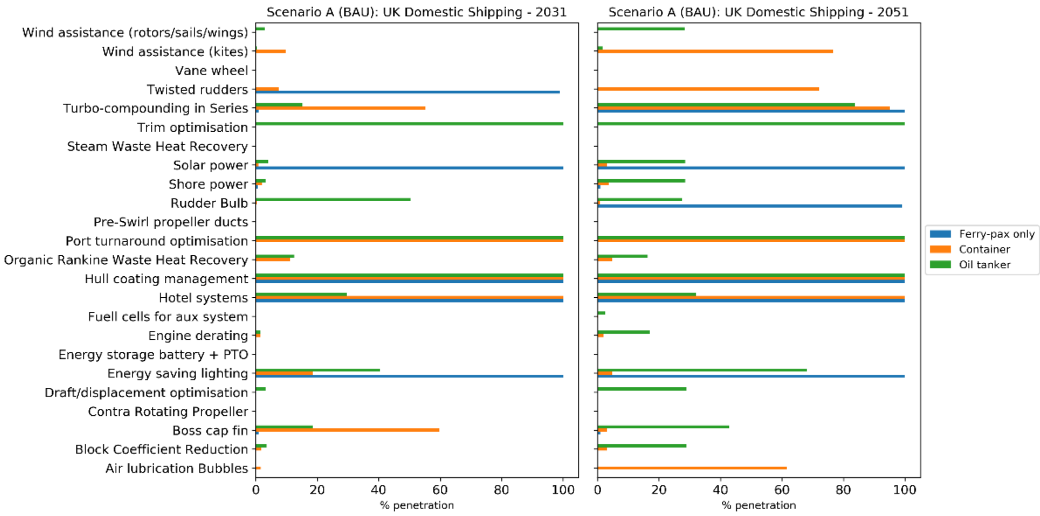
[20] UCL Energy Institute (2012) *LCS Review of CCC's Review of UK Shipping Emissions: Baseline Emissions*

[21] This category includes renewables such as wind and solar power.

(e.g. different design speeds, and different main engine (e.g. propulsion) and auxiliary machinery energy demands), and therefore show the variation in take-up of options between sectors of the shipping industry.

In the modelling, each ship type is broken down by size and age category. The results for '% penetration' shown in Figure 1 represent the percentage of the size and age categories for each ship type that is estimated to have taken up each of the options. These results are just shown for UK domestic shipping for simplicity of presentation. Results for all ship types and for both domestic and international shipping can be found in the Technical Annex.

Figure 1 Take-up of technologies that can increase energy efficiency and operational or behavioural change that can increase efficiency by UK domestic shipping under BAU for three example ship types

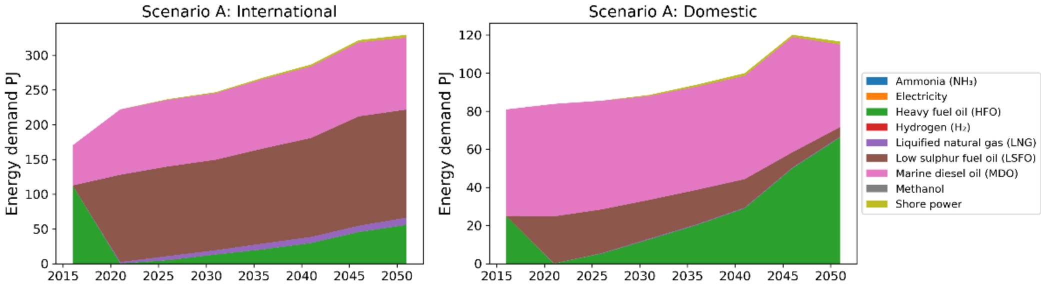


Notes: '% penetration' represents the percentage of the size and age categories for each ship type that is estimated to have taken up each of the options.

Figure 2 presents estimates of the take-up of alternative fuels under BAU for UK domestic shipping and UK international shipping at different times. The quantity of fuel is shown on the y-axis in units of energy (joules)[22], allowing comparison of the shares of the total fuel supply that are accounted for by the different fuels. The relative and absolute quantities of energy use for each fuel vary significantly over the time period from 2016 to 2051.

[22] Specifically, PJ or petajoules are used on the y-axis. 1 petajoule is equivalent to 1 x 10^{15} joules

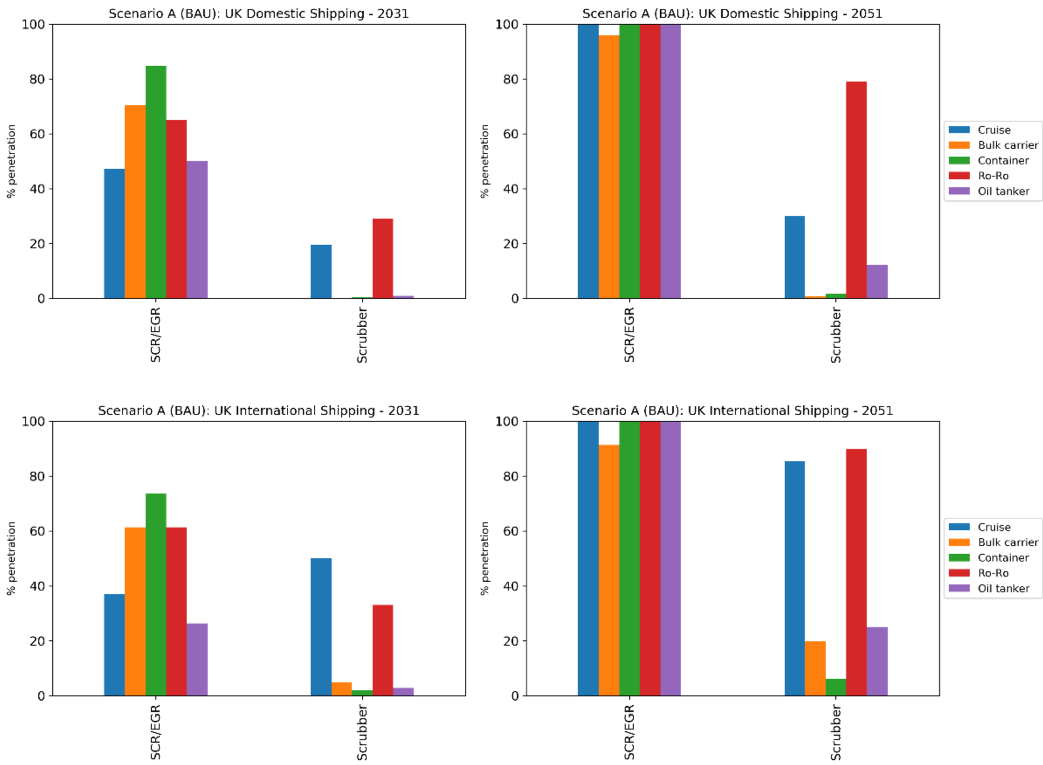
Figure 2 Fuel mix used by UK international and domestic shipping under BAU, 2016 to 2051



Note: see discussion below for explanation of pattern

Figure 3 describes the estimates of the take-up of technologies specific to the capture/treatment of exhaust emissions (GHG and air pollutant emissions) for UK domestic and UK international ships in 2031 and 2051. There are two main options for controlling NO_x emissions in conventional internal combustion engines (ICE): selective catalytic reduction (SCR) and exhaust gas recirculation (ECR). These options are in close competition with each other and uncertainty remains over their relative pricing, so the modelling does not distinguish between these two options. Instead, it only identifies what the level of take-up would be overall across both technologies. The level of take-up is quantified as a percentage of penetration into each of the relevant fleets ('% penetration' has the same definition as for Figure 1) across the same categories of ship size and ship age as are used in Figure 1.

Figure 3 SO_2 scrubber and SCR/EGR (selective catalytic reduction or exhaust gas recirculation technology) take-up by UK shipping under BAU



The results allow us to understand which abatement options are likely to be taken up under a BAU scenario without any further action by UK government or further IMO regulation. This happens largely because these abatement options are cost-effective already or will become cost-effective by 2031 or 2051 due to existing regulations, or they are required for compliance with current policies and regulations.

By 2031, under BAU, the modelling suggests that the options that are likely to reach very high levels of adoption include:

- operational/behaviour options (port turn-around optimisation, hull coating management);
- some modification to the propulsion system (e.g. boss cap fins, twisted rudder); and
- some reduction of hotel energy demand, e.g. systems on the ship associated with the crew or passenger accommodation (hotel systems, energy saving lighting).

Initially ships are expected to comply with the 2020 sulphur limit regulation by using Low Sulphur Fuel Oil (LSFO). For international shipping, which predominantly uses heavy fuel oil (HFO) as a fuel at present, the modelling suggests that many mid-size ships and some of the larger ships gradually switch to use a scrubber (these remove sulphur oxides from a ship's engine and boiler exhaust gases) to enable them to use HFO. Domestic shipping already predominantly uses fuels with lower sulphur content (marine diesel oil, MDO) and so will be less likely to see such significant change in sulphur emissions as international shipping. The subset of domestic shipping capable of operating competitively on fuel oil is expected to initially comply with the 2020 sulphur limit using LSFO and then, as also observed in the international shipping fleet, increasingly employ scrubber technology in order to use HFO. The modelling suggests that compliance with NO_x emission regulations will be achieved by exhaust abatement technology.

Although not included in the figures, the average operating speed of the international and domestic fleet in the BAU scenario increases by an average of approximately 10% by 2031 (relative to 2016). This is driven by an assumption in the modelling that market conditions (which inform the revenues of ships in operation) which have created the incentives for slow steaming currently, return to their higher long-run average values by 2031. As a result of returning to higher operating revenues, there is an incentive to increase speed and this results in a small reduction in efficiency in the BAU scenario acting counter to the efficiency gained through technology.

By 2051, under BAU, the modelling suggests:

- the options likely to be adopted with high penetration include a number of propulsion, hull and machinery improvements. Generally, container shipping has the highest penetration of these options, explained by this sector's high rate of demand growth in the global fleet, and therefore a significant number of new ships entering this fleet with these improvements in place; and
- the fuel mix in the fleet is consistent with that in 2031: crude oil-derived fuels still dominate, with larger ships using a mixture of low sulphur heavy fuel oil (LSFO) and scrubber technology to comply with the sulphur limits, and the

smaller ships (including domestic shipping) using MDO and some HFO (with scrubber technology). NO_x emissions abatement technology increases in penetration.

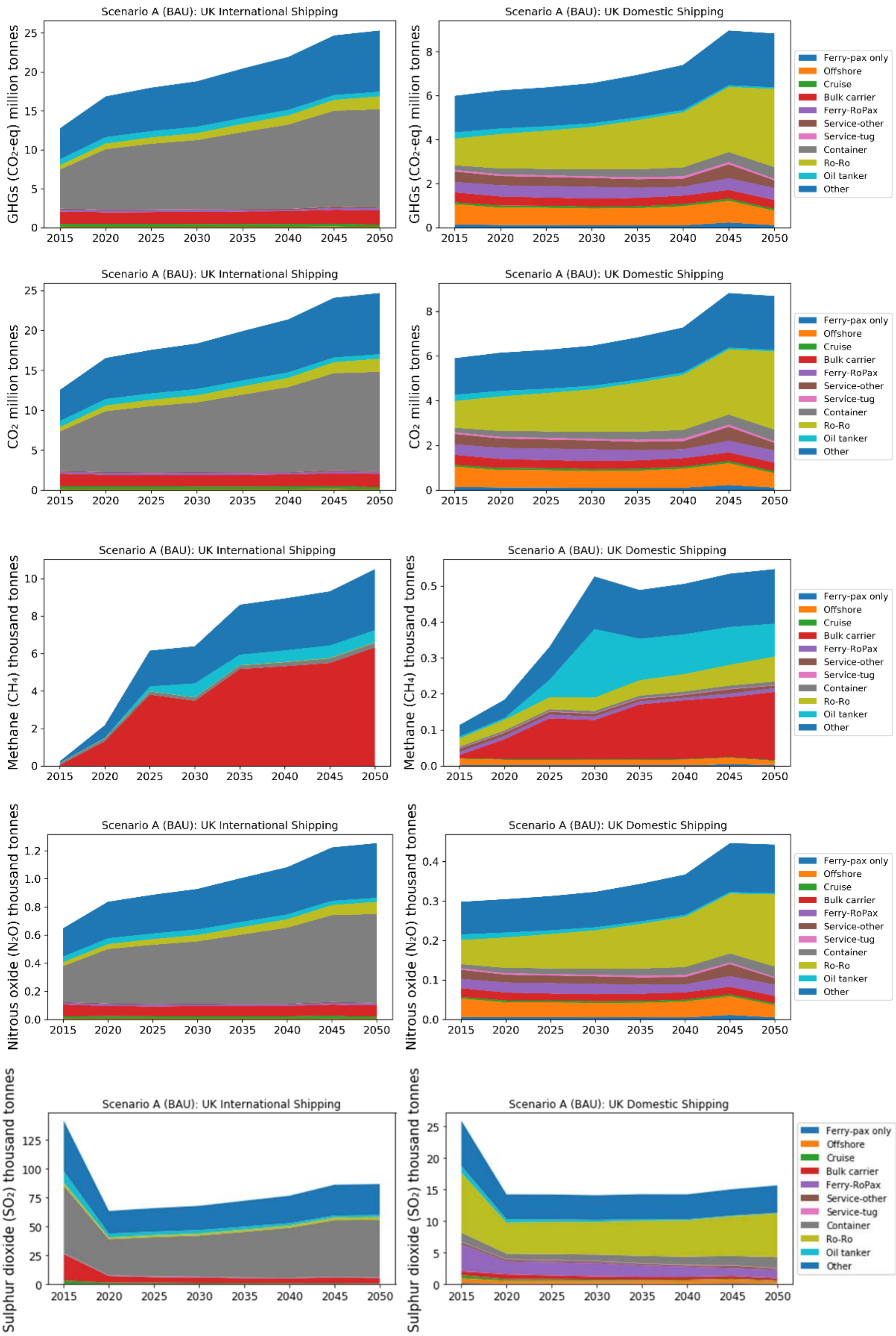
The adoption of these options is estimated to result in lower emissions than would otherwise be the case. Nevertheless, growth in shipping demand is estimated to result in total emissions rising in nearly all categories of emissions. Figure 4 provides an overview of the annual estimates for different types of emissions over time under the BAU scenario for UK international and domestic shipping. In Figure 4, air pollution emissions are global and not constrained to a given geographical area of operation (e.g. only those emissions in close proximity to the UK). Each graph presents the trend over the time period 2016 to 2051 for each gas or set of gases, with the emissions quantified in units of mass (tonnes). In particular, Figure 4 shows that:

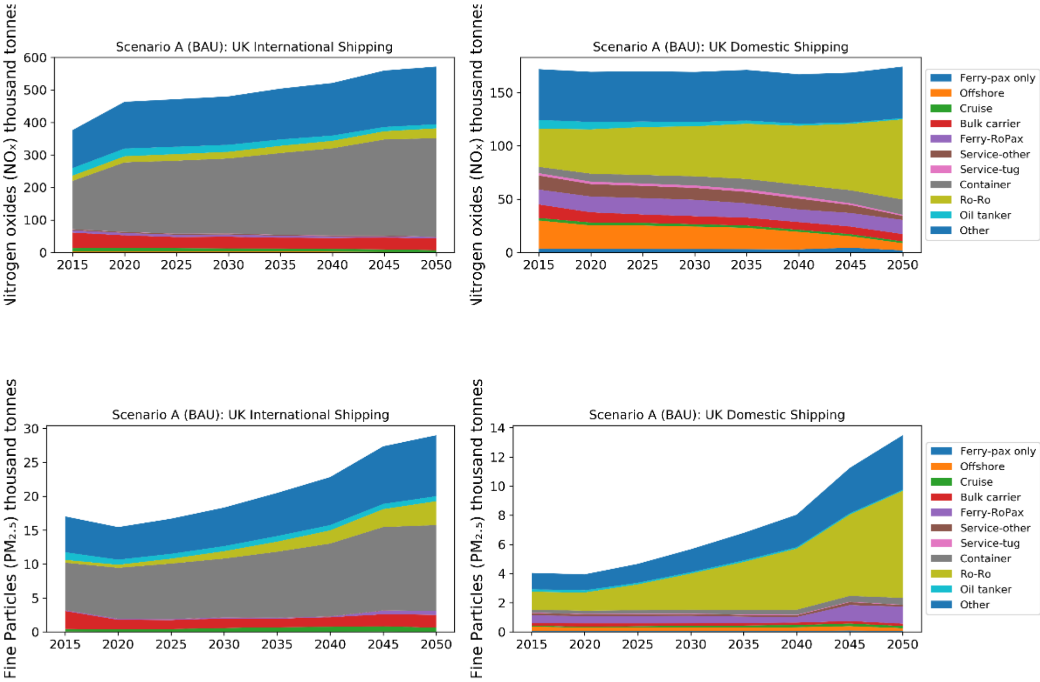
- the total GHG emissions from UK shipping are expected to increase to approximately 34 million tonnes per year by around the middle of the century under BAU, from around 18.5 million tonnes per year in 2016. In particular, the total CH_4 emissions are expected to increase significantly, which is a consequence of the increased adoption of LNG as a marine fuel and the occurrence of methane slip associated with its use (methane, CH_4, is the main component within LNG and is emitted in the exhaust because not all of the fuel is combusted in the engine and any unburnt fuel therefore becomes an exhaust product).
- SO_2 emissions are expected to reduce relative to 2016 levels, which is a consequence of the increased stringency of the fuel sulphur limit in 2020. The stringency is lowered from 3.5% (sulphur content) to 0.5% with direct consequences on SO_2 emissions;
- NOx emissions are approximately stable for UK domestic shipping and show a small increase (approximately 50%), for the UK international shipping. This is explained by increased stringency on NOx emissions (the introduction of NOx tier III in certain areas of operation), and the gradual retirement over time of older ships and engines with lower stringencies of NOx emission regulation. The stringency of regulation is higher for ships operating in Emission Control Areas and so affects domestic shipping more than international shipping; and
- consistent with increased fuel consumption due to demand growth, the level of emissions of fine particles ($PM_{2.5}$) are expected to double by around the middle of the century under BAU, from around 21 thousand tonnes per year in 2016.

Rising shipping emissions under BAU place a burden on other parts of the economy to achieve the UK government's commitment to overall reductions[23]. The BAU scenario shows (in Figures 1 to 3) that many abatement options are only expected to be partly (or not at all) taken up under BAU. Were they to be taken up, there could be substantial additional abatement. The next sections explore the most cost-effective ways to introduce those technologies to different types of ships.

[23] As stated in the UK Climate Change Act 2008.

Figure 4 Annual emissions of GHG and global air pollution from UK shipping under BAU, 2016 to 2051




Scenario A (BAU): UK International Shipping
Scenario A (BAU): UK Domestic Shipping
Nitrogen oxides (NO_x) thousand tonnes
Fine Particles ($PM_{2.5}$) thousand tonnes
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker
Other

3 COST-EFFECTIVENESS OF SHIPPING ABATEMENT OPTIONS

3.1 Introduction

This section presents analysis of the emissions reduction (or 'abatement') potential and cost-effectiveness of all four categories of abatement options that were discussed in Section 2, for the years 2031 and 2051.

The abatement potential is illustrated in terms of marginal abatement cost curves (MACCs). In this context, marginal abatement costs refer to the cost of reducing one additional tonne of GHG emissions from UK shipping in comparison to the BAU scenario.[24] The BAU scenario includes both operational emissions and emissions from ships when they are berthed at port.

MACCs are essentially 'what-if' analyses that show by how much emissions could be reduced by implementing different abatement options and at what cost for each additional tonne of emission. They assume that the order in which those options are implemented is such that the cheapest option is implemented first, followed by the next cheapest, and the next cheapest and so on. They are graphic representations of this analysis: the volume of emissions that could be reduced is shown on the x-axis (this is the 'abatement potential') and the cost for each tonne of emission reduced is shown on the y-axis.

As per standard practice, the cost-effectiveness shown on the MACCs for each abatement option is estimated in terms of the total (net) cost to society of reducing each additional tonne of GHG emissions if each abatement option were implemented by all the ships in the relevant fleet. This is expressed as the £ cost per tonne of carbon dioxide equivalent (£/tCO_2e)[25] and presented in 2018 prices. In addition, the volume of emissions that is estimated to be reduced by each abatement option is expressed in millions (or thousands) of tonnes of carbon dioxide equivalent (MtCO_2e or ktCO_2e). The emissions considered are solely operational emissions (those occurring from the operation of the ship, and not from upstream processes such as fuel production, transport, storage, etc.).

This analysis focuses on the volume of emissions that *could* be reduced by implementing each abatement option; Section 4 considers the volume of emissions that *would be expected to be reduced* under different scenarios. An important distinction between the two sets of results is that results presented in this Section (Section 3) are only inclusive of ship types modelled explicitly by GloTraM. The ship types modelled explicitly are a representative subset making up a large majority (in terms of percentage share of total shipping CO_2 emissions) of all ship types. The results in Section 4 are based on the same set of explicitly modelled ship types, but have been scaled up to reflect all UK domestic and international shipping.

[24] This BAU scenario is referred to as Scenario A in Section 2. Further details on this BAU scenario can be found in Section 2 in this report, and in the separate Technical Annex report.

[25] Carbon dioxide equivalent has been estimated by converting all non-CO_2 emissions to CO_2e by using IPCC conversion factors in line with BEIS (2018).

An estimate of the total emissions reduction achieved for a given marginal abatement cost can therefore be obtained by scaling up the results proportionally. The relevant scaling factors are 1.28 for UK domestic shipping and 1.31 for UK international shipping emissions respectively.

The cost-effectiveness for any particular year is defined in the Technical Annex and can be summarised as:

- **the sum** of annualised investment costs,[26] running costs,[27] changes in charter revenues,[28] fuel cost changes[29] and monetised air pollution emissions changes[30] for that year
- **divided by** the change in GHG emissions saved within that year.

It provides an indicator of the net cost per tonne of GHG saved. Where this is negative it indicates that the benefits of that particular abatement option for that particular ship type outweigh the costs. This does not imply that those measures will be implemented because there may be barriers to the implementation such as split incentives and lack of financial costs of air pollution (Frontier Economics et al, 2019a).

3.2 Marginal abatement cost curves

Figure 5 shows the MACC for UK domestic shipping in 2031. The curve starts at a low, negative level, indicating that it is estimated that some measures to reduce emissions also have the effect of reducing the operating cost of a ship. As can be seen from the colour of the graph, these are predominantly energy efficiency options and slow steaming options (also known as speed reduction). The total emission reduction potential of these options (i.e. breadth of the yellow and orange segments on the x-axis) is estimated to be smaller than the emission reduction potential of the fuel options (indicated in grey).

For the UK domestic shipping fleet, some fuel options, notably ammonia for cargo vessels, are estimated to increase the operating costs of a ship by about £100 per tonne of CO_2e abated (2018 prices), despite the fact that these options also lower emissions to air of pollutants. The most expensive options, on the right of the curve, are fuel cells and batteries, which it is estimated are only applied in ships for which a shift to ammonia or methanol is not possible.

Figure 5 shows that for UK domestic shipping, it is estimated that less than 0.4 $MtCO_2e$ could be saved by implementing measures for which the net social cost is negative, i.e. the benefits outweigh the costs across every tonne of CO_2e saved. In 2031, BAU emissions of CO_2e for UK domestic shipping are projected to

[26] The annualised investment costs can be understood as the payments that a ship owner would need to make if they had taken out a loan to finance the upfront capital cost of a measure, assuming the average cost of capital that shipping companies face (10%) and with the duration of the loan being the lifetime of the measure or the remaining lifetime of the ship, whichever is shorter.

[27] The running costs are the maintenance costs, additional crew costs and any other recurring costs associated with the abatement option.

[28] Changes in charter revenues occur when an option results in a change in the amount of transport work provided, e.g. because a ship changes speed.

[29] Options that reduce GHG emissions typically reduce fuel use. The fuel savings are subtracted from the costs.

