REDUCING THE UK 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 - Technical Annex

A Report for the Department for Transport

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1 GLOSSARY

This report uses several acronyms and terms with which the reader may not be familiar. The list below provides some definitions in the hope that these will help when reading the report.

- AD: Anaerobic Digestion
- AIS: Automatic Identification System
- Auxiliary power unit: is a device on a ship that provides energy for functions other than propulsion
- Baseline ship/fleet: indicates the technical (e.g. size, power installed, design speed, engine/fuel type) and operational (speed) specifications of a ship or fleet at a certain point in time (usually the base year).
- bbl: barrels; unit of volume for crude oil and petroleum products
- Capex / Capital cost: A capital expenditure spent to acquire or significantly improve the capacity or capabilities of a ship
- Cargo capacity: the amount of space that a ship will hold in its cargo areas
- CCS: Carbon Capture and Storage
- CO_2: Carbon dioxide
- CH4: Methane
- dwt: deadweight tonnes
- EEDI: Energy Efficiency Design Index
- Emissions species: different types of emissions CO_2, CH_4, N_2O, SO_2, NO_x, $PM_{2.5}$
- FAME: Fatty acid methyl ester
- Fleet in the stock: the fleet that exists at a specific point in time
- FT(Diesel): Fischer-Tropsch diesel
- Fuel-related operating cost: fuel costs due to a voyage
- GloTraM: Global Shipping Transport Model
- GT: Gross tonnage
- H_2: Hydrogen
- HFO: Heavy fuel oil
- HTL-UPO: Hydrothermal liquefaction - Upgraded hydrolysis oil
- HVO: Hydrotreated Vegetable Oil
- ICE: Internal Combustion Engine
- kWh: kilowatt hour
- LNG: Liquid natural gas

- LSHFO: Low sulphur heavy fuel oil
- MACC: marginal abatement cost curve
- Main engine: is a device on a ship that provides energy for propulsion
- MCR: Maximum continuous rating (MCR) of engine
- MDO: Marine diesel oil
- NH_3: Ammonia
- NO_X: Oxides of nitrogen
- N_2O: Nitrous oxide
- Non-fuel operating cost: Costs associated with the operation of a ship excluding fuel costs
- NPV: Net present value
- Operational emissions: emissions associated with the fuel combustion on board of a ship during the operation of a ship. This does not include emissions at port
- Opex: the sum of non-fuel operation cost and fuel-related operating cost
- $PM_{2.5}$: Atmospheric particulate matter (PM) that have a diameter of less than 2.5 micrometers
- Power: the power of the engines installed in a ship
- SO_2: Sulphur dioxide
- SFC: specific fuel consumption
- SMR: steam methane reforming
- SVO: Straight Vegetable Oils
- Synthetic methanol: methanol produced from synthetic process
- tnm: tonne-nautical-mile
- TEU: Twenty-Foot Equivalent Unit
- TEUnm: Twenty-Foot Equivalent Unit nautical-mile
- Time-step: the incremental change in time for which the GloTraM model provides outputs. The model projects forward in 5-year intervals from a base year of 2016. So, the model provides outputs for 2016, 2021, 2026 etc.
- Transport supply: the amount of useful transport work performed by a ship or a fleet of ships. It includes both the capacity of the ship and its operational characteristics. The units for many ship types are tonne-nautical mile (tnm) referring to the movement of a mass of cargo a given distance (e.g. 1 tnm is the movement of 1 tonne of cargo 1 nautical mile). But for some ship types (work boats, passenger vessels) a suitable alternative measure of useful transport work is applied instead (e.g. TEUnm).

- Upstream emissions: emissions associated with the production, transportation, distribution (including ‘bunkering’) of a fuel. It does not include the emissions associated with the fuel combustion on board a ship.

2 INTRODUCTION

This report provides the technical annexes to the main report: *Reducing the UK 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* (Frontier Economics, UMAS, CE Delft and E4tech, 2019). Throughout this report, this reference will be referred to as the 'main report'. It does not repeat material in the main report but rather complements it by providing more detail on the analysis which is presented in the main report.

In particular, these technical annexes aim to provide detailed information on the modelling approaches used, input assumptions and key points relevant to help interpretation.

These annexes are structured as follows:

- Section 3 provides a detailed description of the modelling suite used in the analysis. This includes the definition of the modelled ship types, the definition of UK domestic and international shipping, and the method used to predict the uptake of electric-ships which were not explicitly modelled in the main modelling framework.
- Section 4 focuses on the analysis undertaken to estimate the annual change in emissions and fuel consumption that could be delivered by each of the shipping emissions abatement options and the associated costs. This section describes the methods used, the abatement options modelled, the detailed input assumptions and output results.
- Section 5 contains detailed information on the methods used to assess the cost-effectiveness of the shipping emission reduction options. It provides a description of marginal abatement cost curves (MACCs) and how they are interpreted; the method used to develop the MACCs, along with the assumptions used in the assessment of cost-effectiveness.
- Section 6 focuses on scenario analysis which explores the costs and impacts on emissions under different assumptions, including varying assumptions about the stringency of policies to address emissions of greenhouse gases (GHG) and emissions to air of pollutants from shipping; assumptions about fuel prices; and assumptions about the availability of different fuels. Detail is provided on the input assumptions and key parameters, along with detailed results across different ship types and size categories.
- Section 7 describes the process of quality assurance undertaken for this work.

3 MODELLING OVERVIEW

3.1 Aims of this section

This section has three aims. The first is to provide information about the modelling suite that underpins the analysis in the main report. The second is to provide the definition of UK international and UK domestic shipping that has been used in the main report because results are commonly presented separately for these two categories of shipping activity. The third is to describe the approach used to project the uptake by ships of electric batteries to reduce their emissions.

3.2 The modelling suite

The UMAS Global Transport Model (GloTraM)[1] enables a holistic analysis of the global shipping system, including how shipping activity, costs and emissions might change in response to developments in economic drivers such as fuel prices and to changing environmental regulation.

GloTraM combines multi-disciplinary analysis and modelling techniques to explore foreseeable futures of the shipping industry. It computationally simulates the evolution of the shipping fleet from a baseline year to a projected future year.

A conceptualisation of the modelling framework can be seen in Figure 1. Each box describes a component within the shipping model. The feedbacks and interconnections are complex and only a few are displayed on this diagram for the sake of clarity. This conceptualisation breaks down the shipping system into manageable analysis tasks, ensures that the analysis and any algorithms used are robust, and then connects everything together to consider the dynamics at a whole-system level. A detailed model methodology documentation can be found in the "Navigating Decarbonisation", "IMO 0.5% Sulphur Fuel Oil Study", "CO_2 Reduction Targets for Shipping", and "Global Marine Fuel Trends 2030" reports which can be downloaded at https://u-mas.co.uk/Project.

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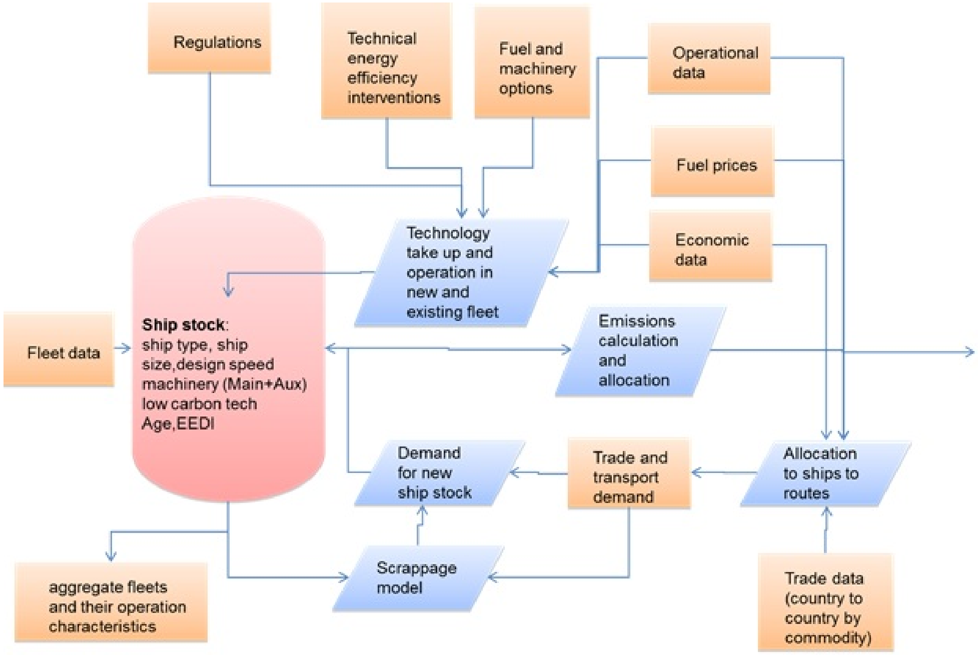
[1] https://u-mas.co.uk/Products/GloTraM

Figure 1 Schematic overview of the GloTraM model



The model is initiated in a baseline year. The baseline year for the modelling is 2016 as it aligns with the best available data of the fleet stock and calibration of the model. Actual data for the fleet and its characteristics were used to define the fleet and voyages in that year. This allows a baseline set of vessels to be defined. Data of the technical characteristic of the fleet (e.g. size, power installed, type of engine, fuel, design speed etc.) are obtained from the World fleet register[2]; and data of the operational characteristics (e.g. operational speed, days spent at sea, etc.) of the fleet are obtained using AIS data[3].

The initialisation of the model characterises the shipping industry at a given point in time, whilst a number of input parameters define the scenarios of interest for this report (see section 6.2 and 6.3). The algorithms embedded in the model then project forwards, simulating the decisions made by shipowners and operators in the management (including the technical specification) and operation of their fleets.

The model assumes that individual owners and operators attempt to maximise their profits at every time step, by adjusting their operational behaviour and changing the technological specification of their vessels. This allows us to explore both the technical and operational evolution of the fleet.

Hence, at each time-step, the existing fleet's technical and operational specification is inspected to see whether any changes are required. Those changes could be driven by regulation (e.g. a new regulation of SO_2 and NO_x emissions) or by economics (e.g. a higher fuel price incentivising uptake of technology or a change in operating speed). Taking the fleet's existing specification as a baseline, the profitability of a number of modifications (e.g. technology, main machinery, design speed, and fuel choice) applied both individually and in combination is considered, and the combination that returns the greatest profit

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[2] UMAS internal dataset derived from vessel tracker (https://www.vesseltracker.com/).

[3] UMAS internal dataset derived from https://www.exactearth.com/.

within the user-specified investment parameters (time horizon for return on investment, interest rate, and representation of any market barriers) is used to define a new specification for the existing fleet for use in the next time-step.

Further, a specification for newbuilds is also generated at each time step. At the baseline year the specification for newbuilds is taken as the average newbuild ship specification in the baseline year. Changes to the technology, main machinery, design speed, and fuel choice of the baseline ship are considered, such that the combination that meets current regulations and generates the highest profits within the constraints of the user-specified investment parameters is selected. The algorithm calculates the operational speed at the year when the newbuild enters the fleet.

GloTraM responds to the specified transport demand. It is assumed that there is no lag or delay from ordering to delivery, such that supply meets demand exactly at every modelled year. A new ship is, therefore, built if there is sufficient transport demand, whilst a ship is scrapped only when it reaches a certain specified age. Expert judgment suggests that most ships can have a lifespan of 30 years. The maximum age before a ship is scrapped is therefore set to 30 years. The demand scenario is specified as a modelling input and is not modified by any of the modelling, e.g. it is fixed and there is no incorporation in the modelling of demand response. The justification for this is that this simplifies the modelling and allows comparability between scenarios based on technical and operational variations.

The key steps used to estimate the uptake of technology and the specification of operational parameters for the new build and existing fleets are listed below.

- Calculate the required energy efficiency design index (EEDI, newbuild only)
- Calculate the return on investment time period
- Calculate the profitability of the baseline ship specification
- For each combination of machinery specification (any alternative fuels which can use the same machinery) and operating main engine MCR %:
    - Find the individual technical and operational option's profitability
    - Prioritise individual options for order of take-up
    - Find all compatible combinations of individual options which are more profitable over the investment time period than the baseline specification
    - Check for compliance with regulation and adjust specification if required
- Select as the new specification for that ship size and age the most profitable combination of alternative fuel, operating MCR %, technical, and operational options that meets the minimum regulatory requirements
- Update the fleet database

Findings from surveying the literature and industry stakeholders show that the most prevalent methods for investment appraisal in shipping are payback period and net present value (NPV) (Parker, 2015[4]; Rehmatulla, 2015[5]). GloTraM forecasts the

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[4] Parker, S 2015 Approaches to investment modelling (working paper), UCL Energy Institute, London

[5] Rehmatulla, N 2015, 'Assessing the implementation of energy efficiency measures in shipping: Survey report', UCL Energy Institute, London

uptake of ship technology by using the NPV method to evaluate investments that could be made by the shipowner. A ship's total value is not modelled or estimated, nor are they used in the ship build decision. Instead the modelling looks at changes to capital and non-fuel operating costs, and estimates whether these changes in combination with changes to fuel costs have the potential to increase or decrease the asset's NPV. The model values the investment over three dimensions, and the selected optima describe combinations of:

- Main machinery and fuel
- Energy efficiency technologies
- Operational speed

These three dimensions are necessary, because all three provide avenues to optimise returns and changes within one dimension typically has effects on the others. For example, a change in engine and fuel affects the specific fuel oil consumption rate (SFC), the emissions factor of the new fuel, as well as the costs (capex and opex) and the transport work that the vessel may be able to complete. A change in energy efficiency technology affects both the sunk costs and operating costs, through effects on SFC and power installed as well as the rate load of the main and auxiliary engines. A change in operational speed, on the other hand, affects transport work and fuel consumption.

In the base year 2016, the model assumes that there are zero installations for energy efficient technologies and any technologies used to capture or treat exhaust emissions, whereas, assumptions relating to main machinery and fuels and operational speeds are derived from the baseline fleet. This implies that the results for the base year do not take into account any energy efficiency technologies and any technologies used to capture or treat exhaust emissions that are currently onboard ships. This approximation is considered acceptable as it is assumed that the number of installations of energy efficiency technologies at base year is relatively small.

The model works on the basis of 5-year time periods. The end year of the model is 2051. The years beyond 2051 were not modelled but are extrapolated from the fleet in 2051. This is because input data (such as fuel prices, demand projections, technology costs) are specified out to 2051; beyond the second half of the century this becomes increasingly uncertain. To undertake analysis to 2100, extrapolation to 2100 was used and is considered a reasonable proxy.

3.2.1 GloTraM modules

The model comprises different modules which rely on robust algorithms and are connected together so that the 'whole system' dynamics are considered. In total there are 8 modules as set out below:

- Transport demand module that estimates for a given year the total mass of freight multiplied by the distance it is transported
- Ship stock module that maintains a database of the ships that make up fleets of ship type/size which is updated every time-step simulated

- Transport supply module; once the transport demand for each ship type is estimated, the characteristic of the actual fleet in the stock is used to calculate the transport supply
- Ship evaluation module that assesses the profitability of any specified ship
- Ship fuel consumption module that calculates the annual fuel consumption and different emissions species emitted per year for each specified ship
- Regulatory module that applies all the existing and upcoming regulations such as EEDI, Sulphur content cap, NO_x limits
- Ships impact module that assesses any change (e.g. cost and performance) due to the adoption of a technology (CO_2 abatement and new machinery technologies) for each specified ship
- Emissions apportionment and climate module that provides national and regional statistics for emissions (CO_2, CH_4, N_2O SO_2, NO_x, $PM_{2.5}$)

A key feature of the model is that investment and operational (speed) decisions are modelled for each ship type, size and age category (the fleet is categorised by type, size and build year in a number of cohort see section 3.3) in a way which maximises a shipowner's profits under a given regulatory and macroeconomic environment. The model is therefore based on a profit maximization approach which takes into account the interaction between speed and technical improvements.

The objective function of the model is

$$\max(NPV = \sum_t^T \frac{365P_{tc\_pd}+B_{tc}(R_{vc\_pa}-C_{v_{pa}}-365P_{tc_{pd}})-C_{s\_base}+C_{s\_delta_t}}{(1+d)^t})$$

where:

- NPV is the net present value
- T is the time horizon for the investment
- t is the time of the cash flow
- d is the discount rate
- Ptc_pd is the time charter per day
- B_tc is the barrier factor for time charter.
- R_vc_pa is the revenue per year of the ship operator
- C_v_pa is the voyage cost per year (only fuel cost)
- C_s_base is the cost base of the shipowner. This cost includes: capital costs, brokerage fees, and operating costs (excluding port/fuel/voyage costs, but including maintenance, wages, and provisions). They are assumed to be covered by the charterer paying market time-charter day rates.
- Cs_delta is the extra investment costs for the shipowner (relative to the baseline fleet). These costs include any additional capital expenditure, beyond

those of a baseline specification, associated with the chosen retrofit/newbuild specification (both capital costs for energy efficiency technology and main machinery and annualised fixed operating costs, excluding voyage costs).

The market barriers[6] are included in the model through a 'barrier factor' that represents the proportion of a charterer's fuel cost savings that are returned to the shipowner. The higher the barrier factor, the fewer market barriers exist, e.g. a 100% barrier factor means that all of the charterer's fuel cost savings are returned to the shipowner and that no market barrier exists. Incorporating the profit of the charterer into the revenue of the shipowner allows the model to consider the trade-off of design speed, energy efficiency and sunk costs. All of these are aligned to a single agent; the shipowner. However, a market barrier is introduced to reflect the possibility that not all of the cost savings of the charterer may be appropriated by the shipowner due to imperfections in the market, e.g. lack of information, information asymmetry, and split incentives (Rehmatulla & Smith, 2015)[7]. In this study, the barrier factors for different ship types are aligned with the values identified in ICF et al. 2019[8] under the current market situation.

The capital expenditure profiles take into account the potential cost reduction of technologies over time (reflected in a 'learning curve' as described in section 6.4.9).

Voyage costs reflect the changes in fuel prices as defined in section 6.4.2.

3.3 Ship types explored

The analysis is based on a number of vessel types, as shown in Table 1. These are consistent with the ship categorisations used by the IMO in the Third IMO GHG Study[9].

A brief description of each of the ship types is provided below:

- Bulk Carrier: A bulk carrier, bulk freighter, or colloquially, bulker is a merchant ship specially designed to transport unpackaged bulk cargo, such as grains, coal, ore, and cement, in its cargo holds
- Container: a ship which is designed to carry goods stored in containers
- Oil tanker: a ship designed to carry oil in bulk
- Ferry-pax only: Ferries designed for the transportation of passengers only
- Cruise: a large ship that carries people on voyages for pleasure

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[6] 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

[7] Rehmatulla, N & Smith, T 2015, 'Barriers to energy efficiency in shipping: A triangulated approach to investigate the principal agent problem in shipping', Energy Policy, vol 84, pp. 44-57

[8] Directorate-General for Climate Action (European Commission) , ICF , Lloyd's List Intelligence , Lloyd's Register, Sintef Ocean , UCL Consultants, A study to estimate the benefits of removing market barriers in the shipping sector https://publications.europa.eu/en/publication-detail/-/publication/97c53cc7-5042-11e9-a8ed-01aa75ed71a1/language-en

[9] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf

- Ferry-RoPax: It is a ro-ro vessel built for transportation of vehicles and passengers
- Ro-Ro: Roll-on/Roll-off also called RORO, these are conventional ferries that can let vehicles easily leave
- Service – tug: this is a type of vessel that manoeuvres other vessels by pushing or pulling them either by direct contact or by means of a tow line
- Offshore: ships that specifically serve operational purposes such as oil exploration and construction work at the high seas
- Service – other: other service vessels

Each type and size category is further divided into age categories (sometimes referred as generation category) according to the build years (the year in which a ship was built).

These ship types were chosen for the modelling because they are representative of the UK domestic and international fleet. For the UK domestic fleet, the non-modelled ships account for 27.7% of the operational energy demand of the total fleet in the base year (not including energy demand at port), while for the UK international fleet, non-modelled ships account for 31% of the total. To obtain the total level of emissions for the respective fleets, the modelled results are scaled up, assuming that the scaling factor is the same across years. For example, projected GHG emissions from UK domestic shipping in the model for 2031 are 4.75 $MtCO_2e$ (i.e. for modelled ships only) so these are scaled up to 6.57 $MtCO_2e$ to represent the projected emissions in that year for all UK domestic shipping.

Table 1: Ship types and size categories used for detailed modelling

Type ID	Size ID	Ship type	Size category	Capacity unit
1	1	Bulk carrier	0-9999	dwt
1	2	Bulk carrier	10000-34999	dwt
1	3	Bulk carrier	35000-59999	dwt
1	4	Bulk carrier	60000-99999	dwt
1	5	Bulk carrier	100000-199999	dwt
1	6	Bulk carrier	200000-+	dwt
4	1	Container	0-999	TEU
4	2	Container	1000-1999	TEU
4	3	Container	2000-2999	TEU

4	4	Container	3000-4999	TEU
4	5	Container	5000-7999	TEU
4	6	Container	8000-11999	TEU
4	7	Container	12000-14500	TEU
4	8	Container	14500-+	TEU
7	1	Oil tanker	0-4999	Dwt
7	2	Oil tanker	5000-9999	Dwt
7	3	Oil tanker	10000-19999	Dwt
7	4	Oil tanker	20000-59999	Dwt
7	5	Oil tanker	60000-79999	Dwt
7	6	Oil tanker	80000-119999	Dwt
7	7	Oil tanker	120000-199999	Dwt
7	8	Oil tanker	200000-+	Dwt
9	1	Ferry-pax only	0-1999	GT
9	2	Ferry-pax only	2000-+	GT
10	1	Cruise	0-1999	GT
10	2	Cruise	2000-9999	GT
10	3	Cruise	10000-59999	GT
10	4	Cruise	60000-99999	GT
10	5	Cruise	100000-+	GT
11	1	Ferry-RoPax	0-1999	GT
11	2	Ferry-RoPax	2000-+	GT
13	1	Ro-Ro	0-4999	Dwt
13	2	Ro-Ro	5000-+	Dwt
16	1	Service - tug	0-+	-
18	1	Offshore	0-+	-
19	1	Service – other	0-+	-

Note: These ship types and sizes align with those used by the IMO

3.4 Defining UK domestic and international shipping

UK domestic shipping is defined as voyages which start and end in the UK.

The UK's share of international shipping is more challenging to define as there is no internationally recognised definition for allocation of a share of international shipping emissions to an individual country.

There are a number of options that can and have been used previously:

1. from last port of call (arrivals), to next port of call (departures), average of arrivals and departures
2. on the basis of the trade flows (from origin to destination) into, out of the country, and the fleet/emissions servicing those trade flows, either:
    - on the basis of imports only (both inbound loaded voyage and outbound ballast voyage)
    - on the basis of exports only (both outbound loaded voyage and inbound ballast voyage)
    - on the average of an import/export basis.
3. on the basis of quantity of bunker fuels sold in a country that is classified as "used for international shipping"

For the UK, option 2 normally produces slightly higher estimates for UK international shipping than option 1. This is because often ships call multiple times before/after the UK at third countries, breaking up the journey to the ultimate destination. This is particularly pertinent to the container shipping fleet which on the Asia-Europe routes (for example) stop at multiple EU ports before and after calling at UK ports. Therefore, a last port of call approach will only apportion UK emissions to and from EU ports, a significantly shorter distance, even when the ship was carrying China-UK origin/destination trade.

The CCC in Review of UK Shipping Emissions published in 2011[10], predominantly used Option 1, but corrected it to be closer to option 2, by estimating the quantity of UK emissions associated with multi-stop voyages (multiple stops between trade flow origin and destination), and transhipment (transfer of cargo from one vessel to another, between origin and destination). Comparative analysis undertaken by UCL and CCC (LCS review of CCC's Review of UK shipping[11]) at the time of their study demonstrated that Option 2 produced similar estimates of transport work, and by association CO_2, as the CCC method that was a transhipment-corrected version of Option 1.

Option 1 poses significant philosophical problems (as noted by CCC in Review of UK Shipping Emissions) given that it would apportion very large shares of

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[10] https://www.theccc.org.uk/wp-content/uploads/2011/11/CCC_Shipping-Review_single-page_smaller.pdf

[11] http://www.lowcarbonshipping.co.uk/

international shipping emissions to transhipment hub countries such as Netherlands and Singapore.

Option 3 normally produces lower emissions for the UK than option 1 and 2, because ships can purchase bunker fuel where it is cheapest and a share of shipping servicing UK appears to favour non-UK fuel. Option 3 is also problematic for use in this study, because it is an aggregate statistic and not broken down by ship type and size – which is necessary disaggregation for the cost benefit analysis.

There are different sources of uncertainty in option 1 and 2. Option 2’s uncertainty is influenced by the uncertainty of the matching between the trade flows and shipping activity servicing the trade flows. Option 1’s uncertainty, is influenced by the accuracy of corrections around transhipment, and the uncertainty of the port call identification and voyage-based inventory.

The main approach used in this study for most ship types is based on option 2 as follows:

- The specific assumption used in this work is to base the trade flows 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.
- To identify the fleet servicing those trade flows, an analysis was undertaken to identify the next and last port of call for each ship that calls at UK ports in order to establish an inventory for UK international shipping’s next and last port of calls. This is then used to define and characterise a subset of the global fleet of ships that are active in UK international shipping (e.g. the number of ships of given ship type and size).
- The GloTraM global fleet[12] (which covers all countries) outputs are then scaled by the ratio between the UK international fleet and the GloTraM estimated fleet (at the level of ship type categories). This ensures a coherent characterisation of UK international shipping emissions, recognising both the distribution of ship type and size categories servicing UK international shipping and the allocation of trade flows to that fleet. This method is used for container ships, bulk carrier and oil tanker ship types, as GloTraM contains baseline and projection data on trade for these vessel types. For other vessel types, option 1, average of arrivals and departures, as this is considered appropriate with the available data for these vessel types.

3.5 Apportioning costs and benefits to the UK

This analysis assumes that the costs and benefits of implementing emissions reduction options are spread out evenly over all of the voyages undertaken by ships servicing UK international shipping. Therefore, the costs and benefits to the UK are taken to be a proportion of the total costs and benefits, representing the share of emissions on UK-relevant voyages.

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[12] Not including passenger vessels and work vessels.

This is illustrated in two hypothetical examples:

- A: 10 ships service UK international shipping for 100% of their voyages, and each ship has 10 voyages per annum to/from UK
- B: 100 ships service UK international shipping for 10% of their voyages, and each ship has 1 voyage per annum to/from UK

In the two examples, UK international shipping performs the same amount of transport work. In example A, the fleet servicing UK international shipping does not sail elsewhere. In example B, the fleet servicing UK international shipping also spends significant time servicing non-UK routes and therefore could mean that non-UK costs and benefits accrue and need to be considered.

In relation to the scenario analysis (see section 6), for the internationally operating fleet, most of these scenarios apply policy equally across all shipping (e.g. in scenario E, decarbonisation by 2050 means all international shipping is on a trajectory to decarbonisation by 2050). The exception is scenario G where the UK places more stringent regulation (on air pollutants), and this could create a difference in the requirements for voyages in/out of UK and other non-UK voyages.

There are three basic areas of costs and benefits that need consideration of how they would be accounted in either example:

1. Capital costs per ship (C_{CS})and Operating costs per voyage (O_{CS}) including ship technology costs and the fuel costs of the ship
2. Capital costs per voyage (C_{CB}) and Operating costs per voyage (O_{CB}) associated with bunker fuel supply
3. Emissions impacts (EI) per voyage

Units per voyage could also be per tkm.

An appropriate assumption applied to this work, given the lack of data on the consistency of bunker purchasing as a function of port calls (e.g. a ship does not necessarily buy bunkers after every port call), is that ships calling at the UK purchase bunkers from the UK for their UK inbound/outbound voyage, but source the fuel from elsewhere if they are sailing elsewhere. Under that assumption, in either example of A or B, the UK demand for fuel is the same (it is a function of the number of voyages not the number of different ships), and therefore cost/benefit 2 is a constant in both scenarios, 100 x (C_{CB} + O_{CB}).

In both examples, the emissions and operating cost impact on UK voyages are the same (100xEI), but in scenario B, emissions impact of 900xEI and 900xC_{OS} are also allocated to non-UK voyages.

In example A, the capital costs C_{CS} of the ship are 10xC_{CS} and all of that cost is allocated to the UK. In example B, the total capital cost is 100xC_{CS}, 10% is allocated to the UK (same as example A), but 90%, 90xC_{CS} is allocated to non-UK.

Therefore:

- The UK cost and benefit data and calculation are the same in examples A and B
- In example B, components of non-UK cost and benefit can be calculated from information on the % of a ship's annual voyages (tkm) that are allocated to

servicing the UK, assuming UK input assumptions (on costs) are good approximations for non-UK. This % can be obtained from estimates of the total number of ships servicing the UK (obtained from AIS data) and compared against tnm derived estimates of the minimum fleet size (if ships were uniquely servicing UK trade).

- However, because the regulation scenario applied to UK international shipping is a mostly (except in Scenario G, see section 6.4.5) global regulation scenario equally applicable to UK and non-UK voyages, non-UK costs and benefits should not be treated as costs and benefits to UK. In Scenario G, following the logic in this example, there may be non-UK costs and benefits. These have not been explicitly calculated or presented because they are highly uncertain (due to uncertainty in how ships servicing UK trade also serve other countries and uncertainty on the policy decisions made by the other countries on whether to adopt similar policy to the UK's policy (in Scenario G)).

3.6 Approach to projecting the uptake of electric ships

The capital costs of the batteries that would be required for large ship sizes make this propulsion configuration uncompetitive for such ships. Only the smallest ship types in the domestic fleet are considered viable to electrify and therefore are modelled in detail. To investigate the viability of full electric propulsion for these ships, the smallest ship size categories are broken down further into smaller size categories and assumptions on average voyage length (as shown in Table 2) are used to estimate the costs associated with battery electric ships.

The average voyage distance travelled for each category was estimated using data from our own datasets[13]. Where data was unavailable for small niche types of vessels, the voyage distance travelled was assumed to be 100nm (based on expert judgement).

The total energy storage required was then calculated alongside the corresponding capital cost for the batteries required for each vessel type. The battery cost was assumed to be $150/kWh (2015 prices). The battery cost was then annualised, assuming a useful life of the battery to be 25 years and a discount rate of 10%. These assumptions were based on expert judgement.

The electricity costs were estimated by considering the annual fuel consumption for each vessel type as estimated in GloTraM. The electricity consumption was calculated by assuming that battery electric technology is 50% more efficient relative to ICE technology. This is because the ICE is assumed to have an efficiency of ~50% (which is the assumed efficiency of an ICE based on existing literature) while battery electric technology does not need ICE, therefore it gains 50% relative to ICE technology.

The electricity costs were added to the annualised capital cost for the battery to give the total annual cost of using electric battery technology for each ship type in its corresponding category.

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[13] AIS data from Exact Earth, WFR World Fleet Register data, internal datasets

These costs were compared with the costs of the zero emission option with the lowest cost (based on the scenario analysis in section 6, the comparison is made against the ammonia vessel), in order to identify whether battery electric or synthetic fuel propulsion might be most competitive (as shown in Table 3). A pragmatic approach is taken to estimate the likely switch to electric propulsion at a single value of electricity price (8.5 (real 2017 p/kWh)) and ammonia price (689 real 2017/tonne)[14], given that these inputs are approximately constant from 2030 onwards. The most competitive solution (battery or ammonia) was then used to correct the outputs of GloTraM and modify the energy demand, costs and emissions accordingly for the presentation of results.

To enable the comparison in a consistent basis[15], the costs of the engines for both battery or ammonia vessels were not taken into account.

Table 2 Input assumptions for the prediction of the uptake of electric ships

type	**size**	**average voyage distance**	**average design speed**	**Power**
		nm	knot/hr	kW
Bulk carrier	dwt 0-3999	100	10.72	1962
Bulk carrier	dwt 4000-6999	500	12.58	2338
Bulk carrier	dwt 7000-9999	800	13.4	3347
Bulk carrier	dwt 0-9,999	1152	12.23	2549
Container	TEU 0-249	100	12.53	2558
Container	TEU 250-499	500	14.28	4103
Container	TEU 500-749	800	16.38	6989
Container	TEU 750-999	673	17.93	10614
Container	TEU 0-999	673	15.28	6066
Oil tanker	dwt 0-999	100	9.4	624
Oil tanker	dwt 1000-1999	500	10.75	1268
Oil tanker	dwt 2000-2999	800	11.75	1938
Oil tanker	dwt 3000-4999	1784	11.8	2681
Oil tanker	dwt 0-4,999	1784	10.925	1628
Ferry-pax only	GT 0-499	60	14.19	1591
Ferry-pax only	GT 500-999	60	18.37	3020

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[14] See section 6.4.2 for further details on fuel price assumptions

[15] The cost of ammonia vessels from the model does not include the cost of the engine as the output is express in terms of cost differential with the existing technologies. The ICE for ammonia vessels is assumed to have the same cost of the existing ICE. For this reason, the cost of the engine for the electric ships is omitted

Ferry-pax only	GT 1000-1499	60	22.06	2217
Ferry-pax only	GT 1500-1999	60	23.31	3442
Ferry-pax only	GT 0-1,999	60	19.4825	2568
Cruise	GT 0-499	25	9.58	973
Cruise	GT 500-999	100	13.65	1688
Cruise	GT 1000-1499	100	12.5	2302
Cruise	GT 1500-1999	100	13.75	2348
Cruise	GT 0-1,999	100	12.37	1828
Ferry-RoPax	GT 0-499	100	10.95	599
Ferry-RoPax	GT 500-999	100	13.27	1208
Ferry-RoPax	GT 1000-1499	100	13.75	1774
Ferry-RoPax	GT 1500-1999	100	15.36	2470
Ferry-RoPax	GT 0-1,999	100	13.3325	1513
Ro-Ro	dwt 0-1999	100	11.14	1459
Ro-Ro	dwt 2000-4999	100	13.98	4951
Ro-Ro	dwt 0-4,999	100	12.56	3205
Service - tug	0-+	100	11.89	2769
Offshore	0-+	100	13.32	2769
Service - other	0-+	100	13.61	2769

Table 3 Detailed results for the analysis comparing the costs of electric ships and ships using ammonia as a fuel (2015 prices)

Type	size	Total annualised extra cost for battery electric ship relative to a baseline year (2016) newbuild specification. Includes capex of batteries and electricity costs	Total annualised extra cost for an ammonia ship, relative to a baseline year (2016) newbuild specification. Taken from GloTraM as the lowest cost zero-emission competitor to a batter-electric ship. Estimate includes annualised changes in capital costs and fuel costs
Bulk carrier	dwt 0-3999	$ 1,218,552	$ 1,207,560

Bulk carrier	dwt 4000-6999	$ 3,757,560	$ 1,438,936
Bulk carrier	dwt 7000-9999	$ 7,544,316	$ 2,059,864
Bulk carrier	dwt 0-9,999	$ 8,594,000	$ 1,568,787
Container	TEU 0-249	$ 1,478,162	$ 1,480,342
Container	TEU 250-499	$ 6,025,502	$ 2,374,744
Container	TEU 500-749	$ 13,447,365	$ 4,045,121
Container	TEU 750-999	$ 16,468,482	$ 6,143,076
Container	TEU 0-999	$ 10,712,801	$ 3,510,821
Oil tanker	dwt 0-999	$ 604,874	$ 460,427
Oil tanker	dwt 1000-1999	$ 2,813,078	$ 935,202
Oil tanker	dwt 2000-2999	$ 5,754,849	$ 1,429,106
Oil tanker	dwt 3000-4999	$ 15,718,450	$ 1,976,742
Oil tanker	dwt 0-4,999	$ 10,231,444	$ 1,200,369
Ferry-pax only	GT 0-499	$ 585,661	$ 742,833
Ferry-pax only	GT 500-999	$ 1,001,510	$ 1,409,772
Ferry-pax only	GT 1000-1499	$ 689,360	$ 1,034,906
Ferry-pax only	GT 1500-1999	$ 1,051,103	$ 1,606,496
Ferry-pax only	GT 0-1,999	$ 833,299	$ 1,198,502
Cruise	GT 0-499	$ 626,393	$ 407,364
Cruise	GT 500-999	$ 1,381,867	$ 707,144
Cruise	GT 1000-1499	$ 1,941,858	$ 964,338
Cruise	GT 1500-1999	$ 1,917,066	$ 983,390
Cruise	GT 0-1,999	$ 1,547,266	$ 765,559
Ferry-RoPax	GT 0-499	$ 357,028	$ 355,594
Ferry-RoPax	GT 500-999	$ 650,821	$ 717,276
Ferry-RoPax	GT 1000-1499	$ 938,822	$ 1,053,173
Ferry-RoPax	GT 1500-1999	$ 1,239,513	$ 1,466,425
Ferry-RoPax	GT 0-1,999	$ 812,987	$ 898,117

Ro-Ro	dwt 0-1999	$ 1,450,584	$ 1,425,616
Ro-Ro	dwt 2000-4999	$ 4,598,343	$ 4,836,820
Ro-Ro	dwt 0-4,999	$ 3,069,619	$ 3,131,218
Service - tug	- 0-+	$ 1,127,066	$ 517,530
Offshore	- 0-+	$ 1,512,703	$ 1,412,653
Service - other	- 0-+	$ 1,329,912	$ 1,197,793

4 SHIP-LEVEL MODELLING OF EMISSIONS ABATEMENT OPTIONS

4.1 Aims of this section

The aim of this section is to describe how the ship-level modelling of emissions abatement options has been undertaken. It provides detail on the method used; the emissions abatement options that have been assessed within the analysis of the main report; the key input assumptions; and the outputs of the modelling.

4.2 Method used

The ship impact module of GloTraM was used to estimate, at the level of the individual ship type, size and age categories, the annual change in emissions and fuel consumption that could be delivered by each of the abatement options. For each of the abatement options described in section 4.3 and, for each combination of ship type/size/age as described in Table 1, the changes to the baseline vessel brought about by the adoption of the abatement option were estimated by the ship impact module and extracted from the model.

Changes were considered relative to the 'Business as Usual' (scenario A described in Section 6.3). The same principles of the GloTraM method are used (as described in section 3.2), however, there is no selection of the most profitable option as all changes by each of the abatement options are extracted.

The ship impact module takes into account the 'impact' that a particular abatement option would have on a specified ship and calculates the annual change in emissions and fuel consumption.

There are a number of other impacts that each of the abatement options can make on the economic and energy performance of a ship depending on the type of technologies associated with the option and the type of ship.

We considered the following potential impacts:

- Impact on capital cost
- Impact on non-fuel operational cost
- Impact on fuel-related operating cost
- Impact on power (main and auxiliary engines)
- Impact on specific fuel consumption of the engine/fuel combination (main and auxiliary engines)
- Impact of engine Maximum continuous rating - MCR (main and auxiliary engines)
- Impact on cargo capacity

The input assumptions associated with these impacts are provided in section 4.4.

4.3 Abatement options modelled

The abatement options modelled are shown in Table 4.

