Department for Transport

Maritime Emissions Model

Modelling Framework

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Contents

Glossary of terms

AIS - Automatic identification system

Bio – Biofuel

CapEx – Capital expenditure

CCUS - Carbon capture, usage and storage

CH_4 - Methane

CII - Carbon Intensity Indicator

CO - Carbon monoxide

CO_2 - Carbon dioxide

CO_2e - Carbon dioxide equivalent

DACC - Direct Air Carbon Capture

DfT - Department for Transport

DWT - Deadweight tonnage (a measure of vessel size)

EEDI - Energy Efficiency Design Index

EEXI - Energy Efficiency Existing Ship Index

EEZ - Exclusive Economic Zone

EIV - Estimated index value

ETS - Emissions Trading Scheme

EU - European Union

GT - Gross tonnage (a measure of vessel size)

GHG - Greenhouse Gas

ICE - Internal Combustion Engine

IMO - International Maritime Organization

IPCC- Intergovernmental Panel on Climate Change

LNG - Liquified Natural Gas

LSFO - Low Sulphur Fuel Oil

MDO - Marine Diesel Oil

MMSI - Maritime Mobile Service Identity (a unique ID issued to ships by their flag state)

MRV - Monitoring, reporting and verification of greenhouse gas emissions from maritime transport

Mt - Megatonne (a million tonnes)

NAEI - National Atmospheric Emissions Inventory

OCCS – Onboard Carbon Capture and Storage

OpEx – Operating expenditure

NMVOC - Non-methane volatile organic compounds

N_2O - Nitrous oxide

NO_x - Nitrogen oxides

Pax - Passenger

PM_{10} - Particulate matter where particles are less than 10 micrometres in diameter

$PM_{2.5}$ - Particulate matter where particles are less than 2.5 micrometres in diameter

Ro-Pax - Roll-on / roll-off passenger

Ro-Ro - Roll-on / roll-off

RPM - Revolutions per minute

SFC - Specific Fuel Consumption

SO_x - Sulphur oxides

Syn - Synthetic

TEU - Twenty-foot equivalent units (a standard twenty-foot container)

TRL - Technology readiness level

TtW - Tank-to-Wake (the emissions that are generated by operating maritime vessels, i.e. operational emissions)

WtT – Well-to-Tank (the emissions from the production and distribution of the fuels and other energy sources that are used by maritime vessels)

WtW - Well-to-Wake (the sum of Tank-to-Wake and Well-to-Tank emissions)

1. Introduction

1.1 This document sets out the methodology and assumptions of the Department for Transport (DfT) Maritime Emissions Model. This model covers both greenhouse gases (GHG) and air pollutants. It has two components:

- Historical estimates: Estimates of activity, fuel consumption and emissions from ships in 2019 and backcasts for earlier years.
- Forecasts: Forecasts of fuel consumption and emissions from ships out to 2050.

1.2 This is the first time we have developed this modelling capability internally and it will be subject to further developments as we improve the methodology and build the evidence base. We would welcome any feedback on the methodology, assumptions, and results to help us develop the model in the future. If you have any feedback, please get in touch at MaritimeForecasts@dft.gov.uk.

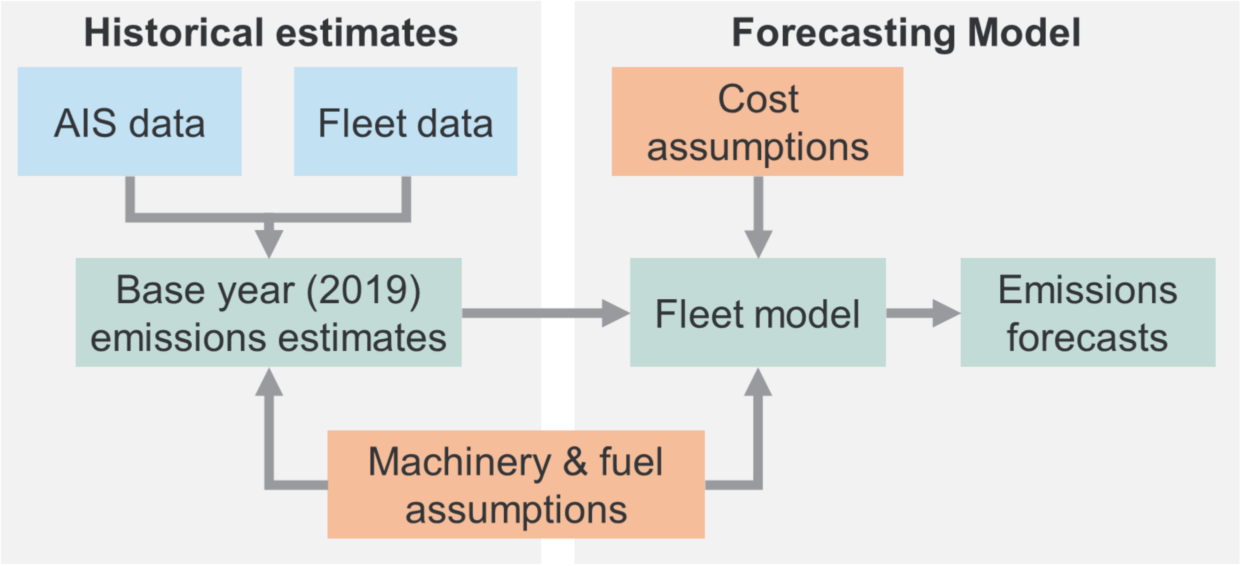

Figure 1 High level model diagram

Model purpose

1.3 We have produced this model to support the development of future maritime policies. Specifically, the model can be used to:

- Understand emissions in the baseline, providing breakdowns of emissions by ship type, route, location and other factors.
- Forecast the impact of different policy measures on emissions over the long term.
- Explore different rates of decarbonisation and the additional costs associated with these.
- Explore the uncertainty around future emissions as a result of factors such as costs and fuel mixes.