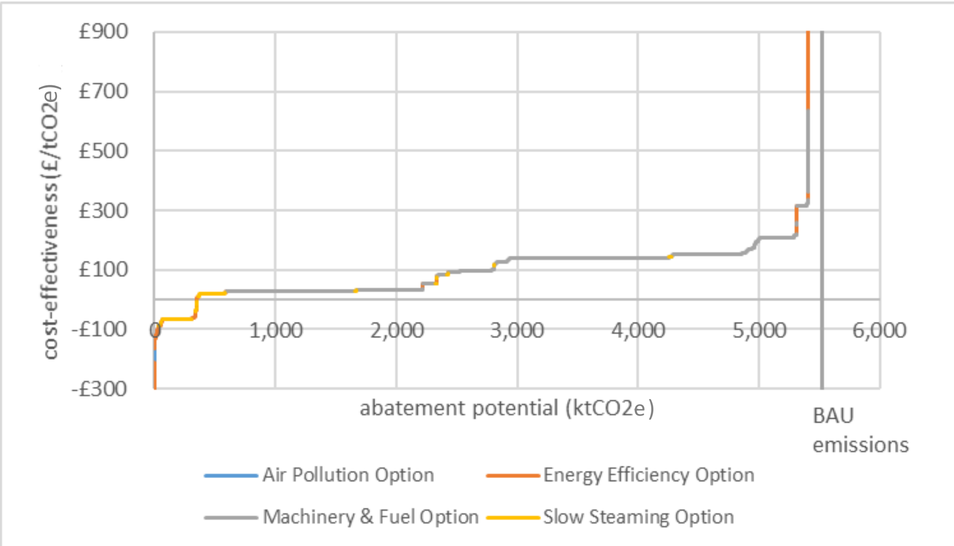
[30] Some options change the amount of air pollutants emitted. These will contribute to changes in air quality. In order to account for these effects, the damage costs of the relevant air pollutant emissions are estimated.

be 5.5 $MtCO_2e$, representing 6% of UK domestic shipping emissions in that year (including emissions from operations at port).

The MACC also shows that, for UK domestic shipping, it is estimated that there are a further 2.1 $MtCO_2e$ (38% of BAU emissions) that could be abated at a cost of less than £88/tCO2e (2018 prices), which is the Department for Business, Energy and Industrial Strategy (BEIS) price of carbon projected for that year[31].

The total abatement potential is estimated to be smaller than the total emissions in 2031 despite the fact that zero carbon fuels have the ability to reduce operational emissions to zero (this is also the case for the other MACCs). The reason for this discrepancy (2%-7%) is that the model constrains the number of engine/fuel options to one: a ship cannot implement both liquefied natural gas (LNG) in an ICE and hydrogen in a fuel cell, for example. Bio- or synthetic LNG have not been included in the options[32]. So, if for a certain ship type, LNG is the most cost-effective engine/fuel option, then LNG will be selected as the engine/fuel option, therefore excluding other engine/fuel options such as hydrogen and ammonia. This means that the MACC will indicate that the operational emissions cannot be reduced to zero for that ship type because that ship cannot convert to other fuel types, and there are no zero emission alternatives for LNG fuels. This occurs infrequently and, in most cases, for ships with a short remaining lifetime.

Figure 5 MACC of UK domestic shipping in 2031 (2018 prices)



Note: BAU emissions include both operational emissions and emissions at port[33].
Source: CE Delft analysis of UMAS modelling

[31] Prices were taken from Department for Business, Energy & Industrial Strategy (2017) 'Data tables 1 to 19: supporting the toolkit and the guidance' and converted to 2018 prices using the GDP deflator. This is available at https://webarchive.nationalarchives.gov.uk/20190105010941/https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/696677/Data_tables_1-19_supporting_the_toolkit_and_the_guidance_2017__180403_.xlsx.

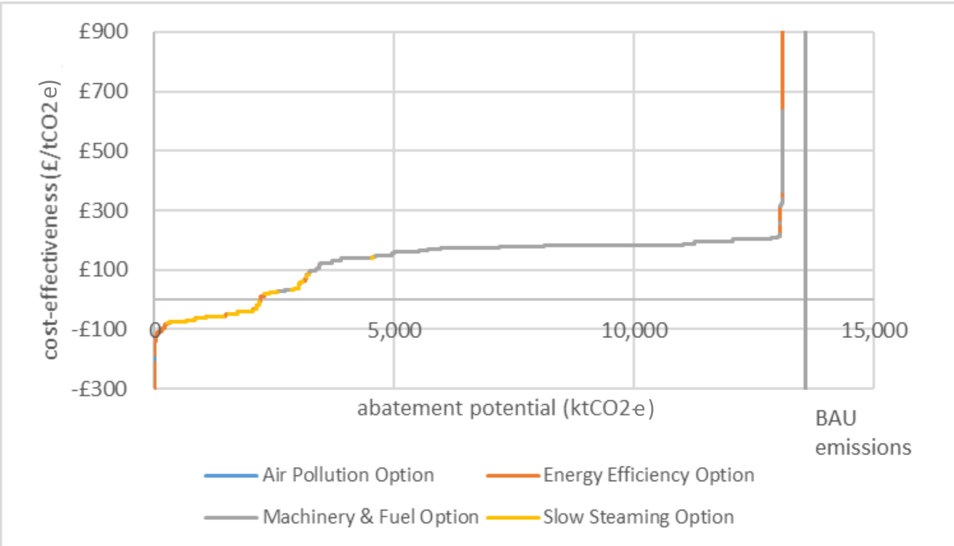
[32] It was agreed with DfT that these options would not be considered. The use of sustainable biofuels is explored in Scenario J in Section 4.

[33] 'Emissions at port' refers to emissions from ships when they are berthed at a port.

Figure 6 shows the MACC of UK international shipping in 2031. The curve has a similar shape to the one for UK domestic shipping, except for the plateau of cost-effective fuel options. This is because the vessels for which some fuel options are estimated to be cost-effective (offshore support vessels, tugs and service vessels) are hardly active in international transport. The abatement potential of slow steaming is estimated to be larger for those ships that sail longer distances and spend relatively more time at sea than ships in the domestic fleet. The curve shows the same plateau for zero carbon fuels, which are estimated to have a cost-effectiveness of between £110 and £200/tCO_2e (2018 prices). This is also higher than for the domestic fleet because the options are estimated to be more costly for larger ships.

The figure shows that it is estimated, for UK international shipping, that more than 2.6 MtCO_2e could be saved by implementing options with a negative net cost per tonne of CO_2e saved. Given that UK international shipping emissions under BAU are projected to be 13.6 MtCO2e, this represents 19% of total UK international shipping emissions. In addition, it is estimated that 1.0 MtCO2e (7%) could be saved at a net cost of less than £88/tCO_2e (2018 prices), which is the BEIS price of carbon for that year.

Figure 6 MACC of UK international shipping in 2031 (2018 prices)



Note: BAU emissions include both operational emissions and emissions at port.

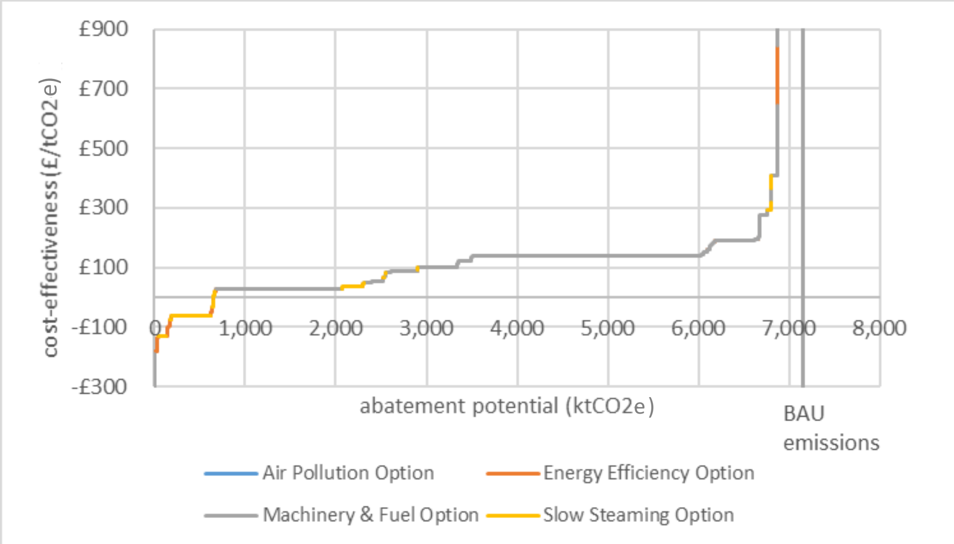
Source: CE Delft analysis of UMAS modelling

By 2051, more abatement options are expected to have been taken up under BAU conditions (as shown in Section 2.3) so there are fewer remaining abatement options.

Figure 7 shows the MACC of UK domestic shipping in 2051. The shape is similar to the 2031 MACC, but there are some notable differences. The cost-effective abatement potential is estimated to be relatively larger in 2051 than in 2031 (9% instead of 6%). These measures (mainly slow steaming options) are cost-effective due to the inclusion of air pollution benefits, as is shown in the MACC without air pollution benefits in Figure 10. In Figure 10, these options are just above the negative net cost per tonne of CO_2e saved.

Figure 7 shows that, for UK domestic shipping in 2051, it is estimated that around 0.7 MtCO_2e could be saved by implementing options with a negative net cost per tonne of CO_2e saved. Given that UK domestic shipping emissions under BAU in 2051 are projected to be 7.2 MtCO_2e, this represents 9% of total UK domestic shipping emissions. In addition, it is estimated that 6.0 MtCO_2e could be saved at a net cost of less than £239/tCO2e (2018 prices) (the price of CO_2e in that year as projected by BEIS[34]). The reason that this potential is so high (84% of total emissions under BAU) is that it includes many zero carbon fuel options, such as ammonia and methanol.

Figure 7 MACC of UK domestic shipping in 2051 (2018 prices)



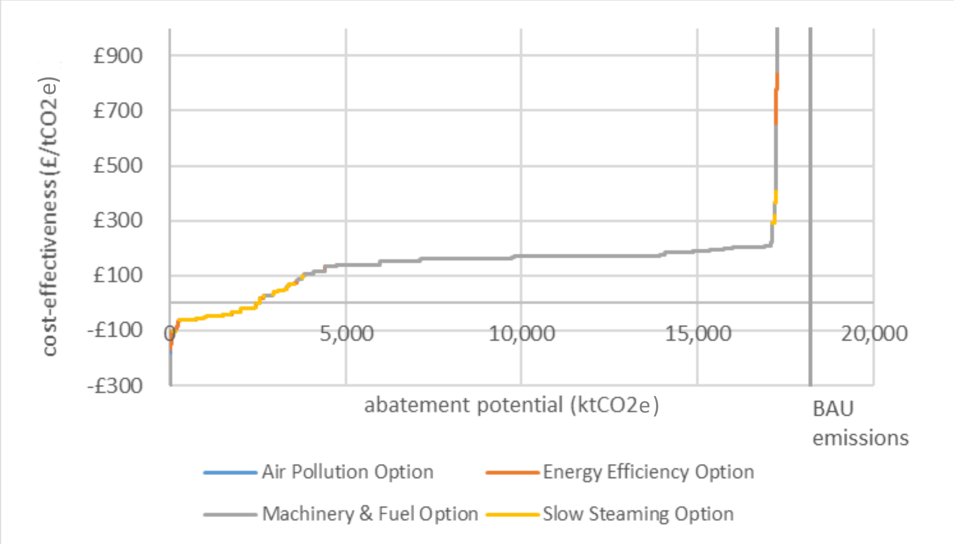
Note: BAU emissions include both operational emissions and emissions at port.

Source: CE Delft analysis of UMAS modelling

Figure 8 shows the MACC of UK international shipping in 2051. Again, the shape is very similar to the one for 2031. It shows that, for UK international shipping, it is estimated that around 2.6 MtCO_2e could be saved by implementing options with a negative net cost per tonne of CO_2e saved. These are predominantly energy efficiency options and slow steaming options. Given that UK international shipping emissions under BAU are projected to be 18.3 MtCO_2e, this represents 14% of total UK international shipping emissions. In addition, it is estimated that 14.6 MtCO_2e (80% of BAU emissions) could be saved at a net cost of less than £239/tCO_2e (2018 prices), which is the BEIS price of carbon projected for that year. These options include the majority of fuel options, almost exclusively ammonia in internal combustion engines.

[34] Prices were taken from Department for Business, Energy & Industrial Strategy (2017) Data tables 1 to 19: supporting the toolkit and the guidance and converted to 2018 prices using the GDP deflator.

Figure 8 MACC of UK international shipping in 2051 (2018 prices)



Note: BAU emissions include both operational emissions and emissions at port.

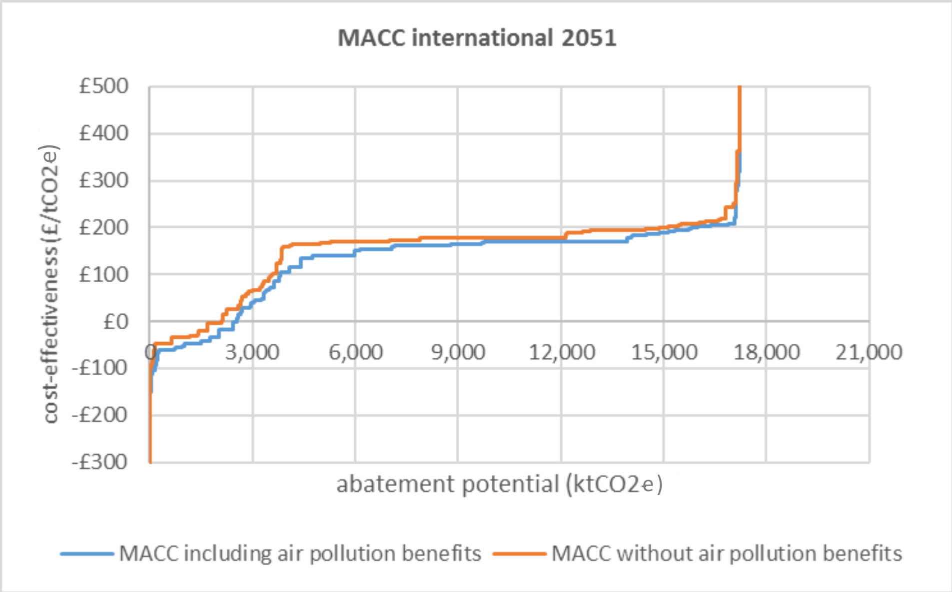
Source: CE Delft analysis of UMAS modelling

Many measures that reduce GHG emissions also reduce air pollutant emissions. For example, measures that result in lower fuel use have lower emissions of SO_2 and often also of NO_x and PM. Similarly, a switch from fossil fuels to cleaner fuels, such as methanol and ammonia, also result in lower emissions of SO_2 and primary PM (although there may be secondary PM associated with the NO_x emission, e.g. secondary inorganic aerosol, SIA). While the impact on total air pollutant emissions may be large, not all of these emissions are relevant to the UK because most emissions occur on the high seas.

To illustrate the importance of reduced air pollutant emissions for the estimated cost-effectiveness, a MACC for UK international shipping in 2051 without accounting for the benefits of lower air pollutant emissions of PM, NO_x and SO_2 is shown in Figure 9 and a comparable MACC for UK domestic shipping in 2051 is shown in Figure 10. These figures show that the impact of including the monetised air pollution emissions changes in the MACC for UK international shipping is not large. This is because most of the change in these air pollutant emissions has not taken been into account due to their distance from the UK[35]. In the MACC for UK domestic shipping shown in Figure 10, the difference is consequently larger.

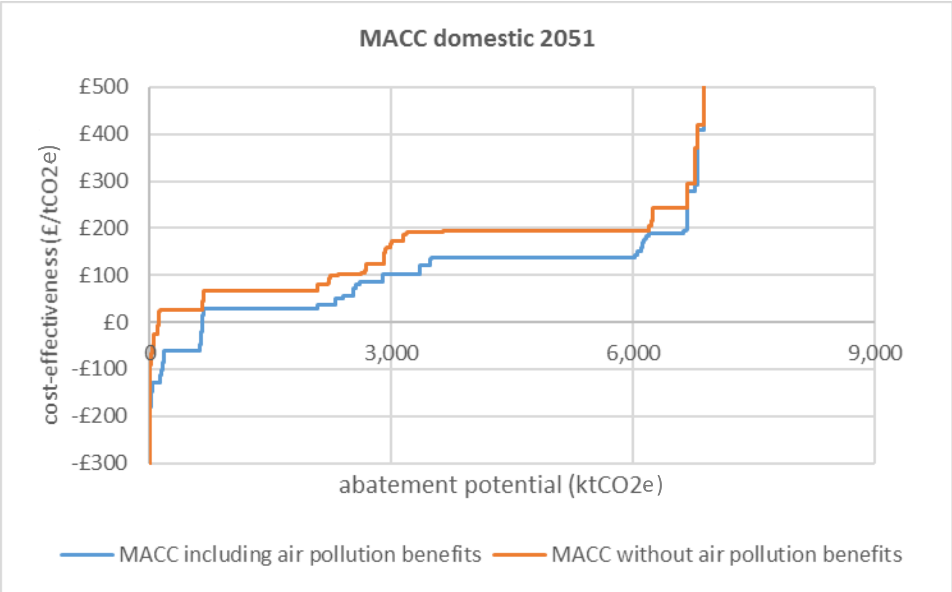
[35] A full explanation of the reasons for this approach is provided in the Technical Annex.

Figure 9 MACC of UK international shipping in 2051 with and without air pollution benefits (2018 prices)



Source: CE Delft analysis of UMAS modelling

Figure 10 MACC of UK domestic shipping in 2051 with and without air pollution benefits (2018 prices)



Source: CE Delft analysis of UMAS modelling

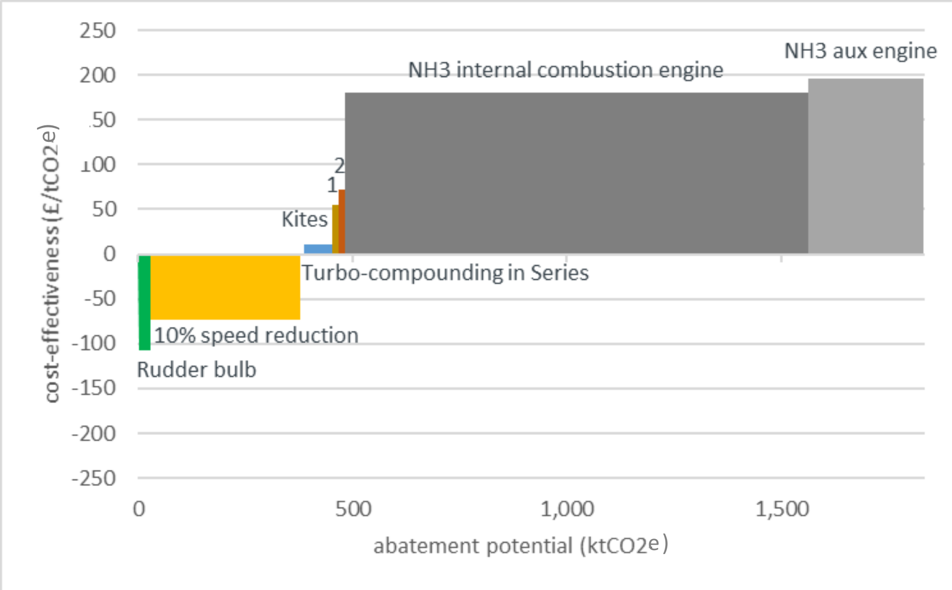
3.3 Take-up of specific emission reduction technologies

The previous MACCs showed aggregate abatement costs for the UK domestic and UK international fleets for 2031 and 2051. They did not show in detail which technologies are the most cost-effective or have the largest potential.

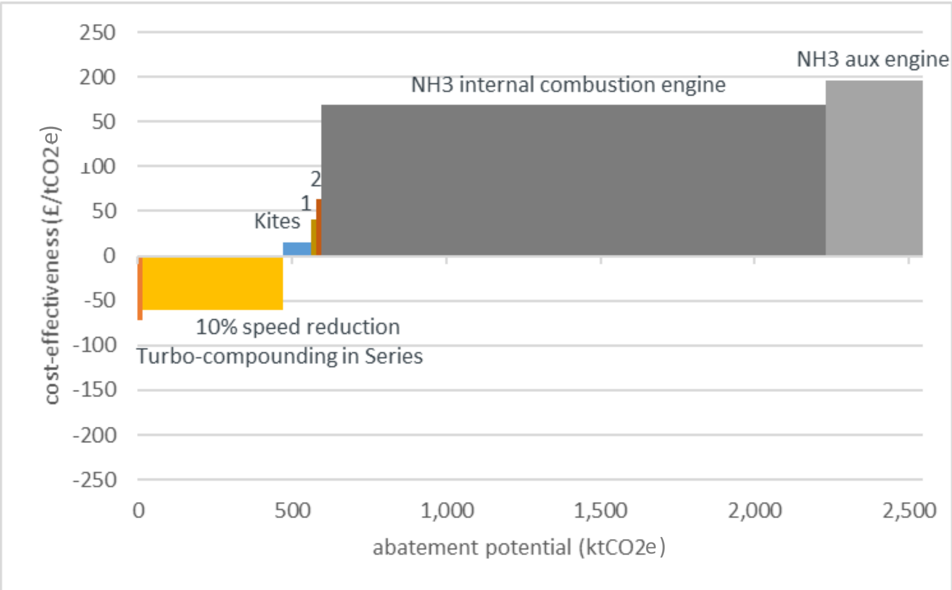
This section presents MACCs of individual ship types that show, for these specific ship types, the order in which the options would be implemented if the cheapest were implemented first and the most expensive last. This representation therefore shows more technological detail than the aggregate MACCs, whereas the aggregate MACCs show the fleet-wide abatement potential and associated costs.

Figure 11 shows the MACC of large container ships (i.e. all ships that are of this particular type) in the UK international fleet in 2031 and 2051. The measure with the largest cost-effective abatement potential is estimated to be a 10% reduction in operational speed; the measure with the largest potential overall is estimated to be the use of ammonia in the main engine. The 2051 MACC is very similar to that for 2031, with the main difference being that one minor option is missing because it is estimated that it has been taken up in the BAU (the rudder bulb), the order of the options changes slightly and the emissions have increased because of the larger fleet.

Figure 11 MACC of 8000-11999 TEU container ships (UK international) in 2031 (top) and 2051 (bottom) (real 2018 prices)



Source: CE Delft analysis of UMAS modelling

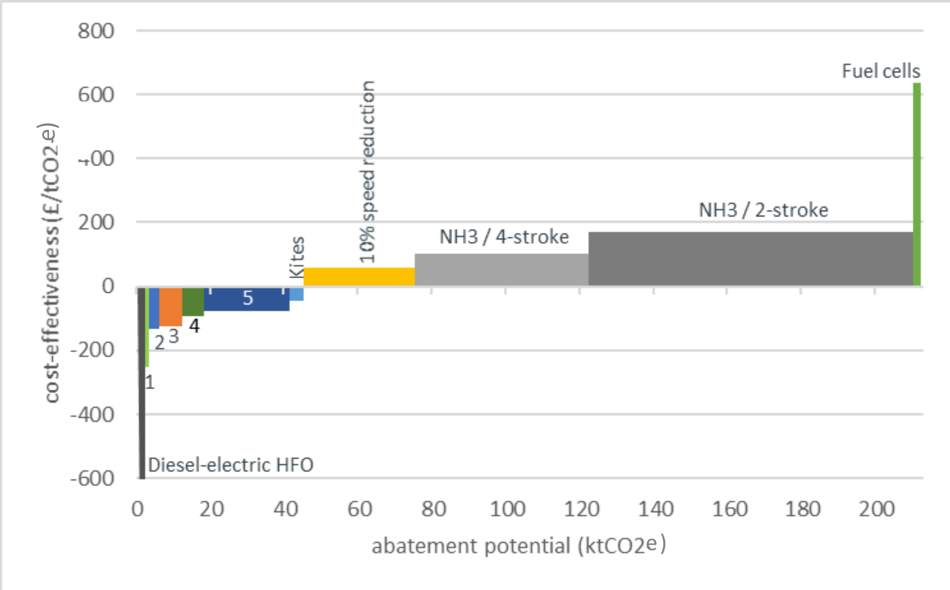


Note: TEU is twenty-foot equivalent unit, a standard size for a container. 1 – Block coefficient reduction; 2 – Air lubrication bubbles

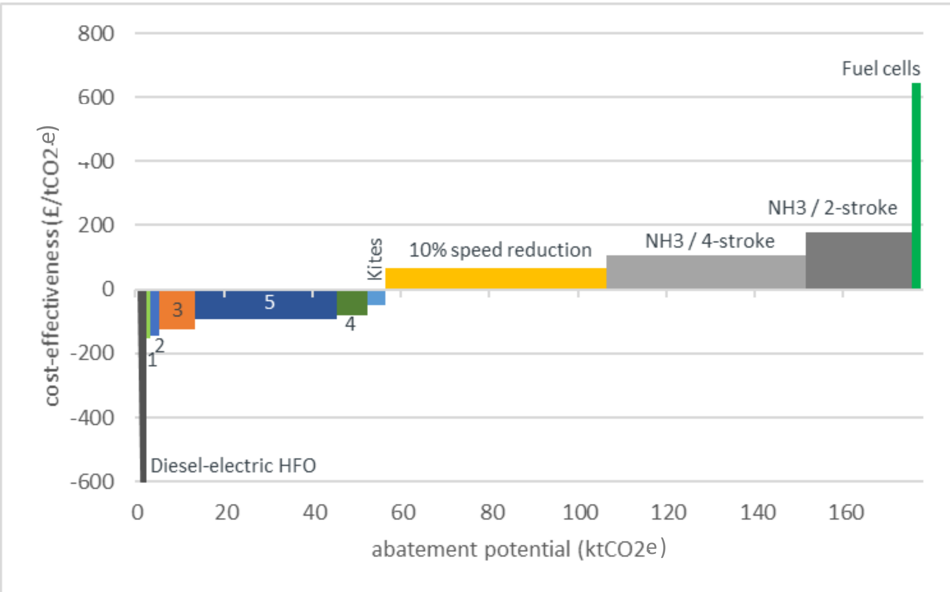
Source: CE Delft analysis of UMAS modelling

Figure 12 presents MACCs for 10,000-34,999 dwt[36] bulk carriers in the UK international fleet in 2031 and 2051.