Table 4 Abatement options modelled

Section 1 - Technologies that can increase energy efficiency	
Rudder Bulb	A Rudder Bulb system consists of a streamlined bulb fixed at the leading edge of the full spade rudder, which is situated aft of the propeller hub. The transition between bulb and propeller hub is bridged by a fairing cap.
Pre-Swirl propeller ducts	A preswirl stator duct is a propeller duct connected to a ship with blades that direct the flow of water into the propeller.
Vane wheel	A Vane Wheel consists of a number of blades that are freely rotating and coaxial to the ship’s propeller, reducing rotational losses from the propeller
Contra Rotating Propeller	A Contra Rotating Propeller is formed by two propellers on coaxial shafts rotating in opposite directions.
Twisted rudders	Twisted rudders equalise pressure distribution on the rudder blades to avoid cavitation and to improve the manoeuvrability performance
Boss cap fin	A device attached to the propeller hub to break up the hub vortex generated behind the rotating propeller. The boss cap fin comprises a small vane propeller fixed to the tip of a cone-shaped boss cap, which may have more blades than the propeller itself.
Air lubrication Bubbles	Reduction in the frictional resistance by injecting air between the hull surface and seawater
Block Coefficient Reduction	Block coefficient reduction reduces resistance, making the ship more slender, whilst maintaining the same waterline length, but comes at the expense of a higher purchase cost
Wind assistance (rotors/sails/wings)	A flettner rotor is a spinning vertical rotor that generates wind power irrespective of its direction. The rotor is driven by a motor to create a propulsive force acting in a perpendicular direction to that of the wind as a result of the Magnus effect Sail: a tensile structure that uses wind power to propel sailing craft Wings: An automated system of large rectangular solid sails supported by cylindrical masts. These would be symmetrical sails which would allow a minimal amount of handling to maintain the sail orientation for different wind angles
Wind assistance (kites)	A kite is attached to the vessel’s bow to use the available power coming from the wind supporting the propulsive power on board
Steam Waste Heat Recovery	Waste heat recovery systems recover the thermal energy from the exhaust gas and convert it into electrical energy, while the residual heat can further be used for ship services (such as hot water and steam)

Organic Rankine Waste Heat Recovery	Waste heat recovery system is designed to absorb part of the waste heat by evaporating a working fluid under high pressure, when the fluid expands in a turbine, it converts the available heat into mechanical and then electrical energy. The recovered energy could be used as part of a marine propulsion system providing additional efficiency benefits
Turbo-compounding in Series	Waste energy recovery system that uses part of the energy available from the high-pressure high-speed exhaust gas to produce electricity via an electric generator. For engines below 2 MW in installed power
Solar power	Usage of photovoltaic cells to convert solar radiation into electrical power using the available space on deck
Hotel systems	Systems that reduce energy consumption in hotel space (e.g. optimisation of air conditioning system)
Fuel cells for aux system	Fuel cells technologies for auxiliary power
Energy saving lighting	Employ advanced technology to reduce the amount of electricity used to generate light
Shore power	Cold ironing, or shore connection, shore-to-ship power or alternative maritime power, is the process of providing shoreside electrical power to a ship at berth while its main and auxiliary engines are turned off.
Engine derating	It is the operation of an engine at its normal maximum pressure as set at its design point but having a lower brake mean effective pressure and shaft speed. This produces a reduction in the engine's specific fuel oil consumption
Energy storage battery + PTO	Batteries technologies to store and manage energy use in the ship's electrical systems, incorporating power take-off (PTO) from the shaft to charge the batteries as required
Section 2 - Operational or behaviour change that can increase efficiency	
Trim optimisation	Providing most favourable trim conditions for the required draught as well as optimising the distribution of cargo or ballast to reduce fuel consumption
Hull coating management	Painting a hull with a special coating to prevent hull fouling and hence reduce the frictional resistance component of the vessel
Draft/displacement optimisation	Adjusting draft/displacement by optimising cargo/ballast ratio to increase vessels' performance efficiency
Port turnaround optimisation	Minimize vessel idle time and turnaround times
Speed reduction	Reduction of speed to reduce fuel consumption
Section 3 - Technologies specific to the capture/treatment of exhaust emissions (GHG and air pollutant emissions)	

NO_x Device	The basic idea of a selective catalytic reduction (SCR) is to remove unwanted NO_x footprint from the exhaust gas via chemical reaction, which relies on the injection of ammonia into the exhaust gas flow, usually in the form of a urea solution. Exhaust gas recirculation (EGR) is a nitrogen oxide (NOx) emissions reduction technique used in petrol/gasoline and diesel engines. EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders
SO_x Device	Scrubbers are designed to utilisation of alkalines HCO_3 and SO_4 present in sea water to neutralise SOx species in the exhaust gas via a chemical reaction. This reaction results in production of sulphates, which are being recirculated back into the sea.
PM Device	Device to reduce PM emissions
Section 4 - Machinery	
2 stroke diesel _HFO	Conventional two-stroke slow speed diesel engine burning heavy fuel oil (HFO)
2 stroke diesel _LSHFO	Conventional two-stroke slow speed diesel engine burning low sulphur heavy fuel oil (LSHFO)
2 stroke diesel _MDO	Conventional two-stroke slow speed diesel engine burning marine diesel oil (MDO)
4 stroke diesel_MDO	Conventional four-stroke medium speed diesel engine burning marine diesel oil (MDO)
4 stroke spark ignition (LNG)	Four-stroke medium speed diesel engine burning liquified natural gas where the burning of the fuel occurs by the spark generated from the spark plug
4 stroke spark ignition (NH_3)	Four-stroke medium speed diesel engine burning ammonia where the burning of the fuel occurs by the spark generated from the spark plug
diesel electric HFO	Electronically controlled marine diesel engine burning heavy fuel oil (HFO)
diesel electric LSHFO	Electronically controlled marine diesel engine burning low sulphur heavy fuel oil (LSHFO)
diesel electric MDO	Electronically controlled marine diesel engine burning marine diesel oil (MDO)
FC+H_2	Hydrogen based fuel cell technology converting the chemical energy of hydrogen into electrical energy (for newbuilds only)
FC+NH_3	Ammonia used in Fuel cells technology (for newbuilds only)
IC+H_2	Hydrogen used in an internal combustion engine (for newbuilds only)

methanol 2 stoke	Conventional two-stroke slow speed diesel engine burning methanol
methanol 4 stoke	Four-stroke medium speed diesel engine burning methanol where the burning of the fuel occurs by the spark generated from the spark plug

Note, that the section 'machinery' refers to the main engine of the ship, although, the auxiliary engine is also modelled. The auxiliary engine is assumed to be the same of the main engine in most of the cases. The ships using LNG, hydrogen, ammonia and methanol are assumed to have the same types of auxiliary engine and main engine, which also are assumed to use the same fuel. Whereas, the ships using HFO, MDO, LSHFO can have auxiliary engines different from the main engine and can use different fuels. In this case, because it is assumed to be possible to switch fuel and use the same auxiliary engine type, the selection of auxiliary fuel varies over time and depends on the regulatory compliance and economic drivers.

4.4 Input assumptions for the abatement options

The ship impact module of GloTraM receives as an input the cost and 'impact' that a particular abatement option would have on a specified ship.

The input data assumptions for each abatement option were collected and reviewed (please see section 7.2.1 for more details on the steps undertaken for quality assurance) and are provided in the worksheet "Input assumptions for the abatement options.xlsx".

The worksheet contains the references for the input assumptions and each tab contains the input data for the impact of a particular abatement option on a specified ship. An emissions abatement option can impact a vessel under one or more of the following factors:

- Capital cost
- Annual non-fuel operating costs
- Main engine power output
- Main engine specific fuel consumption (sfc)
- Main engine Maximum Continuous Rating (MCR)
- Auxiliary engine power output
- Auxiliary engine sfc
- Auxiliary engine MCR

4.5 Detailed results

The results of this analysis produced three output datasets that are provided in a number of worksheets

The first worksheet "absolute_impacts_A.csv" contains, relative to a 2016 baseline, the changes in aggregated annual costs, along with changes in operational and upstream emissions for each ship type/size/abatement option combination. These are presented for the following years: 2020, 2030, 2040, 2050, 2060, 2070 and 2080 for the UK domestic fleet and UK international fleet. In particular, this dataset contains the changes in following aggregated annual costs: fuel operating costs, non-fuel operating costs, capital costs as well as the changes in emissions (CO_2, CH_4, N_2O, SO_2, NO_x, $PM_{2.5}$) for the following emissions types: operational at port, upstream, and operational.

Two others worksheets were produced and they are used as inputs to generate the marginal abatement cost curves in section 5.

One worksheet ("baseline.csv") provides detailed inputs for the years 2031 and 2051, for the BAU (scenario A)

In addition to the information described for the worksheet "absolute_impacts", the 'baseline' worksheet contains further information such as: the number of vessels of UK domestic and UK international fleets, the average build year of the generation category, the fuel consumption for each of the specified fuels, information on the type of main engine, fuel used in the main engine, dwt, and operational speed of the vessel in nm/hr. It also contains an indicator field for each abatement technology (technologies that can increase energy efficiency, and operational or behaviour change that can increase efficiency) to identify whether the technology was installed or not and another indicator field for each air pollution technology to identify whether the technology was installed or not (NO_x Device, SO_x Device, PM Device).

The other worksheet ("impacts.csv"), instead, contains the potential impacts of all technologies and operational abatement options. The impacts are provided on a per vessel and per option basis.

5 COST EFFECTIVENESS ANALYSIS

5.1 Aims of this section

This section is intended to support interpretation of the ‘Cost effectiveness of shipping emissions abatement options” chapter of the main report. It describes what a marginal abatement cost curve is; how they have been developed; and the key assumptions.

5.2 Aims of the Marginal Abatement Cost Curve (MACC) analysis

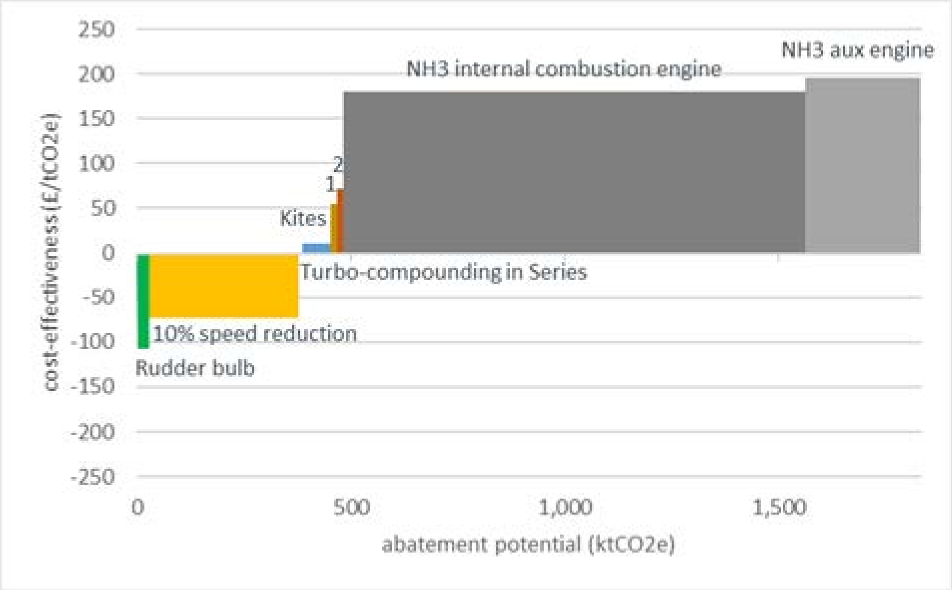
Marginal Abatement Cost Curves (MACCs) allow us to visually describe two important pieces of information that are useful when comparing technologies and other options for reducing GHGs and emissions to air of pollutants from ships.

Firstly, they show, for each technology or ‘abatement’ option, the social cost of reducing an additional tonne of greenhouse gases (expressed as carbon dioxide equivalent, CO_2e) by implementing that technology or abatement option (this is on the y-axis). Secondly, they show the volume of emissions that could be reduced if that technology or abatement option were implemented across all vessels in the particular fleet on which the MACC focuses (this is on the x-axis).

In this study, the MACCs show the estimated cost of reducing an additional tonne of greenhouse gases and the estimated volume of emissions that could be reduced if implementing technologies and abatement options over and above those that are expected to be implemented under the business as usual (BAU) scenario. Under the BAU scenario, all current regulations are assumed to be met (e.g. relating to air quality, design efficiency of new ships, etc). These policies are described in the description of the BAU scenario in Section 6.

MACCs often take the format shown in Figure 2.

Figure 2 **Example of a ship-type specific Marginal Abatement Cost Curve: 8000 – 11999 TEU container ships (UK international) in 2031 (2018 prices)**



Source: CE Delft analysis of UMAS modelling

Note: This MACC relates to one example ship type and size. 'Kites' is short for 'Wind assistance (kites)'. The options labelled 1 and 2 are: 1 - Block Coefficient Reduction; 2 - Air lubrication Bubbles

NH3 internal combustion engine refers to 4 stroke spark ignition (NH3) in table 4.

Each bar in Figure 2 represents an abatement option. For each, the cost per additional tonne of reduced GHG emissions is shown as the height of the bar and is expressed as the net £ cost per tonne of carbon dioxide equivalent that is reduced (£/tCO_2e) in 2018 prices (y-axis); and the volume of emissions that could be reduced if that abatement option were deployed across the relevant fleet is shown by the width of the bar and is expressed in thousand tonnes of carbon dioxide equivalent (ktCO_2e) (x-axis). 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.).

Abatement options for which the costs per tonne CO_2e are negative (such as 10% speed reduction in Figure 2) mean that the financial costs of the abatement option are outweighed by the benefits of fuel savings or the monetised value of reduced air pollutants; options which have a positive net cost per tonne CO_{2e} (such as NH3 internal combustion engine in Figure 2) mean that there is a high cost of the abatement option that is not outweighed by the fuel savings or monetised benefits of reduced air pollutants.

The rest of this Section explains more about how the MACCs are developed and their underlying assumptions.

5.3 Types of MAC curves

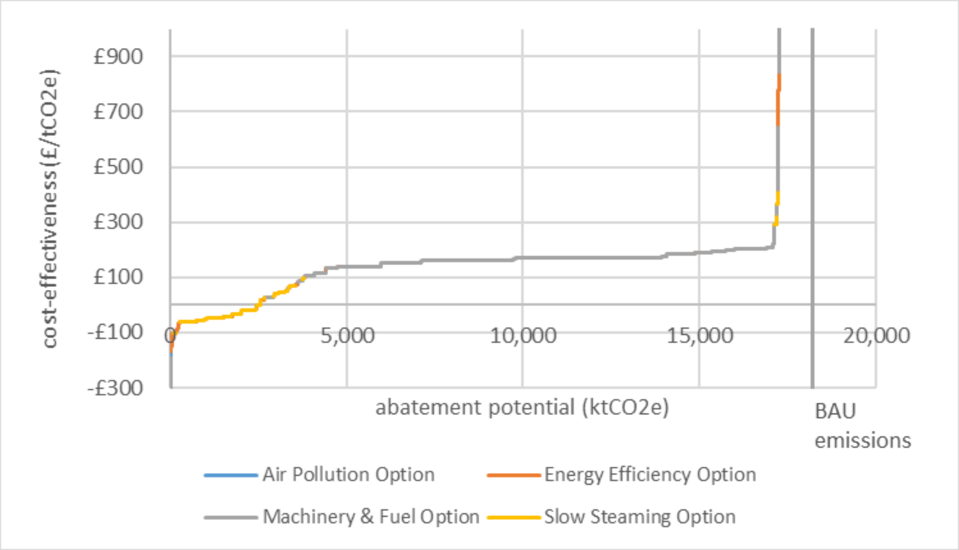
In this analysis, MACCs are drawn for particular years, 2031 and 2051[16], and for both UK domestic shipping and UK international shipping.

Two types of MACCs are included in the main report. The first type of MACC is shown in Figure 2 (above) and takes the form of a bar chart. These are specific to a ship type / size combination (averaged over different vintages), so the MACC reflects the cost effectiveness of abatement options for all ships of that ship type / size (i.e. that particular fleet of vessels). For example, the MACC for the fleet of 8000 – 11,999 TEU container ships (UK international shipping) in 2031 is shown in Figure 2.

In this case, the MACCs are able to show the various abatement options that could be implemented by ship owners or operators (which are represented by each bar), and the estimated cost effectiveness of each of those options if they were implemented in the order shown in the chart (from left to right i.e. most cost-effective first, then the next most cost-effective, and so on). They also show the estimated volume of emissions that could be reduced if all ships of that ship type and size were to use that particular abatement option.

The second type of MACC takes a line-graph form and provides these estimates for the full breadth of diversity in ship types, sizes and ages in the whole fleet under consideration (for example, UK domestic shipping or UK international shipping). They take the form shown in Figure 3.

Figure 3 Example Marginal Abatement Cost Curve: UK international shipping in 2051 (2018 prices)



Source: CE Delft analysis of UMAS modelling

Note: This MACC relates to all UK international shipping ship types

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[16] In practice, the modelling outputs are for 2031 and 2051. This is because the model projects forward in 5-year intervals from the base year of 2016. So, the model provides outputs for 2016, 2021, 2026 etc. Therefore, 2031 and 2051 are the closest modelled years to 2030 and 2050 respectively. There is a negligible difference in values between 2030 and 2031 and 2050 and 2051.

In this form of MACC, the line is essentially formulated by plotting the estimated cost effectiveness for each individual abatement option if applied in each individual ship type, size and age combination (of which there are hundreds). As shown, it is possible to see which abatement options are reflected at a high-level when moving along the curve, as the entries for each abatement option are colour-coded to show which of four broad categories they are classified within. For example, in Figure 3, slow steaming and energy efficiency options are estimated to have a negative cost-effectiveness for many ship type, size, age combinations (left end of the curve) though there are some ship types, sizes and ages for which these options are estimated to be less cost effective and hence are seen in the yellow and orange portions on the curve towards the right of the chart. The total emission reduction potential of these options (i.e. breadth of the yellow and orange sections on the X-axis) is estimated to be smaller than the emission reduction potential of the fuel options (indicated in grey).

In the main report, similar line graph MACCs are shown for the UK domestic fleet and the UK international fleets in 2031 and 2051, with the definitions of these shipping categories as described in Section 3.3 and the definition of UK domestic and international as given in Section 3.4.

For all the MACCs produced in this Annex and Section 3 of the main report, only the GloTraM-modelled fleet of ships is included (see Section 3.3). The total UK domestic and shipping emissions inventories presented in Section 6 of this Annex report and Section 4 of the main report includes further ship types but only by extrapolating from the results for the GloTraM-modelled fleet. Total emissions and total emission reduction potential should therefore be derived from Section 6 of this Annex and Section 4 of the report.

5.4 Formulation of the MAC curves

5.4.1 Abatement options included in the analysis

MACCs are designed to show the cost effectiveness of different abatement options, and the volume of greenhouse gas emissions that could be saved if those abatement options or technologies were to be implemented, in the order of the most cost-effective first to the least cost-effective.

Given that the MACCs look at what additional emissions reductions are possible compared to the BAU scenario, the abatement technology and abatement options that are reflected in the MACCs are only those that would not be widely taken up any way under the BAU situation.

The underlying data used to develop the MACCs in the main report derives from the modelling work described in Section 3.2. An overview of the main aspects of the modelling from Section 3.2 relevant for the development of the MACCs is:

- Transport demand is projected to increase in future years in line with the forecasts provided by DfT (UK port freight traffic, 2019 forecasts)[17]; it is assumed that the supply of vessels increases to match this demand.

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[17] DfT (2019): UK Port Freight Traffic, 2019 Forecasts. Available at https://www.gov.uk/government/publications/uk-port-freight-traffic-2019-forecasts

- Vessels are assumed to be retired and scrapped at the end of their lifetime; and new ships are assumed to enter the market to ensure that supply matches demand.
- Ship owners are assumed to operate in a way which is profit maximising i.e. for the market conditions they are facing, they select and fit the abatement options that are consistent with maximisation of their profits, as well as ensuring their compliance with regulations. Therefore, the modelling begins with the 2016 actual fleet and models this forward under the BAU scenario. Ship owners take up abatement options under BAU if it is consistent with their profit maximising objectives and regulations with which they must comply. Once an abatement option has been taken up under BAU then it is no longer relevant for consideration as a potential abatement option in the MACCs (and neither are other abatement options in the same group).
- Costs are converted into annualised costs (for example, what a ship owner would have to pay each year if they bought a piece of capital equipment, with the cost spread over a number of years, assuming the money is borrowed to finance it). The cost effectiveness is assessed on an annual basis because it allows an estimation to be provided of the annual net costs to be faced within a given year and to compare this against the annual CO_2e savings in that year. This provides a more transparent understanding of the cost effectiveness of the abatement options at a particular point in time, and allows abatement options to be directly compared.

The order in which abatement options and technologies are implemented is important. This is because when an abatement option or technology is implemented, it is likely to affect the emissions reductions that can be achieved from subsequent abatement options and technologies implemented later. The technologies are therefore said to interact. The MACC analysis takes the interaction between abatement options into account in two ways.

1. Some abatement options are assumed to be mutually exclusive; if one of these is included in the MACC of a specific ship category (as defined by type, size and age), then incompatible abatement options will not be included in the MACC. In implementing this, 19 groups of options were defined on the basis of expert judgement (see Table 5). The groups either represent different types of the same technology (e.g. Group 5 has two types of air lubrication) or technologies that apply at the same point of the ship (e.g. Group 2 includes four technologies that can be applied to the propeller and for which it is physically impossible to be installed on the same ship). Options within a group are assumed to be mutually exclusive; while it is assumed that abatement options from different groups can be combined on a ship. Note that auxiliary engines are treated independently from the main engine, so their selection does not depend on the selection of the main engine.
2. Emission reductions are expressed in percentage terms and multiplied with each other, not summed (e.g. two abatement options that reduce emissions by 10% each will reduce emissions by 10% + (0.9*10%) = 19%, not by 20%).

(Adding percentages instead of multiplying them would result in emission reduction potentials of more than 100% which is not possible).

Table 5 Groups of mutually exclusive abatement options

Group 1	Rudder bulb	Twisted rudders	Boss cap fin	
Group 2	Pre-Swirl propeller ducts	Trim optimisation	Vane wheel	Contra Rotating Propeller
Group 3	Hull + Propeller optimisation			
Group 4	Hull coating management			
Group 5	Air lubrication Bubbles	Air lubrication Cavity		
Group 6	Wind assistance (Sails)	Wind assistance (rotors)	Wind assistance (Kites)	
Group 7	Steam Waste Heat Recovery	Organic Rankine Waste Heat Recovery		
Group 8	Turbo-compounding in Series			
Group 9	Solar power			
Group 10	Hotel systems			
Group 11	Fuel cells for aux system			
Group 12	Draft/displacement optimisation			
Group 13	Port turnaround optimisation			
Group 14	Energy saving lighting			
Group 15	Shore power			
Group 16	Engine derating	Speed reduction 10%	Speed reduction 20%	Speed reduction 30%
Group 17	Energy storage battery + PTO			
	diesel electric_HFO	diesel electric_LSHFO	diesel electric_MDO	

Group 18 (main engine)	4 stroke spark ignition (LNG)			
	FC+NH3	FC+H2	IC+H2	4 stroke spark ignition (NH3)
	methanol 2 stroke	methanol 4 stroke		
Group 19	Block coefficient reduction			

5.4.2 Assessing the costs, benefits and cost-effectiveness of the individual emissions abatement options

We assessed the costs and benefits of each individual emissions abatement options for each ship (defined by type, size and age).

The approach for the calculation of cost effectiveness used for this analysis draws on BEIS guidance: “Valuation of Energy Use and Greenhouse Gas: Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government”[18] (page 25). The main variation from the BEIS guidance on the calculation of cost effectiveness is that the MACCs in this report have been developed to show the annualised cost effectiveness per tonne of CO_2e saved within a given year of interest. This is to allow greater comparability across abatement options. An alternative approach, as suggested by BEIS, is to look at the net present value of the abatement option over its lifetime minus the present value of the change in GHG emissions, divided by the total GHG emissions saved over the life of the option i.e. the cost of saving each tonne of GHG emissions over the life of the abatement option per tonne of CO_2e. The method used for the MACCs in this report allows a particular focus on the GHG emissions saved within the particular year of interest (and not the GHG saving over the life of the abatement option).

The inputs for the analysis are largely compiled from GloTraM modelling described in Section 3.2, combined with the modelling of a business as usual (BAU) scenario (described in more detail as scenario A in Section 6).

MACCs are developed in a seven-step process:

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[18] Since this analysis was undertaken, a more recent version of the BEIS guidance has been published, so this analysis is consistent with the guidance published in 2018, and not the more recent version published in 2019. Available at https://webarchive.nationalarchives.gov.uk/20190103113812/https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/671205/Valuation_of_energy_use_and_greenhouse_gas_emissions_for_appraisal_2017.pdf.

1. **Compile cost and impact data**[19]: For an average ship in each vessel category (defined by ship type, size and age) and each abatement option or technology, data from the analysis in Section 6 is compiled including:
    - GHG emissions abatement estimates (estimated in CO_2e, using the factors for converting greenhouse gases to their equivalent in carbon dioxide in BEIS (2018) guidance, which are based on the IPCC’s Fourth Assessment Report[20])
    - Air pollutant abatement estimates (see below for more detail) for primary PM2.5, NO_x and SO_2
    - Upfront capital costs of the abatement options
    - Annual maintenance/operating costs of the abatement options
    - Lifetime of the abatement options
    - Changes in voyage costs for the ship owner (this is the change in fuel costs i.e. the change in fuel consumption multiplied by the prices of the relevant fuels) due to the abatement options
    - Changes in revenues (this is the change in charter revenues to the ship owner which may change due to the change in speed of the voyage). Note that other changes in revenue were not included in the analysis. The reason is that the inclusion of these changes in this approach is considered too uncertain. For example, a ship that uses a fuel with a lower energy density than HFO could sacrifice cargo space, in which case the revenues would be reduced, but it could also bunker more often or be designed in such a way that the cargo space is the same, in which case the revenues would be the same. This is not consistent with the way that alternative fuels are modelled in the scenario analysis, for which reductions in revenue are applied if the alternative fuel does have a lower energy density. The inclusion of these changes is considered acceptable in the scenario analysis because the model allows the calculation of the loss of cargo capacity. This will have an effect to create a small increase in the carbon price needed to stimulate take-up in the scenarios, relative to that implied from the MACC
    - Calculate annual costs and benefits to the UK (i.e. not including non-UK costs and benefits): the annual costs and benefits for each abatement option are calculated for the average ship in each vessel category (defined by ship type, size and age).
    - Costs that are borne annually are used directly from the modelling outputs (e.g. annual maintenance/operating costs and changes in voyage costs,

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[19] Where cost values are used from the GloTraM modelling, they are converted to GBP using the exchange rates advised by DfT for the appropriate future year. These are from BEIS (2018) Updated energy and emissions projections 2017, Annex M: Growth assumptions and prices. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/670353/Annex-m-price-growth-assumptions.xls.

[20] BEIS (2018) Valuation of Energy Use and Greenhouse Gas: Supplementary Guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government. Available at https://webarchive.nationalarchives.gov.uk/20190103113812/https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/671205/Valuation_of_energy_use_and_greenhouse_gas_emissions_for_appraisal_2017.pdf.

converted from $USD to GBP using exchange rates as advised by DfT for the corresponding future year e.g. 2031 or 2051);

- Capital expenditures and other non-recurring costs are converted into annual equivalent cost. This assumes that the abatement technology is purchased by the ship owner and that the ship owner takes out a loan to finance this purchase, therefore incurring a cost of finance (i.e. they do not face the capital cost all in one year but the cost is spread over a number of years). Given the technologies will be financed over several years, the private cost of finance is incurred (with a weighted average cost of capital of 10% as estimated by Imarest (2011) MEPC 62/INF.7[21]) and used to estimate the equivalent annual cost over the remaining lifetime of the ship or the lifetime of the technology, whichever is shorter.

The annualised net costs (costs minus benefits) for each of the abatement options therefore comprise the following elements for the abatement options that are relevant for the MACC (i.e. excluding those that will have already been taken up by the ships under BAU):

- Costs
  - Annualised capital expenditures plus non-recurring costs;
  - Changes in costs that are borne annually (such as maintenance/operating costs);
  - Changes in fuel costs, where relevant (e.g. if the technology leads to higher fuel use); and
  - Change in revenues accruing to the ship owner (change in charter revenues).
- Benefits:
  - Reduced damage from emission to air of pollutants, estimated by taking the change in emissions of primary $PM_{2.5}$, NO_x and SO_2 from shipping activity that occurs within the geographical area covered by the UK National Atmospheric Emissions Inventory maps. The changes in emissions are outputs from the analysis of Section 6. The emissions are converted to monetary values using damage costs from DEFRA. The method for valuing air pollutant emissions is described in the box below.
  - Reduced fuel costs (where relevant): the quantity of the fuel saved is from the modelling and the costs are calculated by multiplying the quantity with the prevailing fuel price (assumptions are in Section 6).
  - In line with the Government's guidance "Valuation of Energy Use and Greenhouse Gas" (BEIS, 2018), the value of the savings in GHGs is not included in the calculation of benefits.

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[21] See https://www.cedelft.eu/en/publications/download/2335

VALUING AIR POLLUTANT EMISSIONS

As described above, an important component of the benefits of the adoption of abatement options is the impact on air pollutants. To place a monetary valuation on these emissions for the purposes of the cost-effectiveness analysis, Defra guidance is used. There are two relevant methods for valuing air pollutants (i) a 'damage cost' approach and (ii) an 'impact pathway' approach (a third option is also suggested by Defra (an 'abatement cost' approach), but that is only used when an intervention is expected to affect compliance):

- The impact pathways approach (IPA) is recommended for use where the air quality impacts are estimated to be significant (>£50 million) or where changes to air quality are the principle objective of the policy or project. It requires the estimation of emissions, dispersion, population exposure and outcomes.
- The damage cost approach uses a set of impact values derived using the impact pathways approach and are defined in terms of a £ cost per tonne of pollutant emissions.

Although the rigour afforded by the impact pathway approach to valuing air pollutants is recognised, given the very limited time available for this analysis, the impact pathway approach was assessed by the authors as not feasible within the time available given the number of locations for which bespoke modelling would have been needed. To apply this method would involve the following: use of dispersion models to investigate how the estimated changes in air pollutant emissions translate to changes in concentrations; estimation of the average relationship between emissions and exposure to concentrations, calculated as the population weighted mean concentration for a pollutant divided by the total annual emissions of that pollutant; then the application of concentration response functions to estimate the changes in outcomes that result from the population weighted concentration changes estimated through the dispersion modelling (outcomes include impacts on public health, the natural environment and the economy). Expert advice suggests that this would have taken more time than was available for this work.

As a pragmatic and proportionate approach, Defra's damage cost approach was therefore used. The limitations of using the damage cost approach rather than the impact pathway approach are recognised. These include, for example, that the damage costs are estimates that are derived from the impact pathway approach, but by necessity draw upon general assumptions that may not hold for every individual case. Results should therefore be considered indicative.

Given the time available for this analysis, as advised by Defra, the specific damage costs in Table 3 of the Defra guidance[22] used to value shipping emissions are as follows:

- SO_2 – National;
- $PM_{2.5}$ – Ships (in the 'PM Source Sector' section); and
- NOx – Ships (in the 'NOx Source Sector' section).

Valuations for the year 2017 for each of these pollutants are increased 2% per annum, in line with the Defra guidance.

Defra experts have advised that these damage costs can be used to value emissions from all types of shipping activity (e.g. domestic, international, and voyages transiting near to the UK). These damage costs account for the fact that some shipping emissions will be further from shore – i.e. the damage costs represent an average. However, these damage costs are estimated based on the emissions included in the National Atmospheric Emissions Inventory (NAEI). In particular, the analysis is based on the mapped NAEI emissions for shipping. In this instance, the 2013 NAEI. Therefore, Defra has advised that the damage costs should not be used to value any shipping emissions beyond the geographical area that the mapped NAEI emissions from shipping covers – emissions further away are not likely to incur the average health and environmental costs to the UK that the damage costs represent. Our approach therefore does not include SO_2, $PM_{2.5}$ and NOx emissions that are outside of the geographical area covered by the NAEI maps.

To estimate the emissions to air of pollutants from shipping (SO_2, $PM_{2.5}$ and NO_x) that are within the geographical area that the mapped NAEI emissions from shipping covers, a derived boundary around the UK is used. This boundary is defined by coverage of UK waters by the Maritime Coastguard Agency's AIS (Automatic Identification System) terrestrial receiver network, extending approximately 40 nautical miles from the UK coastline. This boundary was used to estimate an average "time within boundary" for each ship type and size category, both for UK domestic and for UK international shipping. A ship's total SO_2, $PM_{2.5}$ and NOx emissions produced globally were scaled according to the time spent within the boundary (see Table below).

Ship type	Size	Fraction of time within NAEI Boundary[23] (e.g. 0.3 = 30%)
Bulk carrier	0-9,999	0.3
Bulk carrier	10,000-34,999	0.1
Bulk carrier	35,000-59,999	0.05
Bulk carrier	60,000-99,999	0.05
Bulk carrier	100,000-199,999	0.05
Bulk carrier	200,000-+	0.05
Container	0-999	0.3

Container	1,000-1,999	0.3
Container	2,000-2,999	0.05
Container	3,000-4,999	0.05
Container	5,000-7,999	0.05
Container	8,000-11,999	0.05
Container	12,000-14,500	0.05
Container	14,500-+	0.05
Oil tanker	0-4,999	0.3
Oil tanker	5,000-9,999	0.3
Oil tanker	10,000-19,999	0.05
Oil tanker	20,000-59,999	0.05
Oil tanker	60,000-79,999	0.05
Oil tanker	80,000-119,999	0.05
Oil tanker	120,000-199,999	0.05
Oil tanker	200,000-+	0.05
Ferry-pax only	0-1,999	0.5
Ferry-pax only	2,000-+	0.5
Cruise	0-1,999	0.05
Cruise	2,000-9,999	0.05
Cruise	10,000-59,999	0.05
Cruise	60,000-99,999	0.05
Cruise	100,000-+	0.05
Ferry-RoPax	0-1,999	0.5
Ferry-RoPax	2,000-+	0.5
Ro-Ro	0-4,999	0.5
Ro-Ro	5,000-+	0.3
Service - tug	0-+	0.8
Offshore	0-+	0.8
Service - other	0-+	0.8

For any individual ship, there is uncertainty as to whether the *time* spent within and without the boundary are proxies for the quantity of *emissions* within and outside of the boundary, and uncertainty as to whether the average time spent within the boundary is representative of the specific operation of that ship. These uncertainties will have a small and varying impact on the accuracy of air pollution emissions estimation and if this method is evolved, further work could be focused on reducing the uncertainties. However, the method appropriately reflects that the large majority of international shipping's air pollution emissions occur outside of

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[22] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770576/air-quality-damage-cost-guidance.pdf

[23] These factors are the same for both domestic and international shipping.

the boundary and therefore that large proportion of emissions is excluded from the damage cost estimations.

It is noted that these damage cost values are the most up to date as published by Defra and therefore reflect advice from the Committee on the Medical Effects of Air Pollutants (COMEAP) which provides independent advice to government on the impacts of air pollutants. The valuations also reflect advice from Public Health England.

Defra advises that the damage cost for particular matter emissions could be overestimated because air pollutants are typically emitted in mixtures so there is likely to be a degree of overlap between NOx and PM emissions. The NOx damage costs are adjusted for this but there is no adjustment factor for PM emissions. Therefore the PM damage costs do not account for the potential confounding effects of other correlated pollutants.

Importantly, the damage cost values advised by Defra may not reflect all impacts of air pollutants. For example, there may be additional costs associated with secondary reactions of air pollutants and nitrogen deposition.

2. The cost-effectiveness of each abatement option in any given year is calculated for the average ship in each vessel category (defined by ship type, size and age) by dividing the annual net costs by the annual reduction in CO_{2e} emissions[24] in the year of interest (2031 or 2051).
3. The most cost-effective abatement option for the average ship in each vessel category (defined by ship type, size and age) is estimated and it is assumed that this abatement option is implemented first.
4. The fuel consumption for each vessel category (defined by ship type, size and age) is then recalculated under the assumption that all ships in the vessel category have installed the most cost-effective abatement option. Moreover, the abatement options that are incompatible with the most cost-effective abatement option are eliminated from the list of available abatement options, noting that this may differ for each vessel category (ship type/size/age).
5. For each vessel category (ship type/size/age), the impacts on GHG emissions (calculated from the change/quantity of fuels used, and the GHG emission factors of the fuels), and the cost-effectiveness of each remaining abatement option are recalculated in the way described in step 2 and 3.
6. For each vessel category (ship type/size/age), the process from step 4 – 6 is repeated until all the abatement options have been assessed.

This process yields a matrix for each combination of a vessel category (defined by ship type, size and age) and abatement option listing the abatement potential and the cost-effectiveness. The estimated abatement potential is multiplied by the number of ships in the relevant vessel category (defined by ship type, size and

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[24] Air pollutants are not included in the denominator of the cost effectiveness calculation.

age) and the matrices are sorted on the basis of cost-effectiveness and plotted as appropriate depending on the type of MACC that is being produced.

5.4.3 Limitations of the analysis

There are limitations when using MACCs to represent the cost-effectiveness of abatement options. These include:

- They are static: they are only shown for any given year i.e. a snap shot. They do not relay information about how the profile of the costs or the benefits may develop over time. Therefore, although an abatement option may be assessed as not cost-effective in one time period, there is no way of knowing if this might actually be a better option in the long-run because cost-effectiveness is likely to change over time.
- Barriers: they are not able to reflect the practical barriers that may be faced when implementing different abatement options. These have been discussed in detail in Frontier Economics et al. 2019[25].
- Uncertainties: the MACCs shown in this analysis are for a particular set of assumptions relating to capital costs, fuel prices, maintenance costs, operating costs, charter revenues etc. and particular assumptions about the valuation of GHGs and air pollutants. Given the long time period under consideration to 2051, there are significant uncertainties in the potential values of each of these components of costs and benefits, and hence the MACCs could take different forms depending on the assumptions used. Such sensitivity analysis was beyond the scope of this work but is recommended.

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[25] 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.

6 SCENARIO ANALYSIS

6.1 Aims of this section

This section provides technical detail to support Section 4 of the main report which focuses on the scenarios. It provides a brief description of the scenarios used for the modelling; the detailed input assumptions used; and the detailed results for all scenarios. Inference and interpretation of the results are provided in the main report.

6.2 Scenarios used for the modelling

Ten illustrative scenarios have been modelled (using GloTraM) and are summarised in Table 6. These were developed in discussion with DfT policy officials and are intended to be illustrative of alternative assumptions about key factors that could impact on UK shipping emissions in the future. They do not reflect UK Government policy.

The scenarios have been developed to reflect the following policy variations: the date by which de-carbonisation (meaning the total reduction of all operational GHG emissions) of all UK shipping (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 advanced.

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, hydrogen and ammonia production and the viability of these as marine fuels.

Table 6 Scenarios assessed in this analysis for the purposes of illustration

Scenario	Global GHG Policy	UK domestic GHG policy	UK domestic air quality policy	Fuel prices	Bio-energy
A	Agreed IMO policies (e.g. EEDI)	Agreed IMO policies (e.g. EEDI)	Agreed IMO policies (e.g. North Sea SOx and NO_X ECA, 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)

6.3 The business as usual scenario

Scenario A is also called the Business as Usual (BAU) scenario and reflects a situation in which current policies only are continued.