1.4 Currently, this model does not include inland waterways and leisure craft.

This report

1.5 The rest of this document is structured in the following way:

- Section 2 sets out the methodology used to produce the estimates.
- Section 3 provides details on the assumptions used in the estimates.
- Section 4 discusses the results of the estimates, including comparisons with reported data and previous estimates.
- Section 5 sets out the methodology used to forecast emissions.
- Section 6 sets out the fuel, technology, and operational measures that have been considered within the forecasts.
- Section 7 provides details on the assumptions used in the forecasts and their sources.

1.6 Published alongside this document is a spreadsheet containing the detailed figures for all assumptions (tables A-H).

2. Estimates Methodology

2.1 The model uses emissions estimates from 2019 as a base year for the forecasts. These estimates are produced using activity data (AIS data) following a similar methodology to other estimates, such as the IMO 4th GHG Study.

2.2 We started developing these estimates in 2022 and chose to use 2019 as the base year to exclude any impacts that resulted from the coronavirus pandemic, particularly the impact that travel restrictions had on passenger services during 2020 and 2021. We will look to update our base year in the future and potentially expand the number of years covered by the estimates.

IMO 4th GHG Study 2020[1]

Since 2000, the IMO has commissioned studies to estimate GHG emissions from the maritime sector. The fourth study, published in 2020, produced emissions estimates for the period 2012-2018. It improved on the methodology of the previous studies with a new voyage-based allocation of international and domestic shipping.

The study used two methods for estimating emissions:

- A bottom-up approach used AIS data to estimate shipping activity and combined this with ship specifications from a fleet database to calculate fuel consumption and emissions.
- A top-down approach estimated total fuel consumption by shipping from bunker sales statistics (World Energy Statistics provided by IEA) and combined this with emission factors calculated from the bottom-up estimates.

The methodology for the DfT maritime emissions estimates is based on the bottom-up approach.

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[1] www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

Main data sources

2.3 The estimates use two main datasets: AIS data and fleet data.

2.4 AIS is a system using transponders on board vessels. These broadcast live information including a vessel's speed, bearing, and draught. AIS was originally developed as a safety system, by allowing ships to see and be seen by other ships in the area. However, the collection of AIS data provides a large amount of data on the activity of ships, which can be analysed for many purposes including emission estimates. The AIS data for 2019 was provided by the Joint Maritime Security Centre who compiled the data from multiple sources, including both terrestrial and satellite receivers.

2.5 A fleet database is used to provide detail on the ships, including their type, size, and engine. This data can be matched to the AIS data using one of two ship ID systems (IMO numbers and MMSIs). The fleet database was obtained from commercial data sourced from IHS Global Limited from 1986 to 2021, and from Sea/ by Maritech in 2022. This is the same dataset used in DfT shipping fleet statistics and more information can be found in the published statistics[2].

Scope

Emissions

2.6 The model covers emissions resulting from all fuel use on board ships. This includes fuel used for propulsion and auxiliary services.

2.7 Currently, we have produced estimates for: carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), non-methane volatile organic compounds (NMVOCs), nitrous oxide (N_2O), carbon monoxide (CO), methane (CH_4), particulate matter (PM_{10}, $PM_{2.5}$) and black carbon.

Geographic scope

2.8 We have developed the model to look at ships globally, with the ability to filter the model to UK activity. This was done for two reasons:

- When considering the costs in the forecasting component, the model needs to be able to take into account the total costs across all of a ship's activities, UK and non-UK. Accounting for a ship's global activities allows us to consider the full cost of abatement options.
- Future development of the model will include looking at global maritime emissions.

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[2] www.gov.uk/guidance/maritime-and-shipping-statistics-information

2.9 UK domestic emissions have been identified using the same definition currently used in the National Atmospheric Emissions Inventory (NAEI). This defines UK domestic maritime emissions as the sum of:

- the emissions from journeys between two UK ports or offshore installations in the UK's Exclusive Economic Zone (EEZ);
- the emissions from journeys from one UK port or offshore installation in the UK's EEZ returning to the same port or installation; and
- all emissions from vessels at berth in a UK port or at an installation in the UK's EEZ (including those from vessels performing international journeys), with a vessel being 'at berth' when it is securely moored or anchored in a UK port or at an installation in the UK's EEZ.

Ship categories

2.10 The coverage of the estimates is limited by the two main datasets.

2.11 There are two classes of AIS used on ships - Class A and Class B. Use of AIS A is required by the International Convention for Safety of Life at Sea (SOLAS) for:

- Ships of 300GT and above engaged on international voyages;
- Cargo ships of 500GT and above not engaged on international voyages; and
- All passenger ships regardless of size.

2.12 Other ships can voluntarily use AIS and many do use AIS B transponders, which are designed for smaller vessels with a lower cost. However, AIS B transponders have a shorter range and are not always picked up by receivers, particularly satellite receivers. Therefore, coverage of smaller vessels will be incomplete, with some not using AIS and some using AIS B but not being recorded); however, this is difficult to assess due to the lack of data for these ships. In addition, the fleet data used in these estimates only covers ships of 100GT and above.

2.13 As a result, inland waterways and leisure craft are not included within the scope of the estimates. Leisure craft are filtered out of the estimates where they do appear in the data, but inland waterways vessels are not and therefore some are included in the estimates (typically these would be larger ships engaging in some sea-going activity). This is consistent with the NAEI's categorisation of these ship types[3].

2.14 Naval vessels are also not within scope of these estimates and are filtered out of the data. Again, this is consistent with the coastal shipping and fishing category of the NAEI.

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[3] https://naei.energysecurity.gov.uk/reports/greenhouse-gas-emissions-inland-waterways-and-recreational-craft-uk

Ship type and size categories

2.15 The model uses 19 categories of ship types, each with a set of size categories, based on those used in the IMO 4th GHG Study. The Yacht ship type is excluded from the results as this category is leisure craft and naval vessels, which are not within scope of these estimates. See assumptions table A.1 for more detail on how ships were categorised by types.