Figure 12 MACC of 10,000-34,999 dwt bulk carriers (UK international) in 2031 (top) and 2051 (bottom) (real 2018 prices)



Source: CE Delft analysis of UMAS modelling



Notes: 1 – Energy saving lighting; 2 – Boss cap fin; 3 – Turbo-compounding in Series; 4 – Solar power; 5 – wind assistance (wings/rotors/sails).

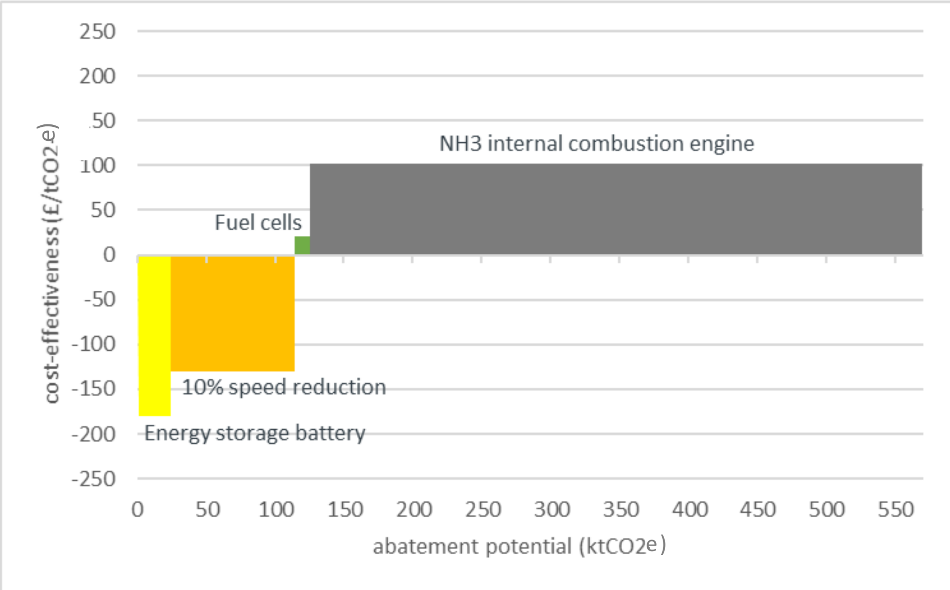
Source: CE Delft analysis of UMAS modelling

[36] Dwt – deadweight tonnes, a measure for the carrying capacity of a ship.

The MACCs shown in Figure 12 contain some options that cannot be installed on the same ship (e.g. 2- and 4-stroke engines are mutually exclusive, as are the two types of wind assistance: kites and wings/rotors/sails). The reason for this is that there are six generations of this type of ship and the option that is most cost effective for each is likely to differ. Consistent with the earlier MACCs, it is estimated that a major share of the abatement potential is from a shift to zero carbon fuel, in this case ammonia.

Finally, Figure 13 presents the MACC of large Ferry-RoPax ships in the UK domestic fleet in 2051. Similar to all the other MACCs, it is estimated that a cost-effective option is slow steaming in the form of a 10% speed reduction. However, here it is estimated that an energy storage battery is the most cost-effective option. After fuel cells, it is estimated that full CO_2 abatement is achieved through application of ammonia as the fuel.

Figure 13 MACC of 2,000+ dwt Ferry-RoPax ships (UK domestic) in 2051 (2018 prices)



Source: CE Delft analysis of UMAS modelling

3.4 Key conclusions

The cost-effectiveness of shipping abatement options is estimated to vary significantly across ship types, sizes and ages. Only a limited number of abatement options are estimated to be taken up under the BAU scenario, despite many being cost-effective (i.e. reducing the overall operating costs of the ship). The reason for this is the existence of barriers like split incentives.

The cost-effective abatement potential (e.g. the share of emissions that can be reduced without increasing the cost of shipping) is estimated to decline over time. The fact that emissions could, at least in theory, be reduced at negative cost implies that some of those same BAU barriers hinder abatement options being taken up. The finding that the volume of emissions that could be reduced at negative cost declines over time reflects that more of these cost-effective options are estimated to be taken up over time.

Although many measures reduce emissions to the air of pollutants as well as GHG emissions, the impact of including the damage costs of air pollution in the cost-effectiveness analysis is estimated to be relatively small for both UK domestic and international shipping. Further verification of this finding could be established through more detailed spatial modelling of emissions to air of pollutants from shipping, using an impact pathway approach.

In the MACCs, a range of technologies are estimated to be taken up in order to reduce emissions compared to the BAU scenario. However, it is estimated that alternative low emission fuels provide the single biggest potential source of abatement. The precise choice of technology varies by timing, routing and ship type. There are no options that are estimated to be cost-effective across all ship types.

Having looked at which options could be cost-effective for different categories of ships and shipping activity, the next section explores scenarios to show the impact on emissions and costs under different policy, fuel availability and price assumptions.

4 ILLUSTRATIVE POLICY SCENARIOS FOR REDUCING UK SHIPPING EMISSIONS

4.1 Developing illustrative scenarios

It is clear from the sections above that there could be many alternative technology–behaviour combinations consistent with meeting the government’s ambitions for zero emissions shipping. To understand the most appropriate combination of technologies and behaviours, it is useful to quantify the trade-offs between environmental objectives and the benefits of reduced emissions on the one hand, and the costs of investing in different technologies, associated infrastructure and behavioural change to reduce those emissions on the other hand.

The costs and impacts of alternatives to meeting government objectives are considered in this section by exploring a number of illustrative scenarios. The scenarios do not reflect government policy, but they are presented for illustration with the intention of providing an evidence base of potential outcomes under different assumptions.

The results are presented in three subsections, each concentrating on a different aspect of comparison between related scenarios:

- the trajectories of GHG and air pollution emissions from UK shipping (Section 4.2);
- the private costs of GHG and air pollution reduction for UK shipping (Section 4.3); and
- the nature of the transition for UK shipping (in terms of timescales and combinations of different abatement options) in the different scenarios (Section 4.4).

Ten scenarios have been modelled (using GloTraM) and are summarised in the table below (Figure 14). Further scenarios and sensitivity analysis could be undertaken to explore particular issues in more depth. This analysis is deliberately broad in order to understand the strategic issues, options, costs and trade-offs in achieving zero emission UK shipping.

The scenarios have been developed to reflect the following illustrative policy variations: the date by which decarbonisation (meaning the total reduction of all operational GHG emissions, i.e. those occurring from the operation of the ship and not from upstream processes such as fuel production, transport, storage, etc.) of all shipping (including UK domestic and UK international) is to be achieved; the speed with which GHG reductions are made in the UK domestic fleet; and the speed with which UK air quality improvements are increased in stringency (see detailed scenario descriptions below).

To reflect uncertainty in the wider context in which shipping environmental policy is being developed, scenarios have also been developed to explore alternative assumptions about the availability of bioenergy, how hydrogen is produced, and the viability of ammonia.

GloTraM estimates both operational and emissions from ships when they are berthed at port. The BAU emissions (both operational and at port) are used in the cost-effectiveness analysis in section 3. When assessing the GHG target of each scenario and the associated costs, the model takes into account the sum of operational and at port emissions. However, for the purposes of reporting results, the emissions presented in section 4.2 show only operational emissions.

When interpreting the detailed results, it should be noted that differences also occur between scenarios because of the model's use of iteration to reach a given GHG target. In this iteration the model applies an estimate of the carbon price trajectory (variation in carbon price over time) needed to achieve a given GHG emissions trajectory (as defined by the scenario, e.g. 50% reduction in GHG by 2050). If the trajectory does not match the objective, the carbon price trajectory is modified and the model is run again. Because of the computational time and cost, this process of iteration is stopped when the model's output GHG emissions trajectory is within certain bounds of the objective (e.g. the model is not iterated until there is a perfect match to the objective). This leads to there being observable small variations in the GHG emissions trajectories between scenarios with the same objectives. In certain cases, when looking at comparisons for a given year, this can reveal counterintuitive results and so these scenario results should predominantly be interpreted as indicative trends and, where possible, differences should be observed as differences in trend rather than specific values.

Understanding how the outcomes vary under the different scenario assumptions is important because there are notable uncertainties when looking over the period to 2051. Of these scenario assumptions, there are two that are particularly important to explore as they can be considered to be largely out of the direct control of the UK government, yet can have a substantial impact on the emissions of UK shipping. They are:

- the global regulation of shipping emissions; and
- the future availability and prices for alternative fuels.

4.1.1 Global regulation of shipping emissions

Global regulation of shipping emissions is led by the International Maritime Organization (IMO). The scenarios in Figure 14 draw on the recently adopted Initial IMO Strategy on the Reduction of GHG Emissions from Ships (IMO, 2018), which suggests GHG emissions from shipping should reduce by at least 50% relative to 2008 levels by 2050. To simulate this initial strategy, the analysis in this section assumes that the start year for any policy mechanism that would be implemented to achieve the aims of the Initial IMO Strategy would be 2025 at the earliest, which approximately coincides with the timescale for the publication of a Revised IMO Strategy (2023).

This scenario analysis also assumes that the policy used to achieve the aims of the IMO's Initial Strategy will be a market-based mechanism (MBM) applied uniformly to all international shipping. In the analysis, this is simulated as a carbon price per tonne set at a level which achieves each scenario's stated GHG reduction objective. No specific assumption is made on the use/redeployment of revenues arising from the simulated MBM.

For most of the scenarios, any IMO policy for international shipping is also assumed to be applied by the UK government to UK domestic shipping. However, for one scenario (Scenario F), the UK is assumed to take a leadership position by increasing the stringency of GHG policy on domestic shipping above the levels set by IMO (global) policy.

4.1.2 Future fuel availability and prices for alternative fuels

Also largely beyond the government’s direct control, yet with important implications for shipping emissions and the take-up of abatement technologies, is the availability and price of innovative potential future fuels. There are uncertainties around the production of alternative fuels, the likely investments and costs of associated shore-based infrastructure, and the nature of the future shipping fleet. These future fuels are a critical part of the scenarios because, as shown in Section 3, they represent a key component of the abatement potential of the sector and are essential for achieving shipping decarbonisation.

The potential low carbon fuels that have been considered in the scenarios can be grouped into synthetic fuels and biofuels:

- **Synthetic fuels**: for the purpose of this study, these include hydrogen, ammonia and methanol which could be produced in a number of different ways, including from fossil fuels (with carbon capture and storage, CCS) or from electrolysis using renewable electricity. The fuel price scenarios adopted for the scenario analysis reflect the costs of the production, distribution, storage and dispensing of these fuels (based on evidence from the literature, as detailed in the Technical Annex). Sensitivity analysis has been carried out to understand the implications of the findings under both production pathways (from fossil fuels or electrolysis). In addition, one scenario (Scenario I) also considers what might happen to outcomes if some fuels (such as ammonia) are not viable.
- **Biofuels**: this includes bio-feedstock variants of conventional fossil fuels: HFO, MDO and LNG. There are notable uncertainties around the future availability of these fuels (given technical and sustainability limits to their production potential) and hence their future price. Best available evidence suggests that the potential availability of these fuels is estimated to be low when considered against the global shipping energy demands, and noting that there are many other sectors that could compete with shipping for the constrained supply (and may be willing to accept higher and more volatile costs). The CCC’s report *Biomass in a Low-carbon Economy* (CCC, 2018) is a key piece of this evidence on both the availability of and applications for biomass. The report recommends a phase-out of biomass use from surface transport and suggests only a limited supply (up to 10% of total fuel demand) of biomass feedstock fuels to aviation by 2050 (and only where the production of the aviation fuel includes CCS). For this reason, for most scenarios, a conservative assumption is adopted such that no biofuel is assumed to be available for shipping. However, one scenario (Scenario J) assumes there is biofuel available for shipping, which helps with understanding the impact on the results if shipping had access to a share of global supply. The scenario estimates that there is an availability of 4EJ (exajoules, $4x10^{18}$ J) for shipping globally. This available supply of biofuel is

derived from literature (Offermann et al, 2011) in combination with an estimate of the share of global bioenergy taken by the shipping industry. The approach is described in the Technical Annex.

Key findings from the scenario analysis are presented in this section with further detail in the Technical Annex. The results described next are presented in terms of:

- the trajectories of GHG and global air pollution emissions (air pollution emissions are global and not constrained to a given geographical area of operation) from UK shipping (Section 4.2);
- the private costs of GHG and air pollution reduction for UK shipping (Section 4.3); and
- the nature of the transition for UK shipping (in terms of timescales and combinations of different abatement options) in the different scenarios (Section 4.4).

Figure 14 Scenarios modelled

	Global GHG policy	UK domestic GHG policy	UK domestic air quality policy	Fuel prices	Bioenergy
A[37]	Agreed IMO policies (e.g. EEDI)	Agreed IMO policies (e.g. EEDI)	Agreed IMO policies (e.g. North Sea SO_x and NO_x ECA (emissions control area), global sulphur cap)	Central fuel price (Hydrogen is assumed to be produced using SMR + CCS; ammonia and methanol prices are also consistent with this assumption)	No use of biofuels for shipping
B	Carbon Price Central	Carbon Price Central	As per Scenario A	As per Scenario A	As per Scenario A
C	Zero GHG from domestic and international shipping by 2040	Zero GHG from UK domestic and international shipping by 2040	As per Scenario A	As per Scenario A	As per Scenario A
D	Zero GHG from domestic and international shipping by 2050	Zero GHG from UK domestic and international shipping by 2050	As per Scenario A	As per Scenario A	As per Scenario A
E	50% GHG reduction from domestic and international shipping by 2050 and zero GHG from domestic and international shipping by 2070	50% reduction of GHG from UK domestic and international shipping by 2050 and zero GHG from UK domestic and international shipping by 2070	As per Scenario A	As per Scenario A	As per Scenario A
F	As per Scenario E	Zero GHG by 2050 from the UK domestic fleet; UK international voyages consistent with global GHG Policy	As per Scenario A	As per Scenario A	As per Scenario A
G	As per Scenario E	As per Scenario E	More ambitious UK air quality policy in ECA	As per Scenario A	As per Scenario A
H	As per Scenario E	As per Scenario E	As per Scenario A	Central fuel price (Hydrogen is assumed to be produced by electrolysis; ammonia and methanol prices are also consistent with this assumption)	As per Scenario A
I	As per Scenario E	As per Scenario E	As per Scenario A	As per Scenario A but no use of ammonia in shipping	As per Scenario A
J	As per Scenario E	As per Scenario E	As per Scenario A	As per Scenario A	Use of biofuels for shipping (central scenario)

Source: Scenarios agreed with DfT

[37] See the Technical Annex for a detailed description of the BAU scenario and the agreed IMO policies.

4.2 Scenario results: trajectories of GHG and air pollution emissions from UK shipping

This section describes the levels of GHG and air pollution emissions from UK shipping in each of the ten scenarios over the period from 2016 to 2051. The focus is on emissions of GHGs and air pollutants (SO_2, NO_x and $PM_{2.5}$). The trajectories of these emissions out to 2100 are included in the Technical Annex. Results are presented across all ship types, sizes and generations modelled.

GHG emissions are presented as CO_2e emissions, using IPCC Fourth Assessment Report (AR4) Global Warming Potential 100-year values to convert CH_4 and N_2O emissions into CO_2e emissions[38].

Scenario A is the same as the BAU scenario discussed in Section 2 and is included for comparison purposes. All the other scenarios focus on levels of GHG reduction and are all estimated to reverse the trend of GHG emission growth that is seen in the BAU scenario.

In order to understand the differences between the scenarios, the results are considered with reference to:

- **Variation 1 – stringency of global GHG policy**: this ranges from stringency in line with the lowest level of ambition in the IMO Initial Strategy to a target of zero (operational) shipping GHG emissions globally by 2040;
- **Variation 2 – stringency of UK domestic policy on emissions**: this relates to the speed with which decarbonisation of UK domestic shipping occurs and the stringency of emissions limits in the North Sea emission control area (ECA); and
- **Variation 3 – fuel availability and prices:** this covers the energy sources or fuels available for UK shipping along with their respective prices and emissions factors.

Upstream emissions from UK shipping (those emissions that occur from any process prior to the fuel's consumption on board the ship e.g. the production, transport, storage, etc.) are also calculated and discussed for the different scenarios.

4.2.1 Variation 1 – stringency of global GHG policy

Figure 15 and Figure 16 demonstrate the impacts on the emissions of GHGs and air pollutants from UK shipping of policies which aim to achieve decarbonisation at different time-points. This is explored using the following scenarios:

- A – BAU (for comparison);

[38] This is in line with BEIS guidance: BEIS (2018) Valuation of Energy Use and Greenhouse Gas Emissions for Appraisal, available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/794737/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal-2018.pdf It is recognised that since this analysis was undertaken, more recent has been published as an update in 2019.

- B – application of BEIS central carbon price (2025 is used as a year indicative of the earliest implementation of an IMO carbon pricing policy and the carbon price is phased in from zero in that start year to align fully with the BEIS carbon price from 2030 onwards);
- C – target of zero (operational) shipping GHG emissions globally by 2040;
- D – target of zero (operational) shipping GHG emissions globally by 2050; and
- E – target of 50% absolute reduction in (operational) shipping GHG emissions globally by 2050 (compared to 2008); zero (operational) shipping GHG emissions globally by 2070.

Figure 15 Annual (operational) UK international and domestic shipping GHG emissions under Scenarios A to E

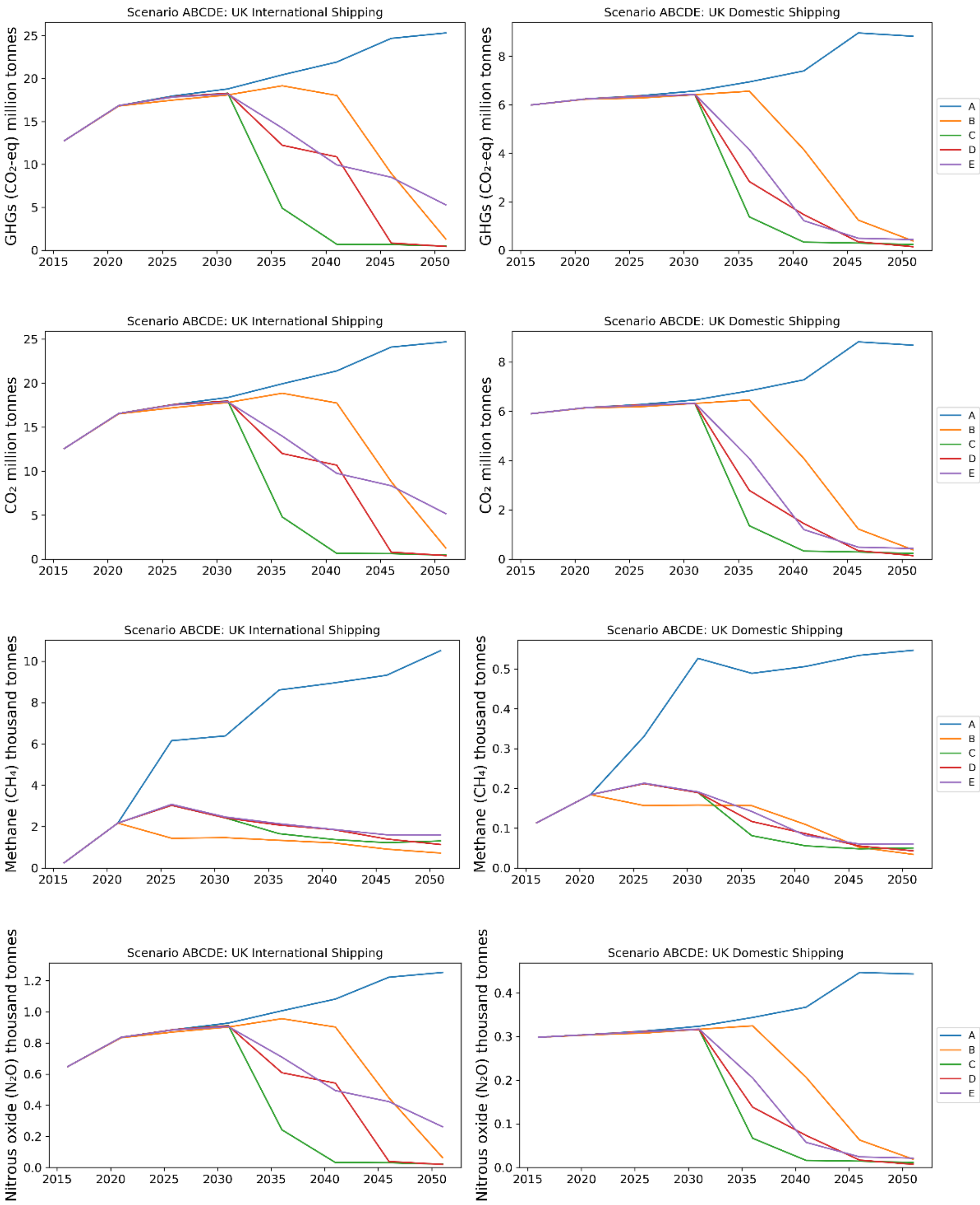


Figure 16 Annual (operational) UK international and domestic shipping air pollutant emissions under Scenarios A to E

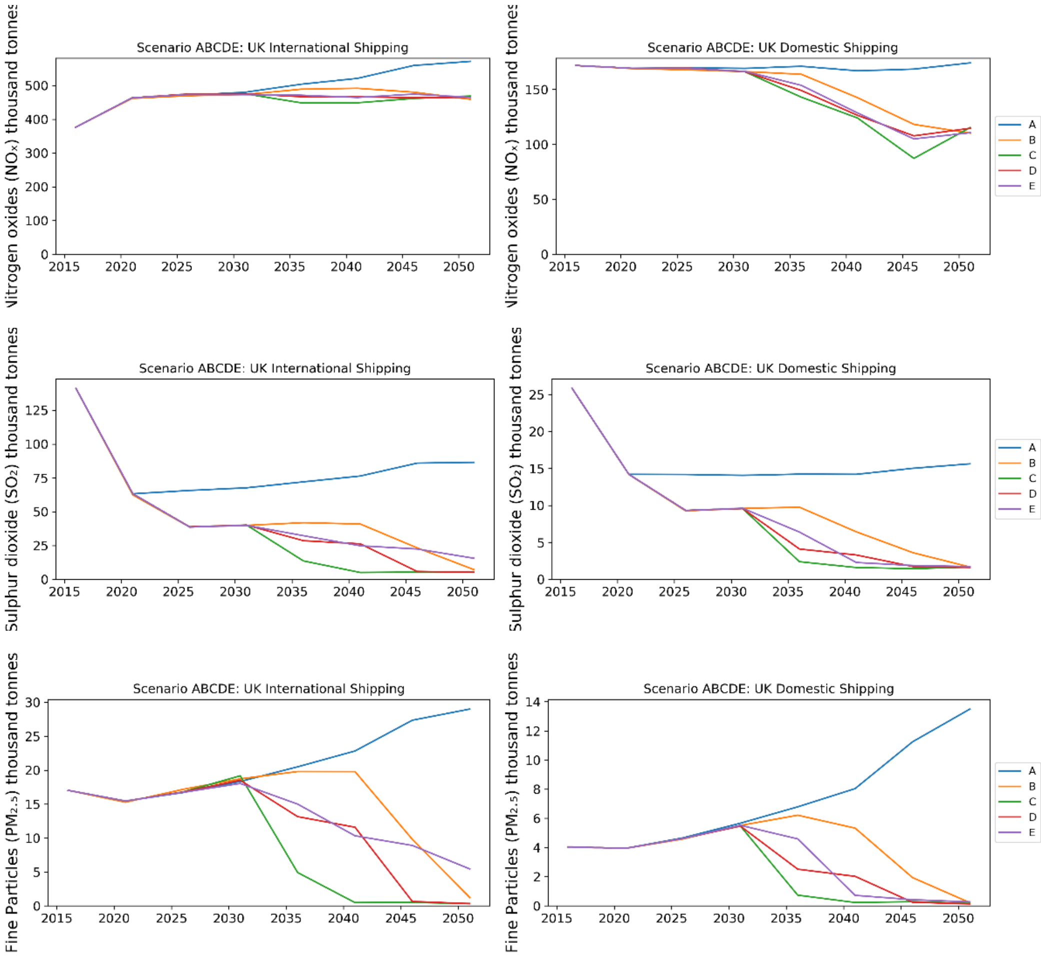


Figure 15 shows that relative to Scenario A (BAU), all other scenarios are able to achieve significant absolute reductions in the (operational) GHG emissions from UK shipping. This is as expected as the modelling was performed to achieve this objective, but this is achieved using different combinations of abatement options, depending on the scenario. Reductions in the (operational) GHG emissions from UK shipping in Scenario E are more modest than for other scenarios because this scenario is aiming for zero (operational) GHG emissions from shipping globally by the later date of 2070 and not 2050 or earlier, as is assumed in other scenarios (apart from the BAU). GHG emissions in Scenario C and D do not completely reduce to zero, but a small residual level of emissions remains. This is a feature of the modelling and the way iteration is used to obtain a given GHG emission trajectory and the iterations stopped once an appropriate accuracy has been reached, see Section 4.1.