With respect to the prevention of air pollution from ships, the BAU scenario models the regulation 14 on sulphur oxides[26] and the regulation 13 on nitrogen oxides[27] of MARPOL Annex VI. Control of air pollutants i.e. emissions of SOx and NOx, in MARPOL is carried out through both regulation of global emissions, and regulation of emissions within defined geographical areas known as Emission Control Areas, ECAs. There is currently an ECA covering the Channel and the North Sea, and an ECA covering the Baltic Sea which impacts on UK air quality. Within these ECAs. Regulations are applied to both pollutants of the following form:

- SOx emissions are controlled by requiring the sulphur content of fuels used within the ECA to be of sulphur (chemical) content of 0.1% or less. Higher sulphur content fuels can be used on the condition that a device is fitted that removes SOx emissions from the exhaust to the equivalent level of the compliant fuel; and,
- NOx emissions are controlled by requiring ships built after 1st January 2021 to be compliant with the highest regulated stringency (known as 'Tier III' compliance). There is no geographical variation to the stringency for ships built before this date.

For global regulation of these pollutants, the stringencies are lower than the limits in the ECAs. Currently, there is a sulphur chemical content limit on fuel of 3.5%, which applies anywhere outside of an ECA. This global limit will reduce to 0.5% on the 1st January 2020. In relation to NOx emissions, globally, ships must meet Tier II standards if built after 1st January 2011, or Tier I standards if they were built before.

The stringencies for the Tiers of NOx regulation, which have varying limits depending on the rated engine speed, are presented in Table 7. In general, larger ships (especially those involved in international transport) use engines with lower

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[26] See IMO webpage for more details http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx

[27] See IMO webpage for more details

http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx rated engine speed and lower stringency on NOx emissions, whereas smaller ships use engines with higher rated engine speed and higher stringency.

Table 7 MARPOL Annex VI NOx emission limits

Tier	Date	NOx limit g/kWh		
		N<130	130≤n<2000	n≥2000
Tier I	2000	17.0	45 n-0.2	9.8
Tier II (outside ECAs)	2011	14.4	44 n-0.23	7.7
Tier III (NOx ECAs)	2021[28]	3.4	9 n-0.2	1.96

Source: *https://www.dieselnet.com/standards/inter/imo.php*

Notes : The ‘date’ refers to the date from which regulation applies to new build ships. For example, ships built after January 1st 2011 must comply with Tier II standards.

Table 8 MARPOL Annex VI fuel sulphur limits

Date	Sulphur limit in fuel (%m/m) Global	
	SOx ECA	Global
2000	1.5%	4.5%
2010	1.0%	4.5%
2012	1.0%	3.5%
2015	0.1%	3.5%
2020	0.1%	0.5%

Source: *https://www.dieselnet.com/standards/inter/imo.php*

As shown in Table 7 NOx emission regulation stringency inside an ECA is approximately 3 to 5 times tighter than outside the ECA for ships built after 2021.

As shown in Table 8, for SOx emission regulation, allowable emission levels in the ECA from 2020 are going to be one-fifth of those allowed globally.

These regulations are embedded in the model GloTraM. This implies that only the compliant options are evaluated by the model.

Two regulations from the Directive 2016/802 at EU level are not taken into account in this analysis because of the current structure of the model. The first is that from 2010, any ship at berth in EU ports must use fuel at 0.1% sulphur chemical composition or less. The second is that passenger ships operating on regular services to or from any EU port must use fuel at 1.5% or less (in terms of sulphur chemical composition).

The BAU scenario also models the currently agreed global GHG policy, specifically the Energy Efficiency Design Index, which is described in section 6.4.3.

The fuel prices projection used in the BAU scenario is the "central" fuel price projection as described in section 6.4.2. In particular, in the BAU scenario, hydrogen is assumed to be produced using SMR + CCS and ammonia and methanol prices are also consistent with this assumption.

In the BAU scenario it is assumed that there will not be any availability of biofuels in shipping as agreed with DfT, however, a different scenario is explored with a different assumption as described in section 6.4.6.

6.4 Input assumptions

This section discusses the input assumptions used in the scenario analysis. It described the key variables and the different input data chosen across the identified scenarios. In particular, detailed information are provided for:

- Fuels included in the analysis
- Fuel price projections
- Global GHG policy
- UK domestic GHG policy
- UK air pollutant policy
- Bioenergy availability
- Combination of engine and fuel included
- Transport demand
- Technology learning curve adopted
- Emissions factors

6.4.1 Fuels included in the analysis

In all scenarios, all conventional marine fuels and non-conventional fuels (except for marine biofuels) are included in the analysis with the exception of scenario I and J. Scenario I assumes that ammonia will not be available, whereas, scenario J is the only scenario that assumes that marine biofuels will be available and blended with the associated non-bio fuels.

Conventional marine fuels included are:

- HFO
- MDO
- LSHFO

Non-conventional marine fuels included are:

- LNG
- Hydrogen (assumed to be produced with SMR +CCS in all scenarios except for scenario H in which it is assumed to be produced with Electrolysis)
- Ammonia (assumed to be produced with SMR +CCS in all scenario except for scenario H in which it is produced with Electrolysis)
- Synthetic Methanol (assumed to be produced with SMR +CCS in all scenario except for scenario H in which it is produced with Electrolysis)

In scenario J, marine biofuels included are:

- BioHFO of which 50% SVO and 50% HTL-UPO
- BioMDO of which 33% HVO, 33% FAME, and 33% FT (Diesel)

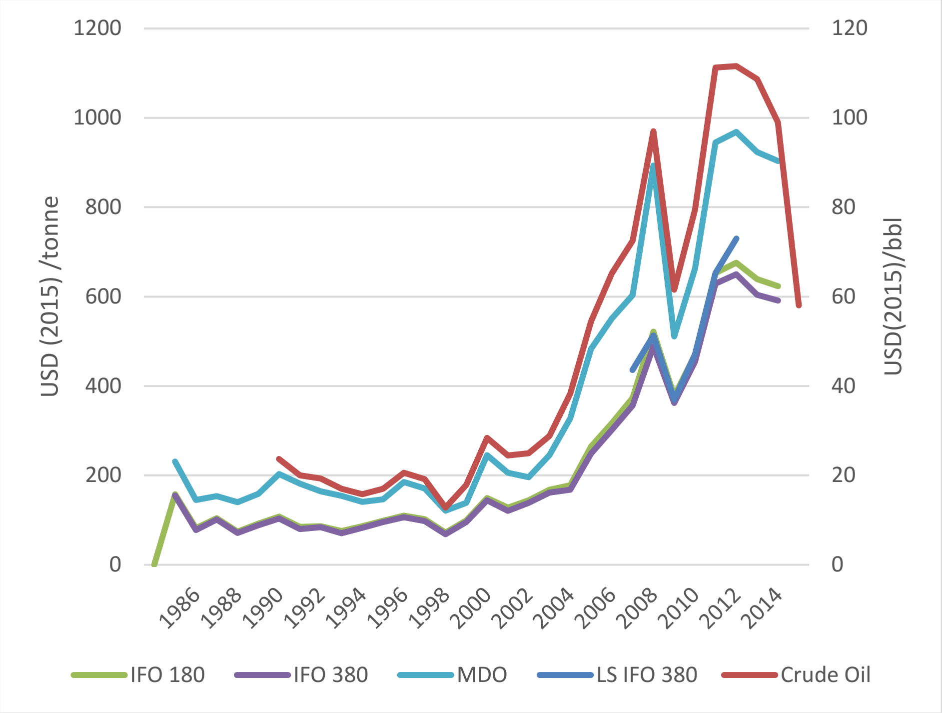
The ratios of the mixed fuels are to be considered representative of a potential fuel blend and are based on expert judgments.

6.4.2 Fuel price projections

Fuel price projections are a key driver as the profitability of any combination of fuel and machinery changes over time because of the evolution over time of the fuel prices. Based on the scenario definition in section 6.2, different fuel price projections were used. A detailed description of how they have been derived and the underlined assumptions is provided in the following text.

HFO, LSHFO, and MDO price projections are based on historical relationships between the price of these fuels and the crude oil price. All scenarios used the same 'central' price projections except for scenario J in which the price projections of blended fuels (mix of conventional fuel and the associated bio variant) were used.

Figure 4 **Historical fuel prices trend**



Sources: IEA and Shipping Intelligence Network. HFO is represented by IFO 180 and IFO 380, whereas, LSHFO is represented by LS IFO 380.

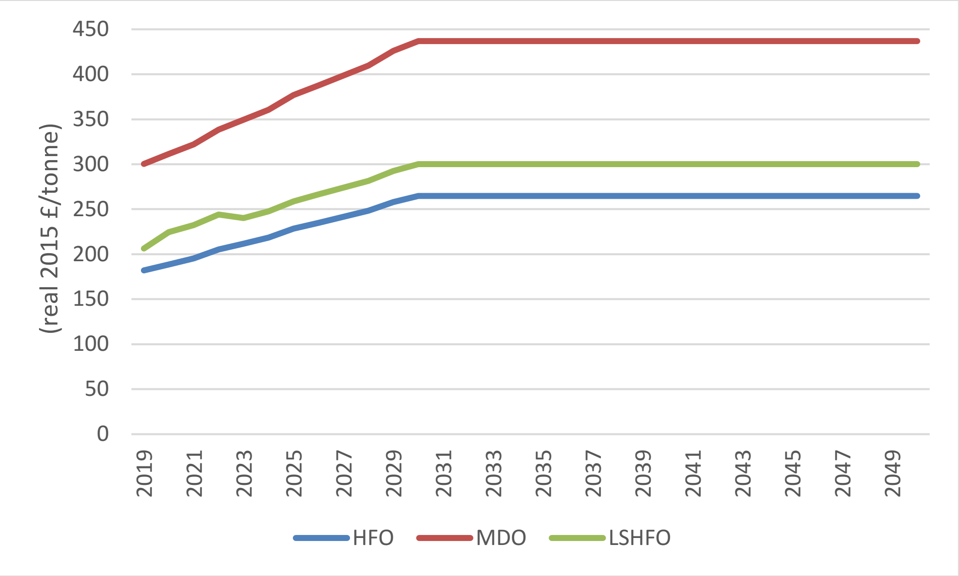
For the 'central price projection, a constant relationship was derived from the trends shown in Figure 4. The following factors have been used which represent the average ratio between the crude oil price (bbl) and the oil-derived marine fuel prices (tonnes) using the available historical data.

Fuel	Factor
HFO	5.2
MDO	8.6
LSHFO	5.9

Using the BEIS oil price assumptions published in December 2017[29] and the factors above (resulting from the historical relationship with crude oil), we derived the price projections for HFO, MDO and LSHFO shown in Figure 5.

The sulphur content of the "LSHFO" modelled is assumed to change in 2020 because it is assumed that a fuel compliant with the Sulphur limit of 0.5% will be available. This implies that the historical relationship with the crude oil price may not be representative. In this study we assume (based on expert judgment) that in the period 2020 to 2022, there will be a spike in price of +5%; however, after 2022, it is assumed that the historical relationship returns to be representative.

Figure 5 HFO, MDO and LSHFO 'central' price projections



Scenario J uses the price projection of blended fuels which depends on the biofuels fuel price projections and the availability of bioenergy for shipping (see section 6.4.6).

The prices of marine biofuels (as defined in section 6.4.1) are provided in Figure 6 (note that the prices from 2040 onwards are assumed to be constant), whereas, the resulting price projections of the blended fuels are provided in Figure 7.

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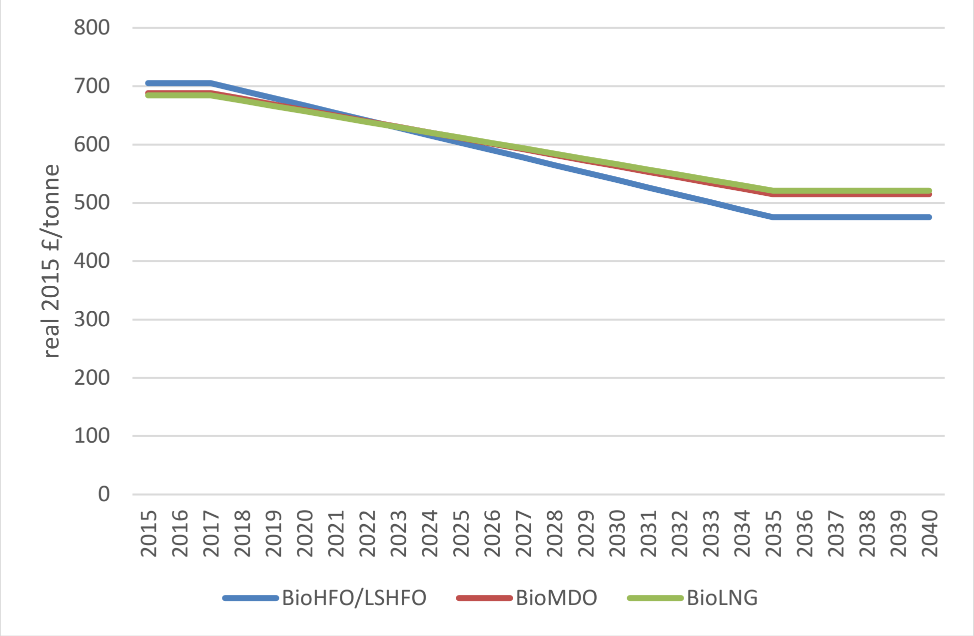
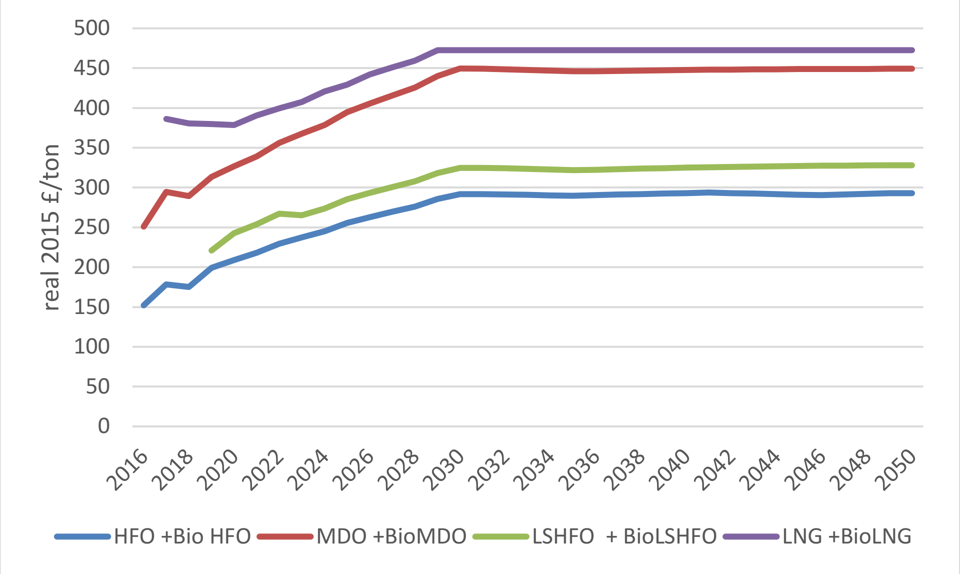
[29] BEIS (2017) 'Data tables 1 to 19: supporting the toolkit and the guidance', available at https://webarchive.nationalarchives.gov.uk/20190105010941/https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/696677/Data_tables_1-19_supporting_the_toolkit_and_the_guidance_2017__180403_.xlsx.

Figure 6 Marine fuel price projections



Sources: https://ycharts.com/indicators/rapeseed_oil_price,SGAB[30]

Figure 7 Price projections of the blended fuels



The **LNG** price projections are based on BEIS natural gas price assumptions published in December 2017[31] and an assumed LNG pathway for UK shipping composed of: liquefaction, transportation, distribution and dispensing costs as each step of the chain is assumed to be required for the supply of LNG to ships in

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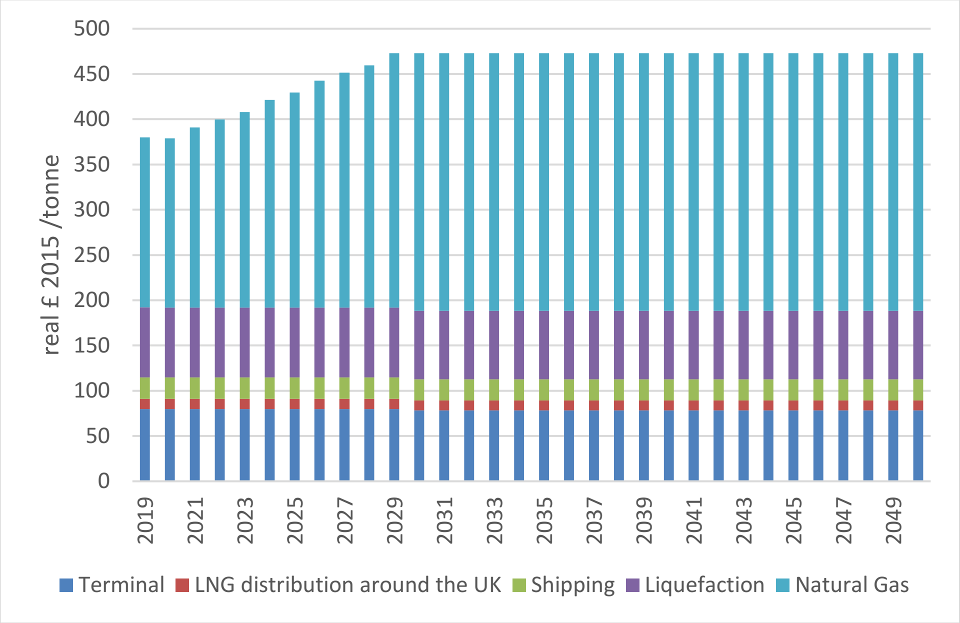
[30] http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=33288&no=2

[31] BEIS (2017) 'Data tables 1 to 19: supporting the toolkit and the guidance', 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

UK ports. The resulting LNG price projection is shown in Figure 8 including the breakdown of the key components.

All scenarios use the same LNG price projection.

Figure 8 LNG price projections



Hydrogen is assumed to be produced from two different energy sources and processes:

- Except for Scenario H, all scenarios assume that hydrogen will be produced from natural gas through reformation (SMR) and CCS.
- Scenario H assumes that hydrogen will be produced from electricity through the use of an electrolyser.

The Hydrogen price projections are based on assumptions about hydrogen production costs as provided by BEIS These include capital costs, operating costs and CO_2 storage and transport costs[32] and fuel costs (using wholesale fuel prices)[33]. For the purposes of this analysis, hydrogen production costs are assumed to remain constant in real terms. However, in practice, these costs would be expected to vary over time. Liquefaction, transportation, distribution and dispensing costs are based on an assumed hydrogen pathway for UK shipping as each step of the chain is assumed to be required for the supply of hydrogen to ships in UK ports.

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[32] BEIS hydrogen supply chain evidence, available at https://www.gov.uk/government/publications/hydrogen-supply-chain-evidence-base

The assumed plant size for SMR is 1000MW and electrolyser is 10MW, with an assumed lifetime of 40 and 30 years respectively and are assumed operate at their maximum technical capacity (95%) year-round.

[33] BEIS (2017) ‘Data tables 1 to 19: supporting the toolkit and the guidance’, 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

The resulting hydrogen price projections and associated breakdown of the key components are shown in Figure 9 for hydrogen produced with SMR+CCS and in Figure 10 for hydrogen produced with an electrolyser.

Hydrogen is assumed to be available for shipping from 2025 in all scenarios (based on expert judgement).

Figure 9 Hydrogen price projection (SMR +CCS)

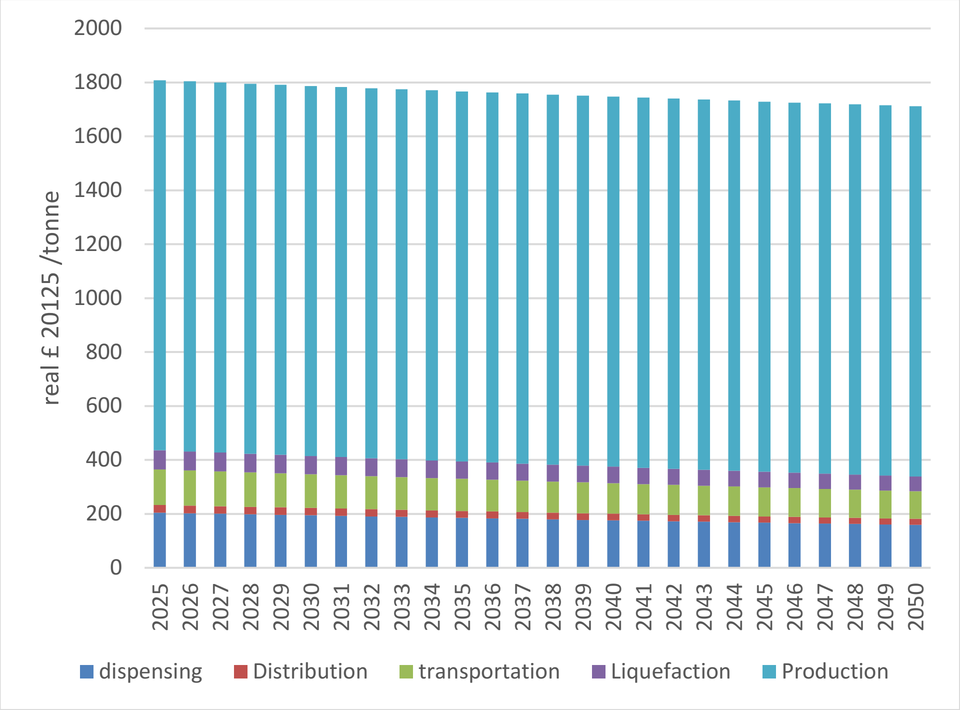
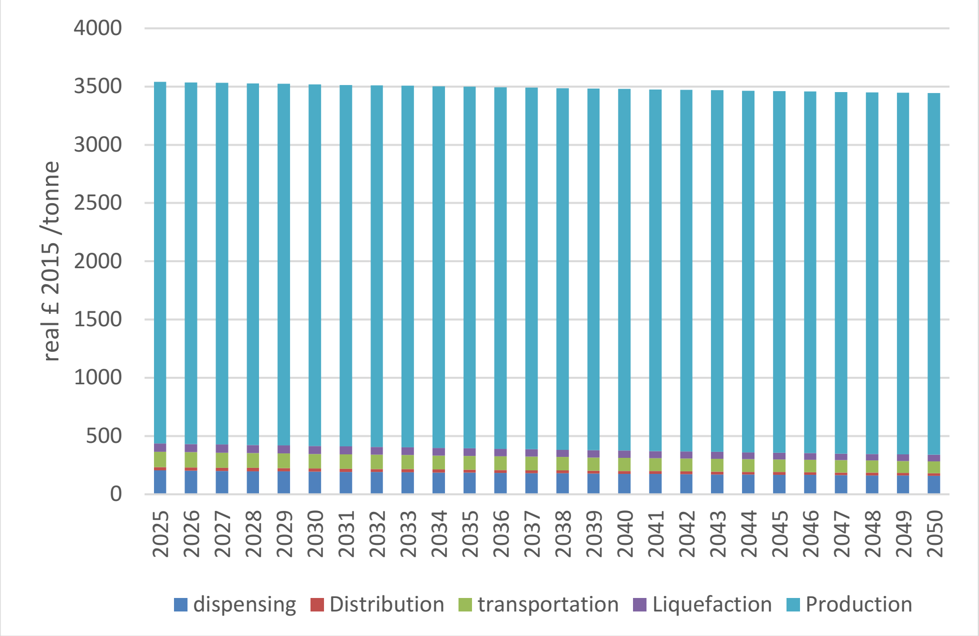


Figure 10 Hydrogen price projection (electrolyser)

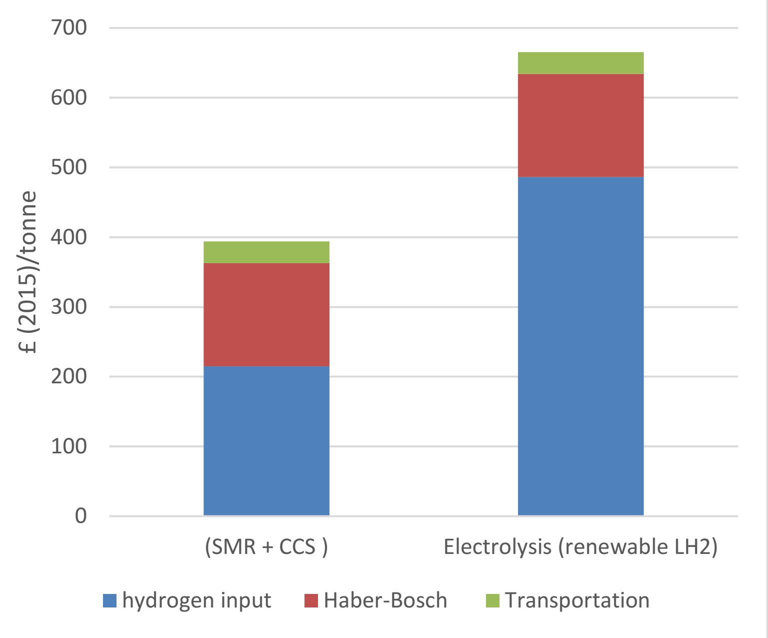


The **ammonia** price projections are derived from assumptions about hydrogen production costs. This is because ammonia is produced using a metal catalyst under high temperatures and pressures that allows the reaction of hydrogen and atmospheric nitrogen to produce ammonia (the Haber Bosh process). It is assumed that ammonia would have an additional cost relative to the hydrogen due to the Haber Bosh process of 0.0433 $ (2015) per kWh (expert judgement from stakeholders). In addition, transportation cost is assumed to be 48 $ (2015) per tonne[34].

All scenarios assume ammonia is produced with SMR +CCS, except for scenario H which assumes ammonia to be produced with electrolysis. All ammonia costs result to be constant from 2025 onwards. Figure 11 shows the breakdown of the ammonia prices.

Ammonia is assumed to be available for shipping from 2025 in all scenarios (based on expert judgement), except for scenario I in which it is assumed that there will not be any availability of ammonia as fuel for shipping.

Figure 11 Breakdown of ammonia price projection



Synthetic **methanol** is assumed to be available for shipping from 2025 (based on expert judgement) and produced from hydrogen and methanol synthesis process. Its price projections are based on the assumptions about hydrogen production costs and derived costs of the synthetic process from Lloyd's Register and UMAS 2019[35]. In addition, transportation cost is assumed to be 16 $(2015) per tonne (Lloyd's Register and UMAS 2019).

All scenarios assume methanol is produced with SMR +CCS, except for scenario H which assumes methanol to be produced with electrolysis. All methanol costs

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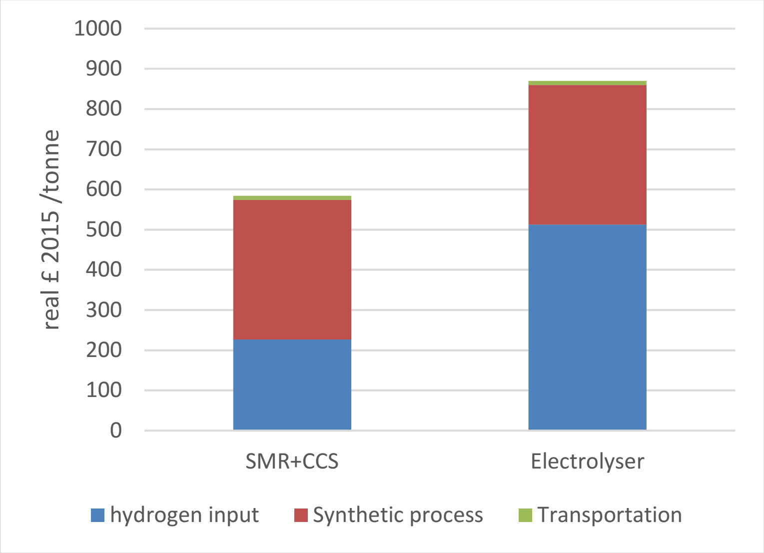
[34] Lloyd's Register and UMAS 2019. Fuel production cost estimates and assumptions, Zero-carbon fuel production pathways

[35] Lloyd's Register and UMAS 2019. Fuel production cost estimates and assumptions, Zero-carbon fuel production pathways

result to be constant from 2025 onwards. Figure 12 shows the breakdown of the methanol prices.

Figure 12 Synthetic methanol price projections



The **electricity** price projections used are the central scenario of the Long-run variable costs of energy supply to industry which were published by BEIS in December 2017[36].

The complete dataset of fuel prices input assumptions is provided in the worksheet "Fuel price Annex.xls" which includes additional references of sources data when applicable.

A description of the quality assurance undertaken for fuel price projections assumption is described in section 7.2.3.

6.4.3 Global GHG policy

Two global GHG policies are introduced in the model: the existing regulation 21 of MARPOL Annex VI (for all scenarios) and a hypothetical introduction of a carbon prices from 2025 for CO_2 operational emissions (for all scenarios except for scenario A).

The regulation 21 of MARPOL Annex VI that entered into force in January 2013, requires the attained Energy Efficiency Design Index (EEDI) of certain categories of new ships not to exceed the required EEDI.

The required EEDI is determined by using a reference line value, which represents an average EEDI value of ships delivered in the preceding 10 years (from 1 January 1999 to 1 January 2009). And the attained EEDI is calculated according to the formula as laid down in the 2014 Guidelines on the method of calculation of

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[36] BEIS (2017) 'Data tables 1 to 19: supporting the toolkit and the guidance', 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

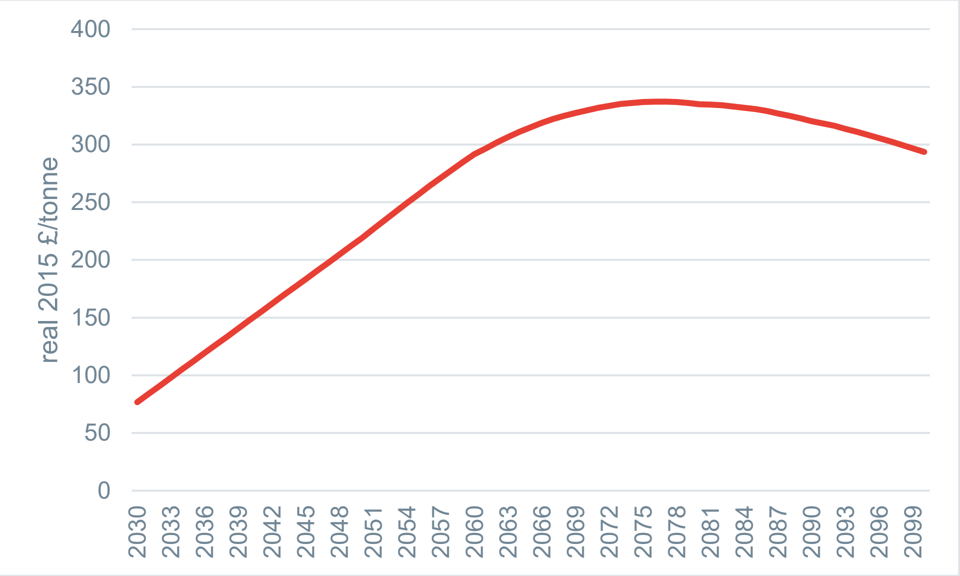
the attained Energy Efficiency Design Index (EEDI) for new ships (Resolution MEPC.245(66); MEPC 66/21/Add.1, Annex 5).

The model evaluates the compliance with this regulation in each year for each ship's size and ship type and excludes the options that are not compliant.

The second global GHG policy is implemented in the modelling by introducing a carbon price on CO_2 emissions emitted during the operation of a ship. This implies that, when the model calculates voyage costs, an additional carbon cost is added which derives from the carbon price and the amount of operational CO_2 emitted.

Scenario A does not have a carbon price. For Scenario B we assumed that, from 2030 onwards, the carbon price equals the central carbon prices for appraisal which were published by BEIS in December 2017[37] and are shown in Figure 13.

Figure 13 Carbon Prices for scenario B



For the other scenarios, global CO_2 policy is defined by the level of ambition:

- Decarbonisation by 2040
- Decarbonisation by 2050
- 50% reduction relative to 2008 level by 2050 and Decarbonisation by 2070

Such levels of ambition were only applied to the CO_2 emissions emitted during the operation of a ship and not all GHGs and refer only to the operational emissions.

It was assumed that to meet the levels of ambition, the CO_2 operational emissions will start to decrease from 2025. The year 2025 is selected as the potential starting year of this policy as it is assumed that negotiation and implementation of the policy will continue to take place until that year.

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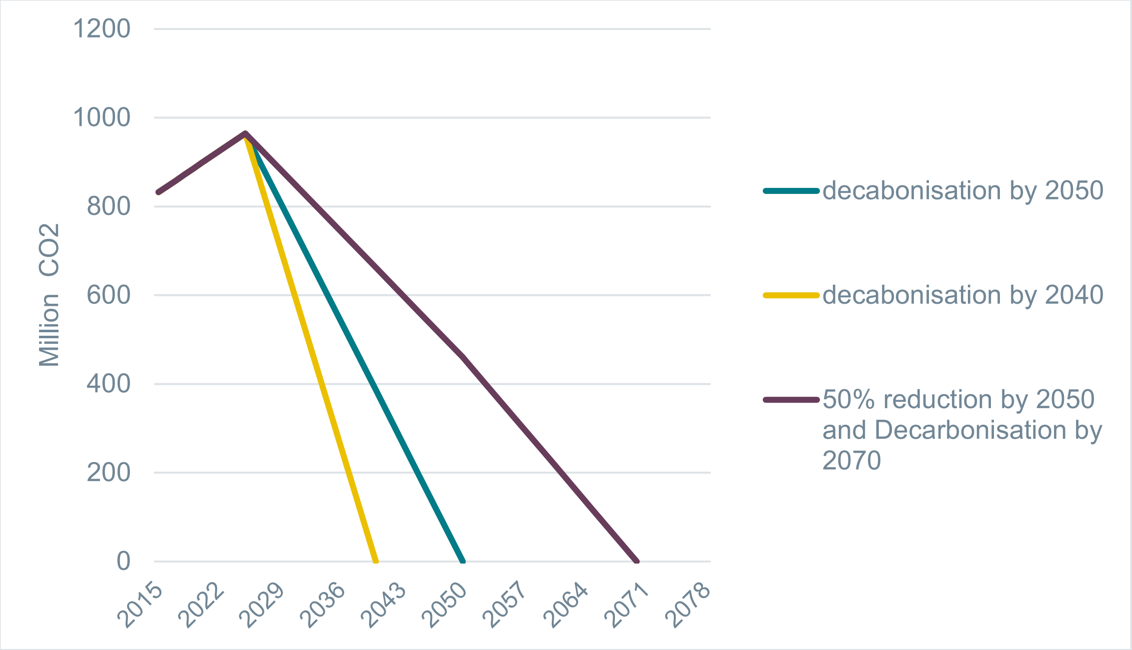
[37] BEIS (2017) 'Data tables 1 to 19: supporting the toolkit and the guidance', available at https://webarchive.nationalarchives.gov.uk/20190105010941/https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/696677/Data_tables_1-19_supporting_the_toolkit_and_the_guidance_2017__180403_.xlsx

Up to the year 2025, the CO_2 operational emissions are assumed to increase as per the BAU scenario (scenario A). After 2025, a target trajectory is identified according with the associated level of ambition. A representation of the target trajectories is shown in Figure 14.

In the scenarios with a defined level of ambition (scenario C to J) the model calculates (in an iterative mode) the carbon price that allows it to meet the associated target trajectory. In other words, the model was then constrained to be in line with the identified target trajectory ensuring that the level of ambition is met.

Figure 14: Global CO_2 operational emissions trajectories used to derive the carbon prices for the scenarios identified in section 6.2



6.4.4 UK domestic GHG policy

UK domestic GHG policy is assumed to be aligned with global GHG policy (see section 6.4.3) in all scenarios except for scenario F, in which it is assumed that the UK has a more stringent GHG policy than that has been assumed at the global level. To represent this, the results of scenario E (50% reduction in GHG by 2050 and decarbonisation by 2070) and scenario D (decarbonisation by 2050) were combined. Then, using post-processing calculations, we developed a scenario in which the UK international fleet will evolve based on the decarbonisation objective identified in scenario E and the UK domestic fleet will evolve based on the decarbonisation objective identified in scenario D.

6.4.5 UK Air pollutant policy

UK air pollutant policy is assumed to be aligned with IMO global air pollutant policy in all scenarios except for scenario G, in which it is assumed that the UK has a more stringent air pollutant policy than that has been assumed at the global level. In particular, it is assumed that the stringency on the sulphur content and NO_x

emissions limits in the ECAs areas is increased of 50%. This implies that the constraint on the sulphur content limit in ECAs is changed in the model from 0.1% to 0.05%, whereas, the NO_x Tier III emissions limits set in the model are halved. For example, the NO_x emissions limit of 3.4g/kWh for engine's rated speed (rpm) less than 130 is changed to 1.7g/kWh. The more stringent air pollutant policy is assumed to be in place from 2030 onwards.

6.4.6 Bioenergy availability

It is assumed that there will not be any biofuels available in shipping in all scenarios, except for scenario J in which it is assumed that biofuels will be used in shipping. The modelled shipping fleet is assumed to adopt biofuels in a similar way as the road transport sector is already doing given the blending targets and mandates for fossil fuels. Therefore, it is assumed that biofuels are blended with marine conventional fuels (HFO, MDO, LSHFO).

We consider the biofuels as defined in section 6.4.1.

The amount of biofuels blended is based on the bioenergy availability selected.

The starting point is the estimated global bioenergy availability in 2050. This is based on a review by Offermann et al. (2011)[38] which considered 19 studies and explored estimates of global bioenergy potential. Based on this review, this analysis assumes that the final share of the shipping industry is expected to be 2.42% of the global bioenergy availability in 2050. The 2.42% is approximately the shipping’s share of global CO_2 emissions and it is assumed that bioenergy is distributed as a supply between all consumers of fossil fuels. This implies that the level of marine bio-energy availability is assumed to be 4 EJ in 2050.

Based on these projected levels in 2050, a linear approach is applied backwards, assuming zero uptake in 2015

The emissions factors of the resulting ‘blended fuels’ are adjusted accordingly, as well as the prices of the blended fuels.

6.4.7 Engine and fuel options

The combinations of engine and fuel that are modelled in GloTraM are described in Table 4 above.

One option that is not explicitly included in the GloTraM is the use of a battery with an electric motor. As explained in section 3.6, the potential uptake of this option has been modelled separately using a different approach.

6.4.8 Transport demand

A global transport demand scenario and an UK specific transport demand scenario were generated for this analysis. This section describes the approaches taken to generate these transport demands, whereas section 7.2.2 provides further details of the steps undertaken for the quality assurance.

The global demand scenario that was used in all scenarios is the RCP 2.6 SSP2[39], and GloTraM global trade datasets were adjusted to match this. This is an iterative process and necessarily an approximation as it is sensitive to costs which in turn drive the average distance to be covered in a journey.