Ship type	Size categories
Bulk carrier	0-9,999 DWT; 10,000-34,999 DWT; 35,000-59,999 DWT; 60,000-99,999 DWT; 100,000-199,999 DWT; 200,000+ DWT
Chemical tanker	0-4,999 DWT; 5,000-9,999 DWT; 10,000-19,999 DWT; 20,000-39,999 DWT; 40,000+ DWT
Container	0-999 TEU; 1,000-1,999 TEU; 2,000-2,999 TEU; 3,000-4,999 TEU; 5,000-7,999 TEU; 8,000-11,999 TEU; 12,000-14,499 TEU; 14,500-19,999 TEU; 20,000+ TEU
Cruise	0-1,999 GT; 2,000-9,999 GT; 10,000-59,999 GT; 60,000-99,999 GT; 100,000-149,999 GT; 150,000+ GT
Ferry - pax only	0-299 GT; 300-999 GT; 1,000-1,999 GT; 2,000+ GT
Ferry - ro-pax	0-1,999 GT; 2,000-4,999 GT; 5,000-9,999 GT; 10,000-19,999 GT; 20,000+ GT
General cargo	0-4,999 DWT; 5,000-9,999 DWT; 10,000-19,999 DWT; 20,000+ DWT
Liquefied gas tanker	0-34,999 DWT; 35,000-64,999 DWT; 65,000-99,999 DWT; 100,000+ DWT
Miscellaneous - fishing	All
Miscellaneous - other	All
Offshore	All
Oil tanker	0-4,999 DWT; 5,000-9,999 DWT; 10,000-19,999 DWT; 20,000-59,999 DWT; 60,000-79,999 DWT; 80,000-119,999 DWT; 120,000-199,999 DWT; 200,000+ DWT
Other liquids tanker	0-999 DWT; 1,000+ DWT
Refrigerated cargo	0-1,999 DWT; 2,000-5,999 DWT; 6,000-9,999 DWT; 10,000+ DWT
Ro-Ro	0-4,999 DWT; 5,000-9,999 DWT; 10,000-14,999 DWT; 15,000+ DWT
Service - other	All
Service - tug	All
Vehicle	0-29,999 GT; 30,000-49,999 GT; 50,000+ GT
Yacht	All
Bulk carrier	0-9,999 DWT; 10,000-34,999 DWT; 35,000-59,999 DWT; 60,000-99,999 DWT; 100,000-199,999 DWT; 200,000+ DWT

Table 1 Ship types used within the model

Methodology

2.16 The estimates use the same bottom-up methodology as used in the IMO 4th GHG Study, although some assumptions are different. A summary of this methodology is provided here. More details can be found in the IMO 4th GHG Study.

2.17 There are four steps:

1. Processing fleet data, including infilling missing data and allocating to categories.

2. Cleaning AIS data.

3. Identification of port calls and classification of routes.

4. Estimating emissions.

Step 1: Processing fleet data

2.18 Some of the fleet data fields needed to produce these estimates were not in the 2019 fleet data, as that was procured before the project to produce estimates started. These were included in the 2022 fleet data and therefore, the two datasets were combined, using IMO numbers to match ships. The 2019 data was used as much as possible, and the 2022 data was only used to infill fields and ships missing from the 2019 data. The ships were allocated to the 19 ship type categories using the StatCode5 ship type fields within the fleet data.

2.19 Some ships were missing data needed to estimate emissions. These were infilled using the methods as set out in the table below.

Field	% of ships missing data	Infilling method
Deadweight tonnage (DWT)	25%	Linear regression model using GT for each ship type.
TEU capacity (container ships only)	0.3%	Linear regression model using GT.
Length	0.5%	Linear regression model using beam, draught and DWT for each ship type where possible. Otherwise, median length by ship type and size category.
Beam	0.7%	Median beam by ship type and size category.
Draught	15%	Median draught by ship type and size category.
Design speed	56%	Linear regression model using length, main engine power, and DWT for each ship type where possible. Otherwise, median design speed by ship type and size category.
Main engine power	5%	Linear regression model using length, design speed, and DWT for each ship type where possible. Otherwise, median power by ship type and size category.
Main engine RPM	49%	Linear regression model using design speed, main engine power and DWT for each ship type where possible. Otherwise, median RPM by ship type and size category.

Table 2 Infilling of missing fleet data

2.20 The IHS data has two fields for the fuel type used. These were used to determine the likely fuel used, except if the ship was a liquefied gas tanker with a steam turbine, in which case it was assigned LNG. The assumptions used to match the fuel types are shown in the table below, based on assumptions from the IMO 4th GHG Study. Some ships were missing any fuel type information. These were assigned the modal fuel type for their type and size category of the ships that did have fuel type data.

Fuel type 1	Fuel type 2	Assigned fuel
Residual fuel	Any	HFO
Any	Residual fuel	HFO
Distilled fuel	Distilled fuel	MDO
Distilled fuel	Empty	MDO
Empty	Distilled fuel	MDO
Coal	Distilled fuel	MDO
Gas boil-off	Distilled fuel	LNG
LNG	Distilled fuel	LNG
LNG	Empty	LNG
Empty	LNG	LNG

Fuel type 1	Fuel type 2	Assigned fuel
Any	Gas boil-off	LNG
Nuclear	Distilled fuel	Nuclear
Nuclear	Empty	Nuclear
Coal	Empty	Coal
Methanol	Any	Methanol

Table 3 Assignment of fuel type

2.21 The IHS data provided the propulsion type for each ship. This was aggregated into the categories shown in the table below, with the criteria applied in the order given.