The scenarios suggest that to achieve decarbonisation (in terms of operational emissions) of the UK domestic and international shipping fleets by 2040 and 2050 (i.e. over a 15-year time frame or 25-year time frame respectively) would require a very steep reduction in emissions over a relatively short period of time.

As was shown in Section 2, under the BAU scenario, UK international and domestic shipping (operational) GHG emissions are projected to increase significantly between 2016 and 2051. This implies that increases in shipping activity are expected to outweigh any increases in fuel efficiency that may otherwise come about over that time period under BAU. So, reducing emissions in line with the scenarios' targets requires a substantive change in the trend.

Under Scenario B, the central BEIS carbon values per tonne of GHG (CO_2e)[39] are applied to the cost of fossil fuels used by shipping, as described in the Technical Annex. This carbon price represents an increase in the cost of operating using fossil fuels and therefore provides the incentive to take up energy efficiency options and improves the relative cost competitiveness of non-fossil alternative fuels. The results estimate that under this carbon price scenario, the UK shipping sector would be expected to experience a significant (operational) GHG reduction relative to BAU, particularly by 2051. By 2051, the (operational) GHG emissions from UK shipping are projected to reduce to around 95% below where they would otherwise be expected to be under BAU, which is very close to achieving full decarbonisation by 2051 (which is also the aim of Scenario D). This implies that the carbon price needed to decarbonise UK international and domestic shipping is similar to standard carbon values used by the UK government for appraisal purposes. It is also worth noting that Scenario B is more ambitious than the Initial IMO Strategy's lowest level of ambition (50% reduction by 2050).

As a result of the current international IMO regulation, which includes a global limit on fuel sulphur content entering into force in 2020, the SO_2 emissions reduce significantly and the primary PM emissions reduce more modestly between 2016 and 2020 in all scenarios (including BAU). The changes to domestic emissions are more modest under BAU between 2016 and 2020. This is because the domestic fleet is already (in 2016) using a larger proportion of low sulphur fuel (MDO) than the international fleet because the domestic fleet comprises, on average, smaller ship sizes. Therefore, domestic ships are less likely to have HFO-compatible machinery and so have no option to burn high sulphur fuel.

NO_x emissions in Scenario B to E, however, generally increase above 2016 levels for international shipping in all scenarios and decrease below 2016 levels for domestic shipping. This is because the domestic fleet spends more time (and by association produces more of its emissions) in the ECA, where the stringency on NO_x regulation is higher. The international fleet spends most of its time outside of the ECA, with lower NO_x regulation and significant demand growth that creates an increase in emissions in these ships' total annual emissions. For both domestic and international shipping, NO_x emissions are not significantly reduced as a result of the GHG objectives of the different scenarios. This is because the most cost-effective pathway to meet the GHG objective as defined in the relevant scenarios is to use ammonia in combination with internal combustion machinery. With this combination, NO_x emissions are not removed, but can be compliant with the regulation on NO_x through the use of exhaust treatment devices (e.g. SCR, which works by reacting the NO_x in the exhaust with a catalyst, or exhaust gas recirculation (EGR), which works to flow some of the exhaust back into the engine). Ammonia, however, has no sulphur content, and, therefore, if it were to be the most

[39] Department for Business, Energy & Industrial Strategy (2018) "Data tables 1 to 19 supporting the toolkit and the guidance". It is recognised that since this analysis was undertaken, BEIS guidance has been updated and was published in 2019.

prevalent fuel in the future, air pollution emissions other than NO_x would be mostly negligible. Furthermore, NO_x emission reductions could be achieved with different machinery options (e.g. fuel cells), or potentially with the use of SCR technology set at higher levels of NO_x reduction (e.g. going beyond the stringency in the IMO regulation).

Therefore, scenarios that achieve significant GHG reductions are also likely to result in significant reductions in emissions of most air pollutants apart from NO_x, but particularly SO_2 and PM.

4.2.2 Variation 2 – stringency of UK domestic policy on emissions

Figure 17 and Figure 18 present the emissions profiles for UK international and domestic shipping for each of GHG emissions and air pollutants over the time period 2016 to 2051. These are shown for three scenarios that are intended to demonstrate the outcomes if the UK domestic emissions policy were more stringent than global policy. The scenarios are:

- A – BAU (for comparison)
- E – target of 50% absolute reduction in (operational) shipping GHG emissions globally by 2050 (compared to 2008); zero (operational) shipping GHG emissions globally by 2070;
- F – as Scenario E, but zero (operational) GHG emissions by 2050 for UK domestic shipping (UK international shipping aligned with global emissions target); and
- G – as Scenario E, but more stringent levels of regulation on UK air pollution emissions (tightening of UK-neighbouring ECAs).

Figure 17 Annual (operational) UK international and domestic shipping GHG emissions under Scenarios A, E, F and G

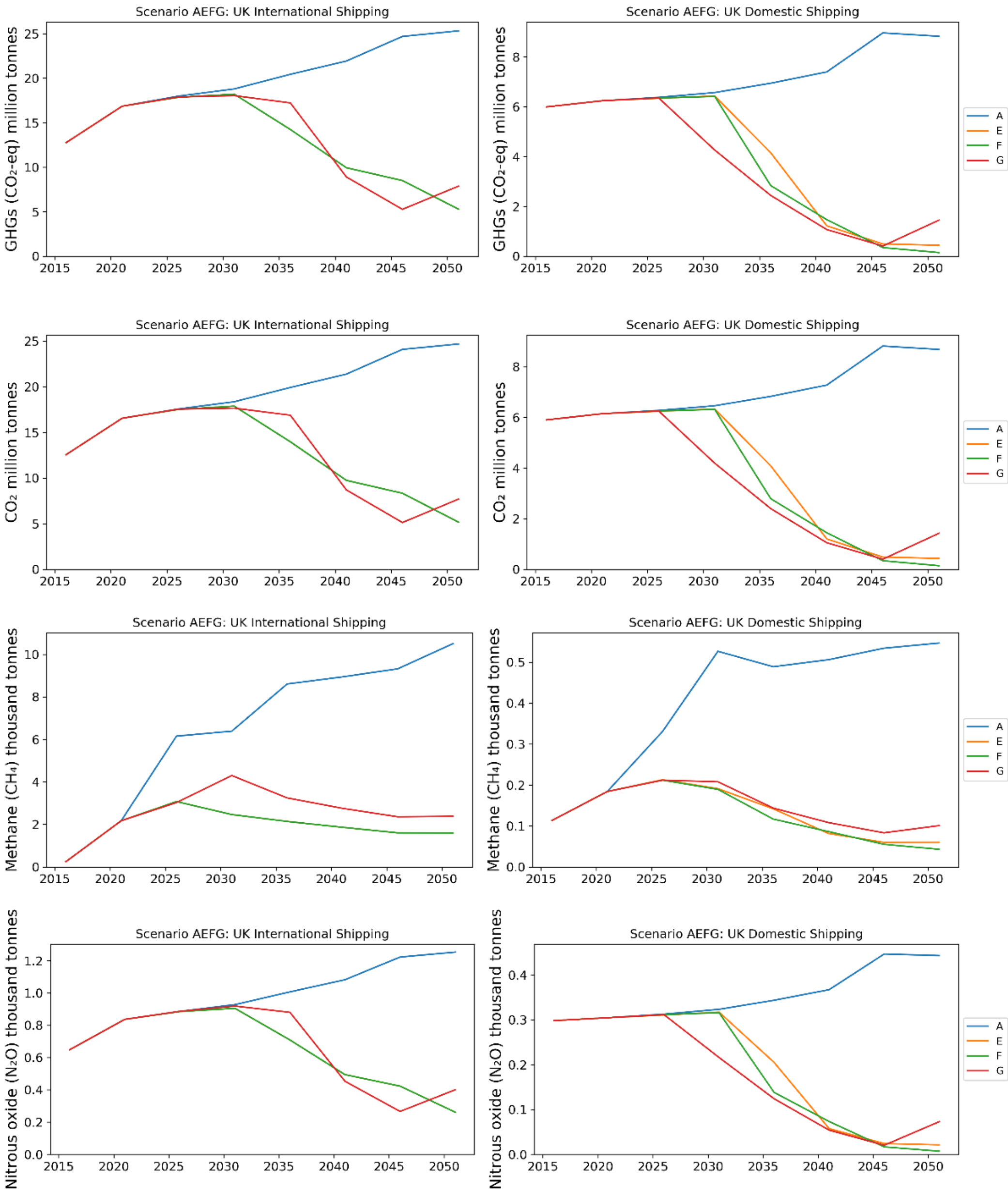
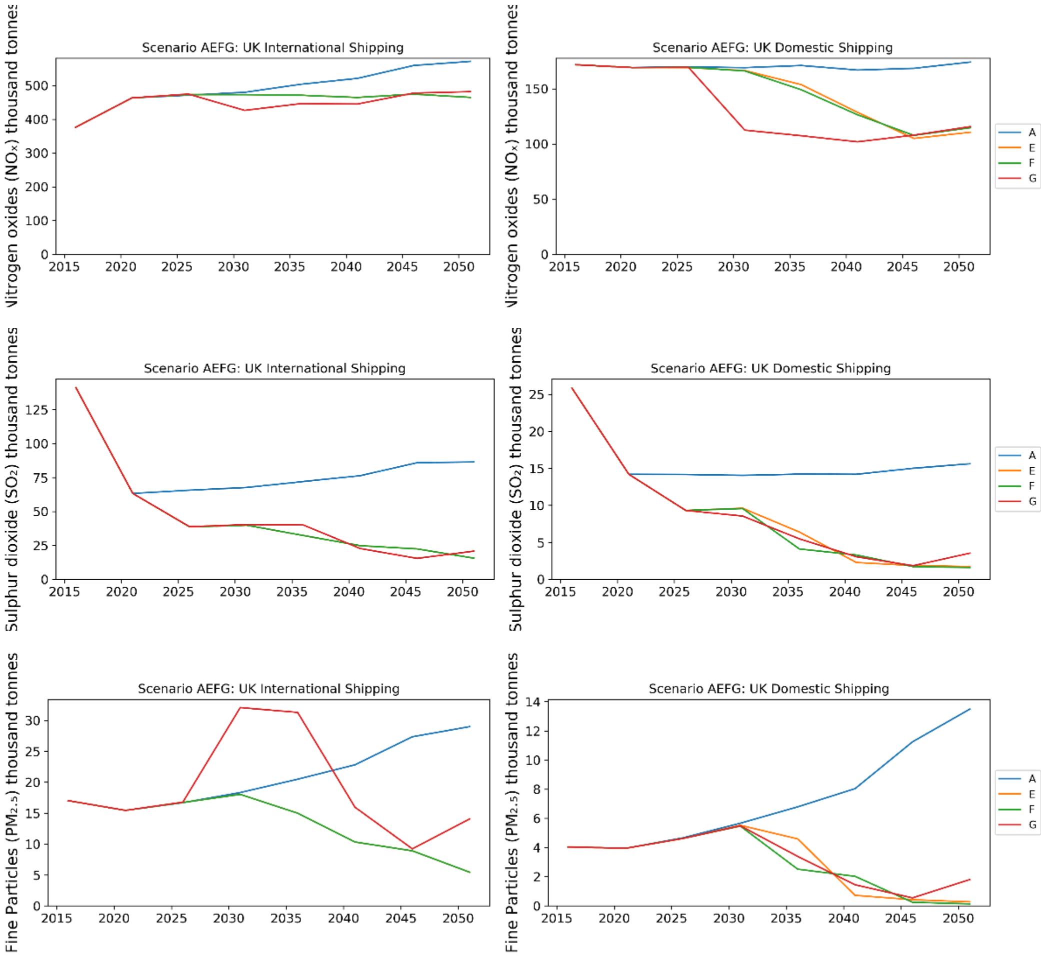


Figure 18 Annual (operational) UK international and domestic shipping air pollutant emissions under Scenarios A, E, F and G



Neither Scenario F nor G has any significant variation relative to Scenario E in terms of UK international shipping (operational) GHG emissions. This is as expected because all three scenarios apply the same GHG stringency on this fleet. Scenario F is actually identical to Scenario E for international shipping emissions (it uses the same results because the applied policy scenario is identical). For this reason Scenario E is not visible in the plots of international shipping. Scenario G has slightly higher GHG emissions than Scenario E in 2051. This small difference should not be attributed any meaning because it is a function of the way the modelling iterates to find a solution, see Section 4.1.

The impacts on UK domestic shipping's (operational) GHG emissions, relative to Scenario E, are modest. Part of the explanation for this is that under the policy needed to drive the international fleet's (operational) GHG emissions to a 50% reduction in 2050 relative to 2008 globally (Scenario E), the UK domestic shipping fleet's (operational) GHG emissions were already approximately zero in 2051. **This implies that the cost of reducing emissions in the domestic fleet is lower relative to the international fleet**.

Scenario G (which tightens air pollution limits in UK-neighbouring ECAs) sees a slightly faster rate of GHG reduction during the 2030s than Scenario F (zero operational GHG emissions from UK domestic shipping by 2050). This implies that the combination of more stringent air pollution emission regulation with this stringency of global GHG regulation closes the gap to zero emission fuels faster than just targeting zero GHG emissions in 2050. A further interpretation of these results is that a higher stringency (of zero operational GHG emissions by 2050) could be applied to the UK domestic fleet without expecting there to be large differences in the nature of the transition, because under any of Scenarios E, F or G, the fleet’s rate of GHG reduction is similar.

The emissions of air pollutants show that in Scenario G (which is showing tighter UK air pollution controls), the UK domestic shipping fleet’s (operational) NO_x emissions reduce faster than in Scenarios E and F during the 2030s. However, there are no significant differences in the levels of (operational) SO_2 emissions. Primary PM emissions are consistent between Scenarios E and F but in Scenario G show a significant increase during the 2030s. This increase is associated with the different choice of fuel mix in Scenario G (relative to Scenario E). There is more use of scrubber technology (and HFO) to comply with the 2020 sulphur limit than other scenarios.

In the 2040’s, the PM 2.5 trend in Scenario G realigns with Scenario E and F as the fuel mix then switches to ammonia. The explanation for the alignments between Scenarios E, F and G on pollutants is that the sulphur and primary PM trends are being driven by GHG regulation and the fleet’s move away from fossil fuels to low GHG fuels, which are naturally low sulphur. A small increase in 2051 in Scenario G relative to Scenario E for some air pollutants can be attributed to the small variability introduced into the results by the iteration in the model, see Section 4.1.

4.2.3 Variation 3 – fuel availability and prices

Figure 19 and Figure 20 show the impacts on the emissions of GHGs and air pollutants for each of UK international shipping and UK domestic shipping over 2016 to 2051 when exploring alternative scenarios relating to the availability and price of fuels.

The relevant scenarios are:

- A – BAU (for comparison);
- E – target of 50% absolute reduction in (operational) shipping GHG emissions globally by 2050 (compared to 2008); zero (operational) shipping GHG emissions globally by 2070;
- H – as Scenario E, but with hydrogen/ammonia/methanol produced by electrolysis instead of SMR with CCS;
- I – as Scenario E, but with no use of ammonia in shipping; and
- J – as Scenario E, but relaxing the constraint of no availability of biofuel to include a supply that can fulfil a part of shipping’s energy demand.

Figure 19 Annual (operational) UK international and domestic shipping GHG emissions under Scenarios A, E, H, I and J

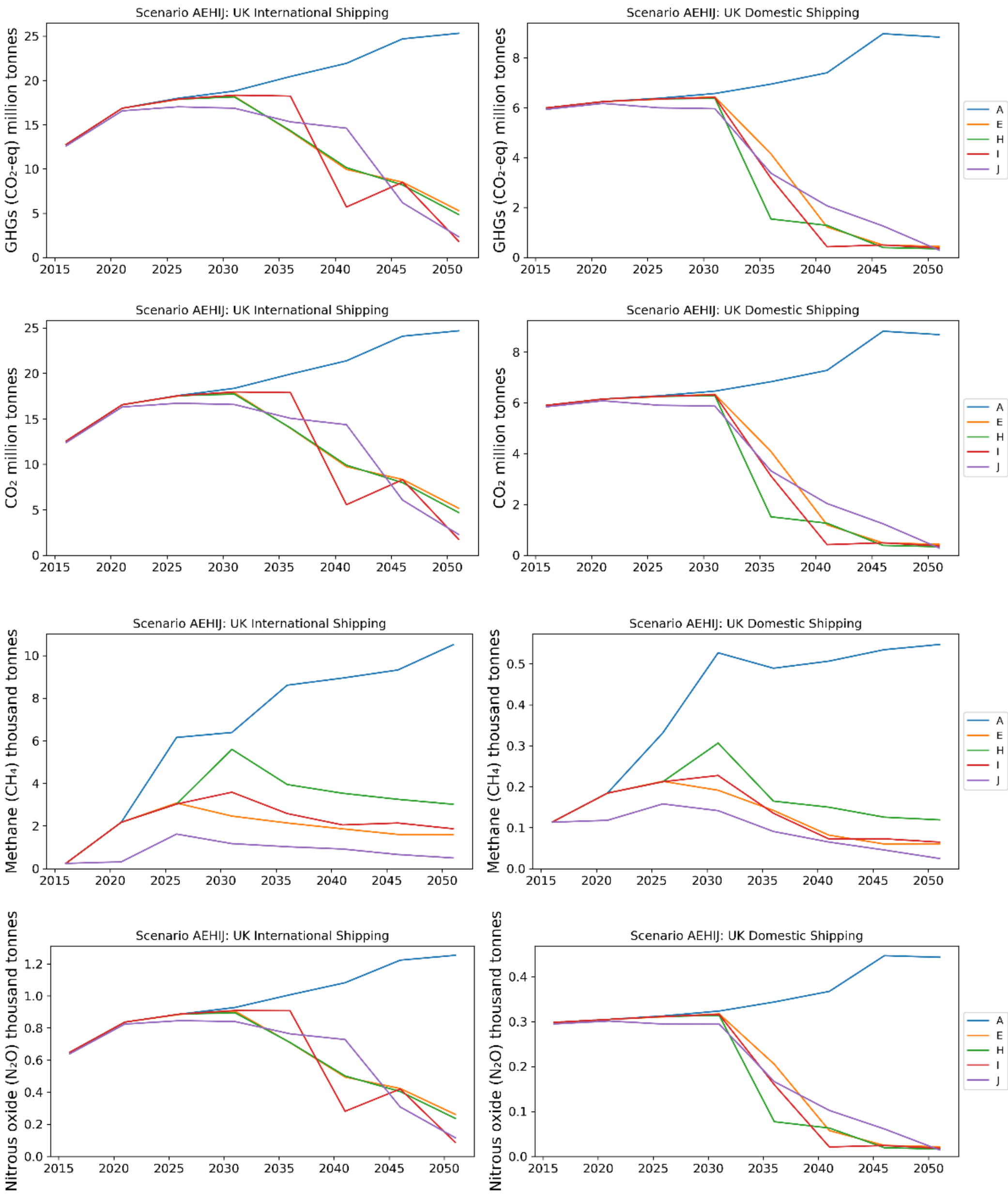
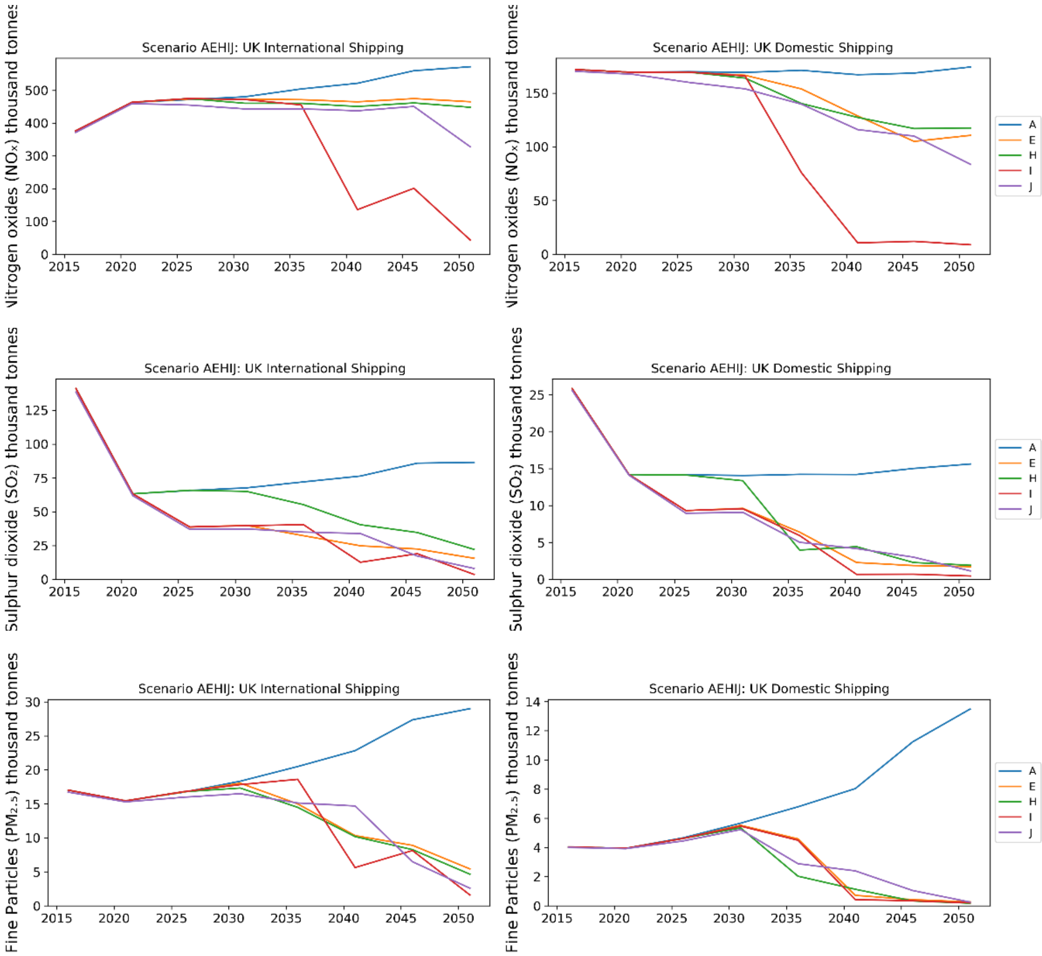


Figure 20 Annual (operational) UK international and domestic shipping air pollution emissions under Scenarios A, E, H, I and J



When comparing the impacts on UK international and domestic shipping emissions across Scenarios E, H, I and J, there are some differences between scenarios, but they each reduce GHG emissions out to 2051. The main explanation for these differences is the way the modelling iterates to find a solution that is close to the intended emission trajectory, as described in Section 4.1. Besides these small variabilities, the similarity in trend and absolute values is to be expected because the scenarios are all defined with the same GHG reduction objective of an absolute reduction of 50% (on 2008 levels) by 2050. Consistent with the findings for Scenario G, the domestic fleet's GHG reduction occurs faster than the international fleet's under these global policy scenarios (e.g. all of Scenarios E, H, I and J), and the domestic fleet is approximately 100% de-carbonised by 2050.