GloTraM uses three different approaches to generating transport demand which convert an input, typically in tonne or teu, to transport work (eg. tonne km). As the

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[38] https://link.springer.com/article/10.1007/s11027-010-9247-9

[39] http://www.iiasa.ac.at/web/home/about/events/8.detlef.ssps_2.pdf

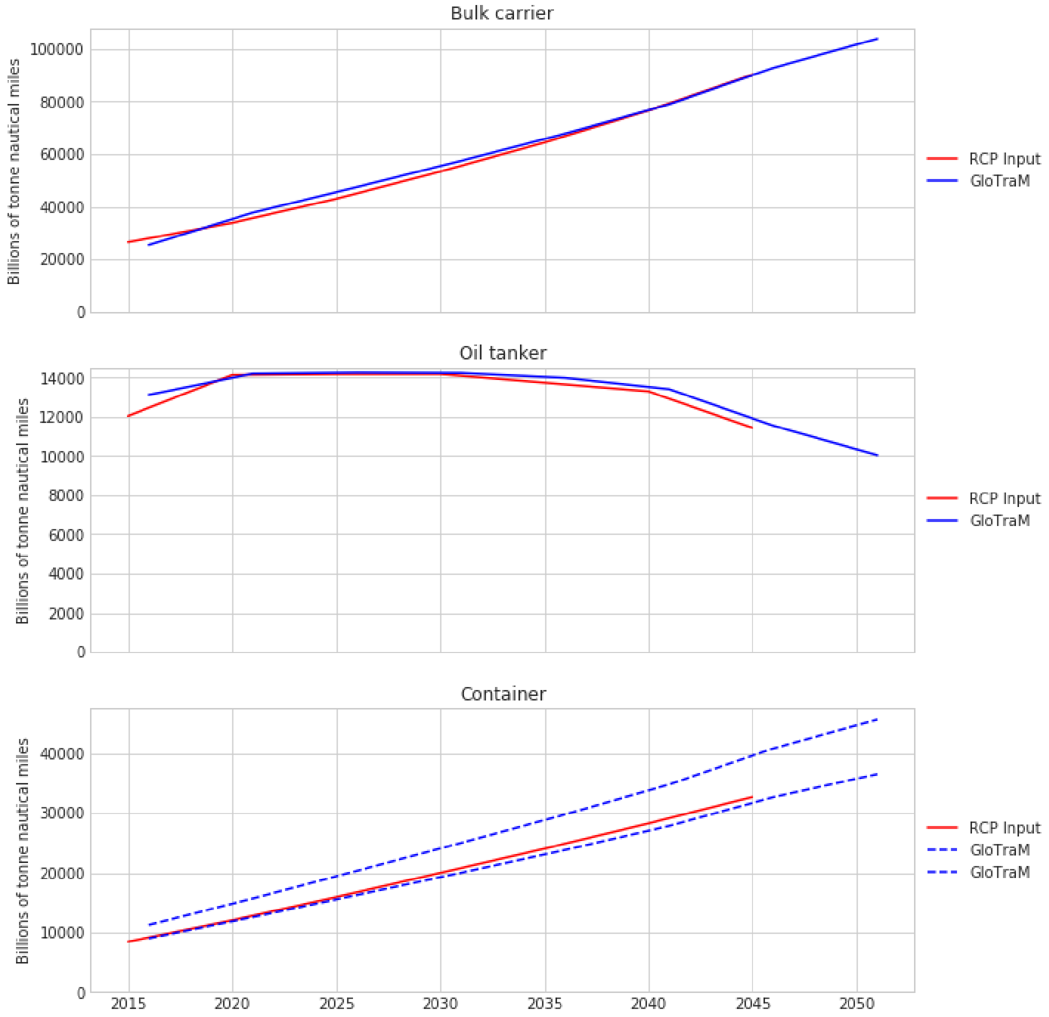
input dataset (RCP 2.6 SSP2) is only available in units of transport work, this process must be reversed to generate the inputs into GloTraM in the required units.

The three approaches are:

- Economic order quantity model: This model allocates the commodity flow to a specific vessel size. The optimum vessel size is identified as the size that minimises the total cost which is dominated by the transport cost plus the cost of capital invested in the cargo. The former reduces with increasing vessel size while the latter increases with increasing vessel size, and therefore the optimum is a trade-off between these factors (and strongly influenced by the total volume and commodity value). This algorithm is a simplification of real-world conditions and doesn't account for: multiple drop-offs; vessel supply constraints, and; efficiency gains by tactical planning of operations. Vessel supply constraints are overcome through sequential mapping of transport demand to available transport supply, where overflow demand in one size is then carried by the next lower size. This model is applied to bulk carriers and oil tankers.
- Network based approach: Containerised cargo is transported largely through liner trades that services multiple countries on a single route. Therefore, the assumption of vessels shuttling cargoes between load and discharge countries is not valid. To overcome these issues, the approach taken in GloTraM is purely empirical and based on connectivity statistics, derived from a number of data sources (e.g. country-country trade data, UNCTAD connectivity index, port throughput, etc.). The approach starts by identifying major hubs around the world. The identification of these hubs is based on the liner shipping connectivity index (LSCI), where a threshold is defined above which the country is defined as a major hub. For countries that are not identified as a major hub, a nearest hub is assigned to it based on proximity. Therefore, a country is either a hub or has been assigned a hub where containers are diverted for transshipment. Two transshipment ports for each origin-destination pair are assumed, therefore the voyage is split into three parts: from port of origin to the first transshipment hub, ocean-going between two hubs, and from second transshipment hub to the port of destination. Depending on the nature of the three journeys (coast-wise or long-haul), the type of the vessel can be determined.
- Direct vessel allocation: This is the most simplified approach, where the input dataset defines the numbers of vessels required. This approach is used for those ship types which data in the unit of transport work (eg. TEU or tonnes) is not available. This approach is deployed for Ferry-pax only, cruise, Ferry-ropax, ro-ro, service – tug, offshore and service – other.

Figure 15 shows the comparison and alignment of global transport demand scenario RCP2.6/SSP2 with the outputted transport demand as generated in GloTraM.

Figure 15: Comparison of generated global transport work demand within GloTraM against RCP2.6/SSP2 transport demand scenario



Notes: The blue lines indicate the GloTraM generated values while the red lines indicate the input data values. Note that for container vessels (unit_cont) there are two blue broken lines: one is based on tonne to TEU ratios of 8 and the other a tonne to TEU ratio of 10. This ratio varies for commodity flows, so the addition of these lines indicates acceptable bounds for the data.

For UK specific transport demand, the modelling uses the trade flow distribution (trade pairs at regional level) of the Committee on Climate Change (CCC) i.e. the region/UK disaggregation (overlaid on the GloTraM trade distribution of country to country flows within this). The CCC data is provided in the worksheet "190109 CCC Shipping Demand scenarios CB5".

DfT's UK Port Freight Traffic Forecasts (2019) data[40] were only available at the aggregated level, and therefore we used the proportional disaggregation as

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[40] Source: DfT (2018), "UK Port Freight Traffic 2019 Forecasts ". Available here - https://globalmaritimehub.com/wp-content/uploads/2019/01/port-freight-forecasts.pdf

provided by the CCC data, applied to the aggregated values provided by the DfT port traffic forecasts.

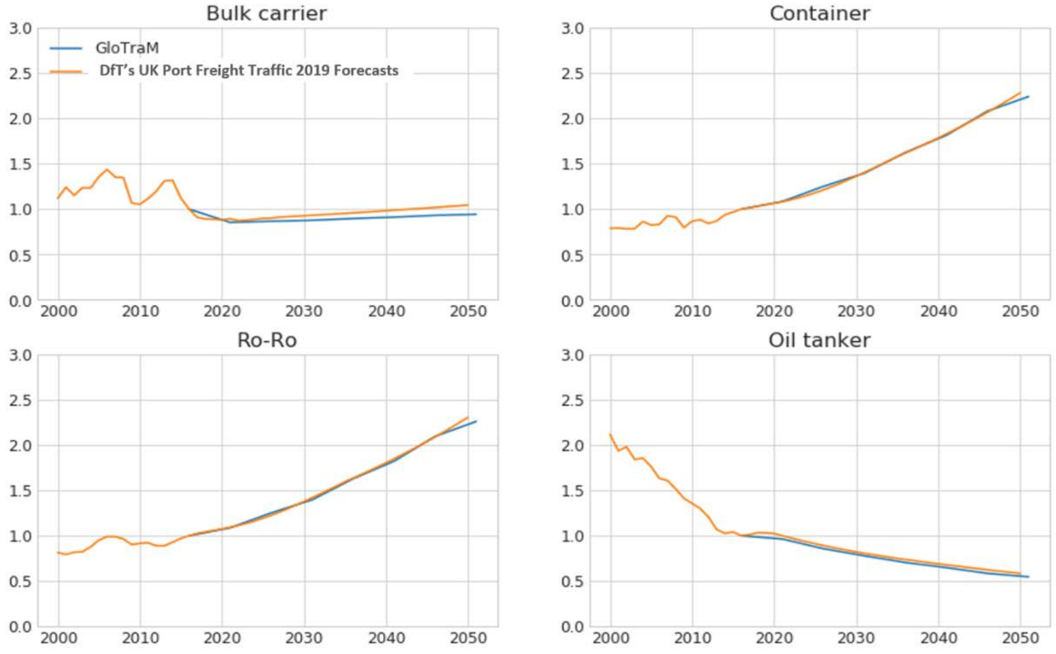
Where forecasts were not available from DfT or CCC on a cargo type/commodity group, we assumed no change in demand.

GloTraM required input transport demand data by origin-destination-commodity. To a limited extent the CCC data satisfies this requirement as it splits data by commodity type and flow direction (unlike DfT's UK Port Freight Traffic Forecasts (2019) data which do not provide flow direction). GloTraM generates a base year transport demand from the Committee on Climate Change (where base year is 2015) and applies growth rates of for each commodity type from DfT's UK Port Freight Traffic Forecasts (2019) where appropriate.

Each category of cargo (or commodity type) have been mapped to the ship types in accordance with the assumptions provided in the worksheet "mapping commodity ship type".

Figure 16 shows the comparison of transport demand trends (tonnes or TEU) between GloTraM and UK Port Freight Traffic 2019 Forecasts[41]. The data have been indexed relative to the first available year of each source. It shows that the growth of the transport supply as deployed in GloTraM is aligned with UK Port Freight Traffic Forecasts.

Figure 16: Comparison of DfT's UK Port Freight Traffic 2019 Forecasts projections of UK (international and domestic) demand against GloTraM demand indexed on 2016



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[41] Source: DfT (2018), "UK Port Freight Traffic 2019 Forecasts ". Available here - https://globalmaritimehub.com/wp-content/uploads/2019/01/port-freight-forecasts.pdf

It should be noted that GloTraM takes input transport demand every decade so data is for 2010, 2020, 2030, 2040, 2050 and 2060. GloTraM then interpolates in between to get the transport demand by commodity, year and country to country pairing (using a time step of 5 years). GloTraM uses this highly disaggregated dataset, transforming input data into transport demand in the appropriate unit (ie. Tkm, teukm, GTkm).

6.4.9 Abatement options learning curves

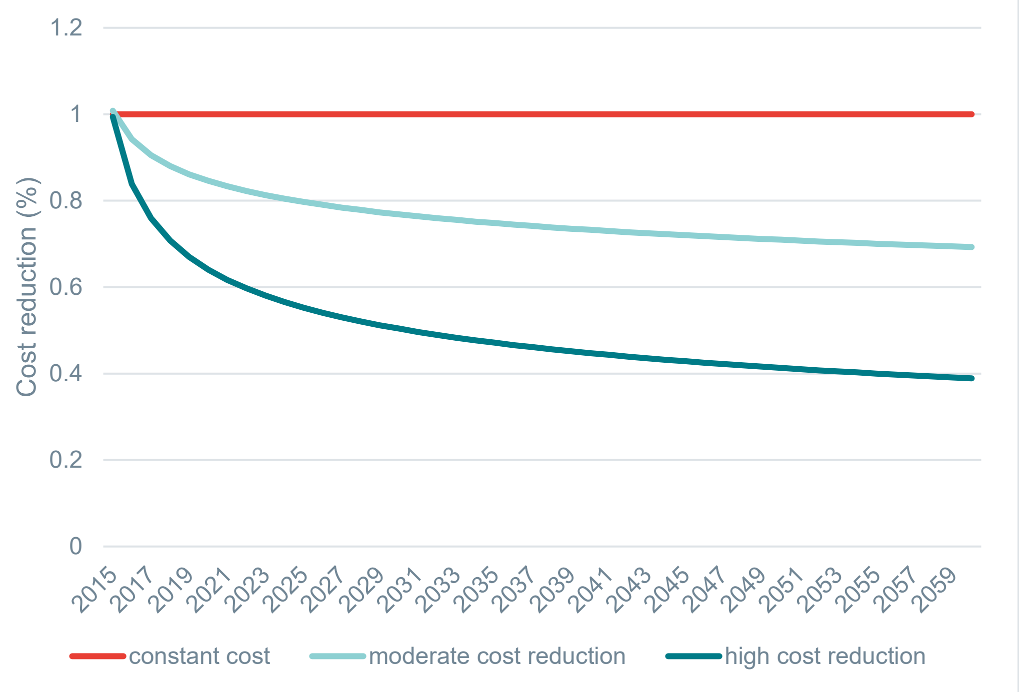
Each abatement technology may reduce its unit cost over time due to its learning curve (as learning increases, an abatement option is expected to decrease the cost per unit of output) and further technology developments. This is true especially for new technologies. Three technology learning curves are implemented in GloTraM:

- ☐ a constant cost under which the technology or its components are considered mature therefore, no further reduction is envisioned in the future
- ☐ a moderate cost reduction under which the technology or one or more of its components may have further development
- ☐ a high cost reduction under which the technology or one or more of its components may have extensive development

The three learning curves are shown in Figure 17 and are based on expert judgement of theoretical cost reduction.

Each abatement option (as described in section 4.3) is then associated with one of the technology learning curves using evidence from existing studies (when applicable) or expert judgement.

Figure 17 Learning curves implemented in GloTraM: constant cost, moderate cost reduction, high cost reduction



Technologies	**Type of learning curve used**
Section 1 - Technologies that can increase energy efficiency	
Rudder Bulb	Moderate cost reduction
Pre-Swirl propeller ducts	Constant cost
Vane wheel	Constant cost
Contra Rotating Propeller	Moderate cost reduction
Twisted rudders	Constant cost
Boss cap fin	Constant cost
Air lubrication Bubbles	Moderate cost reduction
Block Coefficient Reduction	Moderate cost reduction
Wind assistance (rotors/sails/wings)	Moderate cost reduction
Wind assistance (kites)	Moderate cost reduction
Steam Waste Heat Recovery	Constant cost
Organic Rankine Waste Heat Recovery	Moderate cost reduction
Turbo-compounding in Series	Moderate cost reduction
Solar power	Moderate cost reduction
Hotel systems	Constant cost
Fuel cells for aux system	Moderate cost reduction
Energy saving lighting	Constant cost
Shore power	Moderate cost reduction
Engine derating	Constant cost
Energy storage battery + PTO	Moderate cost reduction
Section 2 - Operational or behaviour change that can increase efficiency	
Trim optimisation	Constant cost
Hull coating management	Constant cost
Draft/displacement optimisation	Constant cost
Port turnaround optimisation	Constant cost
Section 3 - Technologies specific to the capture/treatment of exhaust emissions (GHG and air pollutant emissions)	

NO_x Device	Constant cost
SO_x Device	Constant cost
PM Device	Constant cost
Section 4 - Machinery	
2 stroke diesel HFO	Constant cost
2 stroke diesel LSHFO	Constant cost
2 stroke diesel MDO	Constant cost
4 stroke diesel MDO	Constant cost
4 stroke spark ignition (LNG)	Constant cost
4 stroke spark ignition (NH_3)	Moderate cost reduction
diesel electric HFO	Constant cost
diesel electric LSHFO	Constant cost
diesel electric MDO	Constant cost
FC+H_2	High cost reduction
FC+NH_3	High cost reduction
IC+H_2 new	Moderate cost reduction
methanol 2 stoke	Constant cost
methanol 4 stoke	Constant cost

Source: Derived from Schmidt at al 2017[42], ETP Technology Roadmap (2015)[43], and expert judgment

6.4.10 Emissions Factors

The emission factors used in this analysis are shown in Table 9. Data are based on the analysis undertaken in Lloyd’s Register and UMAS 2019[44], Gilbert at al. (2018)[45] and internal datasets based on the work done under SCC[46].

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[42] https://www.sciencedirect.com/science/article/pii/S0360319917339435

[43] https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf

[44] Lloyd’s Register and UMAS 2019. Fuel production cost estimates and assumptions, Zero-carbon fuel production pathways

[45] https://www.sciencedirect.com/science/article/pii/S0959652617324721

[46] http://www.lowcarbonshipping.co.uk/

Table 9 Emissions factors for CO_2, CH_4 and N_2O SO_2, NO_x and $PM_{2.5}$(up= upstream emissions, op= operational emissions)

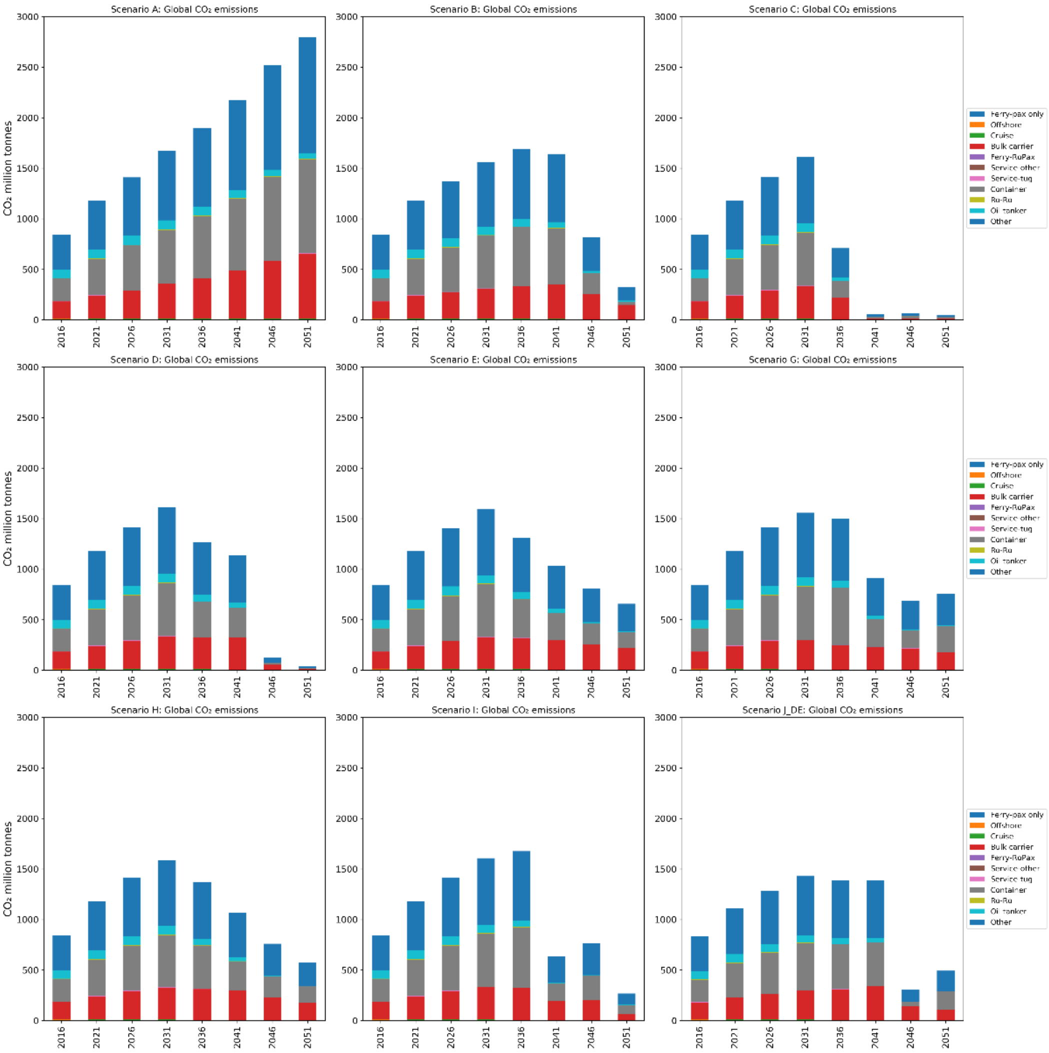
	tonne of emissions / tonne fuel produced	tonne of emissions / tonne fuel consumed	tonne of emissions / tonne fuel produced and consumed	tonne of emissions / tonne fuel produced	tonne of emissions / tonne fuel consumed	Kg of emissions / tonne fuel produced and consumed	tonne of emissions / tonne fuel produced	tonne of emissions / tonne fuel consumed	Kg of emissions / tonne fuel produced and consumed	tonne of emissions / tonne fuel produced	tonne of emissions / tonne fuel consumed	Kg of emissions / tonne fuel produced and consumed	tonne of emissions / tonne fuel produced	tonne of emissions / tonne fuel consumed	Kg of emissions / tonne fuel produced and consumed	tonne of emissions / tonne fuel produced	tonne of emissions / tonne fuel consumed	Kg of emissions / tonne fuel produced and consumed
	CO_2			**CH_4**			**N_2O**			**SO_2**			**NO_x**			**PM2.5**		
	up	op	total	up	op	total	up	op	total	up	op	total	up	op	total	up	op	total
HFO	0.338	3.020	3.36	0.0032	0.0001	3.25	0.00000	0.00016	0.160	0.00192	0.06650	68.42	0.00099	0.09300	93.99	0.00007	0.00728	7.35
MDO	0.341	3.080	3.42	0.0036	0.0001	3.67	0.00000	0.00015	0.150	0.00202	0.00190	3.92	0.00108	0.08725	88.33	0.00008	0.00097	1.05
LSHFO	0.338	3.080	3.42	0.0032	0.0001	3.25	0.00001	0.00016	0.167	0.00000	0.01900	19.00	0.00000	0.09300	93.00	0.00000	0.00426	4.26
LNG	0.316	2.750	3.07	0.0024	0.0512	53.62	0.00012	0.00011	0.231	0.00108	0.00002	1.10	0.00069	0.0078	8.52	0.00001	0.00018	0.19
H2 (SMR +CCS)	0.840	0.000	0.84	0.0403	0.0000	40.32	0.00016	0.00000	0.163	0.01386	0	13.86	0.009361	0.0038088	13.17	0.00064	0.0000156	0.66
H2 (electrolysis)	0.440	0.000	0.44	0.0010	0.0000	1.02	0.00001	0.00000	0.007	0.00059	0	0.59	0.00113	0.0038088	4.94	0.00004	0.0000156	0.06
Ammonia (SMR +CCS)	0.231	0.000	0.23	0.0000	0.0000	0.01	0.00001	0.00000	0.007	0.00160	0.0003132	1.91	0.002180	0.042804	44.98	0.000131	4.698E-06	0.14
Ammonia (electrolysis)	0.168	0.000	0.17	0.0000	0.0000	0.01	0.00001	0.00001	0.024	0.00014	0.0003132	0.45	0.00125	0.042804	44.06	0.000162	4.698E-06	0.17
Methanol (electrolysis)	0.08	0.000	0.08	0.0000	0.0000	0.00	0.00000	0.00000	0.000	0.00033	0.0	0.32980	0.00111	0.00017	1.28060	0.00026	0.00000	0.26
Methanol from SMR+CCS	0.16	0.000	0.16	0.0000	0.0000	0.00	0.00000	0.00000	0.000	0.00033	0.0	0.32980	0.00111	0.00017	1.28060	0.00026	0.00000	0.26

6.5 Detailed results

The worksheet "Emissions results all years.xls" provide all the emissions results out to 2100 for the UK domestic and international fleet.

The following figures provides in the form of aggregated plots some of the detailed results than were not included in the main report.

Figure 18: Global (international and domestic) carbon dioxide (CO_2) operational emissions by scenario

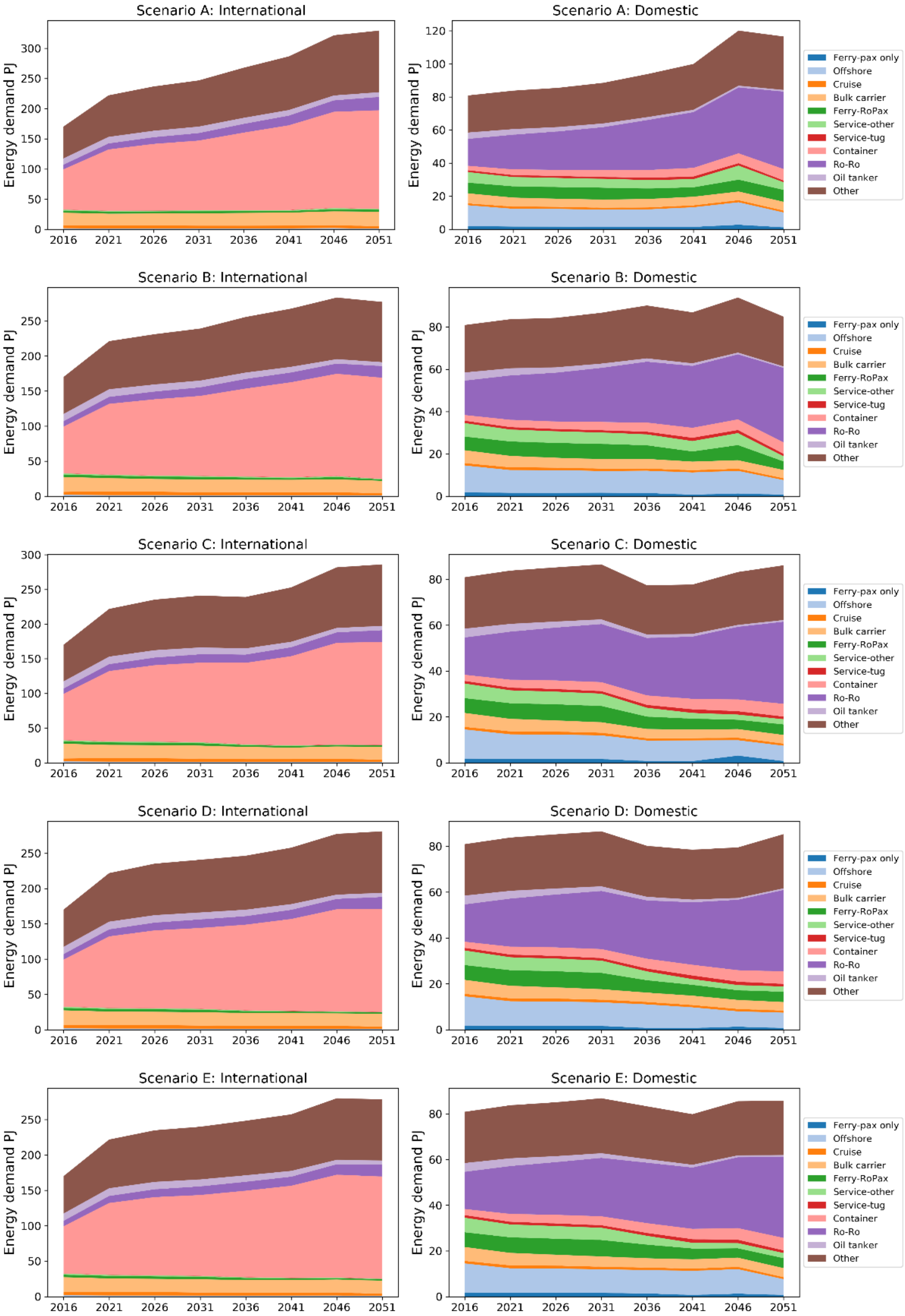


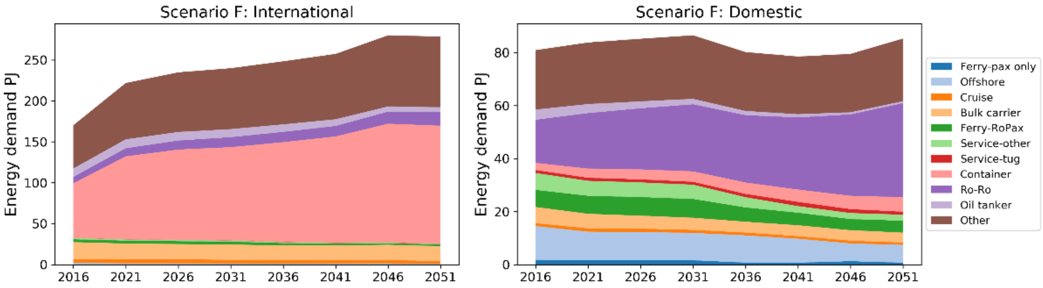
Note: The operational emissions do not include emissions at ports

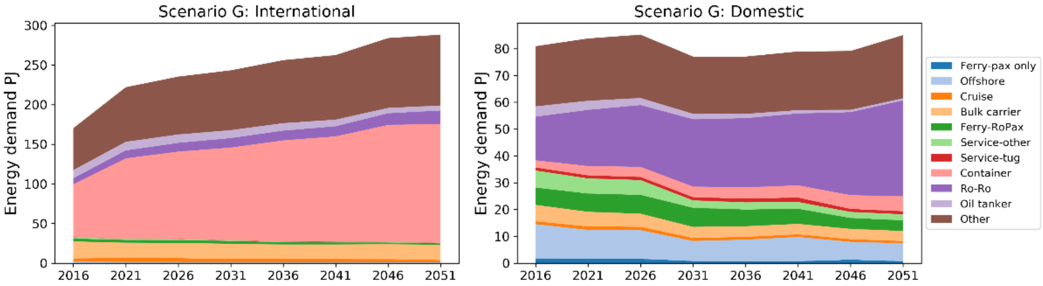
Similar to the results for the UK fleets, when interpreting the global detailed results, it should be noted that differences also occur between scenarios because of the model's use of iteration to reach a given GHG target. In this iteration the model applies an estimate of the carbon price trajectory (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.

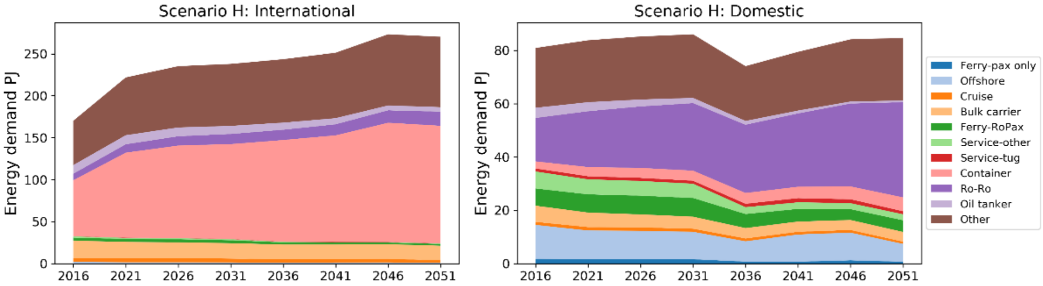
Because of the computational time and cost, this process of iteration is stopped when the model’s output GHG emissions trajectory is within certain bounds of the objective (e.g. the model is not iterated until there is a perfect match to the objective), and this leads to there being observable small 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

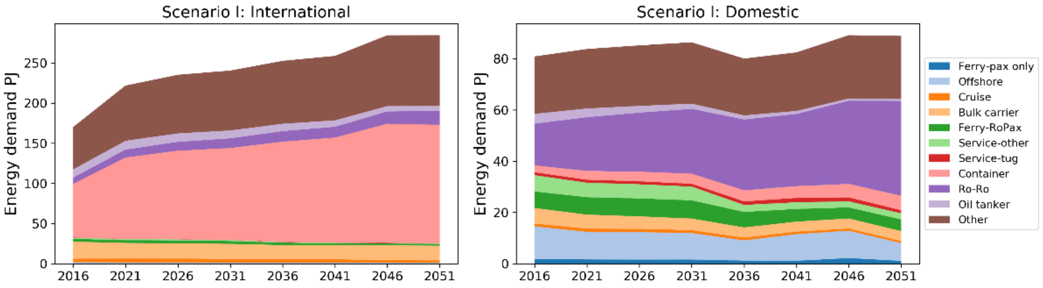
Figure 19: Energy demand by scenario, all ship types, both UK international and UK domestic (excluding energy demand at port)




Scenario F: International
Energy demand PJ
0
50
100
150
200
250
2016
2021
2026
2031
2036
2041
2046
2051
Scenario F: Domestic
Energy demand PJ
0
20
40
60
80
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker
Other


Scenario G: International
Energy demand PJ
0
50
100
150
200
250
300
2016
2021
2026
2031
2036
2041
2046
2051
Scenario G: Domestic
Energy demand PJ
0
10
20
30
40
50
60
70
80
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker
Other


Scenario H: International
Energy demand PJ
0
50
100
150
200
250
2016
2021
2026
2031
2036
2041
2046
2051
Scenario H: Domestic
Energy demand PJ
0
20
40
60
80
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker
Other


Scenario I: International
Energy demand PJ
0
50
100
150
200
250
2016
2021
2026
2031
2036
2041
2046
2051
Scenario I: Domestic
Energy demand PJ
0
20
40
60
80
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker
Other

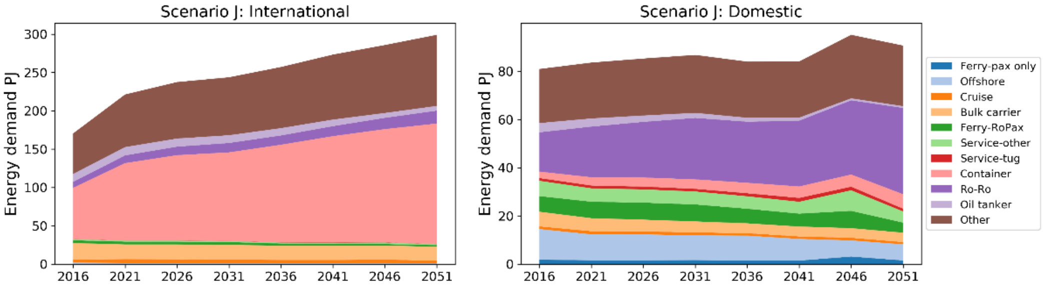
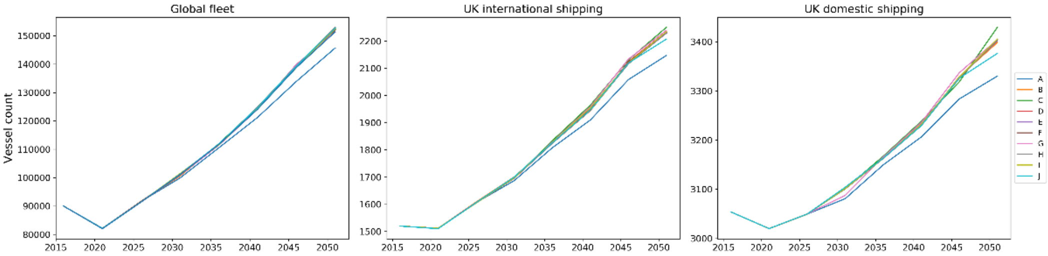
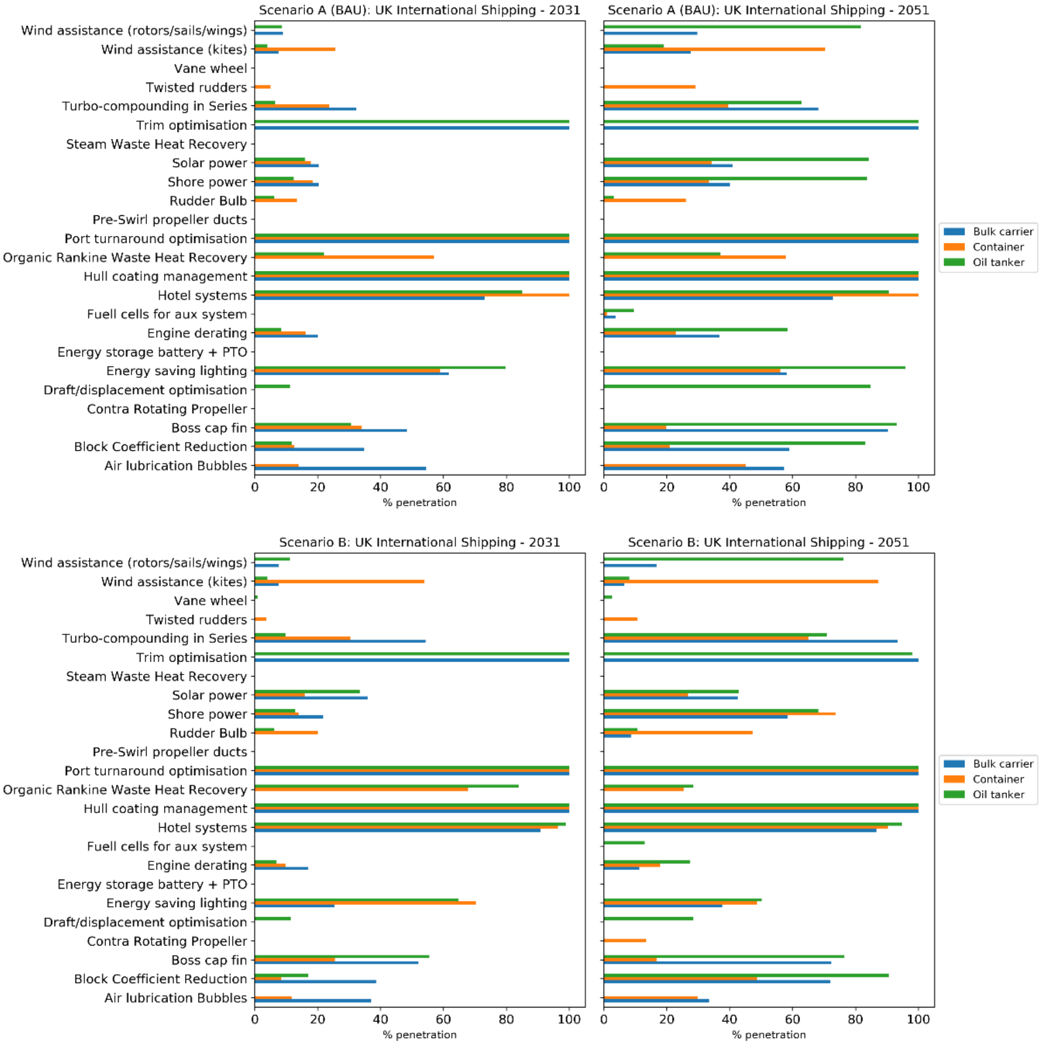

Scenario J: International
Energy demand PJ
0
50
100
150
200
250
300
2016
2021
2026
2031
2036
2041
2046
2051
Scenario J: Domestic
Energy demand PJ
0
20
40
60
80
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker
Other

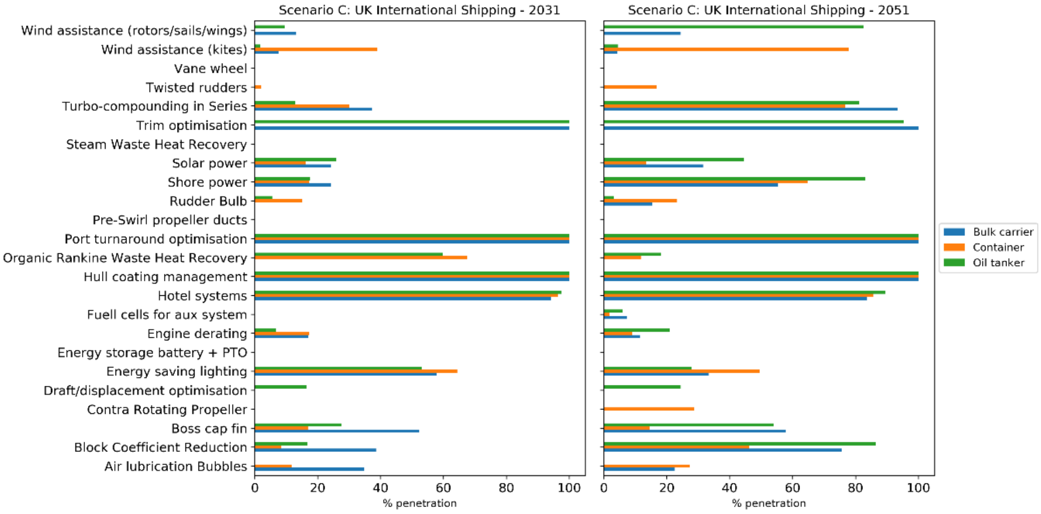
Figure 20: Vessel counts by scenario

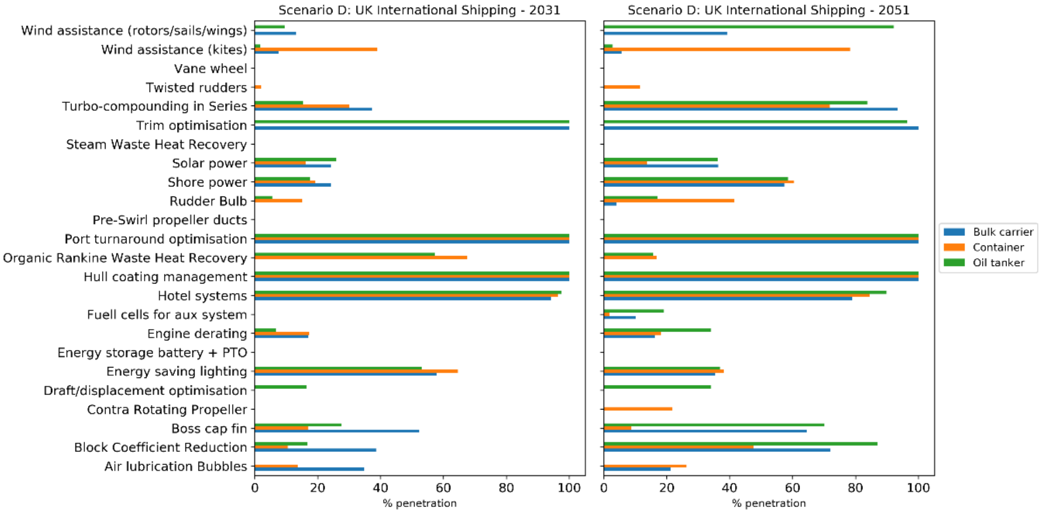


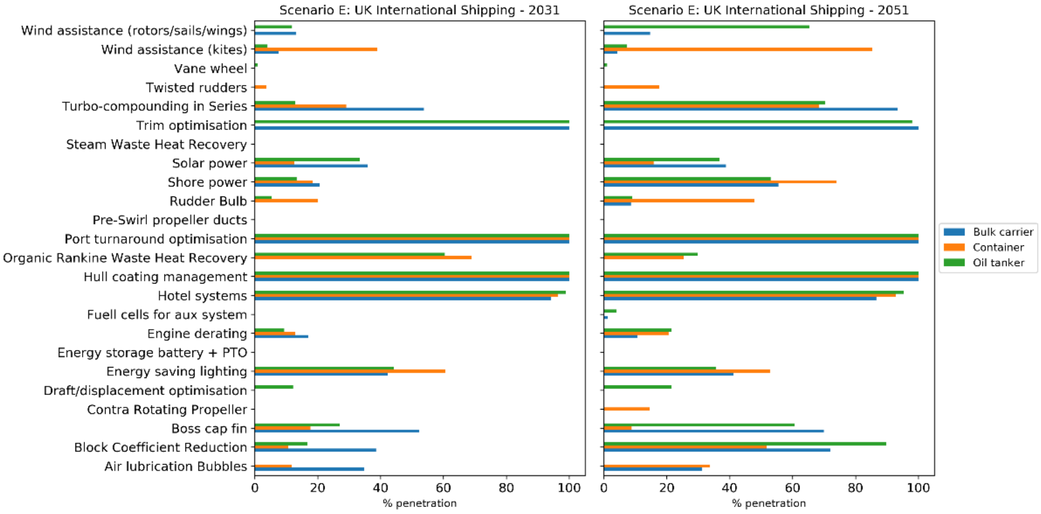
Note: From baseline to 2021 there is a decreasing trend due to the fact that the GloTraM model starts with data from the world fleet register and therefore includes an overcapacity. On the following time-steps it is assumed that there is no lag or delay from ordering to delivery, such that supply meets demand exactly at every time step as explained in more detail in section 3.2.