Propulsion type group	Criteria
LNG	Fuel type is LNG
Methanol	Fuel type is methanol
Oil	Propulsion type contains the word "Oil" or is "Petrol Engine(s), Direct Drive"
Sail	Propulsion type contains the word "Sail"
Steam turbine	Propulsion type contains the term "Steam Turbine" (or a shortened version of this e.g. "St. Turb")
Batteries	Propulsion type contains the word "Battery"
Gas turbine	Propulsion type contains the term "Gas Turbine"
Non-Propelled	Propulsion type is "Non-Propelled"

Table 4 Grouping of propulsion types

2.22 Finally, ships were assigned an engine type based on their propulsion type, RPM, fuel type and engine names, as shown in the table below. This followed the same engine type matching used in the IMO 4th GHG Study.

Engine type	Propulsion type group	RPM	Fuel type	Engine name
Oil-SSD	Oil	300 or less	Any except Methanol	Any
Oil-MSD	Oil	300-900	Any except Methanol	Any
Oil-HSD	Oil	More than 900	Any except Methanol	Any
LNG-Diesel	LNG	300 or less	LNG	Contains "ME" (capturing Diesel cycle engines built by MAN Energy Solutions)
LBSI	LNG	More than 300	LNG	Contains "Rolls-Royce" (as LBSI engines are mainly built by Rolls-Royce)
LNG-Otto SS	LNG	300 or less	LNG	Contains "ME-GA" (Otto cycle engines built by MAN Energy Solutions) or does not contain "ME"
LNG-Otto MS	LNG	More than 300	LNG	Does not contain "Rolls-Royce"
Methanol-SS	Any	300 or less	Methanol	Any
Methanol-MS	Any	More than 300	Methanol	Any
Gas turbine	Gas turbine	Any	Any	Any
Sail	Sail	Any	Any	Any
Steam turbine	Steam turbine	Any	Any	Any
Batteries	Batteries	Any	Any	Any
Non-Propelled	Non-Propelled	Any	Any	Any

Table 5 Assignment of engine types

2.23 Once the fleet data had been processed, it was joined on to the AIS data, matching ships by IMO number if possible, otherwise using MMSI numbers.

Step 2: Cleaning AIS data

2.24 There are sometimes errors in the locations provided in the AIS data. It was necessary to clean the data following this process:

- For each point, calculate how far the vessel can travel at maximum speed.
- If the next observed point is within the possible distance, keep it in the data.
- If the next point cannot be reached within the time frame, remove it.

2.25 This process has limitations and assumes that the first observed point is correct. If the first point is anomalous, then it will affect the results. Due to the volume of data, it was not possible to manually verify every point.

2.26 To produce the emissions estimates, we decided to reduce the AIS data to five-minute intervals, i.e. we selected a data point for each ship for every five minutes over the course of the year. Note that this differs from the IMO 4th GHG methodology where hourly datapoints were used. Using five-minute interval data allows for a greater level of geographic detail in the estimates, for example producing estimates by 1km grid squares.

2.27 In some cases, there were gaps in the AIS data of more than five minutes. These were infilled using a geodesic line between observed points. This was not perfect and did result in some points on land, where the observed points were on either side of land, but these errors were rare.

2.28 Some AIS datapoints were missing speed and draught. These were infilled using the same methodology as the IMO 4th GHG Study. For speed, this involved classifying points into three phases, defined as:

- Port phase: any points where speed is less than 3 knots.
- Voyage phase: Points where the speed is above a calculated threshold and has a standard deviation of less than 2 knots within a six-hour rolling window. The threshold is the 90th percentile of speeds reported above 3 knots.
- Transition phase: All other points.

2.29 Points that were missing speed were allocated to a phase based on the points with known phases. Specifically:

- If a point missing phase had no points with known phase preceding it, then it was assigned the same phase as the next point with known phase.

- If a point missing phase had no points with known phase following it, then it was assigned the same phase as the last point with known phase.

- If a point missing phase was between two points with the same phase, then it was assigned the same phase as those points.

- If a point missing phase was between two points with different phases, then it was assigned to the transition phase.

2.30 Gaps in speed were then classified into small or large gaps, using the threshold of the median port-to-port time bounded by 6 and 72 hours. If there was speed reported for a given voyage, then small gaps on that voyage were infilled with the mean reported speed for that phase on that voyage. Otherwise, small gaps were infilled with the mean reported speed for the phase over all voyages. For large gaps, speed was infilled using this process:

- If there was speed reported for a given voyage, forward- and back-fill the data from known points.

- If there was no data for the voyage, use the average speed for the phase.

- If there was no data for the voyage or phase, use the vessel average speed.

2.31 Draught data was also infilled. If some draught data was available for a vessel, the gaps were forward- and back-filled so that the first half of each gap had the value of the previous known draught and the second half of the unknown block had the next known draught. If no draught data was available for a vessel, the average draught for a vessel of that vessel type and size category was used.

Step 3: Identification of port calls and classification of routes

2.32 We needed to identify port calls so that journeys could be classified by route. Vessels were classed as calling at a port if they were within 3km of the port location and their speed was below 1 knot. If they were within 3km of multiple ports, then the closest port was used. They were assumed to exit the port when their speed exceeded 1 knot, or they were more than 4km from the port.

Step 4: Estimating emissions

2.33 Estimating emissions involved calculating the power demand from the main engines, auxiliary engines and boilers, converting into fuel based on fuel consumption rates and then applying emission factors. As with the IMO 4th GHG Study, we assume that only the main engine is used for propulsion and auxiliary engines cover the electrical demand on-board.