In terms of the impacts on air pollutants, Figure 20 shows that for both UK international and domestic shipping, the changes in the totals of operational air pollutant emissions of SO_2 and primary PM broadly reflect the changes in GHG emissions; in other words that policy to reduce GHG emissions has driven SO_2 and primary PM reduction. This is similar to results for other scenarios and is related to the fact that the movement away from fossil fuels (including through the move to a mix of biofuel and synthetic fuel in Scenario J) naturally reduces SO_2 and PM emissions. There may, however, be important secondary PM air pollution and nitrogen deposition implications resulting from the NO_x emissions, but these have not been considered here (the analysis considers primary PM sources only).

In most of these scenarios, the levels of operational NO_x emissions from UK shipping do not reduce in the same way as SO_2 and primary PM emissions. This is because both biofuel and ammonia combustion (the technology pathways associated with most of these scenarios) still have comparatively high NO_x emissions. The exception to this is Scenario I, which does not allow the use of ammonia and where the fleet moves instead to the use of methanol (see Section 4.4.3), which is associated with lower NO_x emissions.

4.2.4 Upstream CO_2e emissions trajectories for UK shipping, all scenarios

The previous analysis showed the impacts on operational GHG emissions. This section considers upstream GHG emissions. Operational emissions are those emissions associated with ships in operation. Upstream emissions are those associated with any process that is associated with the fuels before they are transferred to the ship (e.g. emissions associated with production, transport, storage etc.). Upstream air pollution emissions can also occur and be different for different scenarios (depending on the fuels used by shipping and how they are produced). They have not been modelled and included here, but instead the focus is on upstream GHG where the most significant risk of unintended consequences (moving GHG emissions from shipping to land-based sources) is considered to occur. Figure 21 shows upstream CO_2e emissions from UK shipping for Scenarios A to J.

Figure 21 Annual Upstream CO_2e emissions for UK international and domestic shipping

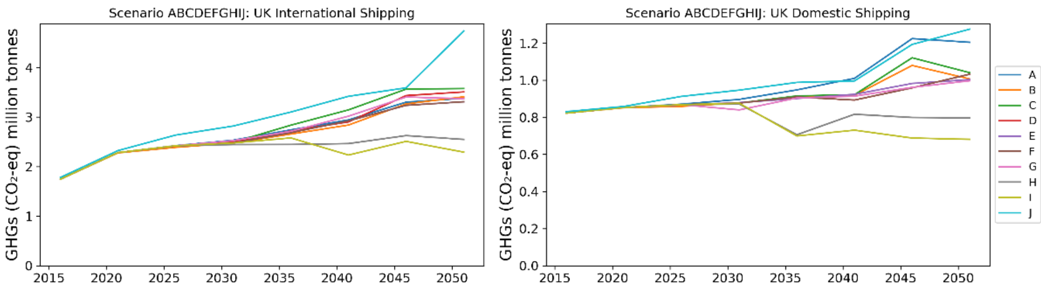


Figure 21 shows the upstream GHG emissions from UK shipping across all of the scenarios modelled. This reveals some differences across the scenarios, particularly by 2051. Overall, upstream emissions are material and remain material out to 2051 in all scenarios. Their materiality is indicated by their magnitude relative to the operational GHG emissions. For UK domestic and international shipping, upstream emissions are estimated to both be approximately 14% of operational GHG emissions respectively in 2016 (domestic upstream emissions are fractionally above 14%; international upstream emissions are fractionally below 14%). Domestic upstream emissions are a slightly higher percentage (relative to operational emissions) because of the greater share of MDO relative to HFO in the domestic fleet's fuel use and the small upstream emission factor difference between these fuels. As the operational emissions reduce in all scenarios (except BAU) out to 2051 and upstream emissions only remain approximately constant or increase, upstream emissions will increase in significance unless action is taken to assist their reduction.

The explanation for upstream emissions remaining material is that even when the sector switches to fuels derived from hydrogen, there remain some GHG emissions associated with the hydrogen's production. In the case of Scenarios B, C, D, E, F, G, I and J, the hydrogen is assumed to be produced from SMR (using fossil fuel as a feedstock) in combination with CCS, and a small residual emission from the use of fossil fuel is expected. Scenario H uses electricity to produce hydrogen and has some of the lowest upstream emissions. But these are still non-zero as there is assumed to still be some fossil fuel used in the production of electricity. However, Scenario H has the potential for the lowest upstream emissions if that electricity supply is further decarbonised. Scenario I has similar upstream emissions to Scenario H, which is because this scenario sees a switch to a synthetic methanol as opposed to ammonia, and the upstream GHG emissions of methanol are assumed to be slightly lower than those of ammonia. This is because for the processes assumed for production of these two gases there is a small emission of CH_4 and N_2O for ammonia, but none is assumed to be produced in methanol production. There is also a slightly higher emission of CO_2 in the ammonia production process than in the methanol production process. These differences are not large and the variability between the assumed upstream ammonia and methanol emissions is smaller than the uncertainty of how these upstream emissions will evolve as the wider energy system evolves over this time period, therefore the result should not be used to conclude a significant comparative advantage of methanol over ammonia in terms of upstream emissions.

Scenario J sees some of the highest upstream emissions, which is primarily because of the assumed higher upstream emissions factors associated with biofuels. The specifics of those emissions factors and their sources are defined in the Technical Annex.

4.3 Private costs of GHG and air pollution reduction for UK shipping

The costs to business associated with achieving different levels of GHG and air pollution emission reduction include capital costs (the costs associated with the purchase of, or investment in, ships and equipment); voyage costs (which are dominated by fuel costs); non-fuel operating costs (e.g. costs to maintain ships and equipment); and opportunity costs (e.g. reductions in revenue that can occur as equipment is fitted to a ship that takes up space that could be used for cargo or because of changes in operating speed). This section focuses on how changes to these costs vary when looking across the ten scenarios.

The focus of this section is on the costs. Benefits should also be considered but are beyond the scope of this particular study. However, there are some benefits to business that are related to the reduction in fuel consumption due to increased take-up of energy efficiency options. The results of these particular benefits to business are integrated into the estimation of the overall costs to business of these scenarios and therefore have been incorporated into the results presented in this section.

The costs to business of the scenarios are explored in detail, recognising that costs to individual businesses (i.e. those who would be responsible for implementing the abatement options) are likely to vary substantially depending on the nature of their shipping activity each year and the characteristics of the vessels they operate.

The costs to business are explored in this section by aggregating across the ship types and sizes, with more detail provided in the Technical Annex.

In order to achieve the GHG emission reduction target(s) in place under a scenario, the model applies a carbon price to the operational CO_2 emissions from shipping, which is calculated to achieve the specified GHG emissions trajectory. The carbon price is only applied to CO_2 and not to CO_2e for simplicity; however, this has the same impact (as applying it to CO_2e) because CO_2 is the dominant operational GHG emission for all the fossil fuels used in shipping, and targeting its reduction therefore also has the effect of reducing emissions of all GHGs in line with the objectives modelled. The carbon prices calculated are shown in Figure 22.

The impact of this carbon price is not included in the estimates of the costs to business that are presented in this section. In effect, while the voyage costs calculated in the modelling include a cost which is related to the total CO_2 emissions and the carbon price, this component of the business cost is then recycled back into the sector. The justification for this approach is that there is not yet any specific policy concept agreed at the IMO on how to achieve the 2050 objective. Some options may pass some of the carbon price per tonne on to business as a cost, but others may not, and because of this uncertainty the assumption that policy would not pass additional cost (beyond that of the technology and fuel) on to business was applied.

The level of carbon price needed to achieve the given GHG target for a scenario is broadly indicative of the different cost levels (over and above BAU) of the different scenarios.

Figure 22 presents the estimates of the different carbon prices derived for each of the ten scenarios over the time period to 2050. It shows that Scenario D (zero shipping GHG emissions by 2050) has the highest peak carbon price; and that sustained high carbon prices are required in Scenarios C, H and I in order to achieve the specific objectives of these scenarios, given the assumptions made. The level of carbon price in a given scenario and a given year is variable depending on the rate of GHG reduction achieved, so these carbon price scenarios should be considered as trends rather than interpreted as precise values. Scenarios which see large reductions in GHG emissions over a short period of time require a higher carbon price to achieve this, rather than those scenarios that have a more gradual rate of GHG reduction. This is the explanation for why the highest carbon price occurs in Scenario D (zero in 2050), rather than Scenario C (zero in 2040), because the path actually taken in the modelling for Scenario D is for a large reduction in GHG in 2040/2045, and is a feature of the way the modelling iterates to match a given GHG reduction objective (see Section 4.1).

In comparative terms, Scenario C requires a high carbon price to achieve the rapid rates of change across newbuild ships and the existing fleet to meet the objective of zero operational GHG emissions in 2040. Scenarios H and I also require a high carbon price because under these assumptions, the most competitively priced zero operational GHG emission fuel and machinery option is constrained to be more expensive than in other scenarios, and so requires a stronger carbon price to enable this to be taken up in preference to fossil fuel.

Carbon prices for the scenario that includes a quantity of bioenergy are not significantly different from the carbon prices of other scenarios with the same objective. This is because the modelling suggests that the availability of bioenergy does not negate the need for significant quantities of synthetic fuels during the key period of transition (2030s and 2040s), which therefore still requires a strong carbon price to enable their take-up.

In scenarios for which zero GHG emissions have been reached by 2050 (Scenarios C, D), the carbon price is not creating any additional change from 2050 onwards, and it is just acting as a measure to prevent the reintroduction of fossil fuels (which could equally also be achieved by other policy measures). For the scenarios which have decarbonisation objectives in 2070 (Scenarios E, F, G, H, I and J), the carbon prices have all 'plateaued' by 2051. This is because to reach even a 50% level of GHG emission reduction by 2050 requires very high penetration of zero GHG emission fuels by 2050 (given the expected growth in global trade and hence growth in traffic), and therefore a strong incentive (in this case a carbon price) to drive achievement of this interim milestone before full decarbonisation.

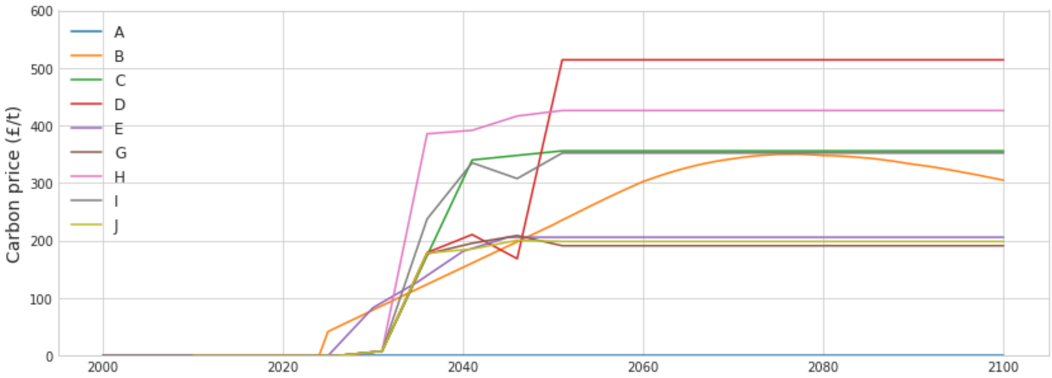
There is no carbon price trajectory for Scenario F, because this scenario is the compound of Scenarios D and E. It applies the carbon price trajectory of Scenario

D for the domestic fleet and the carbon price trajectory of Scenario E for the international fleet.

Overall across all non-BAU scenarios, the maximum carbon price ranges between ~£200 and £500 per tonne of CO_2 (in real 2017 prices) in order to create the necessary adoption of fuels and technologies.

It should be noted that these carbon prices are set at levels that are required to overcome the known market barriers and failures in the shipping markets. Barriers mean that the carbon price required to bring about particular actions to reduce emissions might need to be notably higher than without the barriers. This is because not only does the abatement action have a cost, but there is a cost of overcoming the barrier too, so a greater incentive is needed to overcome it. Further, the modelling is agnostic as to whether this is a carbon price that is ultimately charged and faced by those in the shipping industry, or whether it is achieved through other means (e.g. standards, strategic investment by the public sector).

Figure 22 Carbon prices (£ per tonne of CO_2) calculated using GloTraM in order to achieve the required GHG objective (real 2017 prices)



Key limitations

The limitations of the estimates of the costs to business are associated with the uncertainty in the modelling of the take-up of abatement options in BAU and each of the abatement scenarios, and the uncertainty in the underlying cost data (which influences both the selection of different options and the absolute values of costs). The uncertainty in the underlying cost data exists both in the estimates of current (e.g. present day) costs and in the projection of costs over the period of the modelling.

For present day costs, since this is commercially sensitive information and difficult to verify independently (e.g. unlike performance estimates), uncertainty can exist in the values obtained from literature. For the projection of costs, uncertainty exists because there is significant cost-reduction potential for many abatement options which currently have low levels of take-up. While for some abatement options there is literature which estimates from historical trends how costs may evolve,[40] for many shipping emission abatement options this literature does not exist.

[40] See the Technical Annex.

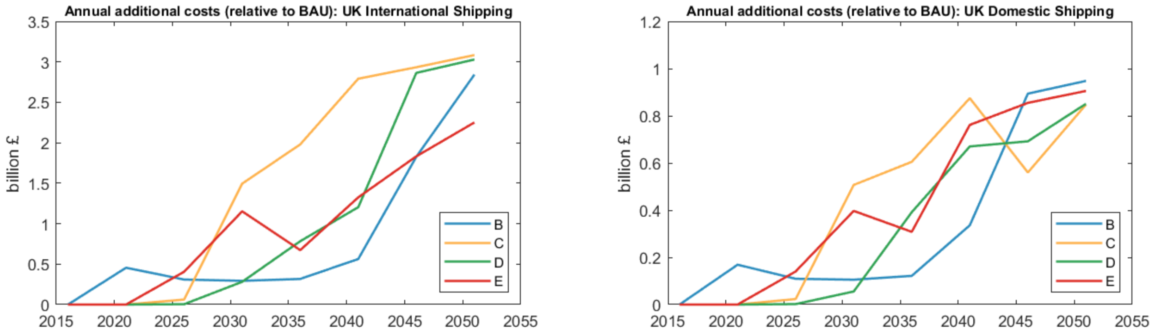
A detailed description of the assumptions and methods used to estimate the costs to business can be found in the Technical Annex.

4.3.1 Variation 1 – stringency of global GHG emissions policy

Figure 23 presents estimates of the total annual additional costs to business under Scenarios B, C, D and E compared to BAU (Scenario A), showing UK international shipping on the right and UK domestic shipping on left. The scenarios are defined as:

- B – application of BEIS central carbon price (2025 is used as a year indicative of the earliest implementation of an IMO carbon pricing policy and the carbon price is phased in from zero in that start year to align fully with the BEIS carbon price from 2030 onwards);
- C – target of zero (operational) shipping GHG emissions globally by 2040;
- D – target of zero (operational) shipping GHG emissions globally by 2050; and
- E – target of 50% absolute reduction in (operational) shipping GHG emissions globally by 2050 (compared to 2008); zero (operational) shipping GHG emissions globally by 2070.

Figure 23 Total annual additional costs to business under Scenarios B, C, D and E compared to BAU (real 2017 prices)



The results show a degree of "noise" with small spikes in values occurring over time. These are an artefact of the model which is estimating behaviour at 5 year time-steps and if there is a significant change in fuel mix over that period then this can create the appearance of an uneven trend in total cost. The results should therefore be interpreted as indicative trends over time rather than precise quantifications of total cost in a given year.

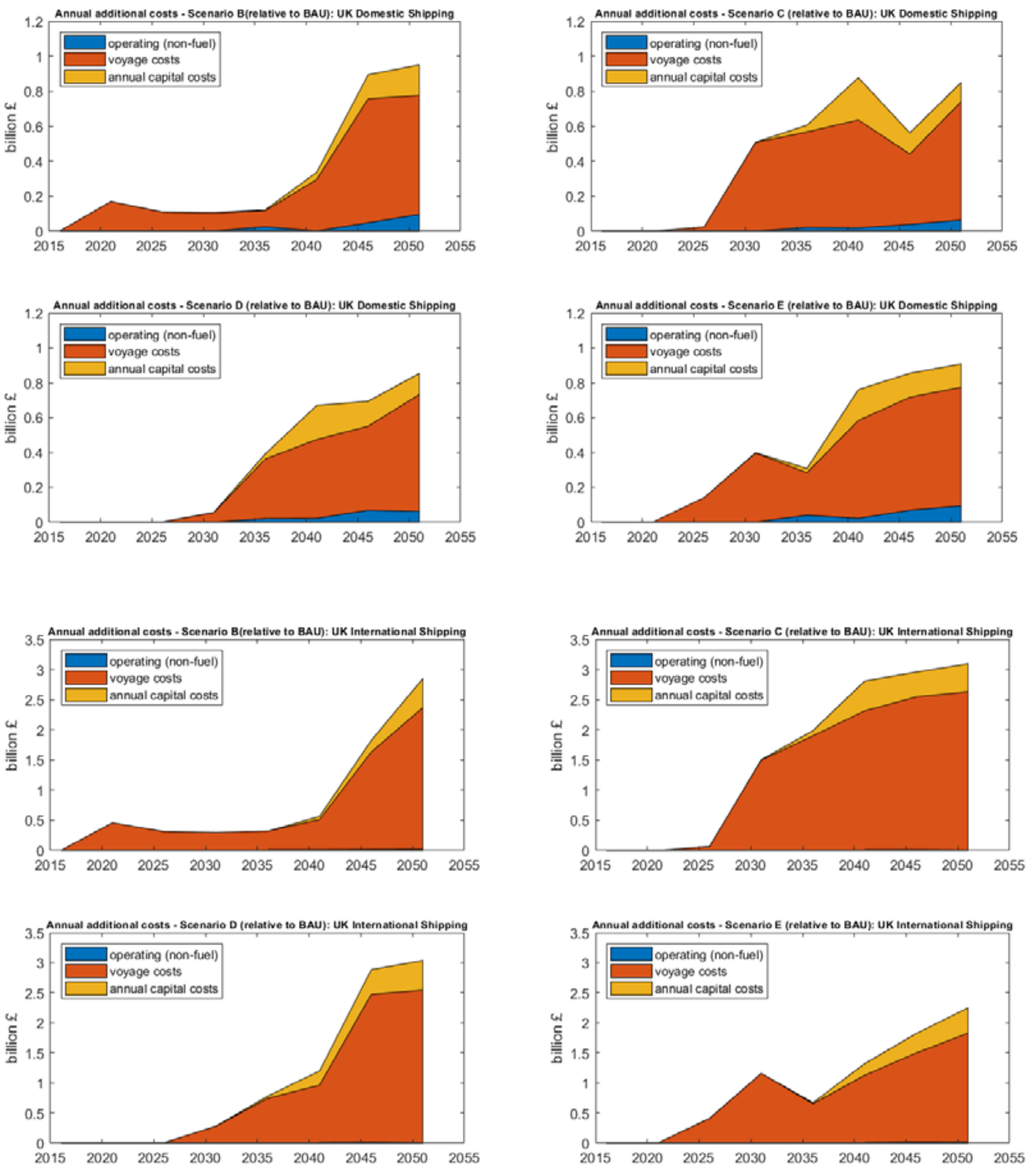
Interpreting as trends, these results show that, generally, increasing the stringency of GHG policy brings the cost increase forward (e.g. earlier), but it does not significantly impact the peak level of the total annual additional costs to business, which reaches approximately £1bn per annum in 2051 for UK domestic shipping and £3bn per annum in 2051 for UK international shipping (2017 prices). Furthermore, there is little difference in the additional costs across Scenarios C, D and E for the case of UK domestic shipping which the results in section 4.2.1 and 4.4.1 all take a similar emissions pathway and a similar technology pathway. In other words, this similarity in total costs to business can be explained by the fact that the domestic fleet has already substantially decarbonised by 2051 under the levels of carbon price required to ensure that the international fleet meets a 50% absolute GHG reduction by 2050. Scenario E results in lower per annum costs by 2051 for UK international shipping, because the sector continues to use a significant share of lower cost fossil fuel (with consequent higher GHG emissions).

Besides the varying levels of GHG emission reduction objective at a given point in time, the variation in additional costs is explained by a combination of factors including:

- The modelling assumes that capital costs of various options important for achieving zero emissions are expected to reduce over time (see the Technical Annex for the detailed assumptions on this). Because of this, the later shipping adopts this technology, the lower the cost is for the sector. This assumption simplifies the process of cost reduction, which is a function both of scaling-up of production of a technology for its application in a sector (e.g. shipping) and the scaling-up of production of a technology for application in other sectors. The assumption is that the latter is the more important driver of costs for shipping (e.g. low-cost ammonia because of widespread availability of low-cost renewable electricity and low-cost electrolysers or widespread availability of production facilities using natural gas and fitted with CCS). However, for certain technologies which are bespoke for shipping, the cost reductions will be less driven by time and more related to the production required in shipping, which would not be expected to create a significant additional cost difference between scenarios of the same ultimate stringency of GHG policy (e.g. zero emissions), but different timescales for reaching zero.
- A higher rate of GHG reduction, as is required in scenarios with earlier target years for zero emissions (such as Scenario C), requires more retrofitting to the existing fleet, which is more expensive than if the same options are only applied to newbuilds.

The additional costs presented in Figure 23 can be broken down into their components, which is shown in Figure 24. These graphs show that the overall additional costs are dominated by the increase in the voyage costs (e.g. fuel costs), with capital and operating (non-fuel-related) costs being only small additional cost components. This is predominantly associated with the higher costs of zero emission fuels relative to the fossil fuels that are used in both the international and domestic shipping fleets in the BAU scenario. For the technology pathway that uses ammonia in internal combustion engines which is the dominant pathway for these scenarios (see Section 4.4.1), there is minimal additional capital cost relative to BAU because the technology is similar (e.g. similar machinery). For different pathways, there might be a difference in these components of cost (for example if liquid hydrogen were the most competitive pathway, this would result in higher capital costs associated with the cryogenic tanks required to store hydrogen on board), but this capital cost increase could be slightly offset by a lower voyage cost increase.

Figure 24 Breakdown of annual additional costs to business under Scenarios B, C D and E compared to BAU (real 2017 prices)



Scenario C (decarbonisation by 2040) is estimated to have higher annual additional costs particularly over the 2030-2040 period and particularly for the international fleet (a maximum additional cost of approximately £1bn per annum during this period). This is consistent with the general observation that increasing stringency (moving the date of zero emissions earlier) brings forward the cost increase.