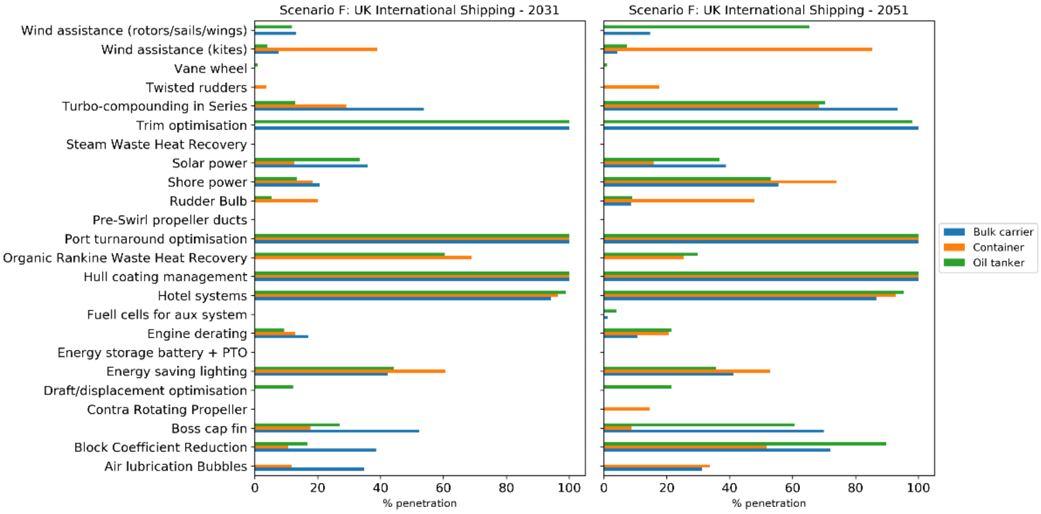
Figure 21: Take-up of measures that increase efficiency in scenarios for bulk carrier, container vessels and oil tankers in UK international shipping




Scenario C: UK International Shipping - 2031
Scenario C: 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
Bulk carrier
Container
Oil tanker


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
Bulk carrier
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
Bulk carrier
Container
Oil tanker


Scenario F: UK International Shipping - 2031
Scenario F: 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
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Hull coating management
Hotel systems
Fuell cells for aux system
Engine derating
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Energy saving lighting
Draft/displacement optimisation
Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0
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40
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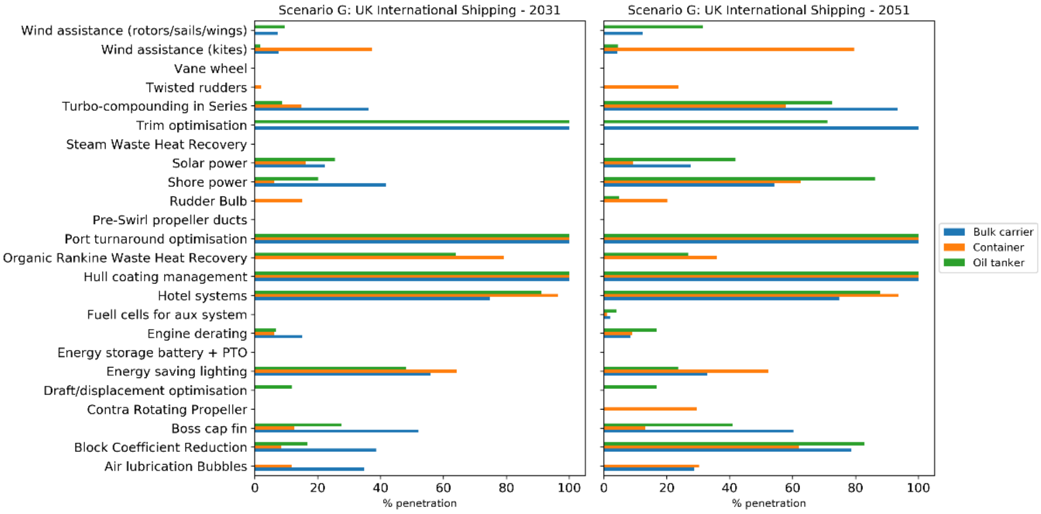
80
100
% penetration
Bulk carrier
Container
Oil tanker


Scenario G: UK International Shipping - 2031
Scenario G: 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
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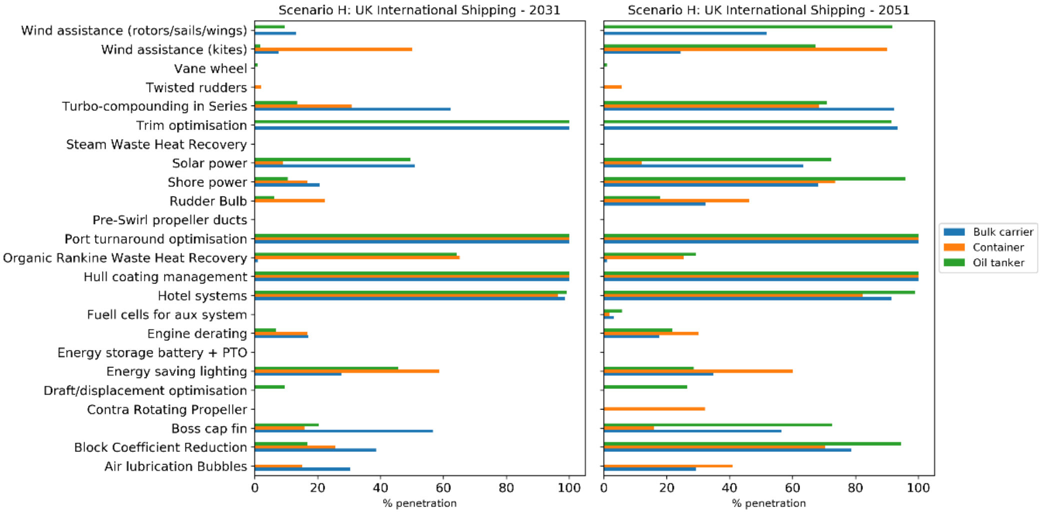
100
% penetration
Bulk carrier
Container
Oil tanker


Scenario H: UK International Shipping - 2031
Scenario H: 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
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Fuell cells for aux system
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Energy saving lighting
Draft/displacement optimisation
Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0
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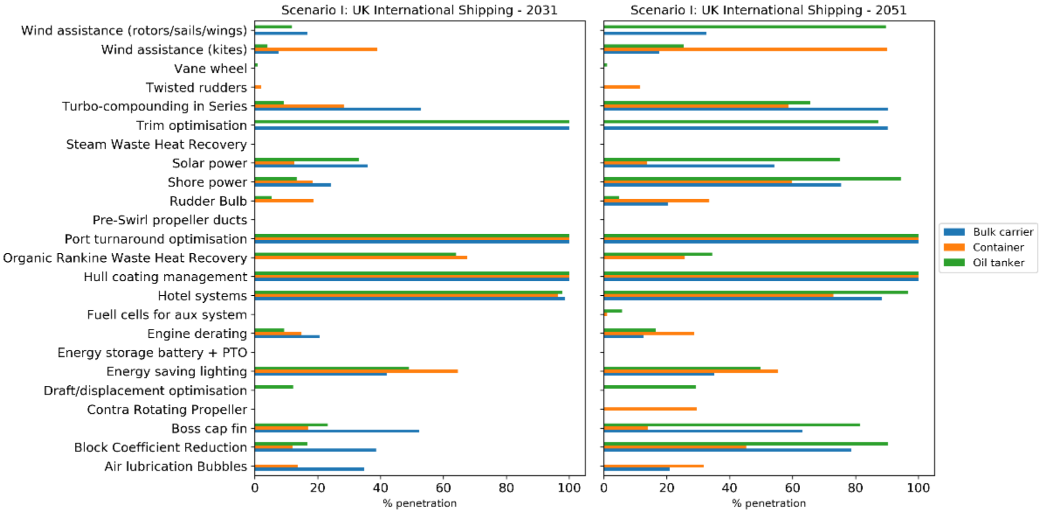
80
100
% penetration
Bulk carrier
Container
Oil tanker


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
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Energy saving lighting
Draft/displacement optimisation
Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0
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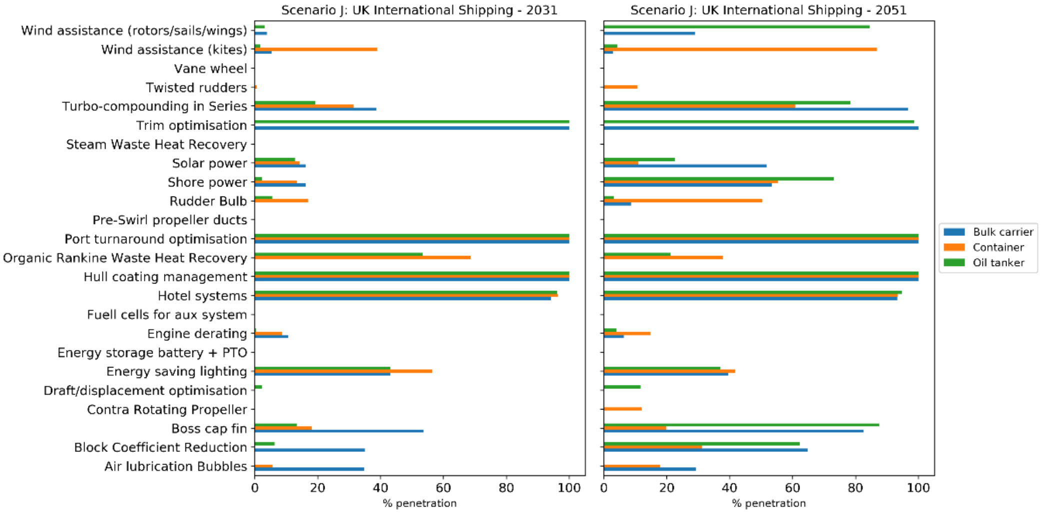
80
100
% penetration
Bulk carrier
Container
Oil tanker


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
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Steam Waste Heat Recovery
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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
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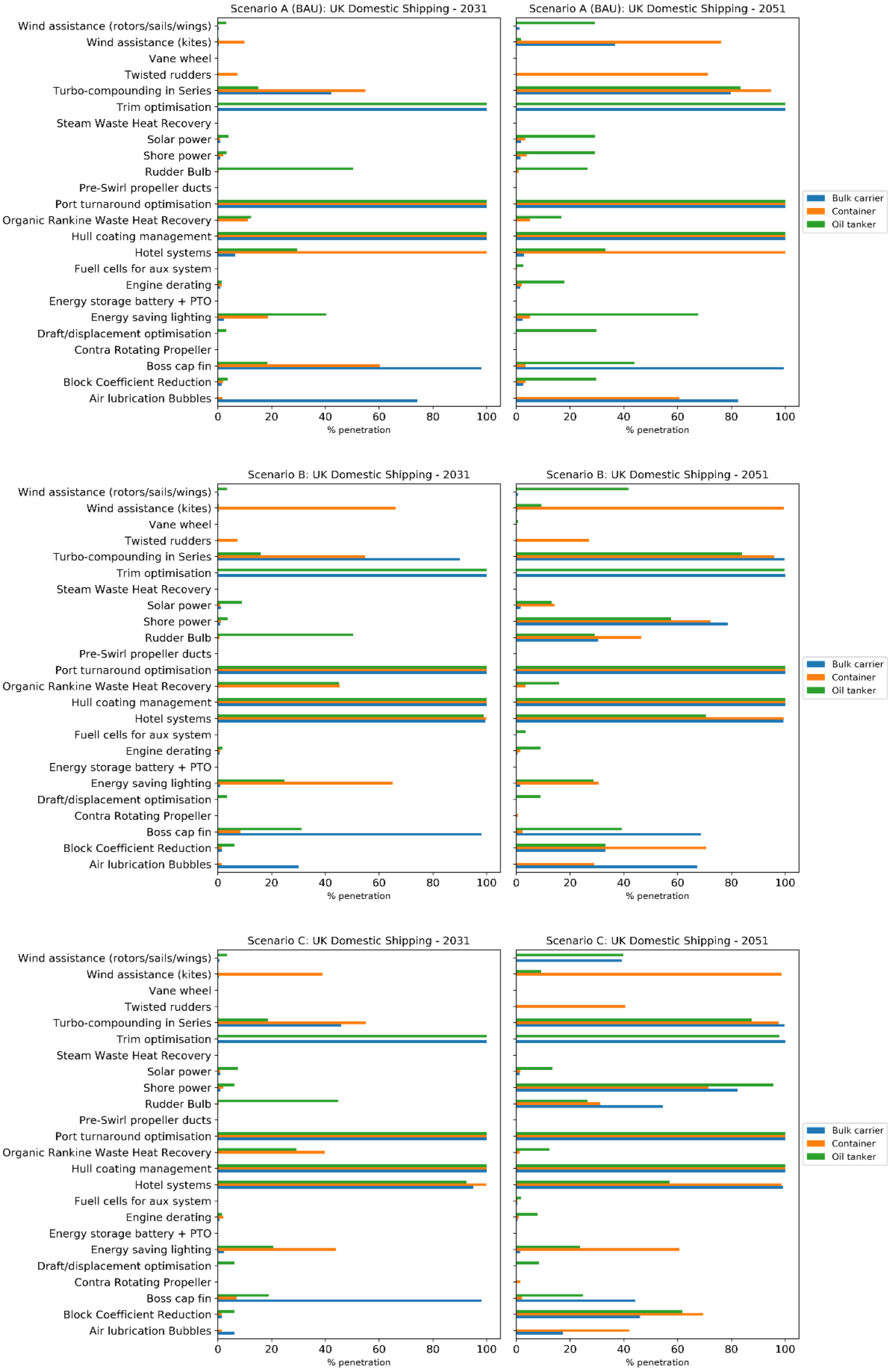
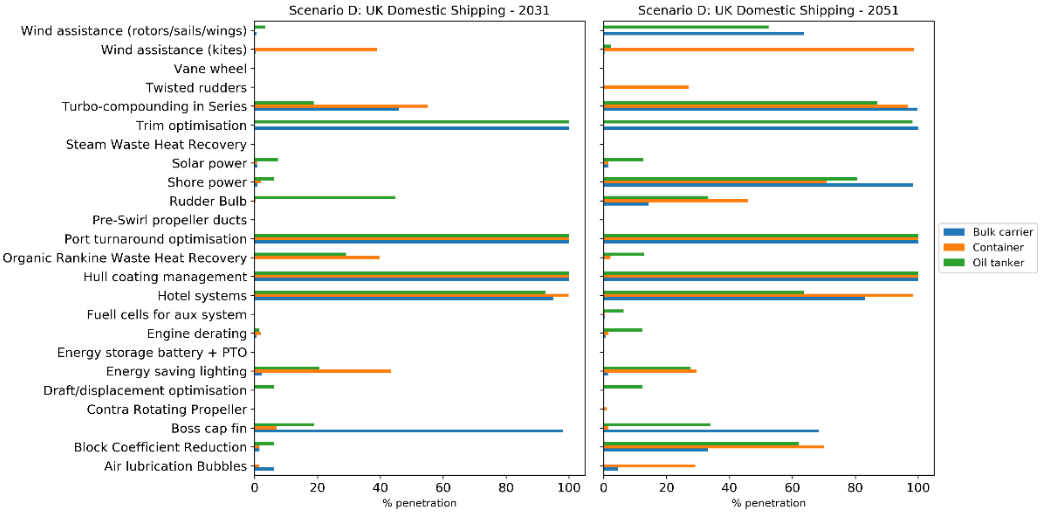
60
80
100
% penetration
Bulk carrier
Container
Oil tanker

Figure 22: Take-up of measures that increase efficiency in scenarios for bulk carrier, container vessels and oil tankers in UK domestic shipping




Scenario D: UK Domestic Shipping - 2031
Scenario D: UK Domestic 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
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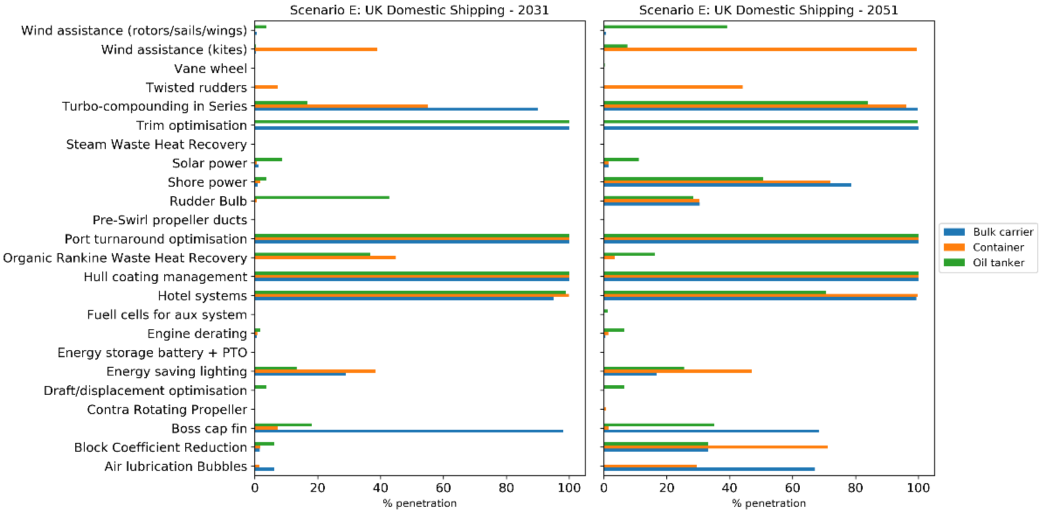
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0
20
40
60
80
100
% penetration
Bulk carrier
Container
Oil tanker


Scenario E: UK Domestic Shipping - 2031
Scenario E: UK Domestic 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
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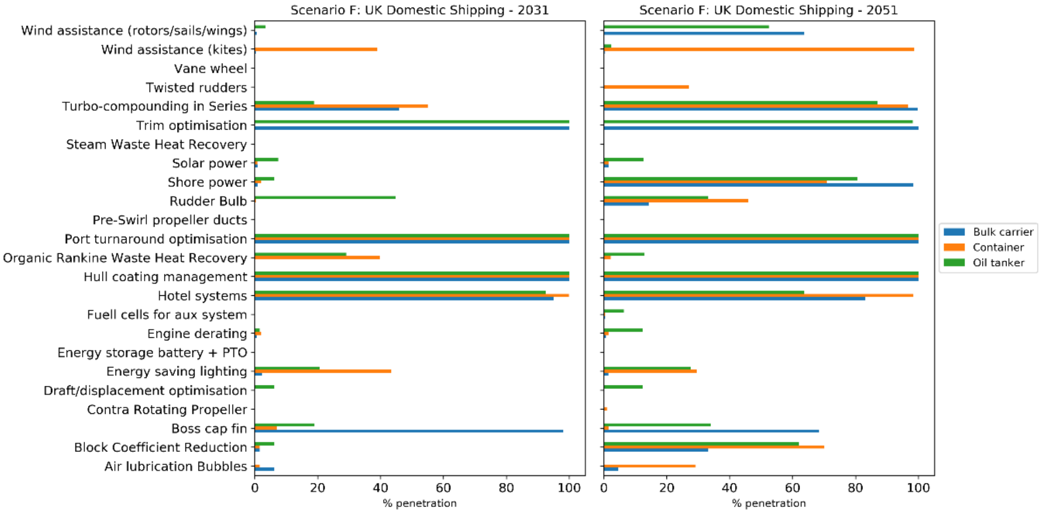
Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0
20
40
60
80
100
% penetration
Bulk carrier
Container
Oil tanker


Scenario F: UK Domestic Shipping - 2031
Scenario F: UK Domestic Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
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Shore power
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Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
0
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40
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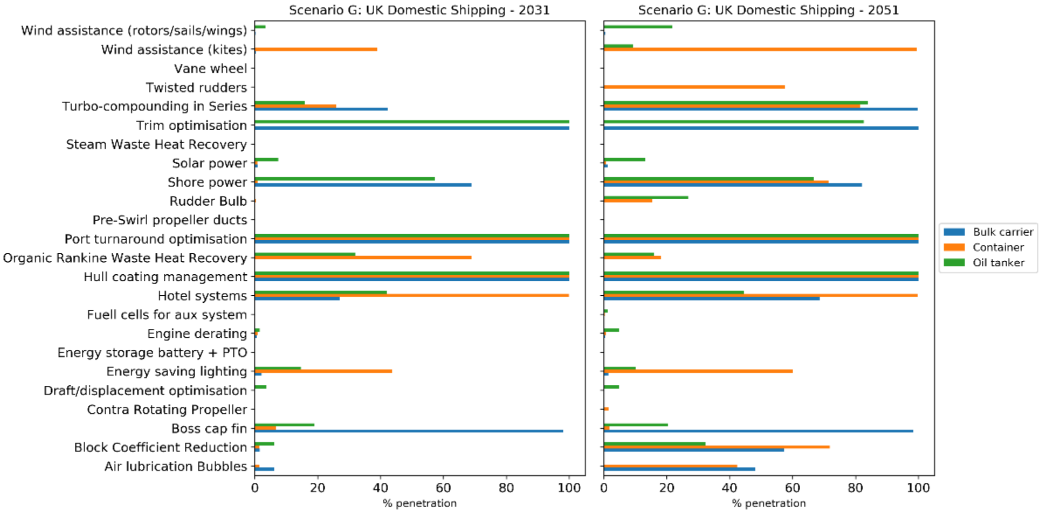
80
100
% penetration
Bulk carrier
Container
Oil tanker


Scenario G: UK Domestic Shipping - 2031
Scenario G: UK Domestic 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
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Port turnaround optimisation
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Energy storage battery + PTO
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Draft/displacement optimisation
Contra Rotating Propeller
Boss cap fin
Block Coefficient Reduction
Air lubrication Bubbles
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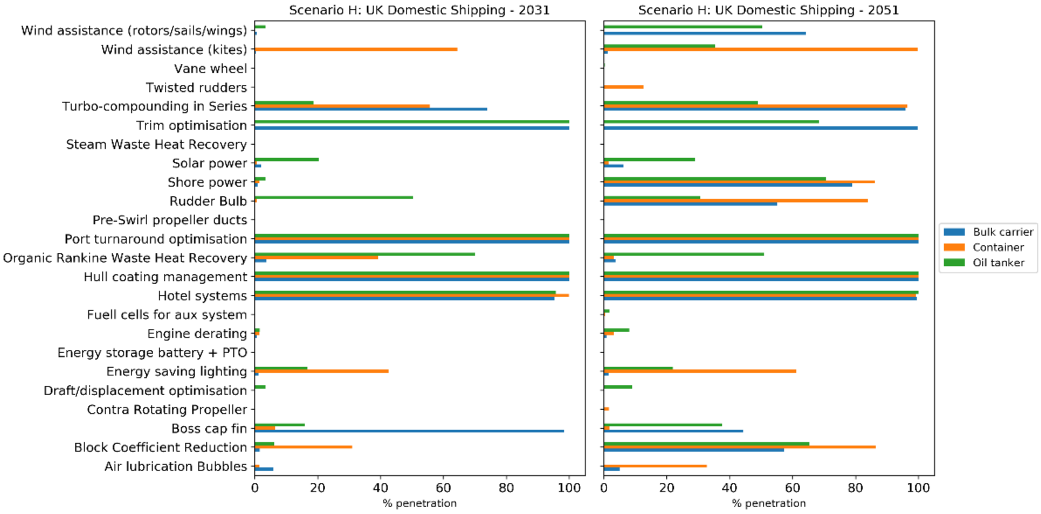
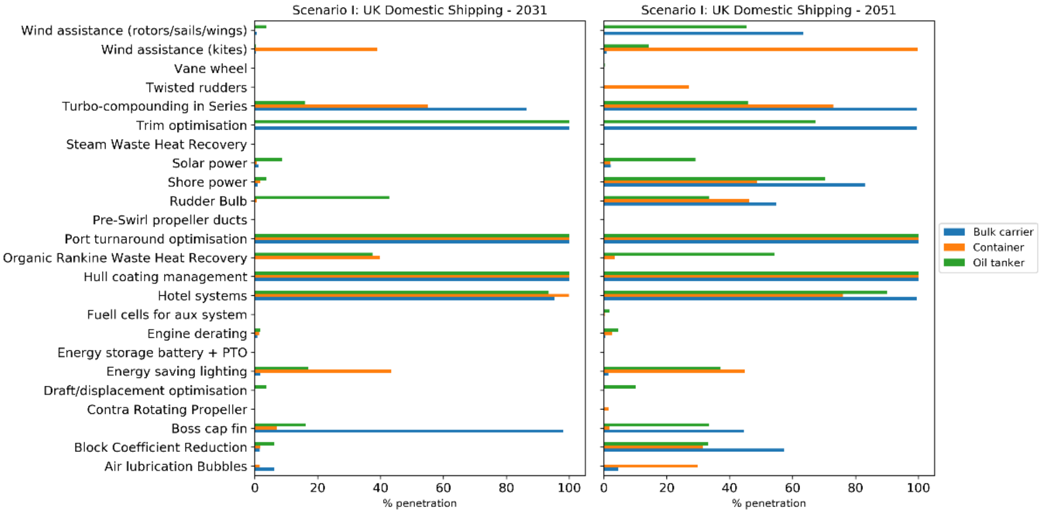
40
60
80
100
% penetration
Bulk carrier
Container
Oil tanker


Scenario H: UK Domestic Shipping - 2031
Scenario H: UK Domestic 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
Bulk carrier
Container
Oil tanker


Scenario I: UK Domestic Shipping - 2031
Scenario I: UK Domestic 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
Bulk carrier
Container
Oil tanker

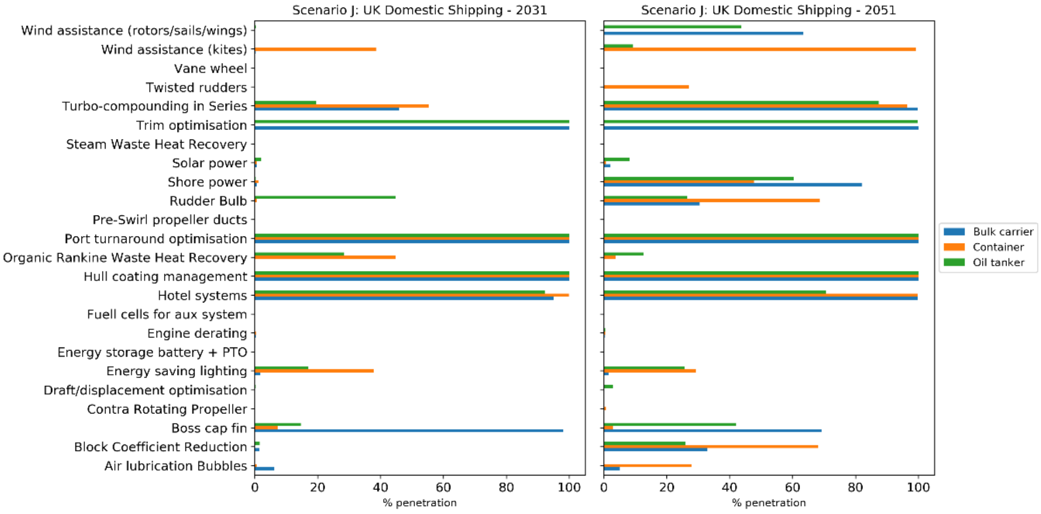
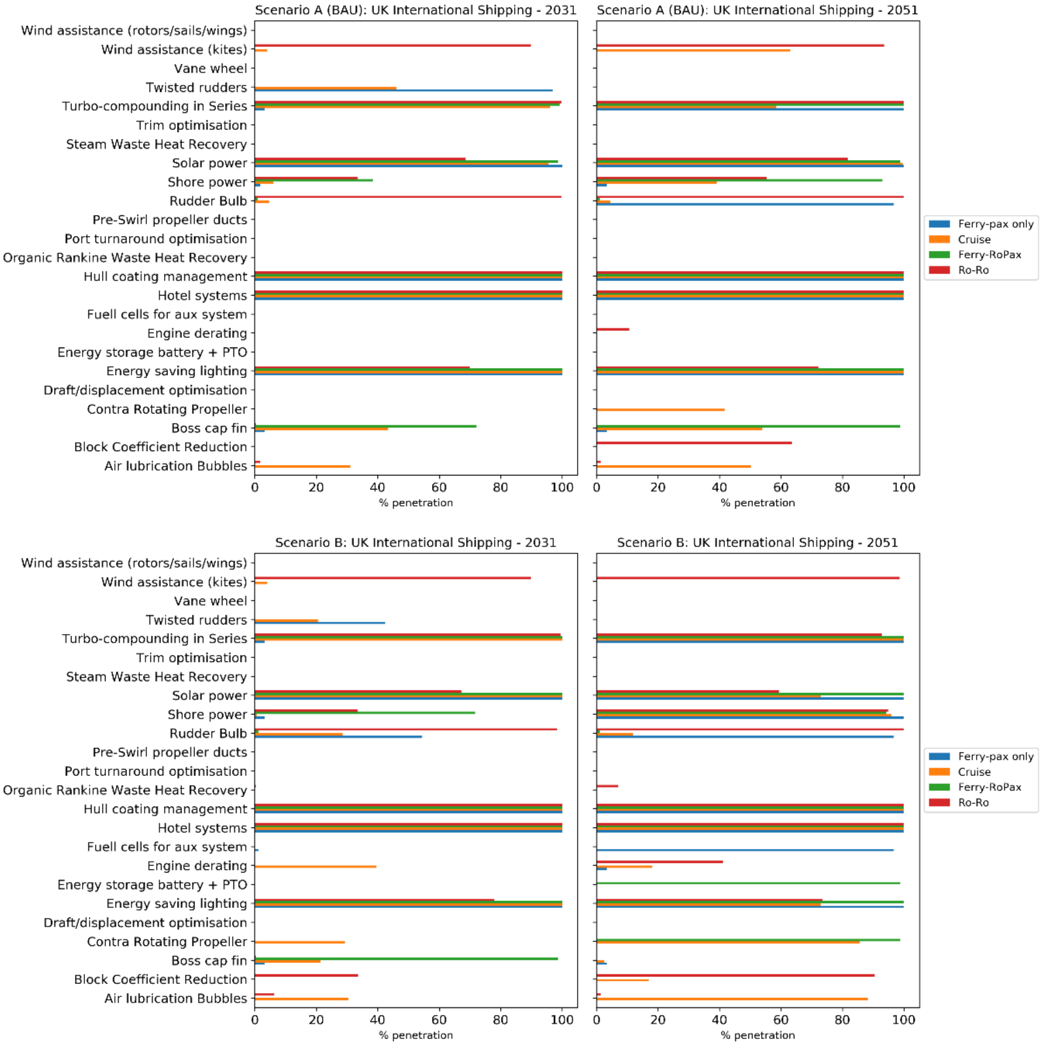
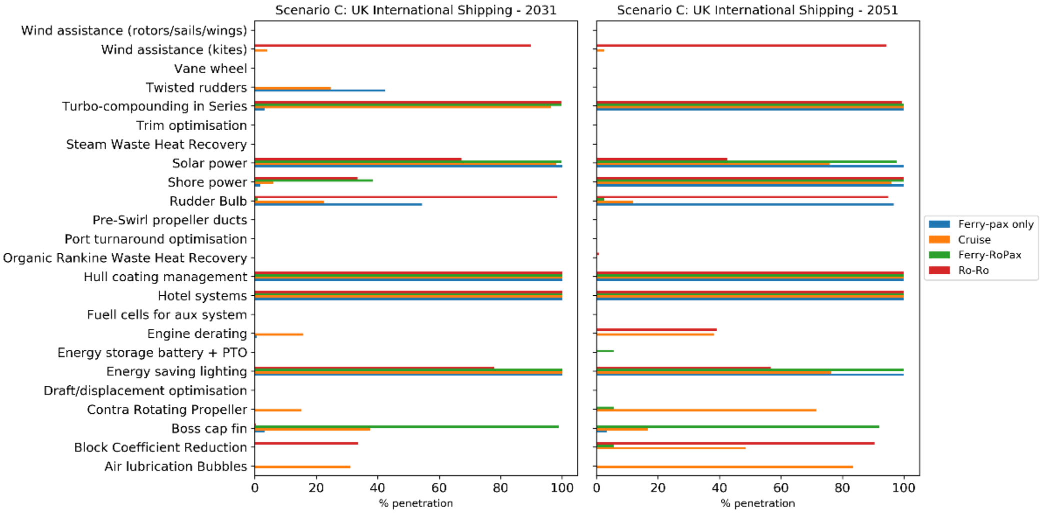
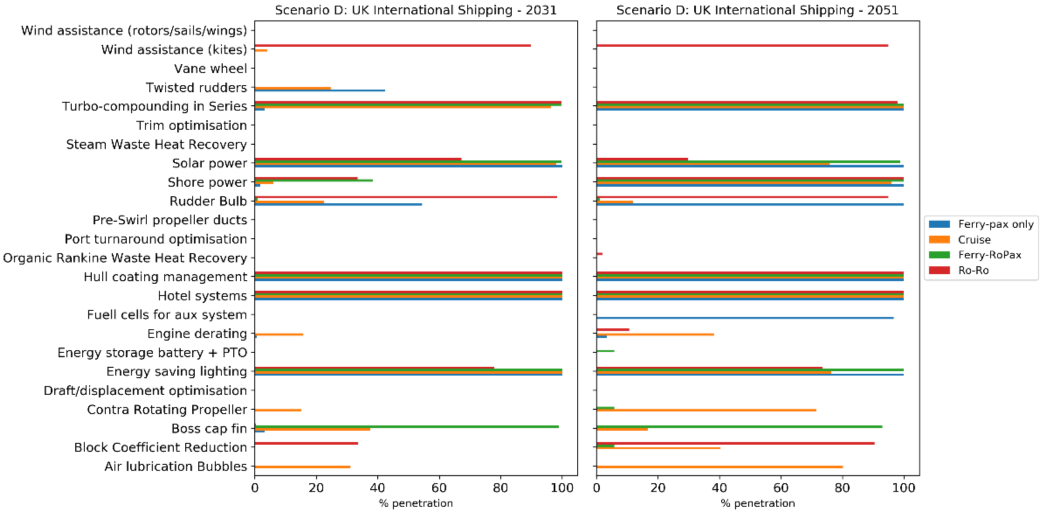
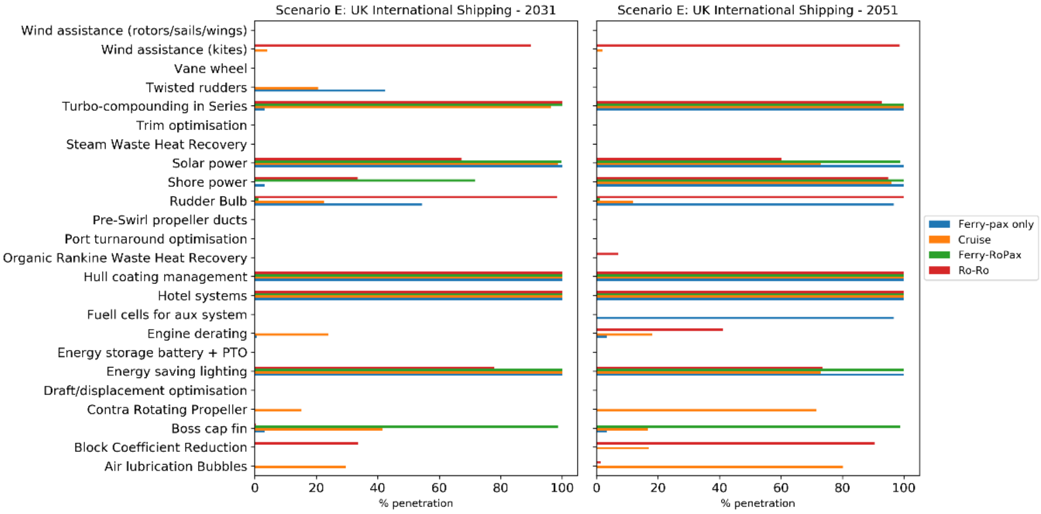