2.34 The main engine power demand was calculated for each data point using the Admiralty formula from the IMO 4th GHG Study:

$$W_i = \frac{\delta_W \cdot W_{ref} \cdot \left(\frac{t_i}{t_{ref}}\right)^m \cdot \left(\frac{v_i}{v_{ref}}\right)^n}{\eta_w \cdot \eta_f}$$

Parameter	Definition
W_{ref}	Reference power of main engine
t_i	Draught at the given data point
t_{ref}	Maximum draught of ship
v_i	Speed at the given data point
v_{ref}	Reference speed
m	Draught ratio exponent (assumed to be 0.66)
n	Speed ratio exponent (assumed to be 3)
η_w	Weather correction factor
η_f	Fouling correction factor
δ_W	Speed correction factor

Table 6 Definition of parameters in the Admiralty formula

2.35 The correction factors were taken from the IMO 4th GHG Study and are defined by ship type and size. The values used are shown in assumptions table D.4.

2.36 The auxiliary and boiler power demand are assumptions based on ship type, size, main engine power and operational phase (assumptions table D.1). Four operational phases were used: at berth, at anchor, manoeuvring, and at sea. Each data point was allocated to a phase based on speed, distance from coast, and distance from nearest port. Liquid tankers have an additional port distance category to reflect the fact that they are often lightered offshore.

Distance from port (nm)	Distance from coast (nm)	≤1 knots	1-3 knots (incl. 3)	3-5 knots (incl. 5)	>5 knots
≤1	**Any**	At berth	Anchored	Manoeuvring	Manoeuvring
1-5 (only applied to tankers)	**Any**	At berth	Anchored	Manoeuvring	At sea
All others	**<5**	Anchored	Anchored	Manoeuvring	At sea
	≥5	Anchored	Anchored	At sea	At sea

Table 7 Assignment of operational phases

2.37 Fuel consumption was calculated by multiplying the power demand by fuel consumption rates for the main engines, auxiliary engines and boilers (assumptions table D.3). For dual fuel engines, pilot fuel was also calculated using a separate fuel consumption rate.

2.38 In 2019, there were four Emission Control Areas (ECAs) with limits on SO_x emissions: Baltic Sea area, North Sea area, North American area, United States Caribbean Sea area.[4] In addition, SO_x limits applied to ships at berth in the UK, the EU and Turkey. We assume that ships using HFO comply with these limits by switching to MDO when in an ECA or at berth in the UK, the EU, or Turkey.

2.39 Finally, emissions were estimated using emission factors (assumptions table C.1). NOx emissions were calculated using an energy-based emission factor applied to the

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[4] www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx

power demand. All other emissions used fuel-based emission factors applied to the fuel consumption.

3. Estimates Assumptions

3.1 This section sets out the assumptions used in the estimates and their sources. Published alongside this document is a spreadsheet containing the detailed figures for all assumptions (tables A-H).

3.2 DfT commissioned a consortium of consultants to produce several of the assumptions used in the model (both for the estimates and the forecasts) by reviewing the existing evidence. More information on this project is given in the box below.

Maritime emissions model assumptions project (2023)

DfT commissioned a consortium of consultants (KPMG, Mott MacDonald, and Houlder Ltd.) to produce several of the assumptions used in the model by reviewing the existing evidence. This project consisted of three workstreams:

- Workstream 1: Estimates related to fuels and machinery required for estimating emissions from ship mileage and main engine power (auxiliary engines and boiler machinery power demand, specific fuel oil consumption and emissions factors).
- Workstream 2: Estimates of engine costs.
- Workstream 3: Estimates of the costs and impacts for a number of technological and operational solutions for reducing the shipping sector's contribution to emissions.

Two principal data gathering techniques were used: desk-based research and stakeholder interviews. Interviews were conducted with:

- Engine manufacturers: Wärtsilä, CAT Marine, GE.
- Oil and gas companies: BP, Shell.
- Universities: Newcastle University, University of Strathclyde.
- Technology providers: L3 Technologies, PMW Technology, Silverstream Technologies, Smart Green Shipping.
- Other relevant organisations: Lloyd's Register, DP World, International Maritime Organization, Stellar Systems.

The outputs of this research are included in the accompanying assumptions tables.

Port locations

3.3 We have used a global anchorages database produced by Global Fishing Watch[5]. This database contains over 160,000 individual anchorage locations and was produced by identifying the points ships congregate in AIS data.

3.4 The database contains an indicator of which stopping points are at a dock. When identifying the operational phase of ships, we used only those points that were marked as "at dock" as we wanted to be able to distinguish between operations at berth and operations at anchor.

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[5] globalfishingwatch.org/datasets-and-code-anchorages/

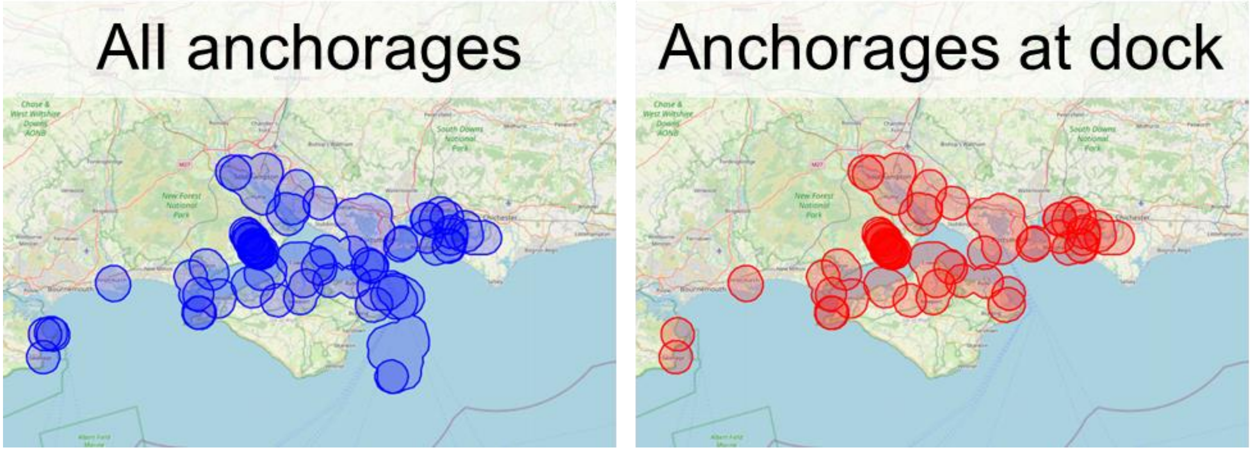

Figure 2 Example comparison of all anchorages and anchorages at dock

3.5 When identifying port calls, we used the full database. We did this to ensure we captured calls at offshore locations, such as oil rigs and wind farms. We also found some port terminals that were not marked as "at dock". The limitation of using the full database is that it results in stops at anchorages being categorised as port calls, however this is mitigated by the fact that in most cases, when a ship stops at an anchorage outside a port it will also call at the port.