4.3.2 Variation 2 – stringency of UK domestic policy on emissions

Figure 25 presents estimates of the total annual additional costs to business under Scenarios E, F and G compared to BAU (Scenario A), with UK international shipping on the right and UK domestic shipping on the left. These scenarios are defined as:

- E – target of 50% absolute reduction in (operational) shipping GHG emissions globally by 2050 (compared to 2008); zero (operational) shipping GHG emissions globally by 2070;
- F – as Scenario E, but zero (operational) GHG emissions by 2050 for UK domestic shipping (UK international shipping aligned with global emissions target); and
- G – as Scenario E, but more stringent levels of regulation on UK air pollution emissions (tightening of UK-neighbouring ECAs).

Figure 25 Total annual additional costs to business under Scenarios E, F and G compared to BAU (real 2017 prices)

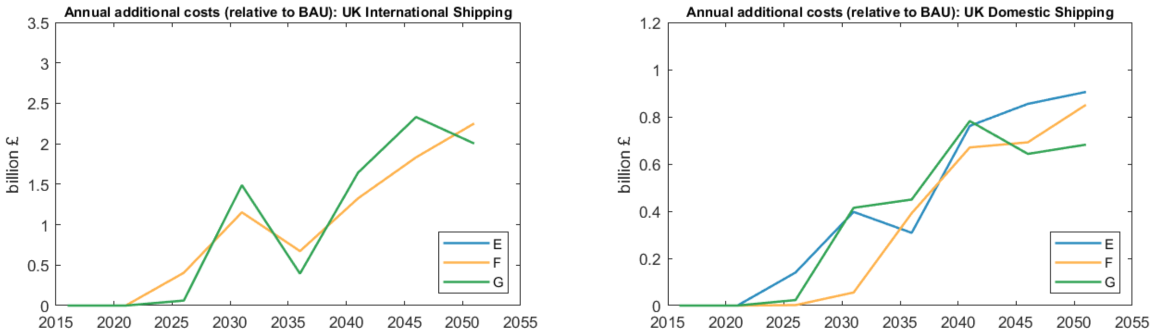


Figure 25 shows that the total annual additional costs to business of Scenarios F (more stringent UK domestic GHG policy) and G (more stringent UK air pollutant policy) are generally estimated to be similar to the costs of Scenario E. That is, there is a gradual increase in annual additional costs from 2025 to a plateau of approximately £0.8bn per annum for UK domestic shipping and £2bn per annum for UK international shipping in 2051 (real 2017 prices).

Increasing the stringency of UK air pollution regulation (Scenario G) can help to further reduce air pollution emissions during the transition period (particularly SO_2 and PM2.5), as shown in Section 4.2.2, and is estimated to result in a small increase in the annual additional costs over the 2030-2040 period for UK domestic shipping (approximately less than an additional £0.1bn per annum), and over the 2030-2045 period for international shipping (approximately an additional £0.2bn per annum) (2017 prices). However, the difference is small relative to other sources of uncertainty in the total cost increase and hard to identify from the results given the "noise" induced in the trend by the model's iteration (see Section 4.1). This suggests that in practice, this additional cost to business increase is not significant relative to the cost to business increase due to achieving the GHG emission reduction objective.

The cost trajectory for UK leadership on GHG emissions reduction in the domestic fleet, Scenario F, does not result in a significant cost difference relative to the lower-ambition Scenario E. This is because, as is shown in 4.2.2, the GHG emissions trajectory for the UK domestic fleet in Scenario E and F are very similar because the incentive (in this case a carbon price) needed to enable the GHG emissions of international shipping to reach a 50% reduction in 2050 enables a near 100% reduction in emissions in the domestic fleet.

The implications of these different costs for the demand for shipping have not been investigated in detail. However, two potential risks associated with the changes in costs are:

- For UK domestic shipping, the risk that additional cost incentivises a modal shift moving demand from shipping to other higher GHG-producing modes of transport for UK passengers and freight (for example road and aviation).
- For UK international shipping, the risk that either a similar modal shift occurs (e.g. to land and aviation modes) or that the additional cost of transport inhibits trade/economic activity and reduces the UK's competitiveness as an exporter.

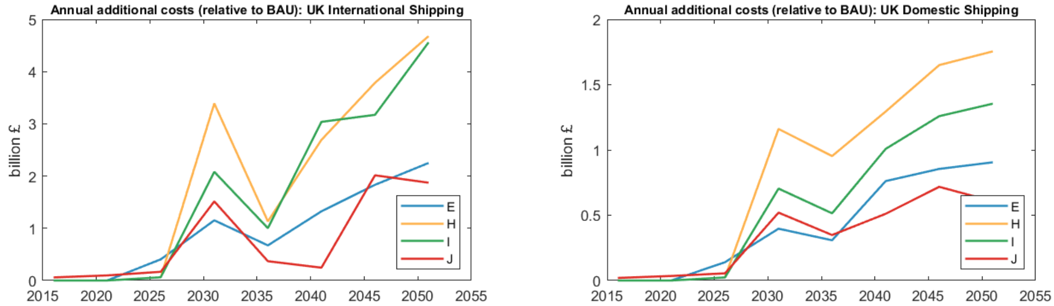
Scenario F is related to UK leadership on the domestic fleet relative to the international fleet's GHG reduction. It therefore does not create additional costs for UK international shipping and so should not incur any of the risks specific to this fleet. The difference in additional costs between Scenario E and Scenario F is small relative to the overall additional cost in either scenario and is therefore unlikely to create any significant difference in risks. This additional cost for shipping's GHG reduction also needs to be placed in the context of the additional costs of GHG reduction in other competing sectors (road and rail freight). Additional costs, and therefore risks, are not significant relative to the UK leaving the GHG reduction of its domestic fleet to be driven by international regulation, which is unpredictable (given the IMO will revise its GHG Reduction Strategy in 2023), and which is currently set lower than the average rate of GHG reduction required to secure the Paris Agreement temperature goals.

4.3.3 Variation 3 – fuel availability and prices

Figure 26 presents estimates of the total annual additional costs to business under Scenarios E, H, I and J compared to BAU (Scenario A) (for UK international shipping on the left and UK domestic shipping on the right).

- E – target of 50% absolute reduction in (operational) shipping GHG emissions globally by 2050 (compared to 2008); zero (operational) shipping GHG emissions globally by 2070;
- H – as Scenario E, but with hydrogen/ammonia/methanol produced by electrolysis instead of SMR with CCS;
- I – as Scenario E, but with no use of ammonia in shipping; and
- J – as Scenario E, but relaxing the constraint of no availability of biofuel to include a supply that can fulfil a part of shipping's energy demand.

Figure 26 Total annual additional costs to business under Scenarios E, H, I and J compared to BAU (real 2017 prices)



Of these variants to Scenario E, which all have the same GHG reduction ambition, it is estimated that Scenario J has a slight reduction in additional costs, whereas Scenarios H and I have increased additional costs. The cost reduction in Scenario J is largest for UK international shipping in 2041 (about £1bn per annum) but negligible by 2051 (real 2017 prices). The magnitude of the additional cost reduction in these respective fleets is influenced by the share of the total supply of bioenergy that is consumed in the respective fleets; the modelling allocates the share approximately evenly across all fossil fuels. But the total bioenergy used by the UK domestic and international shipping depends on the competitiveness of the biofuel option with other zero GHG options (ammonia, methanol), which explains why the impacts on the UK's international and domestic fleets' additional costs are not exactly the same.

The reason that biofuel availability in Scenario J does not create a significant difference in the additional costs of the scenario over time is partly because biofuels still represents a cost increase relative to the BAU fuels and because, with constrained supply of biofuel, there remains a need for synthetic fuel (in this case ammonia), which is reflected in the scenario's costs. Ammonia's take-up is just slightly delayed (see Section 4.4.3).

The explanation for the cost differences in Scenarios H and I is the higher costs of the fuels taken up by the fleet in order to reach the GHG reduction objective. In Scenario H (synthetic fuels produced by electrolysis), all the synthetic fuels have higher relative prices because they are assumed to be produced from a more expensive pathway than the SMR and CCS otherwise assumed. The most competitive fuel choice for much of the fleet remains ammonia (see Section 4.4.3), because the price changes over time are consistent across all fuels and do not alter their competitiveness. The higher additional cost of Scenario H is therefore a result of the increased cost of the fuel. Similarly, in Scenario I, which removes the option for the fleet to use ammonia, there are higher costs because the preferred fuel becomes a more expensive fuel (methanol). Methanol is a more expensive fuel because although also based on a hydrogen feedstock, there are additional processes and feedstocks needed to manufacture synthetic methanol, which in combination are estimated to have higher costs than the processes needed to manufacture ammonia.

The estimated increase in energy efficiency in the higher fuel cost scenarios (increased take-up caused by a better return on energy efficiency investments) is not material to the overall increase in relative cost of the scenarios.

4.4 Descriptions of the nature of the sector's transition

An explanation for the differences in the annual additional costs to business and emissions trajectories across the scenarios can be derived from an investigation into the nature of the different transition pathways and their use of the four different types of abatement options listed in Section 2.1. This section explores, in particular, the differences in fuel use and take-up of energy efficiency options across the scenarios in order to understand how the results differ depending on the GHG and air pollution levels of ambition and the different input assumptions (particularly on fuel availability and prices). The same groupings of scenarios are used as have been used in Sections 4.2 and 4.3.

This section does not include figures presenting changes in operating speed (e.g. adoption of slow steaming). However, operating speed trends are similar across all scenarios with the carbon price applied to incentivise the achievement of a given GHG objective only having a small impact on speed. In 2031, there is a small but negligible reduction in operating speed relative to BAU. By 2051, all scenarios show a small reduction in operating speed (approximately 5-6%). These results can be explained because operating speed is a function of both revenues and costs. There is an underlying assumption in all the scenarios that market conditions, and therefore revenues, return to their long-run average values by 2031. Under those conditions the operating speed at which an owner maximises profits is relatively insensitive to increases in cost, even cost increases of the magnitude associated with the switch away from fossil fuels that occurs in these scenarios.

4.4.1 Variation 1 – stringency of global GHG policy

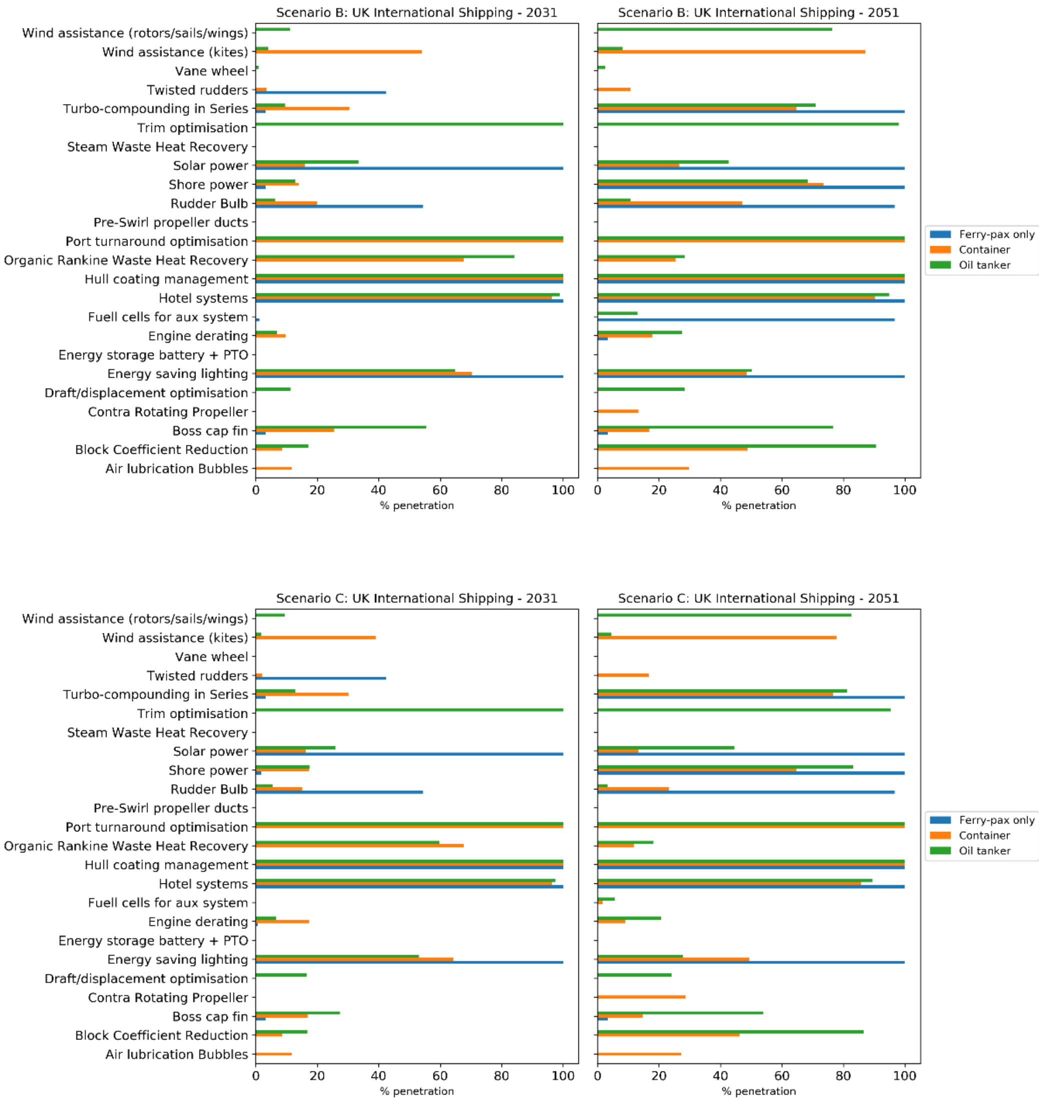
Figure 27 and Figure 28 present the estimates of the technology take-up and fuel mix for UK shipping under Scenarios B, C, D and E.

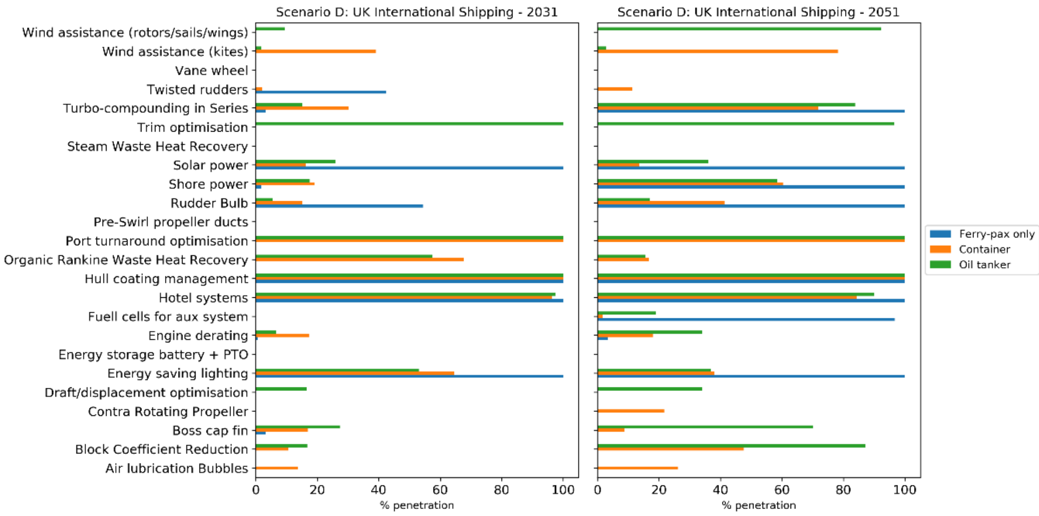
- B – application of BEIS central carbon price (2025 is used as a year indicative of the earliest implementation of an IMO carbon pricing policy and the carbon price is phased in from zero in that start year to align fully with the BEIS carbon price from 2030 onwards);
- C – target of zero (operational) shipping GHG emissions globally by 2040;
- D – target of zero (operational) shipping GHG emissions globally by 2050; and
- E – target of 50% absolute reduction in (operational) shipping GHG emissions globally by 2050 (compared to 2008); zero (operational) shipping GHG emissions globally by 2070.

For the estimates of technology take-up, the results for '% penetration' represent the percentage of the size and age categories for each ship type which is estimated to have taken up each of the options. For simplicity, these estimates are only presented here for UK international shipping and for three ship types, but the full results are provided in the Technical Annex.

For the estimates of the fuel mix, the quantity of fuel is shown on the y-axis in units of energy (joules), allowing comparison of the shares of the total fuel supply that are accounted for by the different fuels.

Figure 27 Technology take-up by UK international shipping in Scenarios B, C, D and E




Scenario D: UK International Shipping - 2031
Scenario D: UK International Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller ducts
Port turnaround optimisation
Organic Rankine Waste Heat Recovery
Hull coating management
Hotel systems
Fuell cells for aux system
Engine derating
Energy storage battery + PTO
Energy saving lighting
Draft/displacement optimisation
Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0 20 40 60 80 100
% penetration
Ferry-pax only
Container
Oil tanker

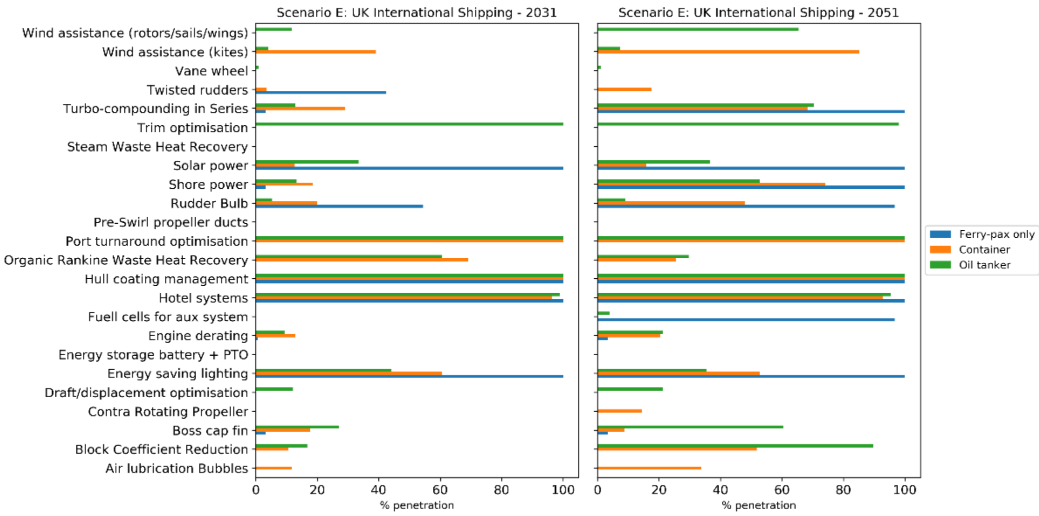
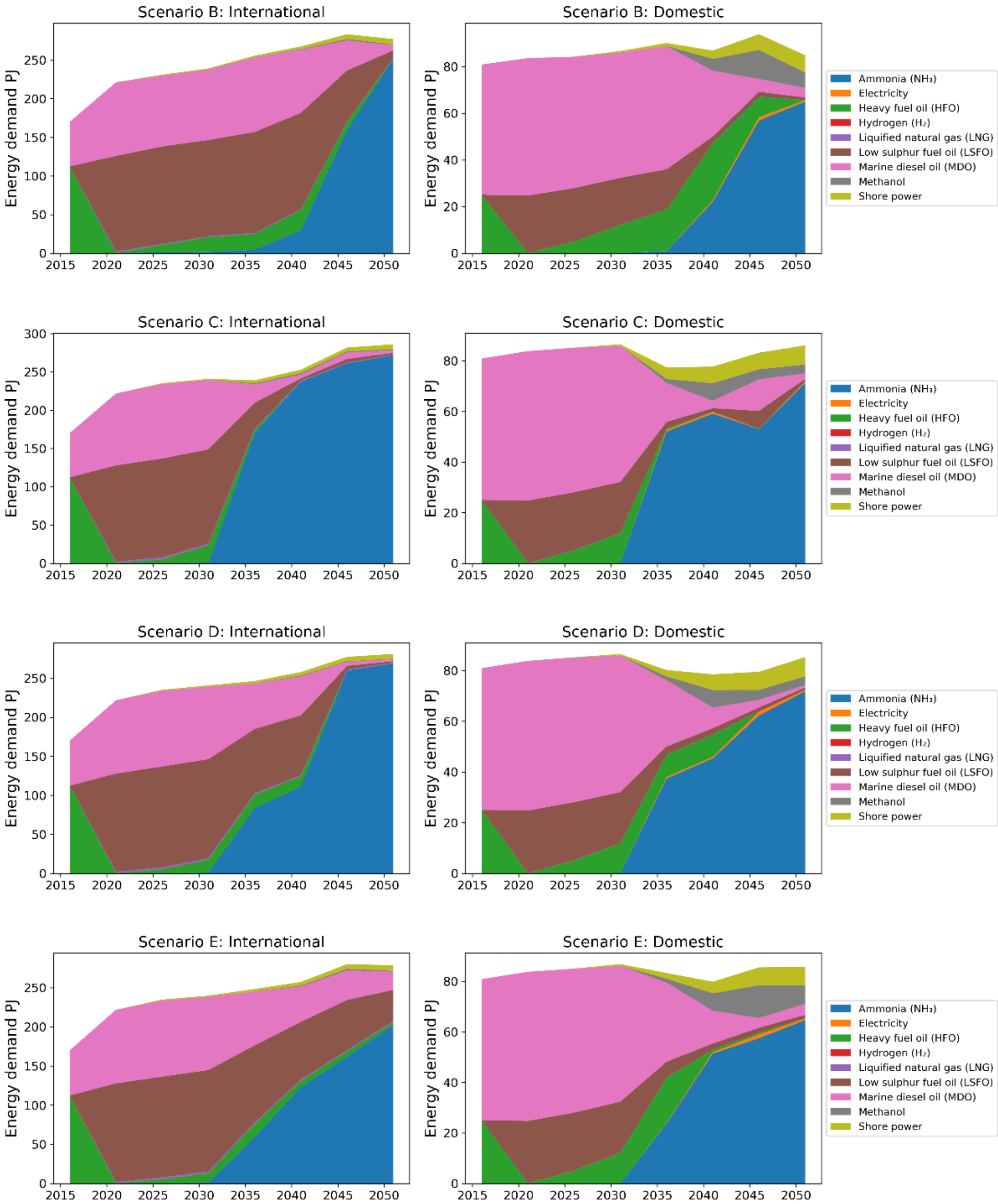

Scenario E: UK International Shipping - 2031
Scenario E: UK International Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller ducts
Port turnaround optimisation
Organic Rankine Waste Heat Recovery
Hull coating management
Hotel systems
Fuell cells for aux system
Engine derating
Energy storage battery + PTO
Energy saving lighting
Draft/displacement optimisation
Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0 20 40 60 80 100
% penetration
Ferry-pax only
Container
Oil tanker

Figure 28 Fuel mix for UK shipping in Scenarios B, C, D and E



Scenarios B, C, D and E are estimated to have broadly similar transitions, taking into account small variability that occurs because of the way the modelling iterates to find a solution and produces small amounts of variability that should not be ascribed meaning in a comparison of scenarios (see Section 4.1). The main differences occur in the timescales associated with the switch away from fossil fuels. Under the assumptions used for these scenarios, all scenarios show a competitive advantage of ammonia (over hydrogen or methanol) from approximately the 2030s onwards, for both the UK domestic and international shipping fleets. Furthermore, in all scenarios, it is estimated that ammonia is the most prevalent fuel for shipping by 2051. There is a point in each scenario where ammonia overtakes the incumbent fossil fuels, and this varies by scenario:

- Scenario B, main transition occurs in the mid-late 2040s;
- Scenario C, main transition occurs in the early-mid 2030s;
- Scenario D, main transition occurs in the mid-late 2030s (domestic) and early 2040s (international); and
- Scenario E, main transition occurs in the early 2040s.

There are also some differences in the level of take-up of energy efficiency options across scenarios. As GHG policy stringency increases, the level of penetration of certain abatement options increases (e.g. wind assistance is taken up more in Scenario C than in Scenario E).