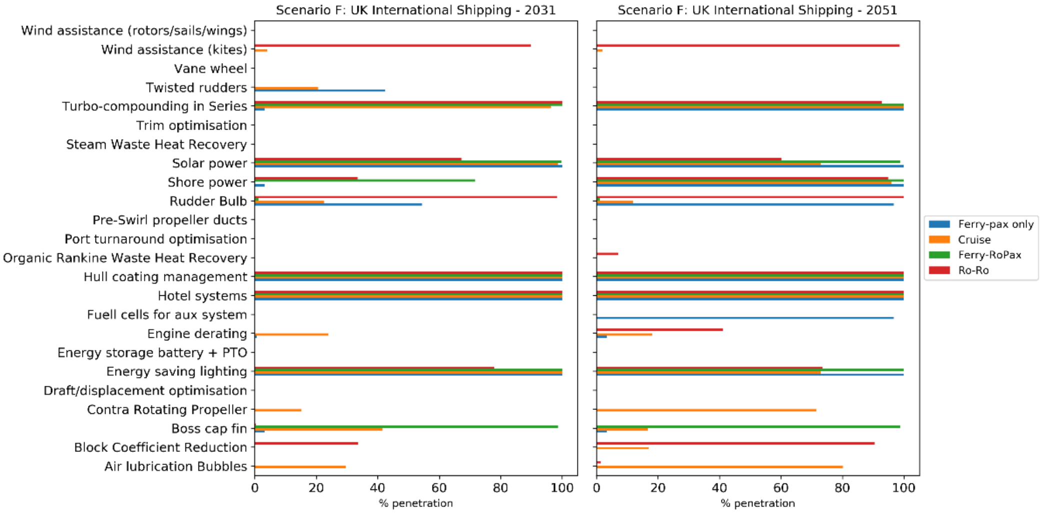
Figure 23: Take-up of measures that increase efficiency in scenarios for ferry pax only, cruise, ferry ro-pax and roll on roll off vessels in UK international shipping

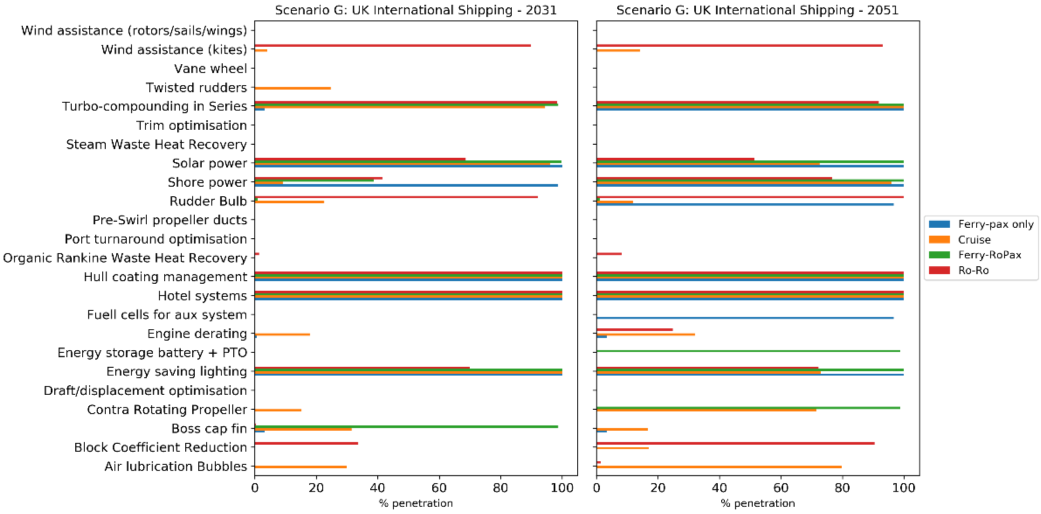


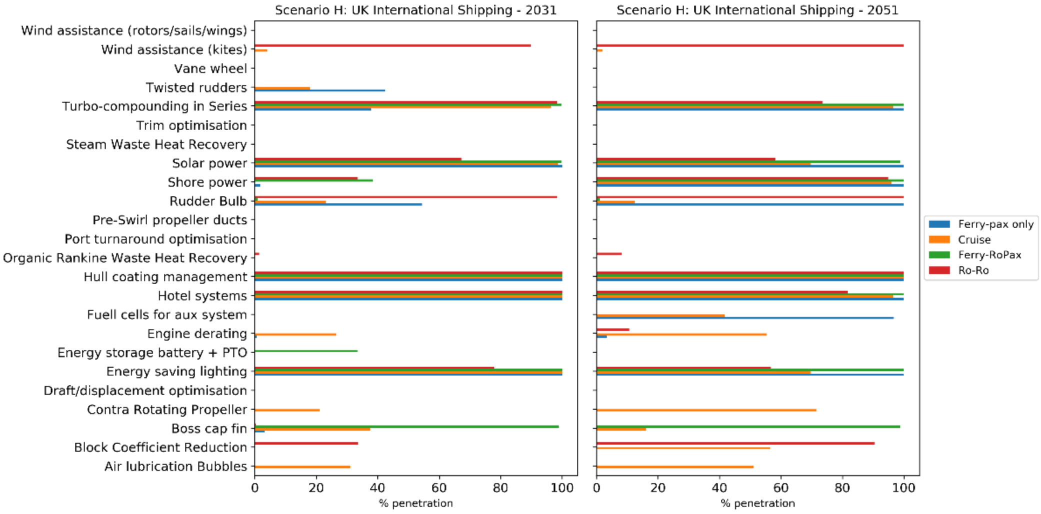

Scenario C: UK International Shipping - 2031
Scenario C: UK International Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller 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
Cruise
Ferry-RoPax
Ro-Ro

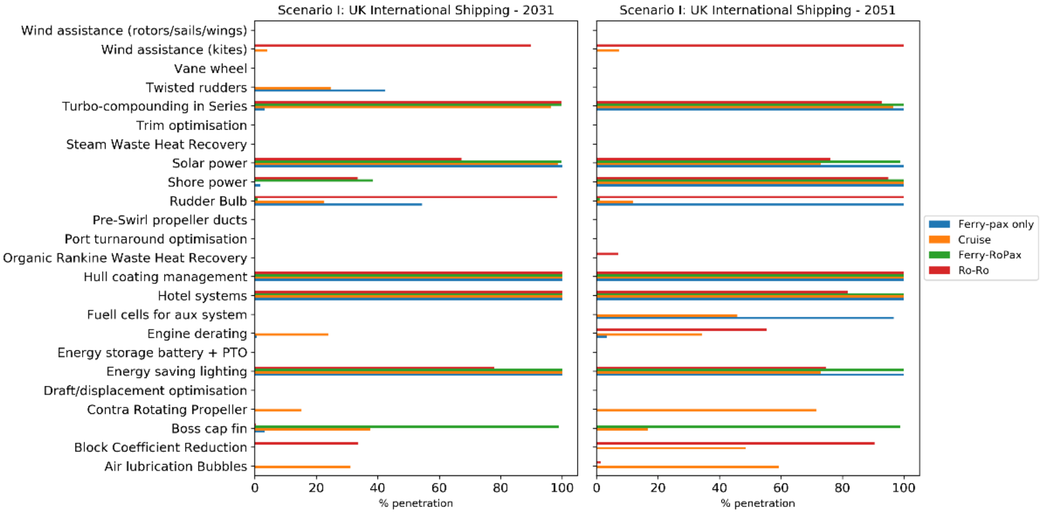

Scenario D: UK International Shipping - 2031
Scenario D: UK International Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller 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
Cruise
Ferry-RoPax
Ro-Ro


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
Cruise
Ferry-RoPax
Ro-Ro


Scenario F: UK International Shipping - 2031
Scenario F: 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
Cruise
Ferry-RoPax
Ro-Ro


Scenario G: UK International Shipping - 2031
Scenario G: 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
Cruise
Ferry-RoPax
Ro-Ro


Scenario H: UK International Shipping - 2031
Scenario H: 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
Cruise
Ferry-RoPax
Ro-Ro


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
Cruise
Ferry-RoPax
Ro-Ro

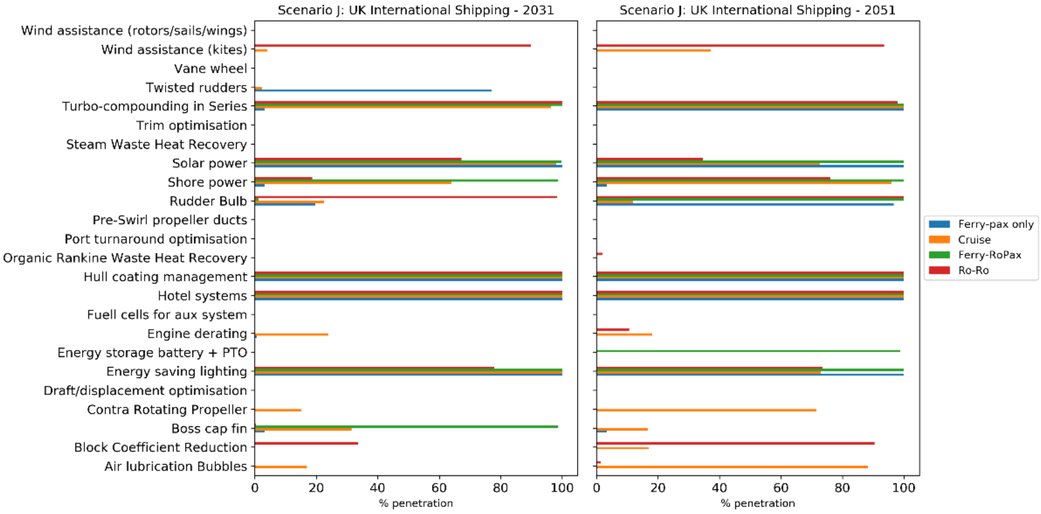
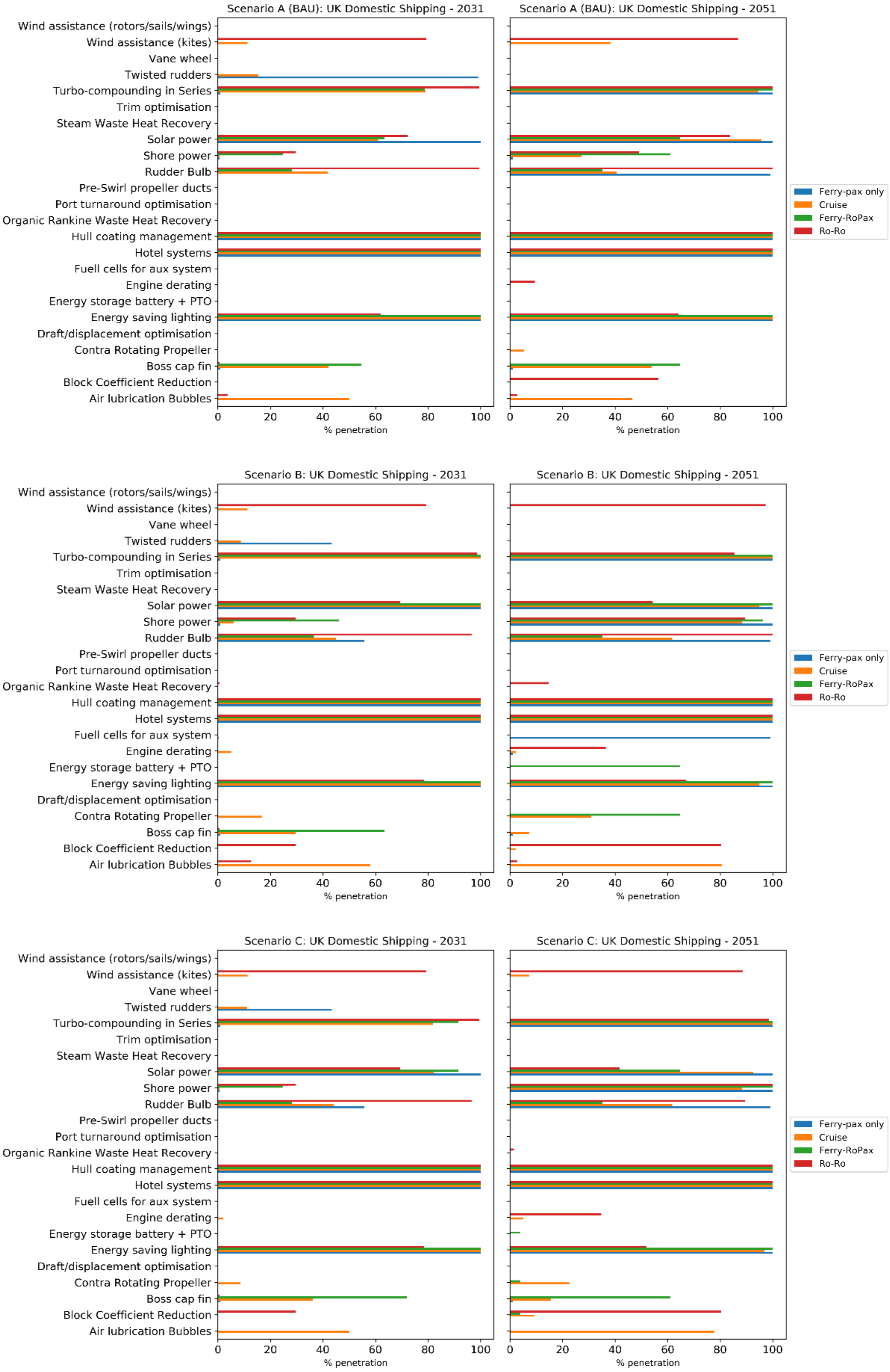
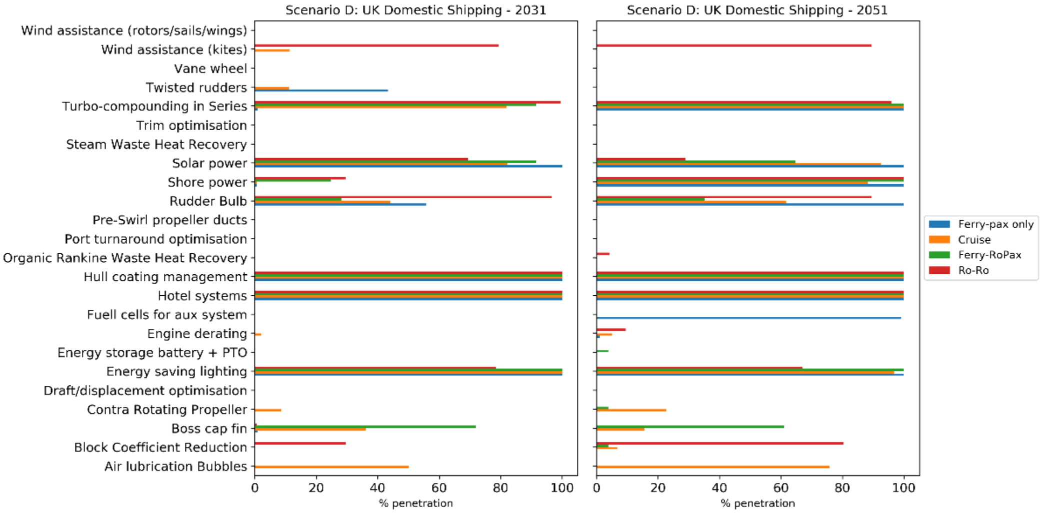
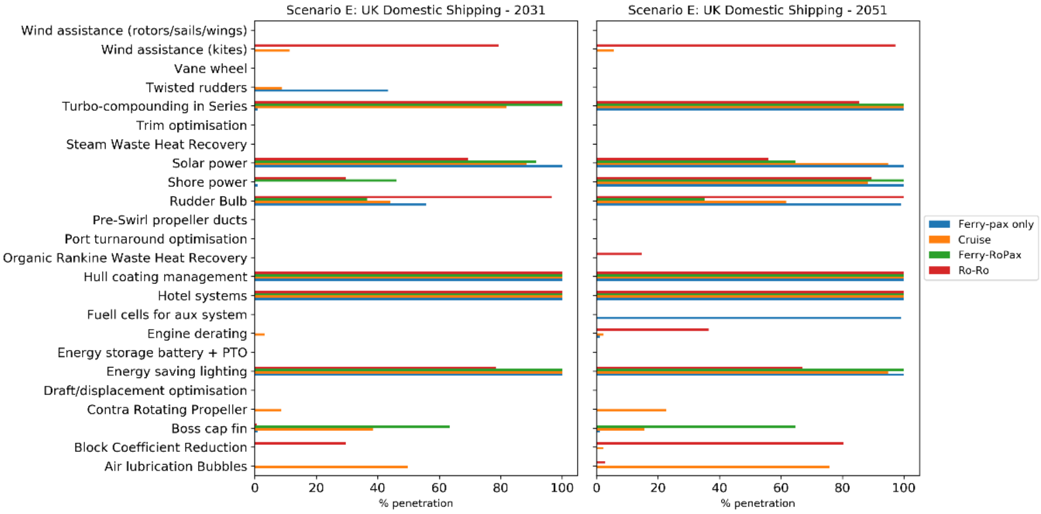
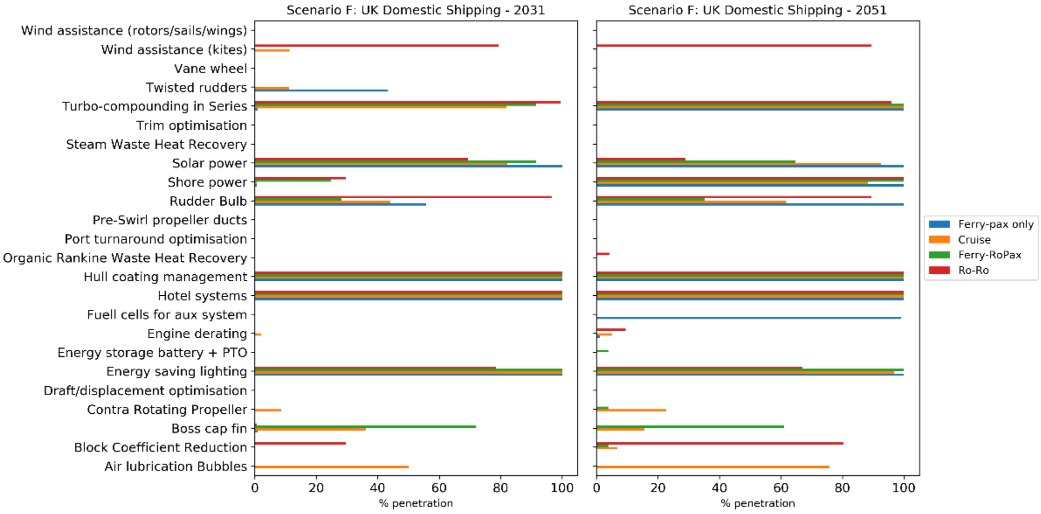

Scenario J: UK International Shipping - 2031
Scenario J: UK International Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller 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
Cruise
Ferry-RoPax
Ro-Ro

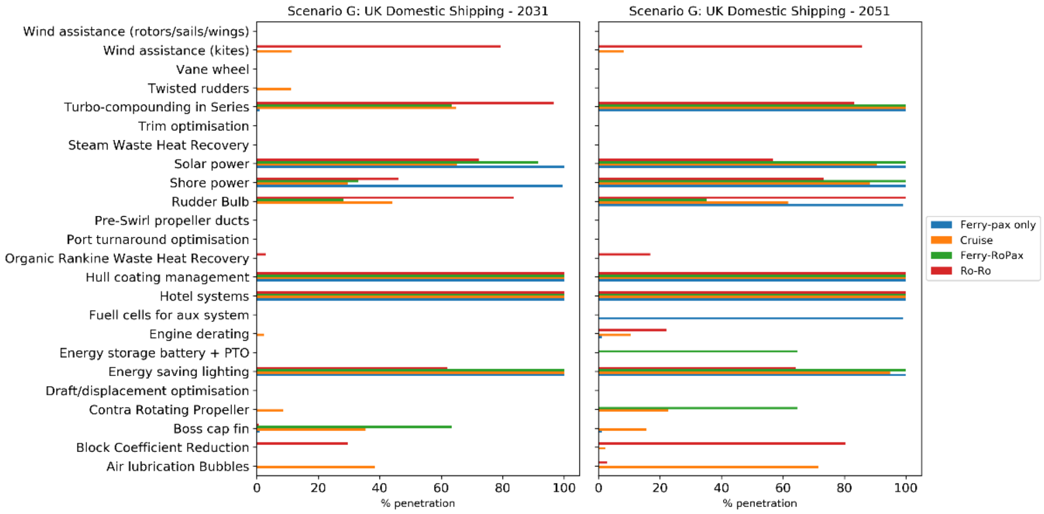
Figure 24: Take-up of measures that increase efficiency in scenarios for ferry pax only, cruise, ferry ro-pax and roll on roll off vessels in UK domestic shipping




Scenario D: UK Domestic Shipping - 2031
Scenario D: UK Domestic 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
Cruise
Ferry-RoPax
Ro-Ro


Scenario E: UK Domestic Shipping - 2031
Scenario E: UK Domestic 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
Cruise
Ferry-RoPax
Ro-Ro


Scenario F: UK Domestic Shipping - 2031
Scenario F: UK Domestic 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
Cruise
Ferry-RoPax
Ro-Ro


Scenario G: UK Domestic Shipping - 2031
Scenario G: UK Domestic 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
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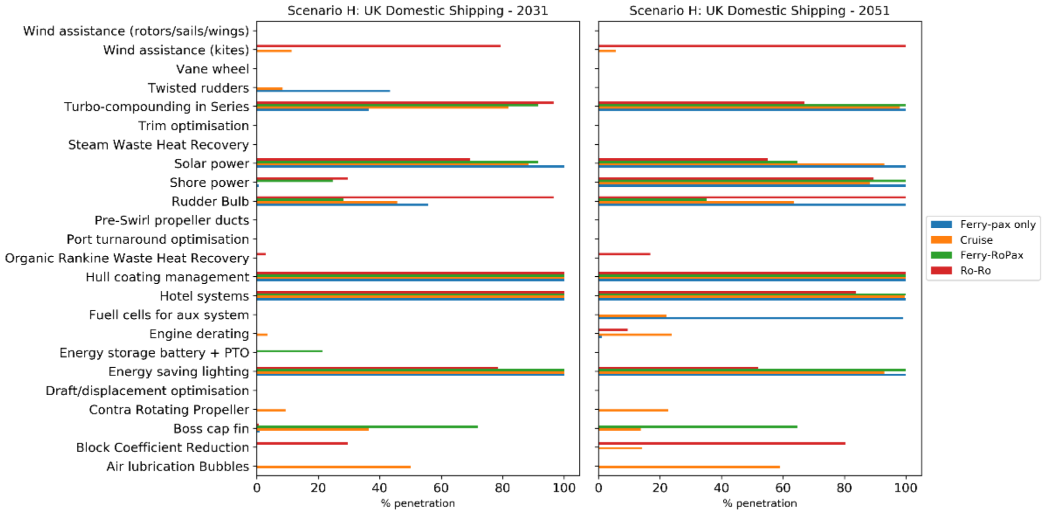
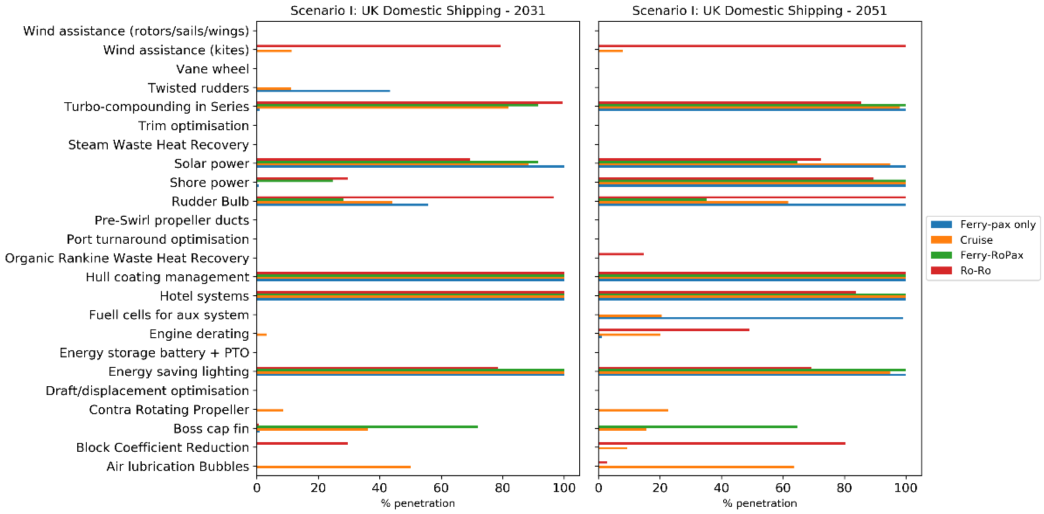
80
100
% penetration
Ferry-pax only
Cruise
Ferry-RoPax
Ro-Ro


Scenario H: UK Domestic Shipping - 2031
Scenario H: UK Domestic 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
Cruise
Ferry-RoPax
Ro-Ro


Scenario I: UK Domestic Shipping - 2031
Scenario I: UK Domestic 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
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100
% penetration
Ferry-pax only
Cruise
Ferry-RoPax
Ro-Ro

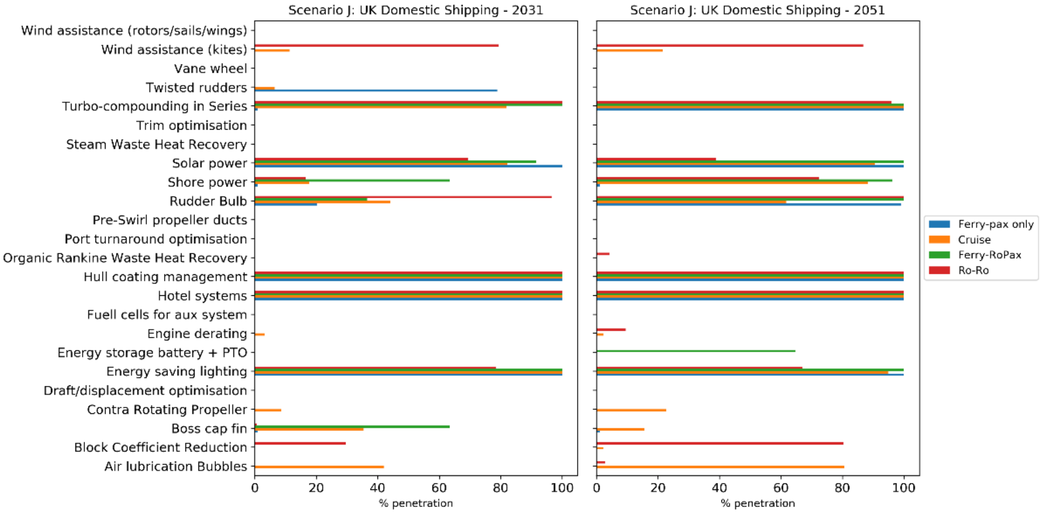
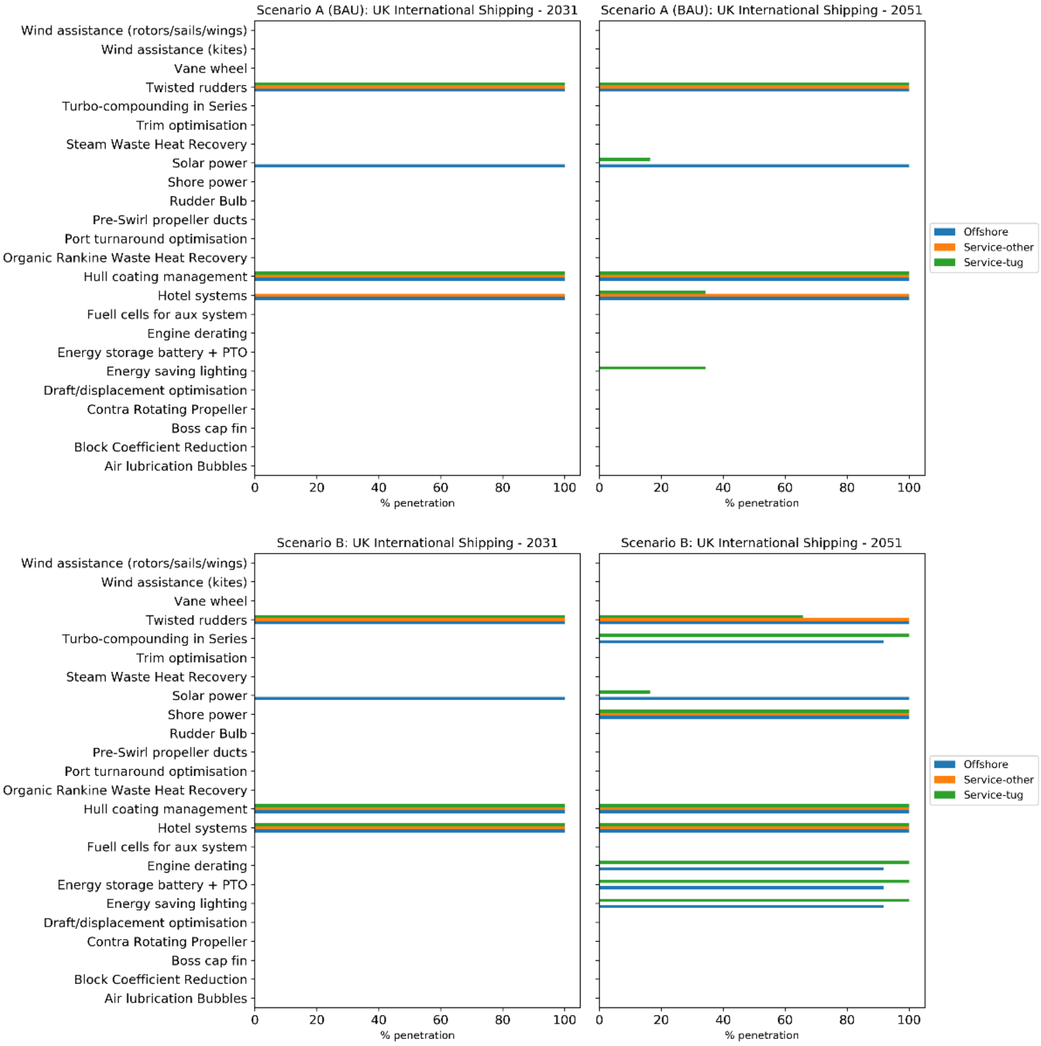
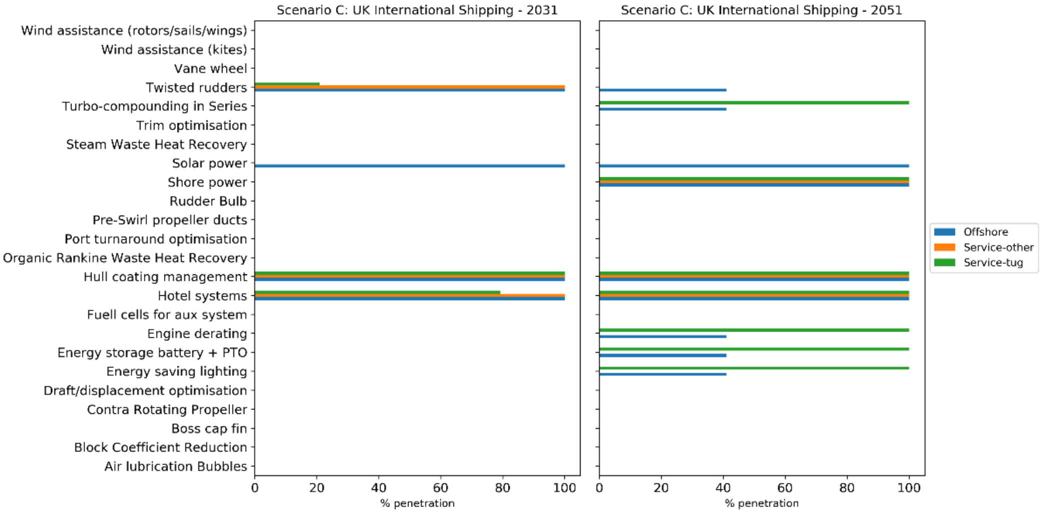


Figure 25: Take-up of measures that increase efficiency in scenarios for offshore, tugs and service vessels in UK international shipping




Scenario C: UK International Shipping - 2031
Scenario C: 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
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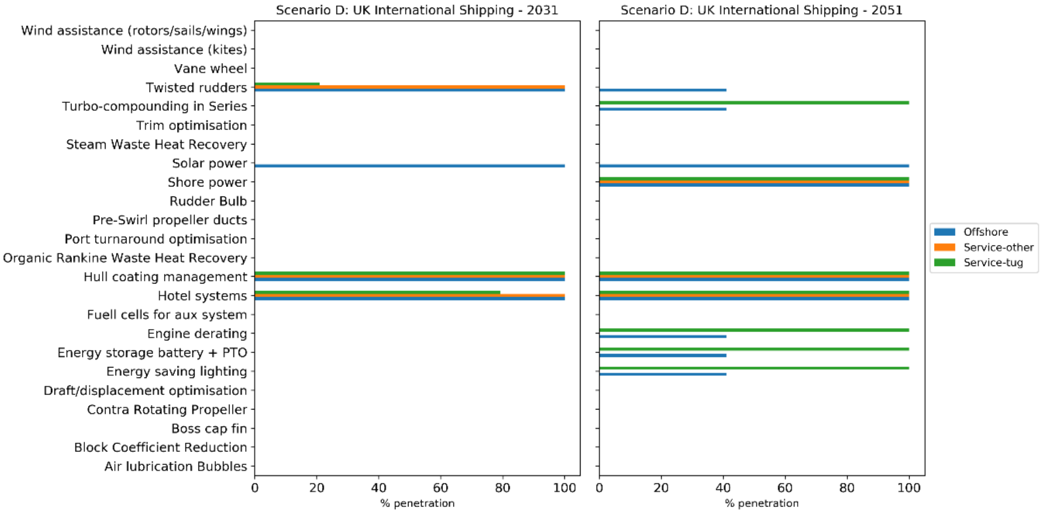
40
60
80
100
% penetration
Offshore
Service-other
Service-tug


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
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40
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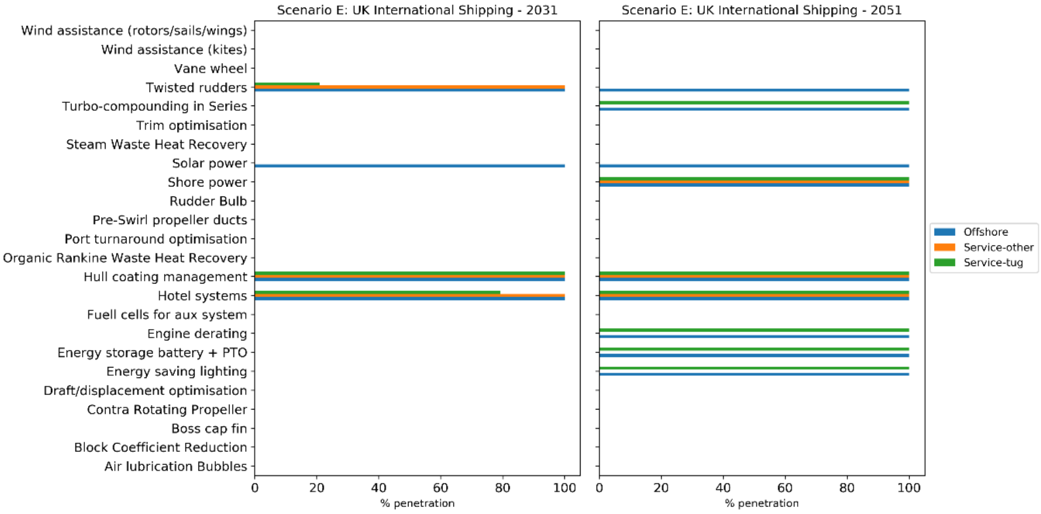
80
100
% penetration
Offshore
Service-other
Service-tug


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
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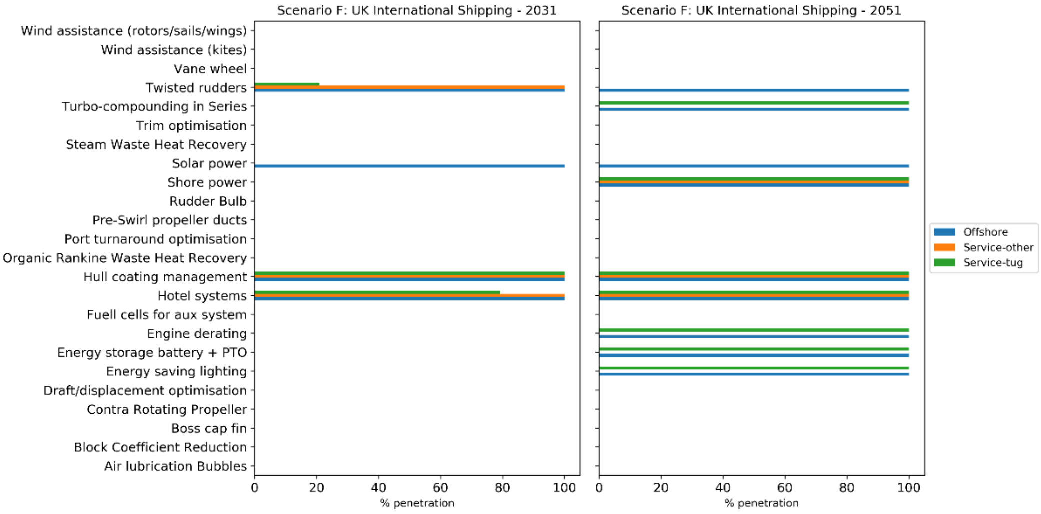
% penetration
Offshore
Service-other
Service-tug