3.6 This does mean that some journeys may be mis-categorised, for example when a ship sails from a non-UK port to a UK port, the last part of the journey from the anchorage outside the UK port to the port may be classed as a domestic journey. Therefore, this should be considered a conversative estimate of UK domestic emissions.

3.7 In addition, there are some places where ships frequently stop without making a port call. A significant example of this is the Suez Canal, where ships queue to pass through the canal. In this case, we are likely to be identifying many port calls which did not occur. It is possible that this would occur even if we used only the anchorages at dock, as there are limitations to the accuracy of the port call algorithm and there are ports close to many stopping points, e.g. Port Said on the Suez Canal. We will explore how to improve this in the future.

Auxiliary engines and boilers power demand

3.8 DfT commissioned a consortium of consultants to produce several of the assumptions in the model by reviewing the existing evidence. This included assumptions on the power demand from auxiliary engines and boilers.

3.9 A power demand calculation methodology for auxiliary and boiler machinery loads was developed and mapped to a matrix comprising:

- Ship type
- Size
- Operational mode

- Main engine power or deadweight depending on ship type

3.10 The auxiliary and boiler power demand were developed based on data from the following sources:

- IMO 4th GHG Study. The IMO data consists of a matrix of fixed auxiliary or boiler demand for each vessel type, size category and operational mode.

- Clarksons' World Fleet Register (a database of ships technical information produced by Clarksons Research). This data includes total installed auxiliary power for vessels.

3.11 The sources listed above were analysed to derive representative equations for auxiliary and boiler power demand based on vessel type and operational mode. Data points from the research were used to plot auxiliary and boiler power demand on a graph against vessel variable, including deadweight, gross tonnage and engine power, to identify any trends. Once a suitable vessel variable had been determined a line of best fit was drawn in the form of $a * b^c + d$ where b is a vessel specific variable, such as main engine power or deadweight, and a, c and d are fixed values.

3.12 The values used for auxiliary engine power demand can be found in assumptions table D.1.

3.13 To be consistent with fuel consumption rate assumptions (see below), we used the IMO 4th GHG Study assumptions for boiler power demand. For transparency, the assumptions produced by the consultants can be found in assumptions table D.2 but these are not currently used in the model

Fuel consumption rates

3.14 As with the auxiliary and boiler power demand, fuel consumption rates were produced by consultants on behalf of DfT. These were produced for both existing engines and fuels, as well as future engines and fuels (for use in the forecasting model). In addition, forecasted changes in engine efficiency were also produced.

3.15 The following fuels were considered:

- Heavy fuel oil (HFO)

- Marine diesel oil (MDO)

- Low sulphur heavy fuel oil (LSHFO)

- Very low sulphur fuel oil (VLSFO)

- Biofuels (bio-MGO, bio-LNG, bio- methanol)

- Electro-fuels (e-MGO, e-LNG, e-methanol)

- Methanol

- Liquefied natural gas (LNG)
- Hydrogen
- Ammonia

3.16 The following engines were considered as part of the study and represent the majority of shipping (~99%) in the case of internal combustion engines (ICEs), or areas of significant future interest in the case of fuel cells:

- 2 Stroke – Slow Speed – Compression Ignition
- 2 Stroke – Slow Speed – Spark Ignition
- 2 Stroke – Slow Speed – Dual Fuel
- 2 Stroke – Medium Speed – Compression Ignition
- 4 Stroke – Medium Speed – Spark Ignition
- 4 Stroke – Medium Speed – Dual Fuel
- 4 Stroke – High Speed – Compression Ignition
- 4 Stroke – High Speed – Spark Ignition
- PEM Fuel Cell – Direct Hydrogen Storage
- PEM Fuel Cell – Indirect Hydrogen Storage
- Solid Oxide Fuel Cell

3.17 Gas turbines and steam turbines were not included in this study. For these the assumptions in the IMO 4th GHG Study 2020 were used.

3.18 The ICE engines were split into three speed categories: slow speed (<300 rpm), medium speed (300-1000 rpm), and high speed (>1000 rpm). Typically, the slower the engine the lower the Specific Fuel Consumption (SFC) (slow combustion is closer to the ideal thermodynamic cycle).

3.19 Compression ignition engines rely on the Diesel cycle[6] and are compatible for all conventional fuels. Spark ignition engines follow the Otto cycle[7] and have been assumed to apply to all alternative fuels in development (ammonia, methanol, hydrogen).

3.20 Both 2 stroke and 4 stroke marine engines are currently available on the market. The main difference between the two is that a 4-stroke engine takes two complete

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[6] In the Diesel cycle, air is compressed to a high pressure, raising its temperature. Fuel is in then injected and ignited by the hot air.

[7] In the Otto cycle, a fuel-air mixture is compressed and then ignited by a spark plug.

revolutions of the crank shaft to complete the power stroke whereas a 2 stroke only takes one. Typically, slow speed marine engines are 2-stroke, and medium and high speed engines are 4-stroke.