The presentation of results does not distinguish the adoption of machinery and fuel technology take-up between new-build and retrofits. However, it can be seen from the results that there is a combination of both, both for adoption of new fuels and for adoption of technology. This can be seen from the speed of the transition. For example, even in Scenario E which is comparatively low in GHG reduction stringency compared to other scenarios, between 2030 and 2040, approximately 50% of the international shipping fuel mix switches from fossil fuel to ammonia. In the same scenario over 60% of the domestic fuel mix switches from fossil fuel to ammonia. Given the average ship life of approximately 30 years, these rates of change are only possible if these changes in fuel mix occur both in new-build and a modest portion of the existing fleet (by retrofit). This same interpretation can be drawn from the results for technology change with very high (e.g. greater than 50%) penetration of certain technologies occurring between 2016 and 2031, or between 2031 and 2051, both periods shorter than the average ship's economic life and therefore time period for full renewal of the fleet by new-build. The portion of the fleet that is most likely to be retrofitted is the portion with the longest remaining life and the most compelling cost-effectiveness for retrofit (as identified in the modelling through the evaluation of the profitability of different GHG mitigation options).

However, variations in take-up between the different levels of shipping GHG ambition are small, and most of the scenarios are similar by 2051. This suggests that in other scenarios, even if there is an incentive to take up non-fossil fuels, there could be several energy efficiency options that are not taken up (either as retrofit options or new-builds) because under the market conditions they do not create a return on investment from fuel cost savings.

The dominant fuel/machinery combination which is being adopted across the scenarios remains a liquid fuel and ICE combination. Therefore, the energy efficiency options associated with internal combustion machinery (e.g. waste heat recovery, turbocharging etc.) remain relevant out to 2051.

This would not be the case for some transition pathways such as fuel cell and electric motor propulsion, which is included as an option in the analysis but is not cost-competitive and sees little take-up in the scenarios tested. The explanation for this is that the relative cost-benefit of the fuel cell compared to the ICE does not enable it to be competitive.

There are two areas which could change with further research, development and demonstration (RD&D) on fuel cells: technology costs could reduce further than currently estimated in this modelling or performance (efficiency) could increase beyond the values assumed. Another area that might tip the competitive balance in favour of fuel cells is that of air pollution emission regulations. An ICE run on ammonia is still estimated to have levels of NO_x emissions equivalent to those of the same engine run on fossil fuel. If NO_x emissions stringencies increased, the cost of managing the pollution from ICE could reduce (because of regulation-induced technology development) relative to the costs of fuel cells. Or in other words, there remains uncertainty as to the most likely technology pathway for a given goal (a given stringency on NOx and GHG emissions). This is because cost-reduction for a given technology is a function of number of units produced and the number of units produced is a function of regulation. Furthermore, there is uncertainty in the wider demand (outside of shipping) both for fuel cells and NOx abatement technology for use on internal combustion engines.

In addition to shore power electricity demands (which are estimated to be small relative to the energy demands of shipping when at sea), there is some small penetration of battery electric propulsion. This is represented with the appearance of electricity as a fuel in all scenarios. The penetration of battery electric shipping occurs more significantly in the UK domestic shipping fleet than in the UK international shipping fleet. Even within the UK domestic shipping fleet, the share of energy supplied to ships directly as electricity is estimated to be small by 2051. This is because over anything other than the shortest voyage distance (or endurance in time), the capital cost of batteries is higher (even allowing for significant cost reductions by 2051) than can be competitive against synthetic fuels (e.g. ammonia).

There is a significant penetration expected of primary renewables technology in all these scenarios. Primary onboard renewables technologies (solar and wind) are included as a selection of energy efficiency options as they reduce the demand for energy from the main and auxiliary engines. The fuel used in those main and auxiliary engines is then quantified separately, modified to account for reduced demand if primary renewables are used on board (hence separate graphs presenting the results). Solar energy and wind propulsion (both kites and rotors/sails/wings) are used across all four scenarios, with the strongest take-up in the most stringent GHG reduction scenario. The penetration of these options is affected by their respective compatibility; for example, it is assumed that rotors/sails/wings are not compatible with container ships and ferry Ro-Pax (due to lack of availability of deck space), which explains why they see take-up for the oil tanker ship type only.

4.4.2 Variation 2 – stringency of UK domestic emissions policy

Figure 29 and Figure 31 present the estimates of the technology take-up (energy efficiency and air pollutant technology, which is shown here because the variation is focused around air pollution regulation and therefore air pollution abatement option take-up is of particular interest) and fuel mix for UK shipping under Scenarios E, F and G:

- E – target of 50% absolute reduction in (operational) shipping GHG emissions globally by 2050 (compared to 2008); zero (operational) shipping GHG emissions globally by 2070;

- F – as Scenario E, but zero (operational) GHG emissions by 2050 for UK domestic shipping (UK international shipping aligned with global emissions target); and
- G – as Scenario E, but more stringent levels of regulation on UK air pollution emissions (tightening of UK-neighbouring ECAs).

For the estimates of technology take-up, the results for ‘% penetration’ represent the percentage of the size and age categories for each ship type which is estimated to have taken up each of the options.

For the estimates of the fuel mix, the quantity of fuel is shown on the y-axis in units of energy (joules), allowing comparison of the shares of the total fuel supply that are accounted for by the different fuels.

Figure 29 Technology take-up by UK international shipping in Scenarios E, F and G

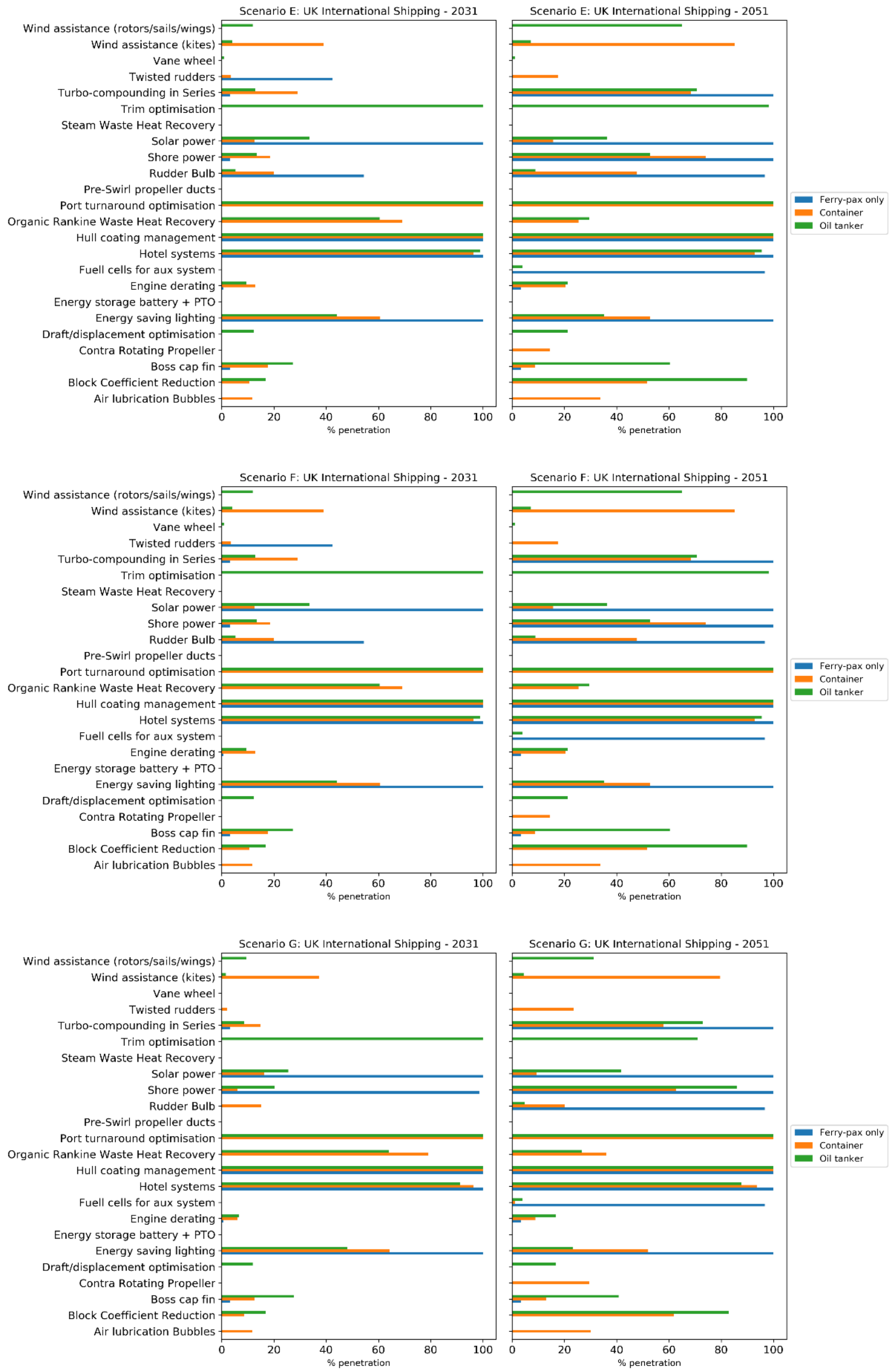
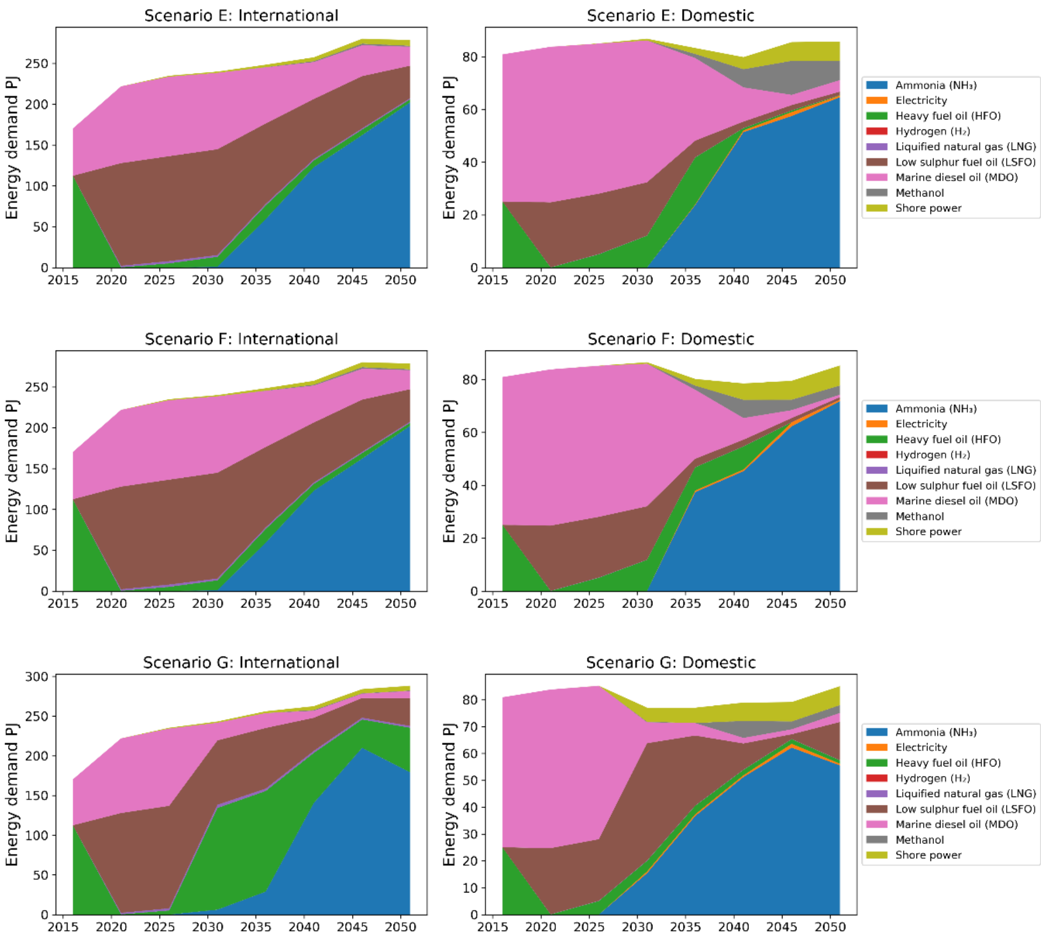


Figure 30 Fuel mix for UK shipping in Scenarios E, F and G



The fuel mix in Scenario G is broadly similar to the fuel mix in Scenario E. Compared to Scenario E, Scenario G has the same GHG trajectory but higher air pollution emission stringency for the ECA areas (higher stringency on both SO_2 and NO_x emissions when in ECA from 2030). This implies that while there is an air pollution emission reduction, it is achieved in this instance by the use of fossil fuels in combination with exhaust emission abatement technology. Therefore, the air pollution regulation does not drive a fundamental shift in the fuel mix away from fossil fuels as a result of the added stringency, at least within the timescale to 2050. However, the results for the fuel mix for Scenario G show a perverse result which is that for the UK domestic shipping fleet there is increased use of low sulphur fuel oil (LSFO) over MDO (compared with Scenario E), and for UK international shipping an increased use of HFO over MDO and LSFO. This is primarily indicating that there can be quite a high sensitivity to the mix of MDO/HFO and LSFO as a function of a scenario's specification and that, as a result, some large variabilities can occur. This is also a representation of the challenge of accurately modelling a market where there is high competitiveness between three very similar options (three variants of fossil fuels made compatible with different regulation stringencies through different combinations of pollution abatement technology).

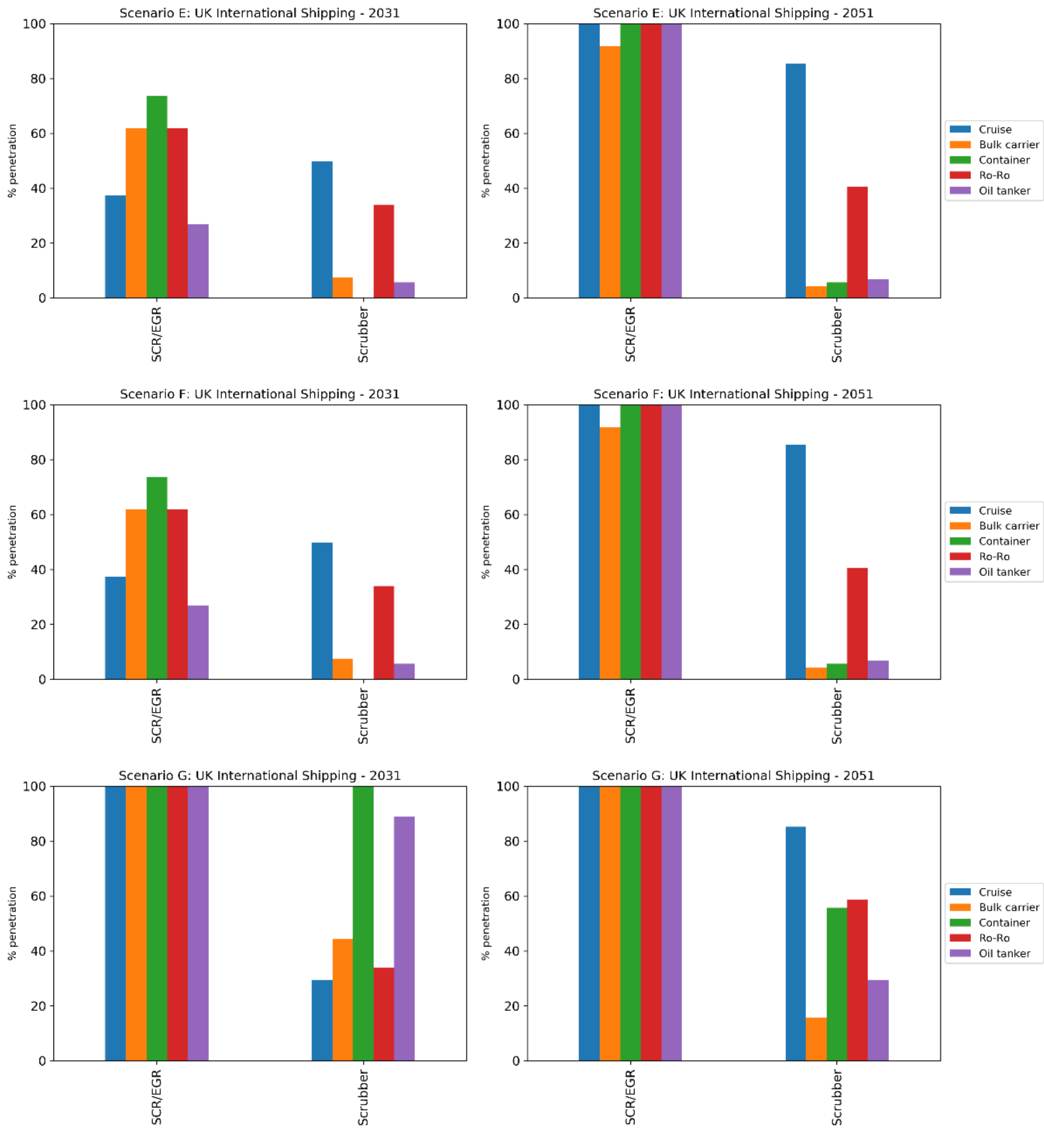
However, there is less of a difference in the fuel mix between Scenario F, in which the UK domestic fleet has an objective to meet zero GHG emissions by 2050, and Scenario E. The UK international shipping fuel mix is identical to Scenario E because the GHG reduction objective and assumptions on the respective fuel prices are identical. For the UK domestic shipping fuel mix, there is also only a small difference with Scenario E. This is because it is estimated that the carbon price needed to achieve even a 50% absolute reduction in GHG by 2050 relative to 2008 levels in the global fleet, still needs to create an incentive for a large switch away from fossil fuel. Within the UK domestic shipping fleet, it is estimated that incentive alone appears to be sufficient to achieve a nearly 100% GHG emission reduction in Scenario E by 2050, which means that no significant additional change to the fuel mix is required to achieve the more stringent UK domestic fleet GHG reduction in Scenario F.

There is no significant difference in the level of energy efficiency technology options deployed in the two scenarios, with both having similar levels of take-up in 2031 and 2051.

As observed across scenarios in Variation 1, Section 4.4.1, change in fuel and take-up of technology is occurring both in the newbuild fleet and a modest portion of the existing fleet (by retrofit), given the speed of adoption of certain fuels (e.g. ammonia) and technologies.

As may be expected, Figure 31 shows that it is estimated that the UK domestic shipping fleet would be likely to have a higher take-up of SCR/EGR, notably so by 2031, under Scenario G (similar GHG policy to global but tighter UK air pollution controls) when compared to Scenario F (more stringent UK domestic shipping GHG policy).)

Figure 31 Air pollutant technology used by UK international shipping in Scenarios E, F and G



4.4.3 Variation 3 – fuel availability and prices

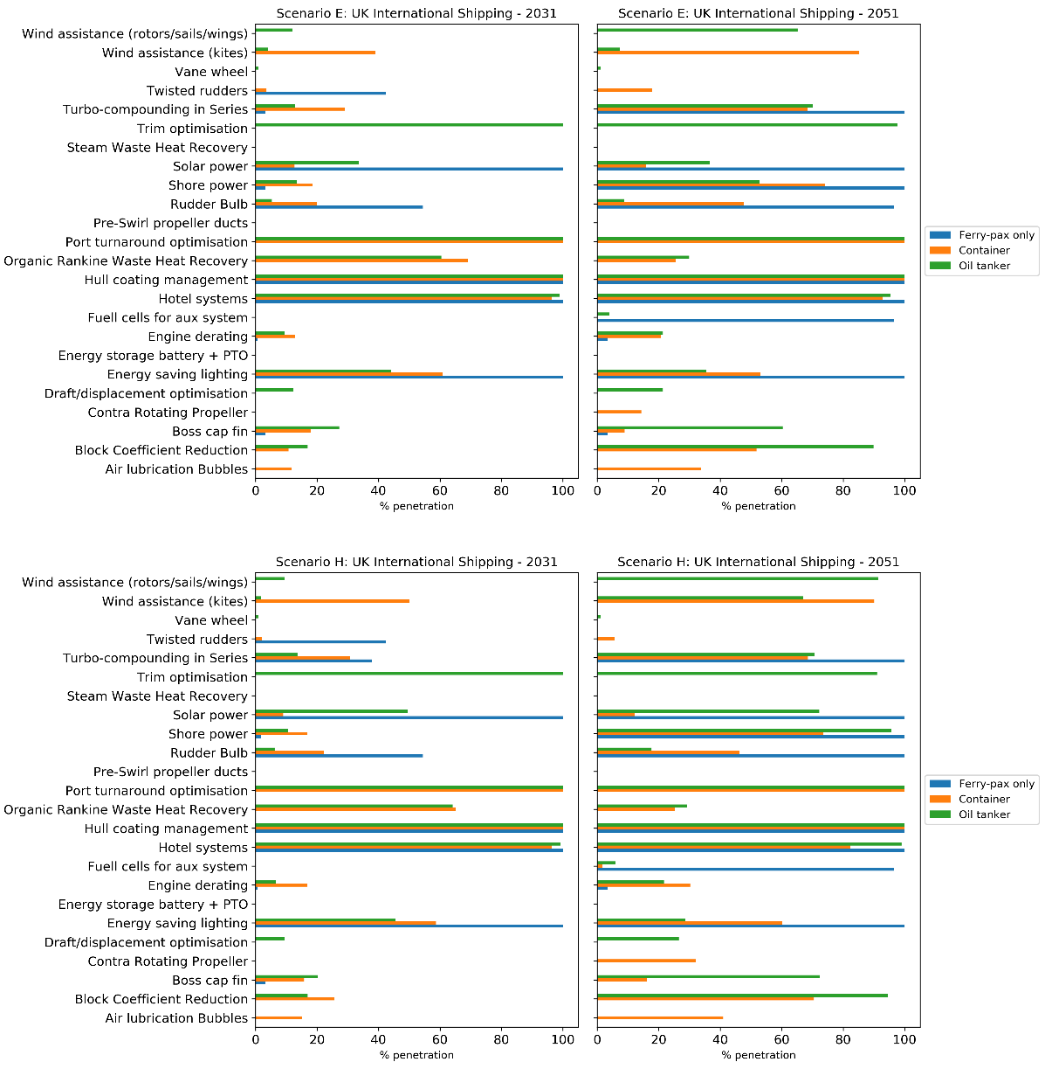
Figure 32 and Figure 33 presents the estimates of the technology take-up and fuel mix for UK shipping under scenarios E, H, I and J:

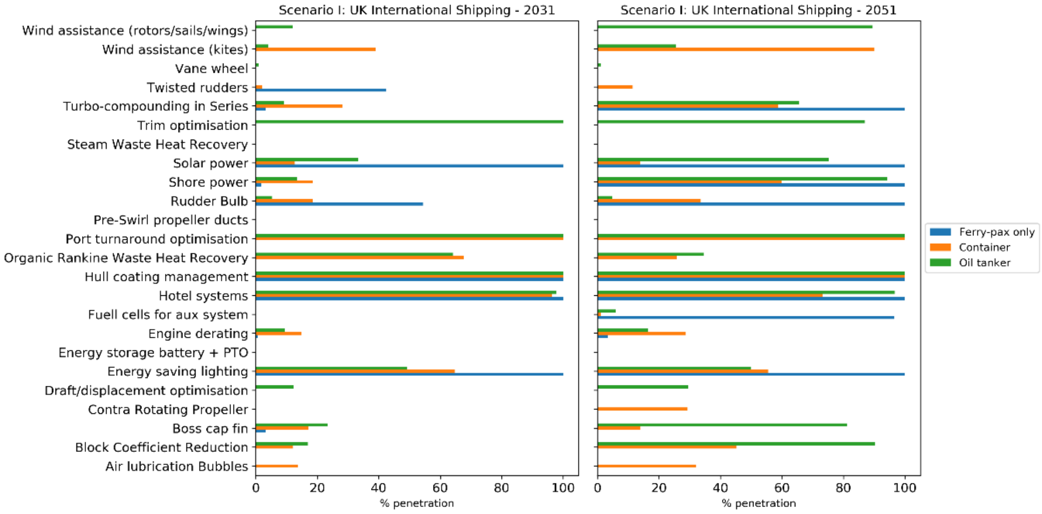
- E – target of 50% absolute reduction in (operational) shipping GHG emissions globally by 2050 (compared to 2008); zero (operational) shipping GHG emissions globally by 2070;
- H – as Scenario E, but with hydrogen/ammonia/methanol produced by electrolysis instead of SMR with CCS;
- I – as Scenario E, but with no use of ammonia in shipping; and
- J – as Scenario E, but relaxing the constraint of no availability of biofuel to include a supply that can fulfil a part of shipping's energy demand.