Scenario F: UK International Shipping - 2031
Scenario F: 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
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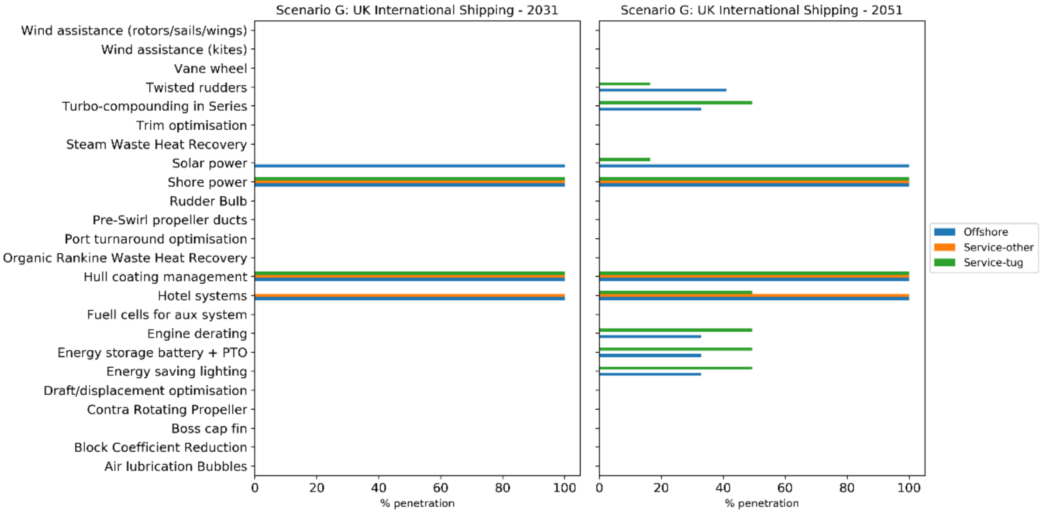
100
% penetration
Offshore
Service-other
Service-tug


Scenario G: UK International Shipping - 2031
Scenario G: 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
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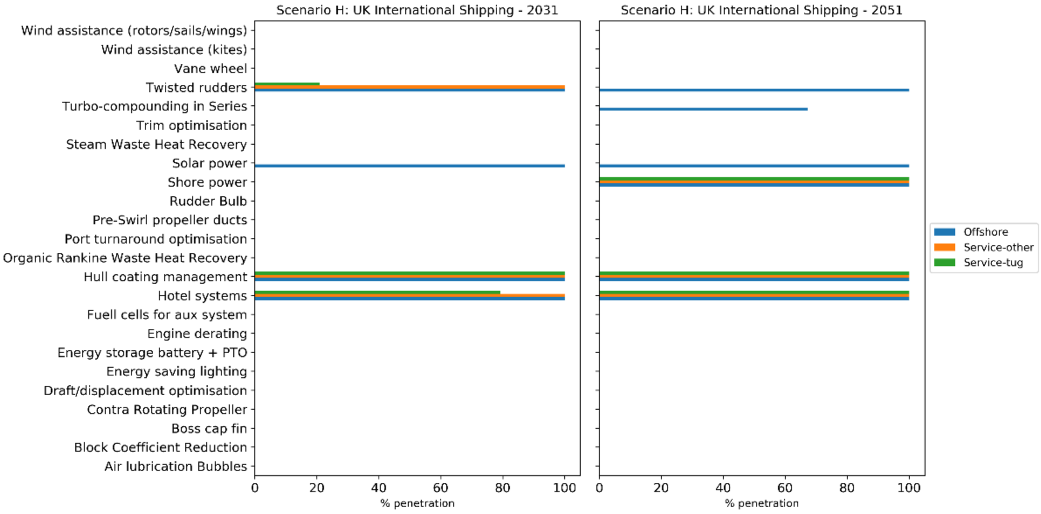
100
% penetration
Offshore
Service-other
Service-tug


Scenario H: UK International Shipping - 2031
Scenario H: 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
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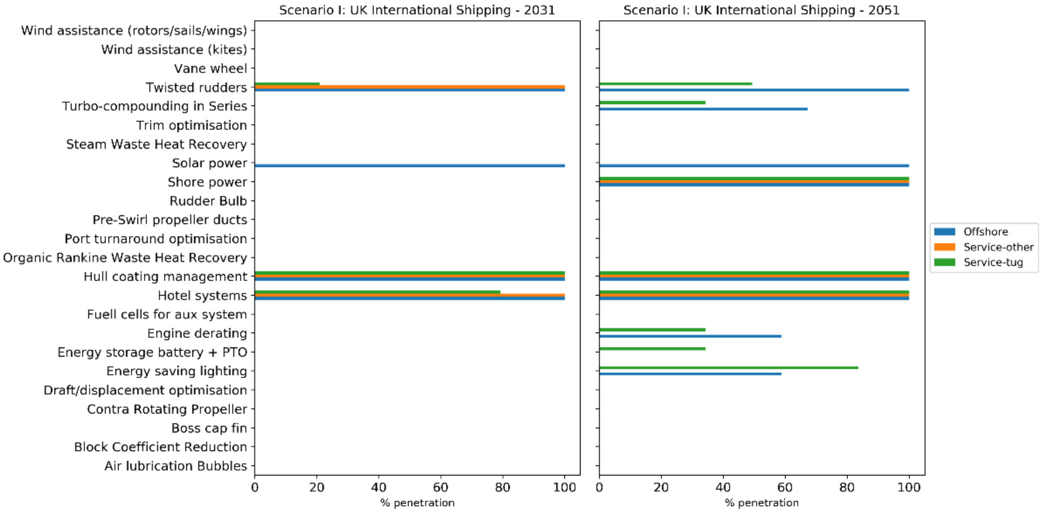
100
% penetration
Offshore
Service-other
Service-tug


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
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Engine derating
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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
Offshore
Service-other
Service-tug

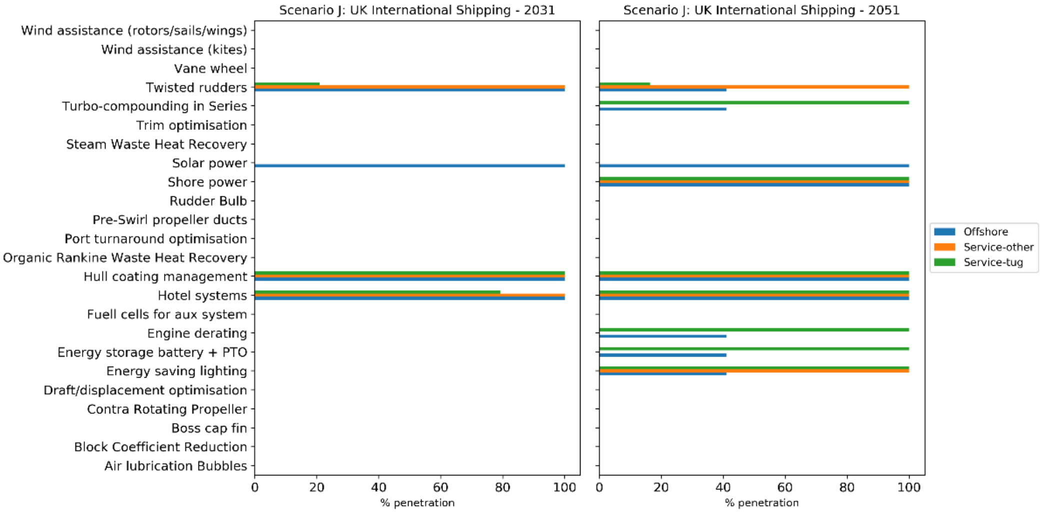
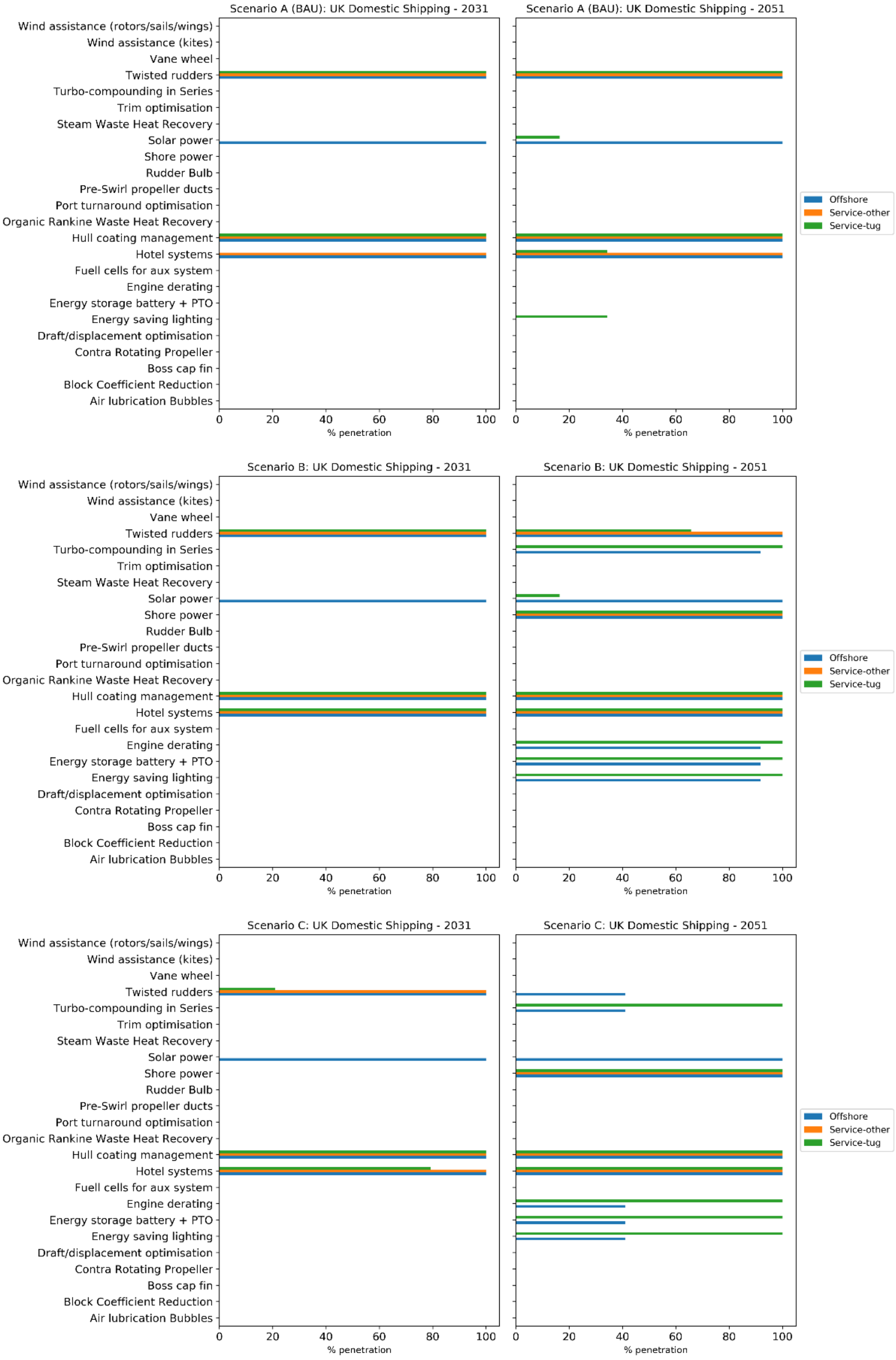
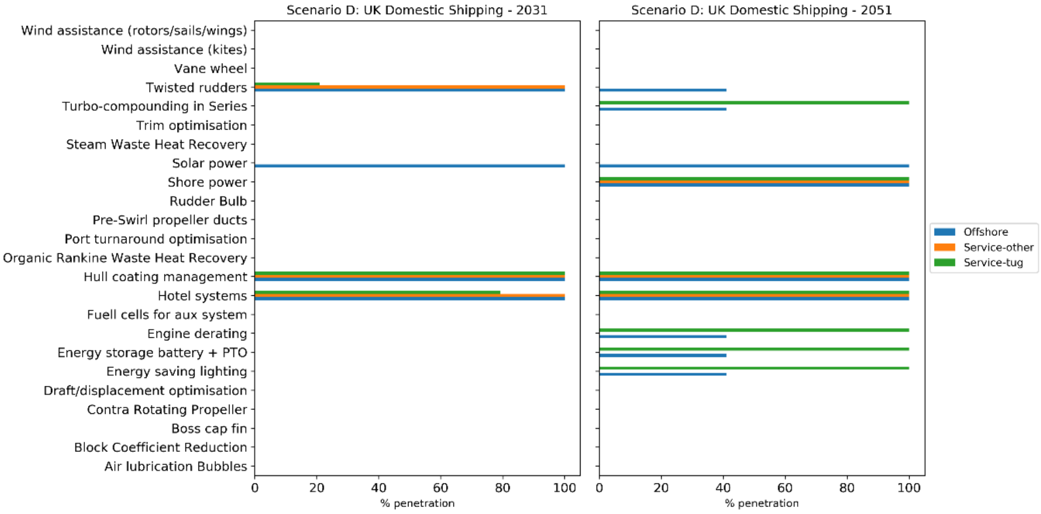
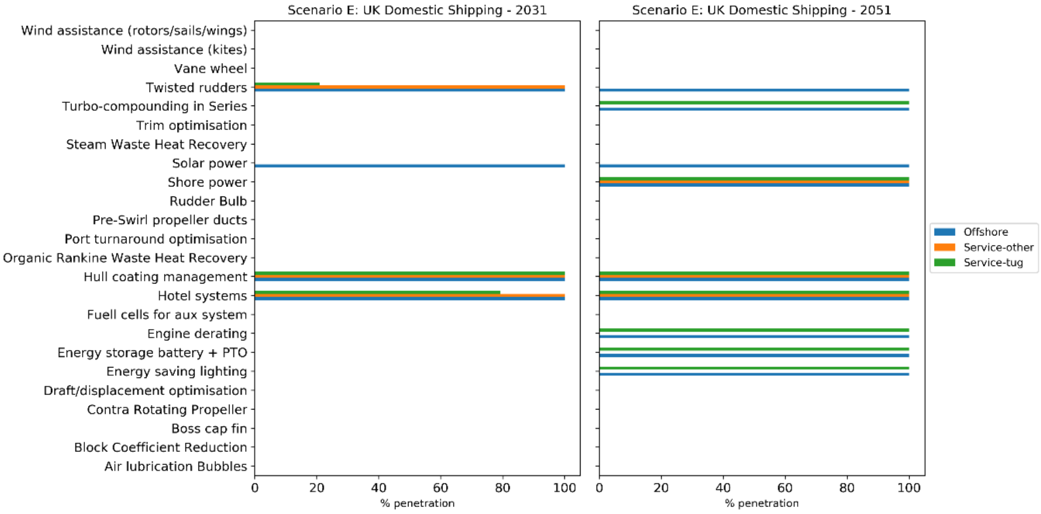
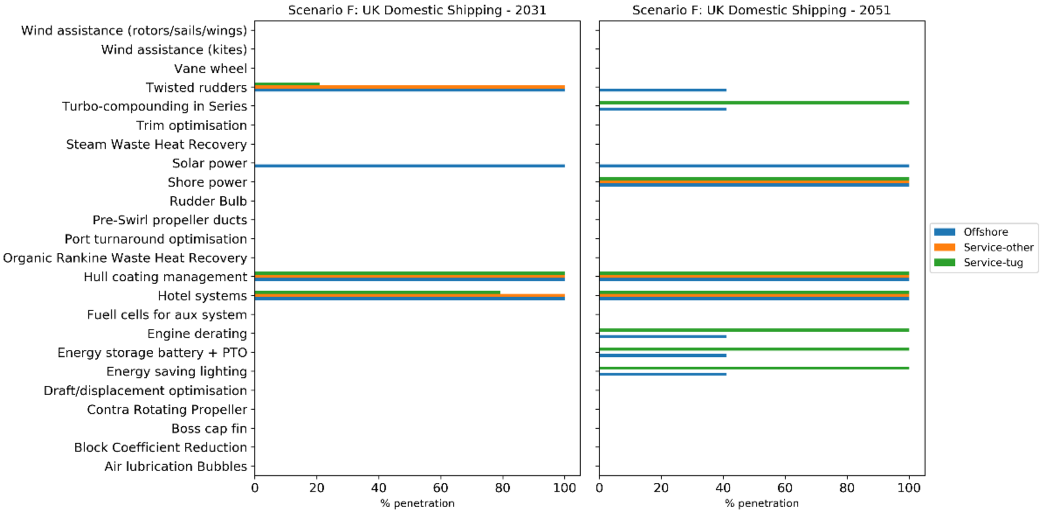

Scenario J: UK International Shipping - 2031
Scenario J: UK International Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller 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
Offshore
Service-other
Service-tug

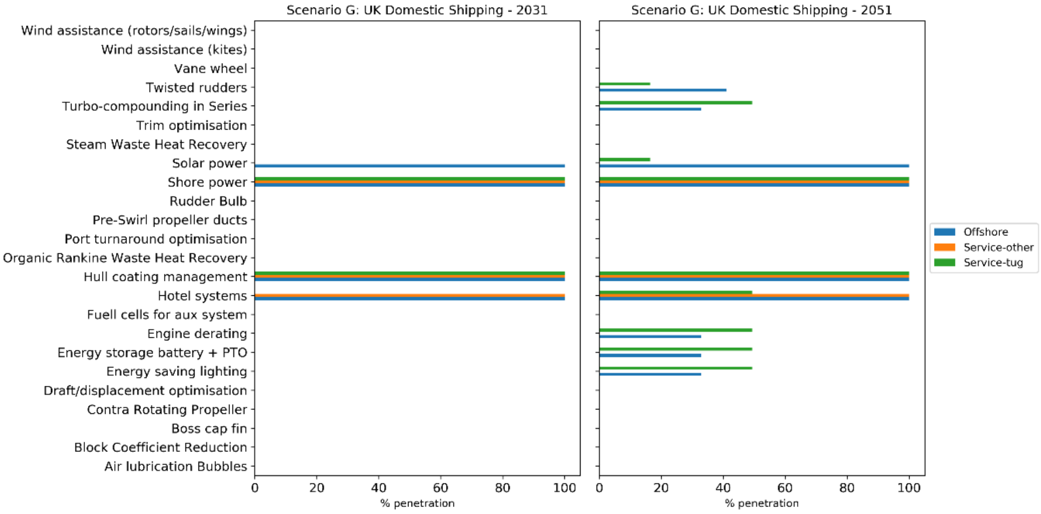
Figure 26: Take-up of measures that increase efficiency in scenarios for offshore, tugs and service vessels in UK domestic shipping

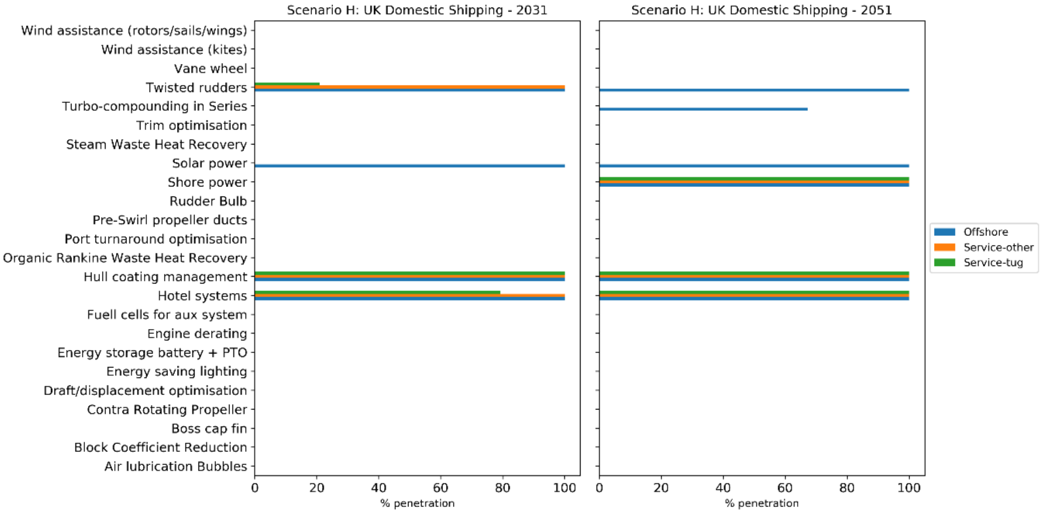


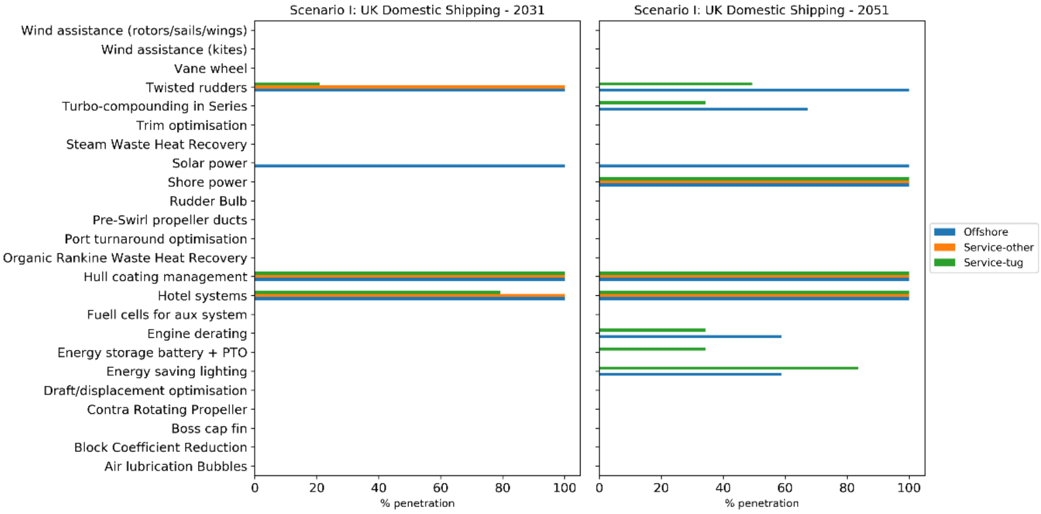

Scenario D: UK Domestic Shipping - 2031
Scenario D: UK Domestic Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller ducts
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
Offshore
Service-other
Service-tug


Scenario E: UK Domestic Shipping - 2031
Scenario E: UK Domestic 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
Offshore
Service-other
Service-tug


Scenario F: UK Domestic Shipping - 2031
Scenario F: UK Domestic 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
Offshore
Service-other
Service-tug


Scenario G: UK Domestic Shipping - 2031
Scenario G: UK Domestic 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
Offshore
Service-other
Service-tug


Scenario H: UK Domestic Shipping - 2031
Scenario H: UK Domestic 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
Offshore
Service-other
Service-tug


Scenario I: UK Domestic Shipping - 2031
Scenario I: UK Domestic 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
Offshore
Service-other
Service-tug

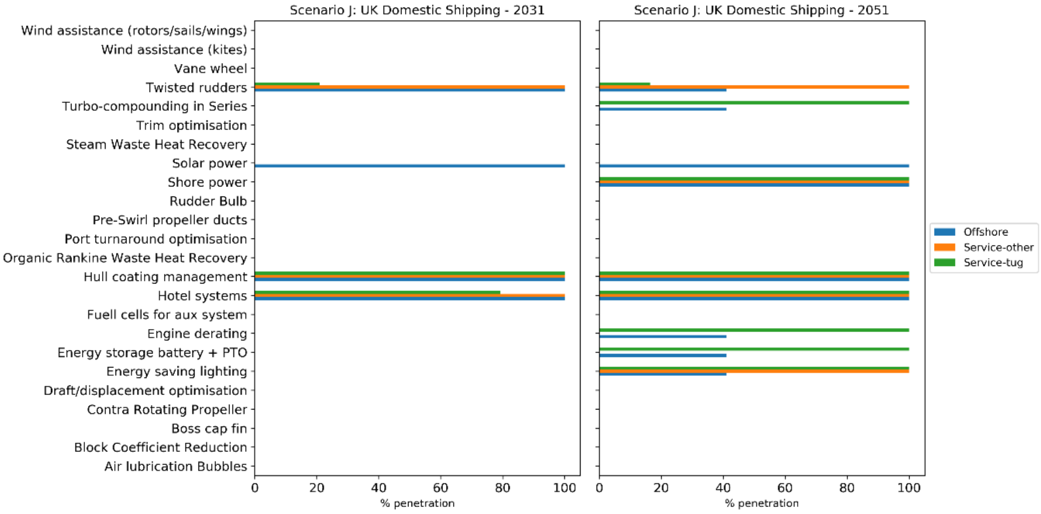
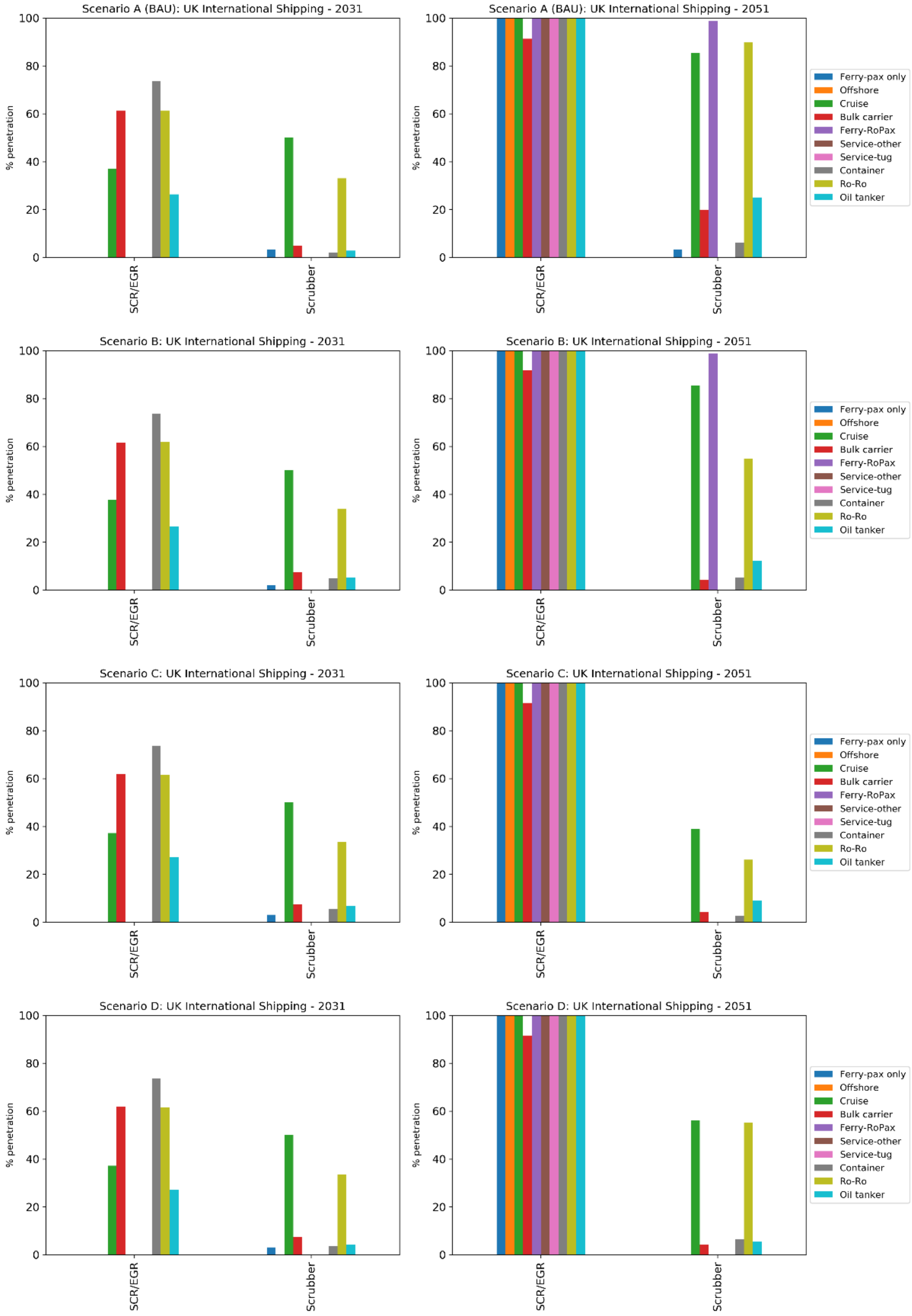

Scenario J: UK Domestic Shipping - 2031
Scenario J: UK Domestic Shipping - 2051
Wind assistance (rotors/sails/wings)
Wind assistance (kites)
Vane wheel
Twisted rudders
Turbo-compounding in Series
Trim optimisation
Steam Waste Heat Recovery
Solar power
Shore power
Rudder Bulb
Pre-Swirl propeller ducts
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
Offshore
Service-other
Service-tug

Figure 27: Take-up of air pollutant technology in scenarios in UK international shipping


Scenario A (BAU): UK International Shipping - 2031

Scenario A (BAU): UK International Shipping - 2051

Scenario B: UK International Shipping - 2031

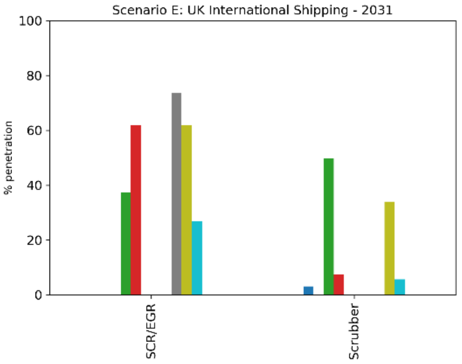
Scenario B: UK International Shipping - 2051

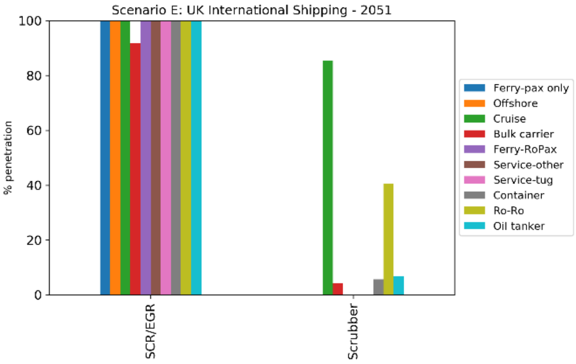
Scenario C: UK International Shipping - 2031

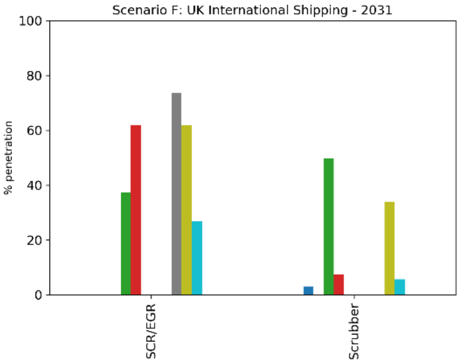
Scenario C: UK International Shipping - 2051

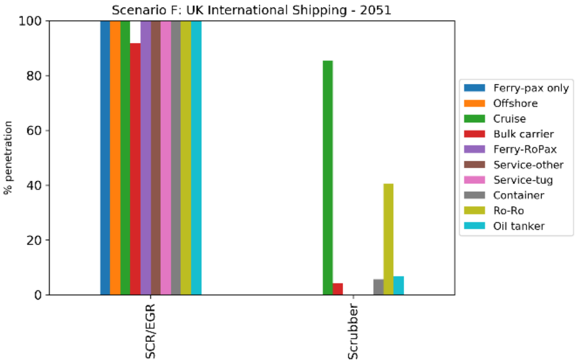
Scenario D: UK International Shipping - 2031

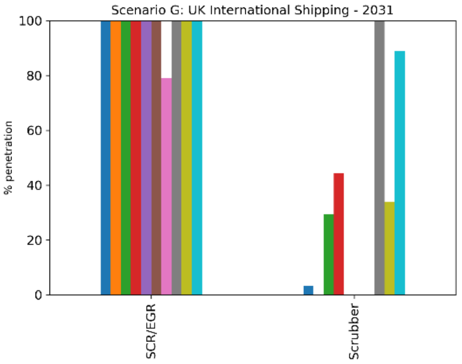
Scenario D: UK International Shipping - 2051

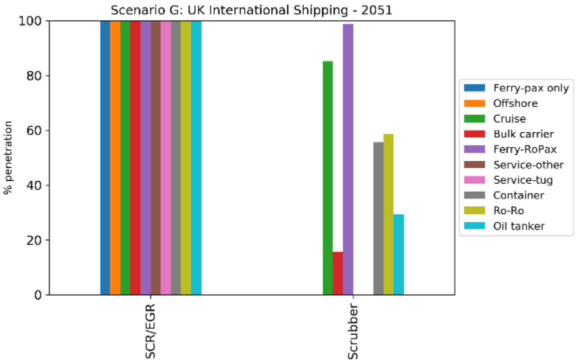

Scenario E: UK International Shipping - 2031

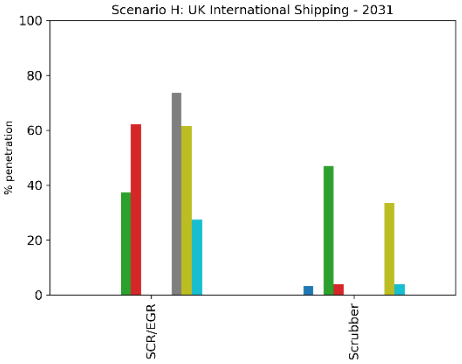

Scenario E: UK International Shipping - 2051

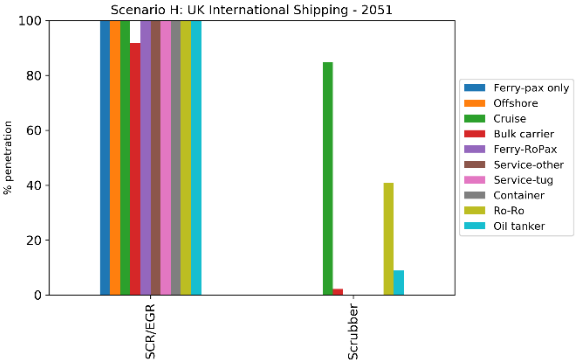

Scenario F: UK International Shipping - 2031


Scenario F: UK International Shipping - 2051


Scenario G: UK International Shipping - 2031


Scenario G: UK International Shipping - 2051


Scenario H: UK International Shipping - 2031


Scenario H: UK International Shipping - 2051

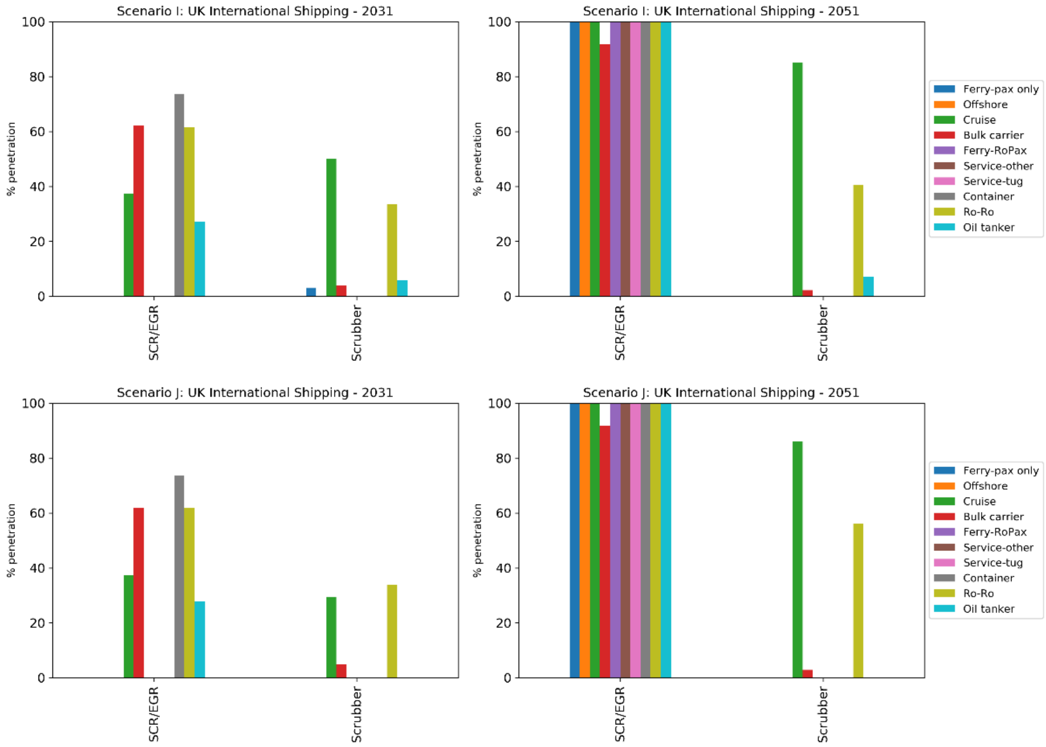
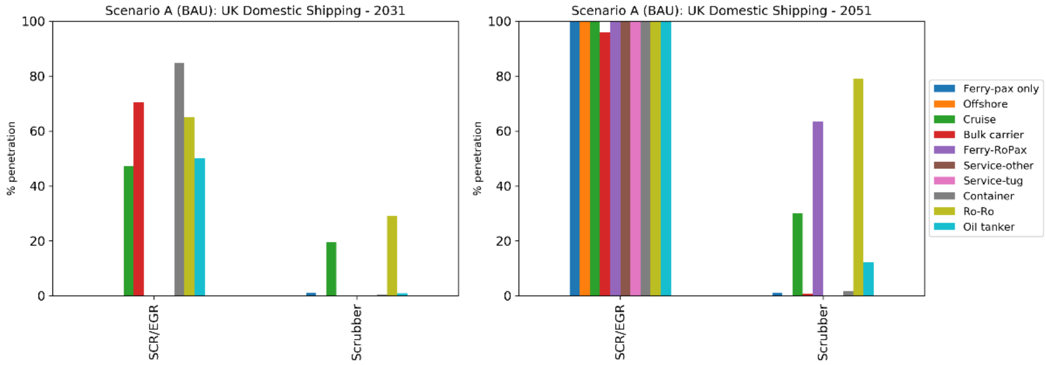
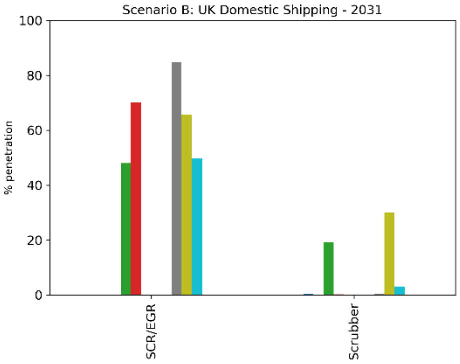
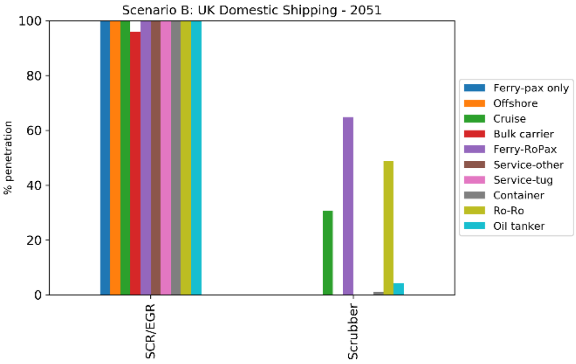
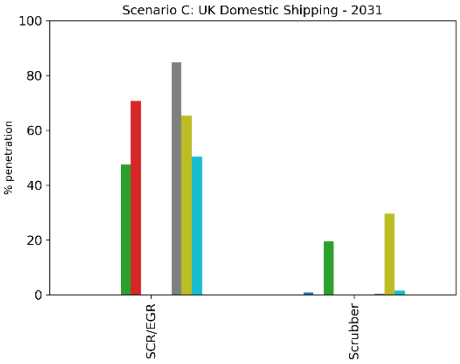