3.21 The Specific Fuel Consumption (SFC) of engine types fuelled by HFO or MDO was taken from publicly published data of various engine manufacturers. Multiple manufacturers were considered for each engine type in order to derive a representative trendline, which gave a good visual fit, in the form $a * b^c + d$ where b is the engine speed at its maximum continuous rating and a, c and d are fixed values provided in this report.

3.22 The engine speed was used in the calculation as engine efficiency within the speed ranges provided above varies by as much as 10% from the bottom to top end of the speed ranges. Other studies have looked at engine load as a variable and, whilst engine efficiency does reduce at part load, this is less significant within normal operating ranges and has therefore not been considered within the scope of this study.

3.23 Engines operating on these fuels are well established and no significant improvements in efficiency are foreseen. As such the fuel consumption figures are assumed to be the same today as they will be in 2060.

3.24 As little or no data was available for alternatively fuelled engines, the SFC was estimated using data for HFO/MDO scaled on the energy content of the fuel and the current overall efficiency of the engine technology.

3.25 The SFC of engines fuelled with alternative fuels is expected to improve as these technologies improve over time. This was reflected in the provision of two SFCs for these engines, for 2023 and for 2060, based on the year of build of the engine and where the 2023 SFC was taken as a 30% increase from that of 2060 based on academic data, with SFC for intermediate dates calculated by linear interpolation.

3.26 Where a pilot fuel is used in conjunction with a gaseous fuel, the pilot fuel is assumed in all cases to be MDO.

3.27 The values for SFC can be found in assumptions table D.3.

3.28 There were significant differences between the boiler SFC assumptions produced by the consultants and the assumptions used in the IMO 4th GHG Study. We decided to use the IMO 4th GHG Study assumptions for boiler SFC as these performed better when validating the estimates against reported data. For transparency, the unused assumptions produced by consultants are included in table D.3.

Tank-to-wake emission factors

3.29 Tank-to-wake emission factors were produced by consultants based on an evidence review. These were produced by engine type and fuel type consistent with the fuel consumption assumptions.

3.30 Following an internal DfT review of these emission factors, some of these were identified as being significantly different from other emissions estimates, such as the IMO 4th GHG Study, and relying on low quality evidence. These were changed to match other sources, which were better aligned with other estimates. The final set of emission factors and their sources can be found in assumptions table C.1.

3.31 There were several limitations in developing emission factors. The availability of fuel consumptions and emission-related data is not consistent for all engine and fuel types. The available data tended to be skewed towards the engine and fuel types most commonly used together (such as HFO).

3.32 Additionally, engine and fuel types which are emerging as technologies will have fuel consumptions and emission factors that are estimated based on theoretical experiments and calculations (if data is available). Other fuels have contradictory and inconsistent data regarding their emissions: this was particularly the case for biofuels and e-fuels, where a common consensus could not be found on the impact of their use on tank-to-wake emissions.

3.33 As there was a lack of consensus on the impact of biofuels and e-fuels on tank-to-wake emissions, we have assumed that these are equal to the emissions of the fuel that they synthesise, except for CO_2 emissions which are assumed to be offset in the production of the fuel.

3.34 For biofuels, this is in line with IPCC guidance that biofuels are treated as zero CO_2 emission on a TtW basis. As synthetic fuels are not yet deployed at scale, international carbon reporting practice for their production and combustion on a TtW basis is as yet undefined. In line with previously published analysis, such as the forecasts produced for the Clean Maritime Plan[8], the model assumes that synthetic fuels are zero emission on a TtW basis, noting this may be subject to change as international accounting protocol evolves.

Well-to-tank emission factors

3.35 Well-to-tank emission factors for GHGs have been taken from a (currently unpublished) research project commissioned by DfT and undertaken by a team of experts from UMAS, UCL and E4tech. These mainly draw on the JEC Well-to-Tank Report v5[9]. These can be found in table C.3.

3.36 We conducted a literature review and concluded that this was the best available source of well-to-tank emissions. We will review and update these in the future as the evidence base develops.

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[8] www.gov.uk/government/publications/clean-maritime-plan-maritime-2050-environment-route-map

[9] https://publications.jrc.ec.europa.eu/repository/handle/JRC119036

4. Estimates Results

Validation

4.1 Validation of the tank-to-wake estimates was conducted using two sources: fuel consumption figures submitted to the IMO Ship Fuel Oil Consumption Database and emissions estimated in the EU MRV system (monitoring, reporting and verification of GHG emissions from maritime transport).

4.2 The validation did highlight some limitations in the estimates, particularly accuracy at an individual ship level. But overall, the results showed that the estimates performed well at fleet level.

IMO Ship Fuel Oil Consumption Database

4.3 The IMO Ship Fuel Oil Consumption Database collects fuel consumption data for ships of 5,000GT and above. DfT fuel consumption estimates for ships of 5,000GT and above were compared with figures from the IMO summary report for 2019[10].

4.4 The number of ships and total gross tonnage in the DfT maritime emissions model were 21% and 14% higher than the number included in the IMO database, respectively. The reason for this difference is likely due to some vessels not reporting their fuel consumption and some vessels that were out of scope of the IMO database.

4.5 The distance travelled and HFO fuel consumption were also higher in the model outputs than in the IMO report, but only by a margin that is approximately in line with the difference in the gross tonnage of ships covered by each analysis. Note that we would not necessarily expect the percentage difference in these other metrics to align exactly with the difference in the gross tonnage, as a considerable proportion of ships not included in the IMO database are thought to be domestic operating ships, which will have different distance and fuel consumption distributions than international ships.

4.6 The percentage differences in MDO, LNG, and methanol consumption are more significant, with the model estimates showing half as much LNG (despite having

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[10] www.imo.org/en/ourwork/environment/pages/data-collection-system.aspx

more ships included) and around four times as much methanol consumption. The quantity of these fuels that was consumed is much smaller than HFO (particularly methanol which is several orders of magnitude smaller) so will be subject to more variation depending on precisely which ships are and are not included in each analysis and that may explain some of the difference.