For the estimates of technology take-up, the results for '% penetration' represent the percentage of the size and age categories for each ship type which is estimated to have been taken up in each of the options.

For the estimates of the fuel mix, the quantity of fuel is shown on the y-axis in units of energy (joules), allowing comparison of the shares of the total fuel supply that are accounted for by the different fuels.

Figure 32 Technology take-up by UK international shipping in Scenarios E, H, I and J




Scenario I: UK International Shipping - 2031
Scenario I: UK International Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller ducts
Port turnaround optimisation
Organic Rankine Waste Heat Recovery
Hull coating management
Hotel systems
Fuell cells for aux system
Engine derating
Energy storage battery + PTO
Energy saving lighting
Draft/displacement optimisation
Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0
20
40
60
80
100
% penetration
Ferry-pax only
Container
Oil tanker

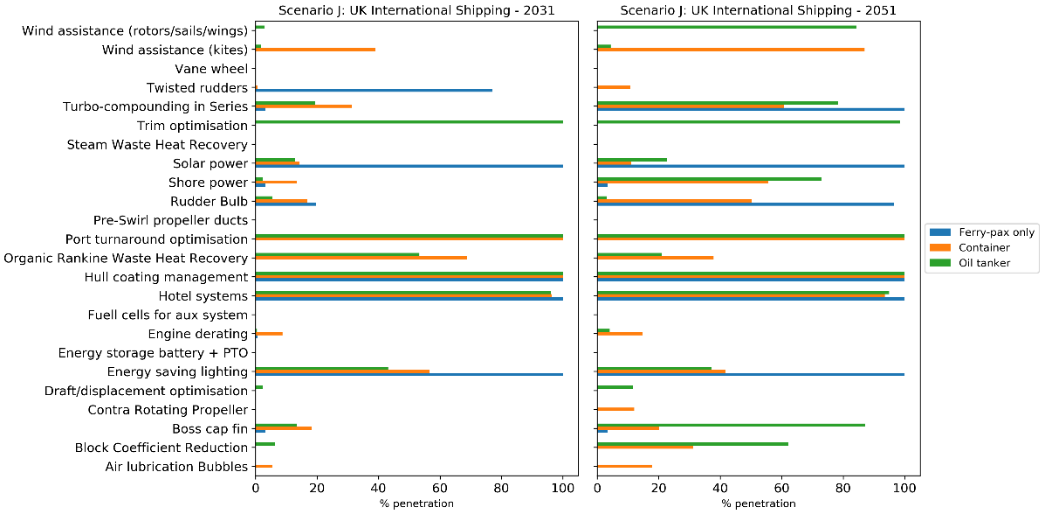
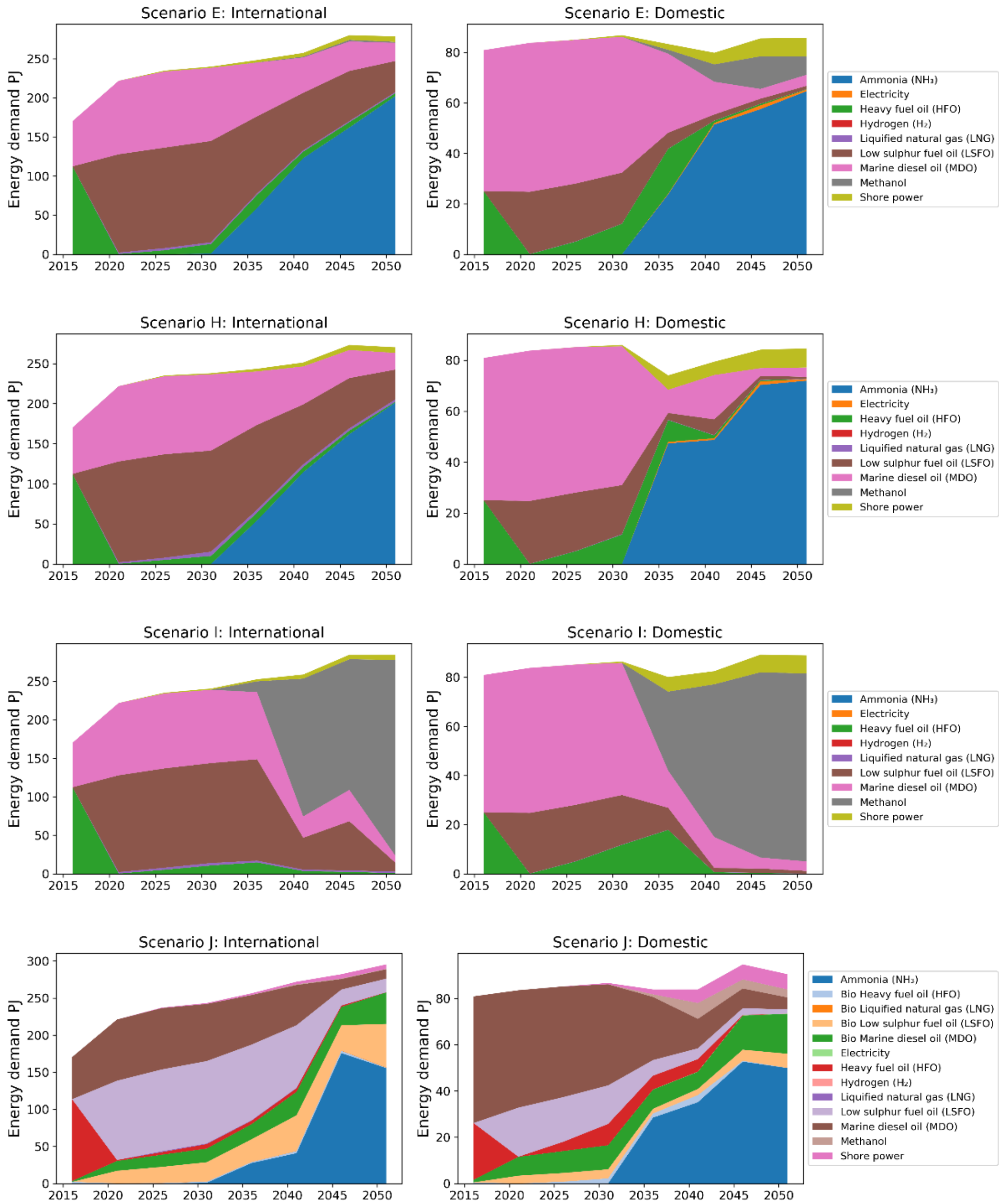

Scenario J: UK International Shipping - 2031
Scenario J: UK International Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller ducts
Port turnaround optimisation
Organic Rankine Waste Heat Recovery
Hull coating management
Hotel systems
Fuell cells for aux system
Engine derating
Energy storage battery + PTO
Energy saving lighting
Draft/displacement optimisation
Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0
20
40
60
80
100
% penetration
Ferry-pax only
Container
Oil tanker

Figure 33 Fuel mix for UK shipping in Scenarios E, H, I and J



The results for these scenarios show that variations in the assumptions and sources of energy and fuel for shipping can create some important differences in the fuel mix and therefore the transition pathway for the sector.

In Scenario H (with hydrogen/ammonia/methanol assumed to be produced by electrolysis) the fuel mix remains similar to Scenario E. This is in spite of the costs of the non-fossil fuels increasing due to the assumed costs being derived from electrolysis production pathways instead of Scenario E's use of SMR and CCS as the means to produce the basic fuel feedstock (input to the fuel production process) hydrogen. The assumed higher costs of electrolysis-produced hydrogen affect the total costs of other fuels which are assumed to be produced using hydrogen (i.e. ammonia and methanol. It is estimated that ammonia (in combination with an ICE) remains the most cost-effective solution for achieving the targeted levels of GHG reduction and, in fact, becomes more competitive than methanol at these higher prices, as evidenced by the reduction to zero in Scenario H of the small quantity of methanol that appears in the UK domestic fleet's fuel mix from 2031 in Scenario E.

In Scenario I, ammonia is assumed not to be available as an option in order to consider what the consequence might be if production or use did not prove viable. The results show that in the absence of the ammonia option, it is estimated that the preferred pathway to zero emissions becomes methanol used in combination with an ICE. The switch to methanol occurs in a similar way to the switch to ammonia across other scenarios with similar GHG reduction objectives.

In Scenario J, an amount of biofuel is assumed to be available for use in shipping. The biofuel is assumed to be used as a drop-in fuel alongside conventional fossil-derived fuels in appropriate proportions; for example, HFO, MDO, LSFO and LNG all receive a similar reduction in net operational carbon emissions as represented by the entry into the fuel mix of biofuel. In practice, the concept of this mix of fuels could be that a percentage of every tonne of these fuels sold is made up of biofuel, or that an individual ship sometimes uses 100% biofuel and sometimes uses 100% fossil fuel resulting in a reduction in their annual average carbon emission factor, or it could be that a certain percentage of the fleet run on 100% (or high) biofuel, with the remainder using 100% fossil fuel. These different options allow for the fact that there may be some constraints on directly blending together biofuels and fossil fuels to meet various fuel product specifications, so there is no implicit assumption in the method that blending is viable for all uses.

The Scenario J results suggest that the potential consequence of the availability of biofuel in the quantities assumed is to delay the transition to the use of ammonia and to enable a subset of the UK's domestic and international shipping fleets to continue to operate on conventional fuels even in 2051. It is estimated that ammonia becomes the most prevalent source of energy for UK domestic shipping in the early 2040s in Scenario E, whereas the equivalent transition occurs in the mid-2040s in Scenario J, even though it has the same GHG reduction target. In the UK international shipping fleet in 2051, it is estimated that ~30% of the fuels remain conventional fuels (with a significant blend of biofuel), whereas in other equivalent scenarios the quantity is 20% or less.

All four scenarios show very similar levels of take-up of energy efficiency options both in 2031 and 2051. This suggests that for the variations in fuel price that result from the different scenarios, the return on investment and therefore the take-up rates of the different options are not significantly affected/sensitive.

As observed across scenarios in Variation 1, Section 4.4.1, change in fuel and take-up of technology is occurring both in the newbuild fleet and a modest portion of the existing fleet (by retrofit), given the speed of adoption of certain fuels (e.g. ammonia) and technologies.

4.5 Concluding remarks on the potential for electrification of shipping

The majority of shipping's current energy demand and energy use is mechanical (e.g. based on the internal combustion converting chemical energy directly into kinetic energy). While electrical power is used on board for certain services (e.g. hotel energy loads for lighting and to power control, navigation and communication systems etc.), this currently originates in the large majority of ships from diesel generator sets. One potential development for the sector is to increase the use of electricity on board and to use a supply of electricity directly to the ship while it is in a port and to charge onboard batteries that can reduce the demand for a liquid fuel. A number of the key electrification technologies have been considered throughout the work, described in Section 2, 3 and 4, and can be summarised as:

- Shore power – this involves switching off diesel generators when in a port and, instead, using electricity supplied by the port to power the ship's system. The ship is 'plugged in' and the port must have capacity to meet these additional electricity needs;
- Full-electric battery propulsion – this refers to a ship which carries sufficient batteries to store all of the ship's energy requirements when underway at sea and charges the batteries when in port;
- Battery storage / hybrid – a smaller quantity of batteries can be useful to provide either short endurance (e.g. when leaving a port) and/or to manage variability onboard the ship (in particular, to assist diesel generators in being operated at their maximum efficiency); and
- Electric propulsion – this refers to using an electric motor to drive the propeller as opposed to a direct mechanical coupling between the propeller and an ICE. The electricity could come from a variety of sources e.g. batteries, fuel cells or diesel generators.

There are only specific implications for the demand for electricity for two of these technologies – shore power and full-electric battery propulsion. Both have been explicitly modelled and included in the scenario results presented in Section 4.4, including in that section's figures of the shipping energy demand broken down by different sources. The battery storage/hybrid and electric propulsion technologies are also included, the former as a potential energy efficiency option and the latter as a propulsion machinery component in a number of the propulsion options (fuel cells, diesel electric and battery – see Technical Annex for more detail).

Overall, the electricity demand for shore power and full battery electric propulsion, remains small relative to UK domestic and international shipping's overall energy demand in all the scenarios considered. There are two main explanations for this:

- The majority of ships' total energy demand is dominated by propulsion energy demand. Shore power only substitutes the smaller portion of energy demand (auxiliary power) and only when a ship is in a port. When underway or at anchor, the ship will still need to use diesel generators for auxiliary power demands. Therefore, the total share of a ship's energy demand that can be met through shore power is small.

- The costs of batteries and electricity, and the implications for the competitiveness of full-electric ships relative to those using liquid fuels, mean that full battery electric propulsion is assumed to be limited to ships that operate on short endurance (e.g. are only away from a charging point for a short period of time). These include short ferry crossings, for example, and are predominantly ships in the UK domestic shipping fleet rather than the UK international shipping fleet. Because these ships are smaller than many of the internationally trading ships, they also have some of the lower overall power requirements. Due to them being only a small subset of the overall UK shipping fleet and being smaller ships, their overall share of the energy demand from UK shipping is small.

Besides implications for energy demand and decarbonisation, there are significant potential benefits from shore power for controlling air pollution emissions when ships are in port and close to centres of population where impacts of those emissions may be greatest. Although the overall shares of shipping's energy demand for grid electricity may be small (relative to the demand for grid electricity by other UK sources of demand), the technology take-up results in Section 4.4 show there are likely to be significant roles for a number of electrification technologies, indicating that this is a growth technology area for shipping.

A description of the subsets of the UK shipping fleet that are estimated to switch to full-electric propulsion is given in Table 1. Because for larger ship size categories the capital costs of the batteries are assumed to make this propulsion configuration uncompetitive, only the smallest ship types in the UK domestic and international fleets are considered viable to electrify and be modelled in detail. To investigate the viability of using full-electric propulsion, the smallest ship sizes are broken down further into even smaller size categories and assumptions on average voyage length are used to estimate the costs associated with battery electrifications. These costs are then compared with the costs of the lowest-cost zero emission competitor (ammonia), in order to identify whether battery electric or synthetic fuel propulsion might be most competitive. A detailed description of the approach used is provided in the Technical Annex.

The results show that for many of these ship types full battery electric propulsion is estimated to be competitive with synthetic fuel, and this estimation of relative competitiveness for this portion of the fleet is incorporated into the scenario results to estimate the total demand for electricity.

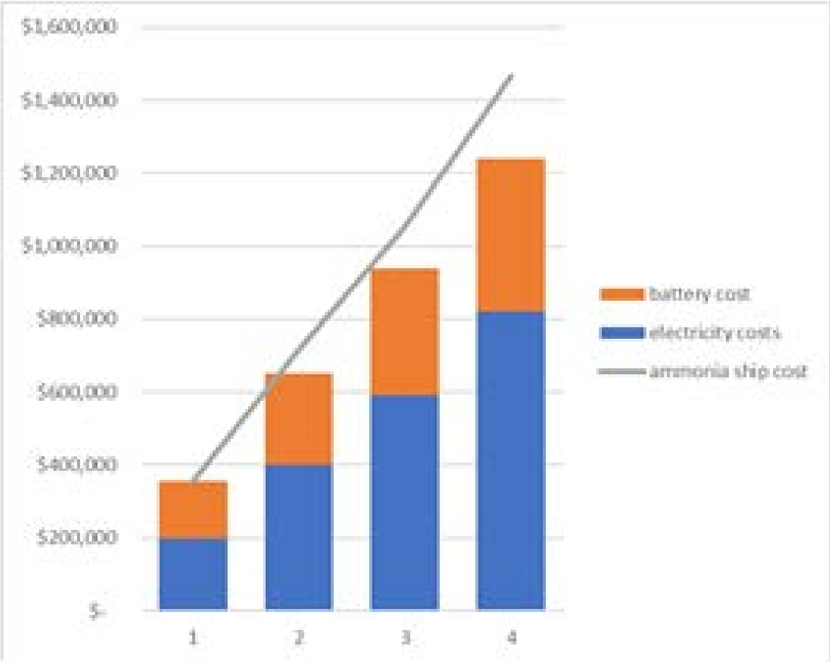
Table 1 Ships in UK domestic shipping fleet that are estimated to convert to full-electric propulsion

Aggregate size category	Ship type	Disaggregate size range	Most competitive technology, only those labelled 'electric' are assumed to adopt full-electric propulsion
0-999 TEU	Container	0-249 TEU	Electric
		250-499 TEU	Synthetic
		500-749 TEU	Synthetic
		750-999 TEU	Synthetic
0-1999 Gt	Ferry-pax only	0-499 Gt	Electric
		500-999 Gt	Electric
		1000-1499 Gt	Electric
		1500-1999 Gt	Electric
0-1999 Gt	Ferry-RoPax	0-499 Gt	Synthetic
		500-999 Gt	Electric
		1000-1499 Gt	Electric
		1500-1999 Gt	Electric
0-4999 dwt	Ro-Ro	0-1999 dwt	Synthetic
		2000-4999 dwt	Electric

The results of this comparative competitiveness analysis highlight a key sensitivity which is associated with the assumptions made about endurance and voyage length. These assumptions influence viability due to the implications for the capital costs of batteries (if endurance and voyage length are overestimated, then the modelling will have assumed a conservative quantity of batteries and by association a conservative capital cost which will reduce competitiveness relative to non-battery solutions) and have resulted in this analysis implying that in some ship types (container, Ferry-RoPax, Ro-Ro), the smallest ship size considered would be more likely to use synthetic fuel and only switch to full-electric battery propulsion for larger sizes.

Figure 34 presents results illustrating the respective roles of battery costs (capital costs) and electricity costs (operating costs) at influencing the competitiveness of full-electric propulsion compared to a synthetic (ammonia) propulsion system configuration for the four sizes of Ferry-RoPax considered. The results show that in many cases the competitive difference is marginal, and the future comparative competitiveness will be strongly linked to how electricity prices, battery prices and synthetic fuel prices evolve.

Figure 34 Analysis of the comparative competitiveness (capital and operating costs) of a full battery electric propulsion system for four sizes[41] of Ferry-RoPax compared with an ammonia propulsion system (2017 prices)



Source: UMAS

[41] Size ranges being: size 1 (0-499 GT), size 2 (500-999 GT), size 3 (1000-1499 GT), size 4 (1500-1999 GT)

5 POLICY INSIGHTS

Emissions of GHGs and air pollutants contribute to climate change along with environmental and health problems. The government is committed to tackling all those emissions, including those from ships. As such, successive governments have already put in place measures (either domestically or through international agreements) which will reduce emissions below where they would otherwise be. However, in the UK shipping industry, under a BAU scenario, it is estimated that most emissions will continue to rise as demand for shipping rises.

A wide range of technologies, behavioural changes and alternative fuels are available to reduce GHGs and emissions to air of pollutants from UK shipping. Analysis in this report has shown that:

- Some GHG emissions reductions could be achieved while also reducing the overall operating costs of the ship (i.e. at negative cost-effectiveness). These are typically options which improve energy efficiency. However, there are barriers that would need to be overcome for the uptake of these options to increase in practice; and
- The cost-effectiveness of abatement options varies substantially across ship types, reflecting the diversity of ships in operation. Common across all ship types is the finding that a shift to low or zero emission fuels is needed for material emission reductions to be realised of the scale required to achieve the IMO's Initial Strategy or UK government's ambitions for zero emission shipping.

The cost-effectiveness analysis in this report reveals that there are many options available to reduce emissions and the cost-effectiveness of each varies depending on several factors such as the ship type under consideration; prevailing fuel prices; and the UK and international policy environment. Scenario analysis has therefore been used to explore different levels of UK and international policy stringency in relation to emissions as well as different assumptions about fuel prices and the availability of alternative fuels.

A scenario in which the government's central carbon values are applied to increase the cost of fossil fuel used by shipping so that it better reflects its climate change impacts and there is no biofuel supply for the sector, achieves operational GHG reductions for both the UK domestic and international shipping fleets close to zero by 2051. By association, it is estimated that SO_2 emissions from UK shipping are also reduced to close to zero with substantial reduction in primary PM emissions from UK shipping.

In all scenarios explored in this report, it is estimated that the NO_x emissions from UK shipping are not significantly reduced but remain close to current levels (depending on the scenario, they can be higher than current levels or approximately the same). This is because NO_x emissions are expected to rise under BAU as the growth in shipping traffic outweighs any reductions made through the current regulations. Furthermore, it is estimated that the most cost-effective fuel and machinery combinations that achieve zero emission shipping do not reduce NO_x emissions below current levels. Therefore, this implies that further NO_x emission reductions would require additional regulation.

The costs of reducing UK domestic shipping emissions are lower than the costs of reducing UK international shipping emissions: UK domestic shipping GHG emissions are estimated to be reduced by nearly 100% by 2051 (relative to 2008) at the same carbon price as is needed to reduce emissions in the global fleet by just 50% (the minimum requirement of the IMO's Initial Strategy, 2018).

Alternative, low emission, fuels will be essential to achieve the ambitions for zero emission shipping, particularly beyond 2031. There are a number of fuels that could be used. For the purposes of this analysis, ammonia, methanol and hydrogen are considered and are included in the modelling in combination with a variety of compatible machinery options (for example, internal combustion machinery and fuel cells). The analysis suggests that under the assumptions used in this analysis:

- Ammonia and methanol are the preferred options over hydrogen for most of the fleet because of the higher costs of onboard storage for hydrogen (it takes up space that lowers the commercial returns from the ship); and
- Ammonia is generally preferred over methanol for the majority of ship types and sizes,[42] although an adverse side-effect of this is the scale of associated NO_x emissions that would need to be addressed.

There is, however, substantial uncertainty around both the costs and efficiency of low emission fuels in both the near and long terms. Even small changes in the costs and efficiency of the low emission fuels could change the commercial incentives to shift towards any of these three options – hydrogen, ammonia and methanol. This points to facilitating the flexibility to keep open multiple options for alternative low emission fuels for the time being, until there is greater clarity over the potential speed and magnitude of potential changes in the costs if using these fuels in the maritime sector.

The production of the fuels in sufficient quantity is a significant challenge, the consideration of which is outside the scope of this analysis. Using hydrogen, ammonia or methanol would require a source of low carbon hydrogen, either through steam methane reforming (SMR) with CCS or by electrolysis using renewable power.

The preferred engines for use with the low emission fuels considered remains the ICE, under the assumptions used about their capital costs relative to alternatives (they are assumed to be lower cost than the alternatives, e.g. fuel cells). This reliance on ICE could support a simpler transition for the sector given the existing knowledge and experience with this technology and its prevalence in the fleets.

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[42] The assumption used in this study is that the NO_x emissions from the combustion of ammonia would be equivalent to the Tier III limits. This is based on the assumption that while without any management, the NO_x emissions from ammonia combustion are expected to be higher than this limit, that this limit would still apply for new fuels such as ammonia, and so management solutions (e.g. selective catalytic reduction (SCR)) would be applied (and so we therefore assume in this work that they would be applied). Further reduction below the Tier III limit is technically possible but not assumed to be achieved without the motivation of regulation. It should be noted that there is some uncertainty about the impact on NO_x emissions from the use of ammonia in internal combustion machinery. Exhaust technology should be able to assist with the control of NO_x (and we assume in this work that it does) but further research, development and demonstration (RD&D) is needed to establish this in detail (e.g. performance consequences, costs, emissions consequences). There could also be a risk of ammonia emissions (e.g. through slip). And there could be other non-modelled risks (fuel spill/pollution/safety) that could be material to ammonia's viability. As the costs of pathways that do not use ammonia generally appear to be higher, it is worth progressing RD&D on ammonia and for other potential synthetic fuels in parallel.

The analysis in this report covers various dates by which the zero emission shipping ambition is to be achieved, and shows how impacts on emissions and costs differ under alternative assumptions about the costs and availability of different low emission fuels. These scenarios do not reflect government policy but are intended to illustrate how the costs of achieving those ambitions could differ under alternative assumptions. It is recommended that further scenarios, which consider different assumptions on the costs and availability of low emission fuels, are explored. This would provide deeper insights into the most cost-effective transition pathways when shifting to zero emission shipping, paying particular attention to the potential machinery options to accompany low emission fuels.

The analysis in this report has shown that several abatement technologies can be cost-effective. Recognising the diversity of the shipping sector, a package of complementary abatement options is likely to be needed to achieve zero emission shipping, key among which is a shift to low or zero emission fuels.

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