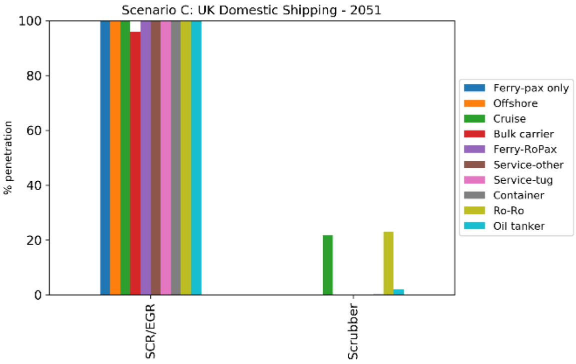
Figure 28: Take-up of air pollutant technology in scenarios in UK domestic shipping

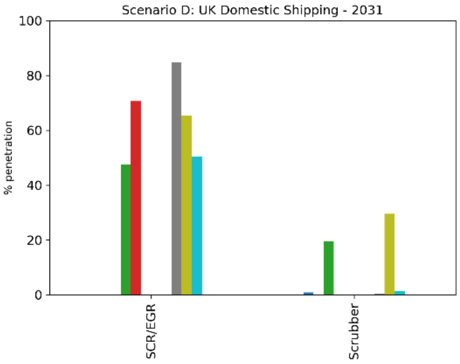


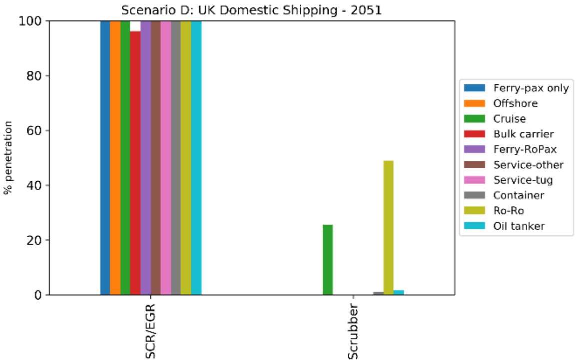

Scenario B: UK Domestic Shipping - 2031
% penetration
100
80
60
40
20
0
SCR/EGR
Scrubber

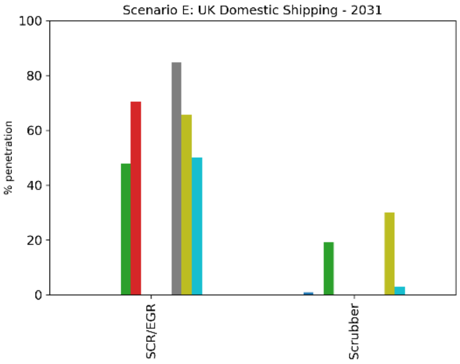

Scenario B: UK Domestic Shipping - 2051
% penetration
100
80
60
40
20
0
SCR/EGR
Scrubber
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker

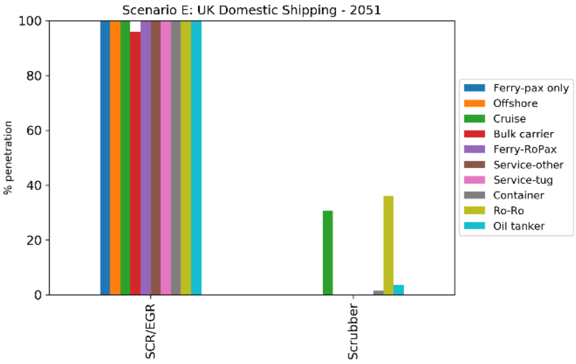

Scenario C: UK Domestic Shipping - 2031
% penetration
100
80
60
40
20
0
SCR/EGR
Scrubber

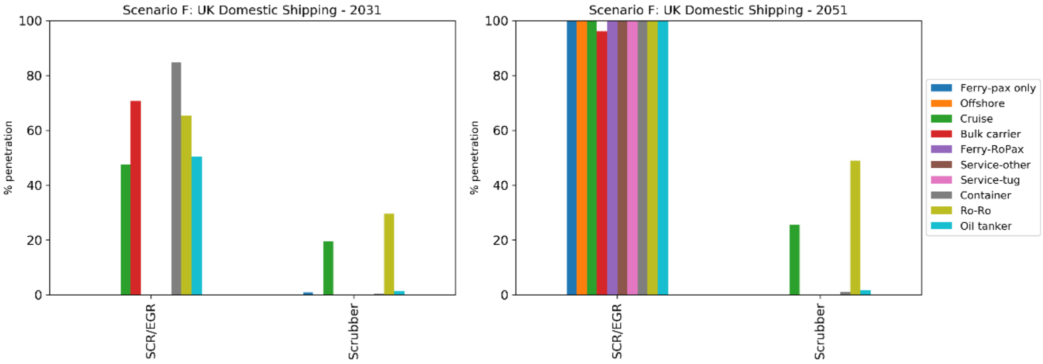

Scenario C: UK Domestic Shipping - 2051
% penetration
100
80
60
40
20
0
SCR/EGR
Scrubber
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker

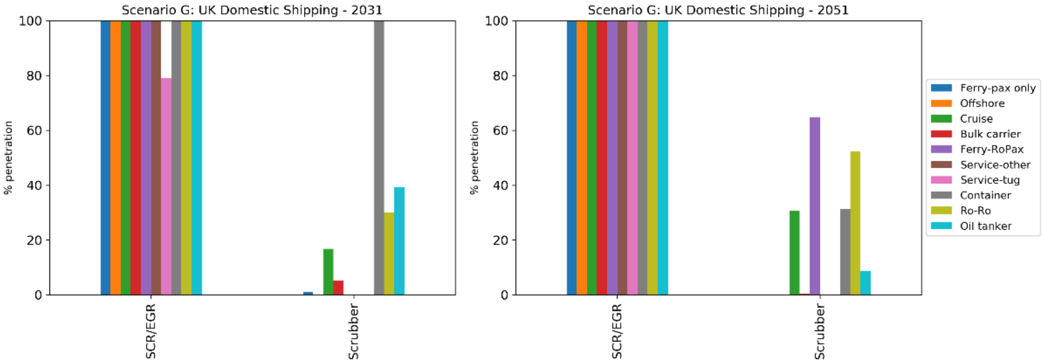

Scenario D: UK Domestic Shipping - 2031
% penetration
100
80
60
40
20
0
SCR/EGR
Scrubber

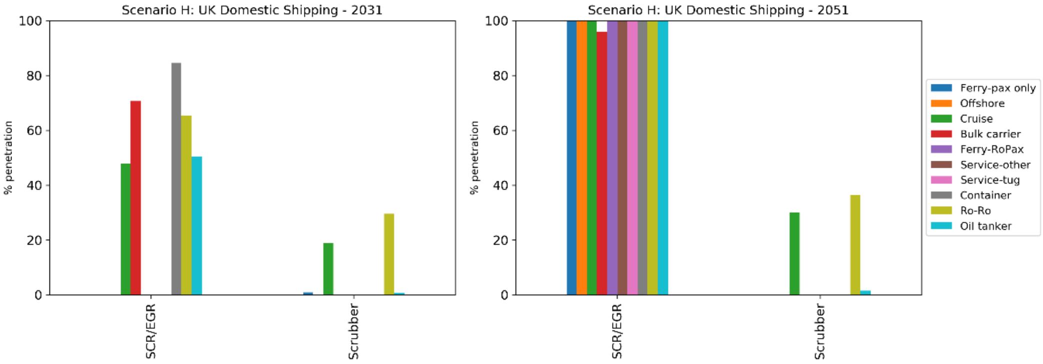

Scenario D: UK Domestic Shipping - 2051
% penetration
100
80
60
40
20
0
SCR/EGR
Scrubber
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker

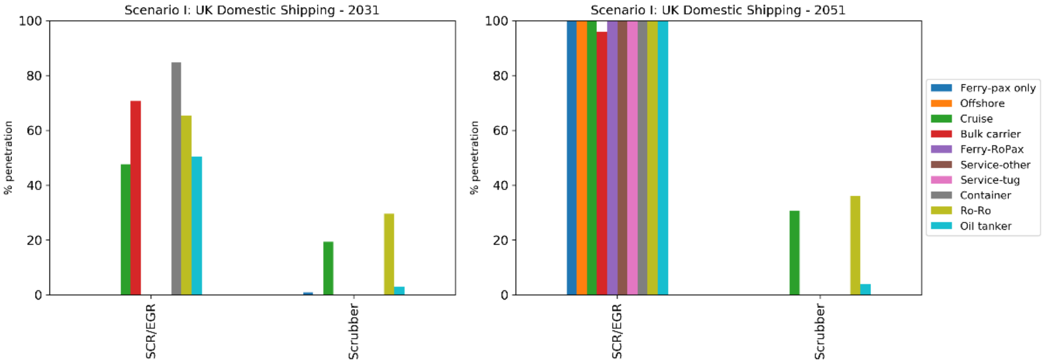

Scenario E: UK Domestic Shipping - 2031
% penetration
100
80
60
40
20
0
SCR/EGR
Scrubber

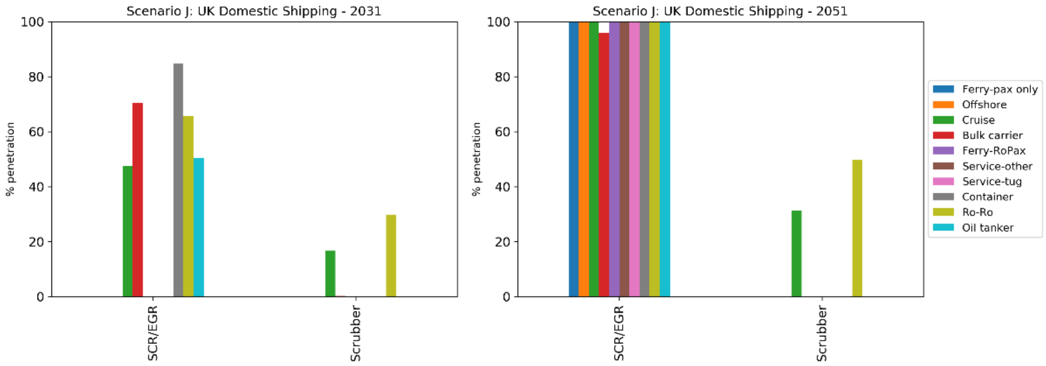

Scenario E: UK Domestic Shipping - 2051
% penetration
100
80
60
40
20
0
SCR/EGR
Scrubber
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker


Scenario F: UK Domestic Shipping - 2031
Scenario F: UK Domestic Shipping - 2051
% penetration
0
20
40
60
80
100
SCR/EGR
Scrubber
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker


Scenario G: UK Domestic Shipping - 2031
Scenario G: UK Domestic Shipping - 2051
% penetration
0
20
40
60
80
100
SCR/EGR
Scrubber
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker


Scenario H: UK Domestic Shipping - 2031
Scenario H: UK Domestic Shipping - 2051
% penetration
0
20
40
60
80
100
SCR/EGR
Scrubber
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker


Scenario I: UK Domestic Shipping - 2031
Scenario I: UK Domestic Shipping - 2051
% penetration
0
20
40
60
80
100
SCR/EGR
Scrubber
Ferry-pax only
Offshore
Cruise
Bulk carrier
Ferry-RoPax
Service-other
Service-tug
Container
Ro-Ro
Oil tanker



The worksheet “Fuel cells uptake in aux.xls” contains the uptake of fuel cells technology as auxiliary engine in terms of market penetration and equivalent market size. It should be noted that there is no observation of uptake of fuel cells technology as main engine in any explored scenarios.

7 QUALITY ASSURANCE

7.1 Aim of this section

This section provides detail on the quality assurance processes that have been implemented for this study. This covers both the data and modelling work. Outputs from the analysis in some tasks are inputs to other tasks so a holistic approach is taken to check for errors at multiple points.

The quality assurance that has been carried out is considered proportionate and appropriate in the time available for this study. Every feasible effort has been taken to review and quality assure the inputs and results and to minimise the risk of errors. Proportionality principles have required quality assurance to be undertaken pragmatically and systematically, with greater priority and attention placed on those aspects of the modelling that have the greatest consequence for the results and findings.

The following sections describe the steps taken for quality assurance across the consortium’s work. In particular, two different type of action taken to mitigate errors are discussed:

- Action taken to mitigate errors in model inputs and parameters; and
- Action taken to mitigate errors in model method/calculation and errors in the use of the model.

7.2 Mitigating errors in model inputs and parameters

There were three core inputs to the modelling which required careful processing and quality assurance to mitigate errors in the model. They include:

- Costs and impacts of the abatement options
- Specification of the UK fleet (domestic and international)
- Data and assumptions on fuel prices and emissions factors (of different fuels)

For these inputs specific actions have been undertaken and reported in the following subsections. For all the other input assumptions, a review by a consortium member not involved their initial generation was conducted as well as an internal review by different team members within the same organisation.

7.2.1 Costs and impacts of abatement option process and quality assurance

Data on the costs and impacts of different abatement options have been generated through a number of steps:

- data on the costs and impacts were collected for each emissions abatement option with associated descriptions of sources and references used (please see section 3 for more details).
- This data was then reviewed by a consortium member not involved in its initial generation.

- The data was then formatted into GloTraM input assumptions (see each tab in the spreadsheet attached above) and reviewed internally by different team members for quality assurance.
- Development of a GloTraM module that estimates the impacts of an option on a ship's performance. Impacts are defined across three MCR values: 0.4; 0.6, and 0.8. A nearest neighbour model allocates these impacts for each type/size/age category based on the MCR of the vessel category.

Data collection was generated both in the CE Delft team and the UMAS team. Both teams have experience with this data from several years of relevant projects and draw upon this when sourcing and validating the data. Many data cross reference multiple sources to derive credible assumptions and parameters and so naturally have a degree of intrinsic QA built into their production. Validation with manufacturers has been undertaken where feasible.

Basic QA of the data collected involved each data being checked by at least one other member of the team producing the input. Key inputs (those with significant new additions to pre-existing material) were reviewed by an independent member of the team (from a different organisation).

Reviews were conducted against engineering first principles expectations of impacts (based on the nature of the option), and against literature and trials data (where available).

The conversion of data into GloTraM outputs on ship performance was checked by simplified calculations with simplified assumptions (of a ship's costs and performance) taken from Third IMO GHG Study[47] data. GloTraM BAU scenarios also provide information on take-up rates of different technologies which have been tested for consistency with published literature – this includes previous GloTraM-derived publications, and third-party publications.

Quality review of GloTraM outputs on BAU take-up was also carried out by the CE Delft team, who used that data for the MACC modelling.

7.2.2 Specification of the UK fleet

The definition of the UK fleet includes an identification of the numbers and types of different ships that service UK, the total activity (transport supply) they perform, and the operational/activity parameters describing these ships.

The specification is derived from a top-down calculation within GloTraM which fits a UK trade scenario to fleet operational parameters to estimate the number of ships of different types and sizes and their activity.

This has been compared against bottom-up calculations, both those published in literature and analysis of the activity of vessels operating in UK territorial waters identified in AIS data.

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[47] Source: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf

Fleet operational parameters (speeds, time at sea, utilisation) were checked for the domestic fleet with the data taken from Ricardo (2017)[48] and they were found within reasonable margins.

The UK transport demand was cross-checked to DfT's UK Port Freight Traffic Forecasts 2019[49] as described in section 6.4.8 and shown in Figure 16. The growth of transport supply (e.g. scenarios showing the increase in tonnage and numbers of ships) as calculated from GloTraM was found to be in good alignment with those port freight traffic forecasts data.

Quality assurance of the estimated disaggregated UK domestic fleet was established by comparing this study's estimation (obtained using AIS data) against the equivalent data from Ricardo (2017). This comparison by type and size is shown in Table 10 and was found to be generally within reasonable margins in total. Some discrepancies occur between individual ship types and sizes which can be attributed to discrepancies in the ship type allocation and source data, but which are not material to the overall estimate of domestic emissions used in this study (see Section 7.3), or the estimate of the costs and benefits of domestic GHG or air pollution reduction.

There is general agreement in the absolute and relative magnitudes of the different size and type categories. There are two particularly significant discrepancies: bulk carrier size 1 and fishing vessels (not shown as they are out of scope for detailed modelling). This is due to a significant number of vessels having no entry in the vessel technical specification database and no AIS reported features (e.g. Length or beam) to indicate vessel type. To allocate these vessels, a nearest neighbour classification model was developed, trained and tested on correctly allocated vessels (accuracy score of 63%), to allocate the unallocated vessels. The classification model allocated vessels on the basis of speed at sea, the standard deviation of speed at sea and the number of voyages that the vessel undertook in a year. Additional discrepancies can be explained by changes in year of interest (Ricardo is based on 2014 and this study is based on 2016), variations in definition of vessel type (e.g. Ferry-ropax was not used in Ricardo (2017) and therefore it is possible that some vessels allocated to Ferry-pax only in Ricardo (2017) may be Ferry-ropax in this study), and also the coverage area for Ricardo (2017) (which can be seen in the report and was the full extent of MCA's terrestrial AIS data's geographical coverage and which extends further into the North Sea in particular than the UK territorial waters from which this study's vessels were determined for the purposes of this quality check).

Table 10: Comparison of vessels counts identified in UK waters for this study and those from Ricardo (2017).

Type	Size Category	This study (AIS data)	Ricardo (2017)
Bulk carrier	1	721	3130
Bulk carrier	2	617	995

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[48] Scarbrough, T. et al. A review of the NAEI shipping emissions methodology. (2017).

[49] https://www.gov.uk/government/statistics/port-freight-statistics-april-to-june-2018

Bulk carrier	3	821	954
Bulk carrier	4	896	796
Bulk carrier	5	321	390
Bulk carrier	6	33	46
Container	1	240	334
Container	2	95	125
Container	3	118	95
Container	4	198	200
Container	5	128	128
Container	6	146	181
Container	7	138	130
Container	8	67	27
Oil tanker	1	33	88
Oil tanker	2	15	33
Oil tanker	3	14	22
Oil tanker	4	210	705
Oil tanker	5	198	196
Oil tanker	6	375	302
Oil tanker	7	202	212
Oil tanker	8	118	84
Ferry-pax only	1	191	832
Ferry-pax only	2	7	17
Cruise	1	16	39
Cruise	2	18	65
Cruise	3	46	13
Cruise	4	24	0
Cruise	5	18	0
Ferry-RoPax	1	41	0
Ferry-RoPax	2	106	0
Ro-Ro	1	99	80
Ro-Ro	2	408	595
Service - tug	1	429	829
Offshore	1	634	1812
Service - other	1	597	458

7.2.3 Fuel prices and emissions factors

Fuel prices and emissions factors have been sourced from existing literature and a series of assumptions as described in sections 6.4.2 and 6.4.10. The work has been undertaken both within the E4 Tech team and UMAS teams of the consortium and as such underwent continuous review and scrutiny by multiple personnel.

Key assumptions that were quality assured include:

- Data on the production costs of different fuels and associated emissions factors

- Data on the downstream processes (distribution, storage, dispensation) and associated costs and emissions

Multiple sources exist for both of these, both for the specific fuel options considered and for proxies to these fuel options. Both the published literature and proxies were used to draw comparison and form a set of consensus data used in the scenarios.

7.3 Mitigating errors in model method/calculation and errors in use of the model

The GloTraM model and MACC model includes a series of calculation steps that embody engineering, economic and environmental theoretical relationships. Errors that could occur here could be because of incorrect selection of theoretical relationships or incorrect implementation of theoretical relationships.

Both models, however, have been used extensively in previous projects, with their associated QA steps. Both models have been previously published and exposed to scrutiny at detailed levels by stakeholders and expert panels. In combination this provides the first QA/QC step on model method/use.

In this study further independent review was undertaken. There are two teams in the consortium with overlapping experience in modelling, who have each developed both scenario and MACC analysis tools. They were allocated in this project as follows:

- CE Delft (MACC lead, scenario model QA/QC)
- UMAS (scenario model lead, MACC QA/QC)

This QA step was to expose the detailed modelling outputs produced by one party to the other for critical review. This involves both checking outputs align with previous work undertaken (or if they differ that the explanation is justified), and that where appropriate results are compared and validated with third party literature.

In addition to the QA of previous projects, and the critical review by members from across the consortium of other partner's work, a number of aggregated outputs from the modelling work were directly compared against relevant published results and critically analysed.

7.3.1 Baseline year UK Domestic Shipping GHG and air pollution emissions comparison

Table 11 shows the comparison of UK domestic shipping emissions from a previous study for different base years. This study estimates similar magnitudes for GHG emissions species for domestic shipping, but there are significant differences for air pollutants relative to the estimates in Ricardo (2017).

The main reason that can account for the NO_x discrepancy is the use of slightly different emissions factors (EFs). Difference in EFs for NO_x emissions appear when comparing the two studies. For NO_x emissions the values used in this study are ~40% higher than Ricardo (2017) (for both MDO and HFO). This discrepancy seems likely to be due to Ricardo allocating the majority of domestic voyages to high / medium speed diesel engines whereas this study allocates them to slow speed diesel engines. For this study, GloTraM models an average vessel within each size, type and generation category at global level, rather than model the actual vessel that performed the voyage, as Ricardo (2017) would have done. This similarly affects SO_2 and $PM_{2.5}$ emissions calculations.

Table 11: Comparison of emissions (operational and at port) for UK domestic shipping from this study with those from Ricardo (2017) in thousand tonnes

	GloTraM 2016 (detailed modelled vessels)	This study base year 2016 (including non-modelled vessels)	This study base year 2016 without fishing	Ricardo (2017) base year 2014
CO_2	5226	7228	5730	4309
CH_4	0.1007	0.14	0.11	0.05
N_2O	0.26	0.36	0.29	0.2
SO_2	21.6	29.94	23.74	16
NO_X	151.6	210	166	80
$PM_{2.5}$	3.45	4.78	3.79	2.01**

** Estimated from reported PM10 value using the conversion factor from DEFRA (2019)[50]

7.3.2 Baseline year UK International Shipping GHG emissions comparison

Table 12 shows the comparison of the estimates of UK international shipping CO_2 emissions from CCC (2011) in 2006 and this study in 2016. CCC estimates a greater quantity of UK international shipping emissions as their central value (12 Mt), but this study’s estimate of total UK international CO_2 emissions is both similar in magnitude to CCC (2011) and the same as the lower bound estimate (10Mt). We compare our estimate with this study rather than the Ricardo (2017) approach as it is unclear from that study how the significantly larger estimate of 56.2Mt of CO_2 was estimated[51]. CCC (2011) estimate CO_2 emissions to be 10Mt CO_2 based on ships arriving at UK, which is then increased to 12Mt to account for transhipment. The key indicator should therefore be the activity at port. Comparing the port calls as shown in Table 13, it can be seen that there was a significant increase in containerised cargo traffic and a significant decrease in non-containerised cargo traffic between 2006 and 2016. A uniform increase in demand across all types would have indicated an inconsistency between these studies estimate and CCC (2011). However, it is feasible that the decrease in demand for non-containerised is not fully offset by the increase in demand for containerised, and therefore a decrease in international emissions, as shown in the emissions comparison, for UK international shipping is possible and therefore this study is considered consistent with those figures from CCC (2011) and this provides a

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[50] DEFRA, 2019. Air quality damage cost guidance. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770576/air-quality-damage-cost-guidance.pdf

[51] Both studies however do recognise that high uncertainty affects estimates of domestic and international emissions, and indeed CCC (2011) recognises that emissions for UK international shipping could be between 11 and 41 $MtCO_2$ for 2006 using a top down methodology, and therefore the estimate provided by Ricardo (2017) should not be discounted.

further level of quality assurance on this study. Air pollution emissions were not calculated in CCC 2011 and so no comparison is drawn here.

Table 12: Comparison of UK international shipping CO_2 operational and at port emissions estimated in this study compared to CCC (2011). The CCC study also indicates upper and lower bounds of estimates.

	CCC (2011) 2006	GloTraM 2016 (detailed modelled vessels)	Other vessels	This study base year 2016 (including non-modelled vessels)
CO_2	12.0 (10 to 16)	9.33	4.19	13.52

Table 13: Port Freight Statistics data for 2006 and 2016 in thousand tonnes of freight traffic at UK ports.

	2006	2016	% Change
Lo-Lo	54,359	65,331	20%
Ro-Ro	98,697	99,731	1%
Crude Oil	142,200	87,090	-39%
Coal	57,282	12,011	-79%
Ores	18,301	15,714	-14%

Source: DfT (2017), "Port and domestic waterborne freight statistics: data tables (PORT)". Available here - https://www.gov.uk/government/statistical-data-sets/port-and-domestic-waterborne-freight-statistics-port

7.3.3 UK shipping emissions future scenarios

Quality assurance was also performed on this study's scenarios of future UK shipping emissions. Much of the difference between this study and other studies can be attributed to differences in scenario assumptions (not least in scenarios where we are estimating the costs and benefits of significant GHG emission reduction). Figure 29 shows the comparison between the results of scenario-based emissions projections (Frozen technology, High emission scenario, Central emissions scenario and Low emissions scenario) generated by CCC (2011)[52] and the results of this study. The comparison shows that relative to CCC's earlier work this study forecasts an increase in emissions (UK domestic and international) out to 2050 in BAU of a magnitude greater than even the CCC (2011) High Emissions scenario. The main explanation for this is that transport demand is different (and lower) for the CCC study than that used in this study. In particular, this is the case for containerised transport where demand increases by about 80% for CCC compared with an increase of approximately 120% in this study. The discrepancy

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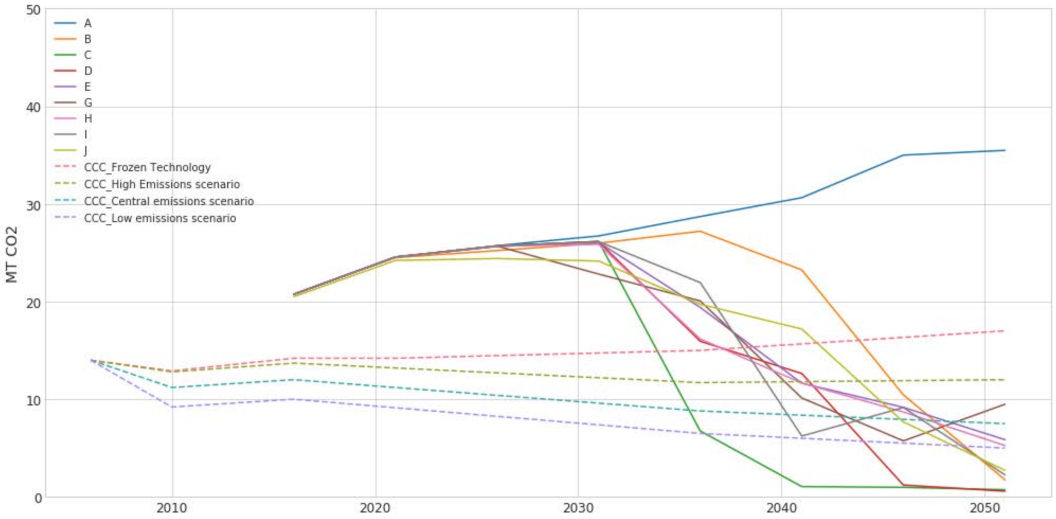
[52] Committee on Climate Change. *Review of UK Shipping Emissions*. (2011).

is explained by this study's alignment to the DfT's new UK port freight traffic forecasts and so is not a reason for concern about this study's quality.

Other differences occur in the extent to which this study estimates overall reductions in emissions, which is explained by the fact that even in the CCC low emissions scenario, there was no consideration of zero emission abatement options such as synthetic fuels (which are included in this study's scenarios).

Figure 29: Comparison of UK shipping CO_2 operational and at port emissions (domestic and international) estimates with CCC (2011) emissions projections



For a comparison and quality investigation of the global emissions estimates which are the basis of this study's UK international shipping emissions estimates, Figure 30 draws a comparison between five scenarios in this study (A, B, C D, E) and the Third IMO GHG Study results for two scenarios (a BAU scenario and scenario 4 which explores potential for reduced emissions).

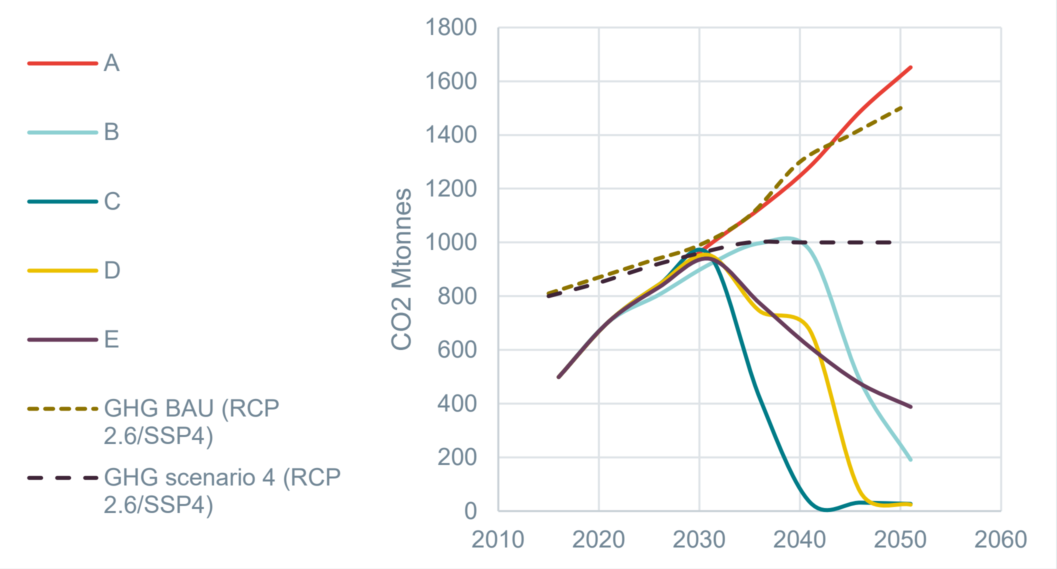
The discrepancy in the baseline year (2016 in this case) is explained by the fact that comparison is only drawn between this study's detailed modelled fleet (which only account for a subset of international shipping emissions), and the Third IMO GHG study estimate which is representative of all ship types and sizes involved in international shipping.

Scenario A and the equivalent BAU scenario in the Third IMO GHG Study see similar increasing trajectories of emissions from 2030 but differ in that the year on year emissions rise less fast in the Third IMO GHG study.

The difference can be explained by the fact that the relatively lower GHG emissions of the Third GHG BAU scenario is due to assumptions related to the productivity of the fleet (the base year of the Third IMO GHG Study in 2012 had a historically low productivity and average fleet speed), whereas this study allows the fleet's average speed and associated productivity to increase as market conditions return to long-run conditions. The higher average speeds in this study's BAU scenario result in a reversal of a short-term trend in efficiency improvement (occurring between 2007 and 2012), and therefore given a similar underlying demand driver the emissions are relatively larger. A further explanation is also characterised by assumed changes in the vessel size mix within each type category. In particular in the Third IMO GHG Study there is an assumed shift towards larger container vessels which results in energy efficiency improvements which are not incorporated in this study's model.

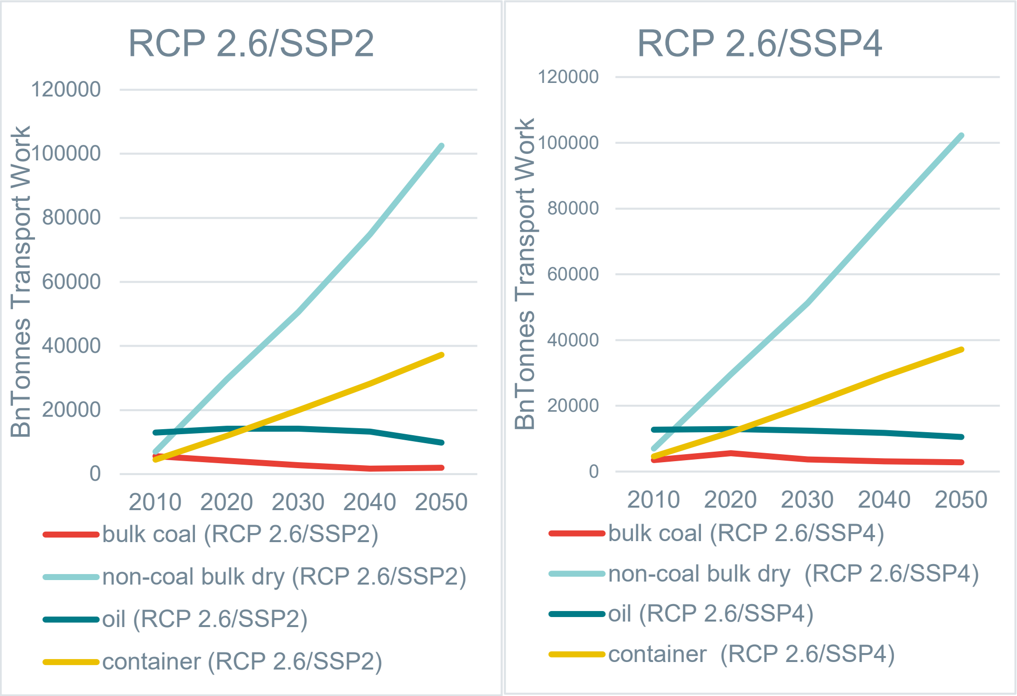
Some quality assurance can also be obtained by comparing this study's decarbonisation scenarios with Scenario 4 from the Third IMO GHG study. Scenario 4 is characterised by a high penetration of LNG into the fleet (10% in 2020 rising to 25% in 2050), but does not include the alternative fuel options used within this study. In addition, scenario 4 does not include the stringent regulatory scenarios that are investigated within this study. Both of these factors, for the most part, explain the significant divergence between scenarios B to E and scenario 4.

Figure 30: Comparison of global CO_2 operational and at port emissions scenarios A to E (modelled fleet only) to Third IMO GHG scenario projections.



The Third IMO GHG Study does not provide projections for RCP2.6 SSP2, therefore RCP 2.6 SSP4 is provided. Figure 31 shows the comparison of transport work scenarios, which are almost identical and therefore cannot be considered an explanatory factor for the difference in CO_2 trajectories between the BAU scenario of Third GHG Study and scenario A of this study.

Figure 31: Comparison of transport work for RCP 2.6/SSP2 and RCP 2.6/SSP4 scenarios



The modelling outputs generated in relation to the specific examples of UK GHG and global/international GHG emission scenarios shows a good level of alignment. Where discrepancies have been identified these can be attributed to differences in assumptions used in the BAU scenarios, specifically in relation to speed and ship size trends.

7.4 Quality Assurance Statement

7.4.1 Reasonableness of the analysis/scope for challenge

Producing this analysis has required the development and deployment of a number of new input assumptions and modelling capabilities in order to align and upgrade pre-existing modelling capability (for producing both MACCs and scenarios). In particular these modifications have required ensuring that models’ inputs and outputs were aligned to UK Government sources.

The nature of modelling a fleet with significant heterogeneity in technical specification and operational specification mean that in the time available for this study, priority has been given to the analysis of the subsectors of UK shipping which make the greatest contribution to overall emissions (GHG and air pollution). More time would have permitted more in-depth analysis of subsectors of the domestic and international fleets to have been undertaken. However, there is no evidence to suggest that this would have produced significant differences in the main findings of the results or conclusions. The key finding that there are limited opportunities for further energy efficiency, and that the fleets will have to switch from fossil fuel to a mix of battery/shore power electrification and synthetic fuel use (or potentially some bioenergy use) is expected to be common even to the minority of the ship types that were not modelled in detail. So, whilst different conclusions might be reached for the specific decarbonisation and air pollution pathways for individual ship types, the specific costs and emissions for this minority of the overall UK fleet would not materially change the estimated aggregate results.

The analysis produced estimates of emissions (impacts and benefits) and costs in a bottom-up model with inputs and assumptions assembled from a variety of sources, many of which are state of the art reports, given that the subject of the study is a rapidly evolving area of ongoing research and industry practice. The study incorporates UK Government evidence on key assumptions wherever possible, in line with UK Government guidelines, and supplements this with third party data which has been compiled and cross-checked from multiple sources. Many assumptions (e.g. the costs of individual technologies or future prices of fuels) are liable to change as technology and related information matures. But the data that is used is representative of state of the art at the point of publication and therefore reasonable within the scope of the study's objectives.

7.4.2 Risk of Error / Robustness of the Analysis

The study that has been undertaken has required the use of a complicated set of models, in order to work at disaggregated levels of detail (e.g. assess individual ship type and size responses), and capture the dynamics of investment and operation behaviour that occur across technology selection, operation selection (speed) and fuel choice.

However, the approach taken is not highly innovative and incorporates techno-economic modelling techniques used across the energy and transport modelling domains. The models used both to estimate scenarios of emissions and Marginal Abatement Cost Curves have been developed over ten years and are well used and tested in a variety of studies.

The team undertaking the research comprise a number of individuals with PhD level qualifications in subjects related to shipping emissions modelling, and has professional experience across a number of studies used at the highest levels internationally. This is therefore a highly qualified team capable of minimising the risks of error and maximising the robustness of the analysis.

The production of a series of aggregate outputs that represent all of the detail within the modelling, by more than one consortium member organisation, has ensured that in combination with the experience of this work, and in spite of the complexity of the modelling, the overall risk of error is low and the robustness is high.

7.4.3 Uncertainty

Prior to this study there were very few studies estimating the cost and specific benefits of reducing GHG and air pollution emissions of UK domestic and international shipping. Other studies have been carried out on other countries or on the global fleet, however, they lack the specificity of the UK fleets, and would be unlikely to be aligned with UK-specific input assumptions (for example on fuel prices, carbon prices, damage costs (for air pollutants)).

This study has rigorously derived the UK fleet's specific characteristics and incorporated these in models informed with UK specific input assumptions derived from relevant departments across government where possible. Inputs on the rapidly emerging field of zero emission fuel options, costs and benefits have been taken from the best available peer reviewed literature. The level of uncertainty of both the costs and the relative benefits for a range of levels of GHG and air pollution has therefore been significantly reduced. There remains some inevitable uncertainty both due to the model methods and baseline data, but also to the projections of key model assumptions which look forward over several decades. Expected and unexpected technology developments could significantly reduce the cost and may increase the benefits of GHG and air pollution emissions. The dominant driver of the cost estimations (marginal abatement costs and the cost estimates of decarbonisation scenarios) is the price of the alternative (non-fossil) fuels necessary to achieve significant reductions. Relative to existing literature, the assumptions of the alternative fuel prices used in this study are based on government guidance and are towards upper bound values, and therefore a current assessment of the uncertainty in this study's findings is that the costs are credible but conservative. As further evidence arises on future costs, this can be used to review and consider this study's conclusions and key findings and can help manage this uncertainty.

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