4.7 The difference in MDO is likely to be partly due to domestic operating ships included in the model outputs and not in the IMO database. However, it may also demonstrate the limitations of the ECA correction assumption, where the model assumes all ships switch to MDO, while in reality some will use HFO in combination with exhaust treatment systems or a low sulphur version of HFO.

4.8 Given the small amount of fuel accounted for by LNG and methanol, these differences will not have had a significant impact on total emissions estimates. But it does suggest there could be some improvements to the fuel type allocation process. We will explore this in the future.

	Maritime Emissions Model (restricted to ships over 5000GT)	**IMO Ship Fuel Oil Consumption Database**	**% Difference**
Ships in analysis	33,036	27,221	21%
Gross tonnage	1,351,777,702	1,187,155,816	14%
Distance (nm)	1,738,891,425	1,562,499,142	11%
HFO (tonnes)	178,482,203	171,428,136	4%
MDO (tonnes)	34,467,502	24,125,110	43%
LNG (tonnes)	5,127,182	10,482,742	-51%
Methanol (tonnes)	148,582	29,551	403%
Light fuel oil (tonnes)	N/A	6,930,061	N/A
Other	N/A	75,193	N/A

Table 8 Comparison of DfT estimates and IMO reported fuel consumption

EU MRV system

4.9 Ships above 5,000GT are required to report fuel consumption and carbon dioxide emissions for voyages to or from EEA ports and all time spent in an EEA port. This data is published by ship[11] and in 2019, journeys to or from UK ports were included in the figures.

4.10 The 2019 MRV data was matched to the emissions model estimates using ship IMO numbers and emission estimates from the model for these ships were filtered to those journeys within scope of the MRV.

4.11 In total, for those ships which could be matched between the two datasets, the MRV reported 145Mt CO_2 and the model estimated 131Mt CO_2, a difference of 10%. However, at an individual ship level there were many larger errors, as shown in chart 1 below.

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[11] https://mrv.emsa.europa.eu/#public/eumrv

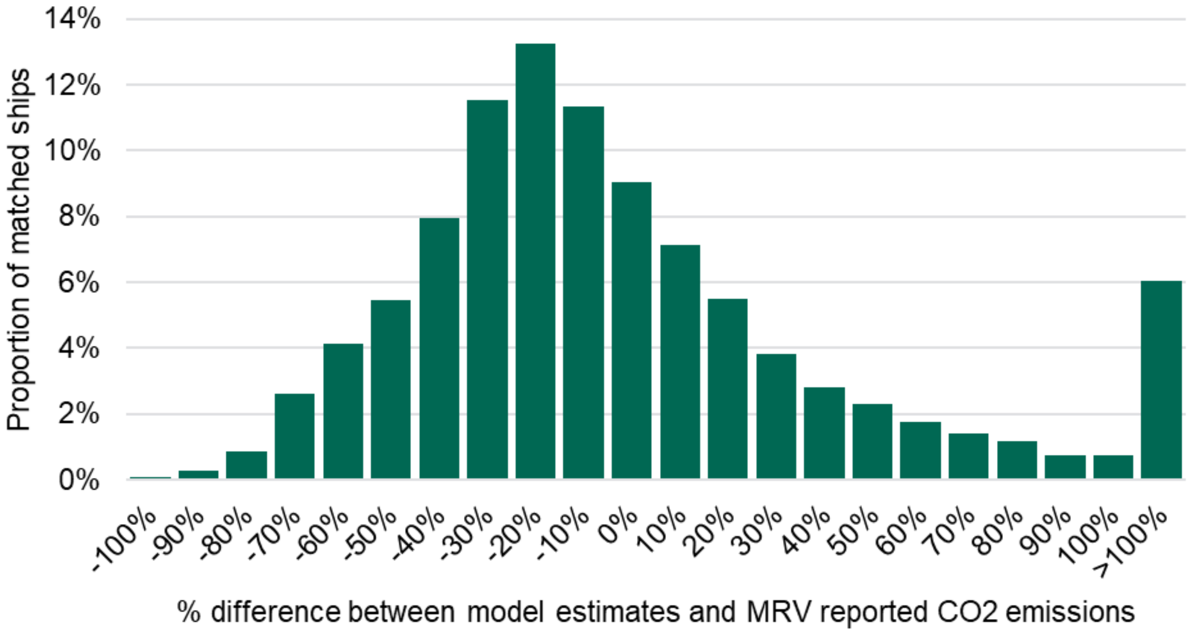

Chart 1 Distribution of differences between ship level estimates of CO_2 emissions

4.12 Some of these differences may be due to the errors in the identification of port calls. For example, if the model missed an EEA port call or falsely identified a non-EEA port call, then it will exclude journeys or parts of journeys that should be within scope leading to an underestimate. Similarly, the model may have falsely identified an EEA port call or missed a non-EEA port call, leading to an overestimate. This can be seen in the estimates for container ships (chart 2), where the model underestimates the emissions on EEA journeys as there are points on the main container routes where the model tends to identify a port call that did not occur, such as at Port Said on the Suez Canal.

4.13 We have conducted analysis of journeys to or from the UK to estimate the impact that the Suez Canal has on estimates. The estimates contain 686 journeys between the UK and ports on the Suez. There were 1.4 MtCO2e emissions from journeys either directly preceding a Suez-UK journey or directly following a UK-Suez journey. If all of these port calls were false, then this would increase UK international emissions by 9%.

4.14 However, this does not explain all of the differences and there is likely some inaccuracies in ship level estimates. This is to be expected as the model uses some generic assumptions across ship types, such as the auxiliary engine power demand, which are unlikely to be accurate for every ship - instead they aim to reflect the average across a ship type. Therefore, we do not judge these differences at the individual ship level to be a significant concern, given that the total CO_2 emissions are relatively close. This demonstrates that the model is suitable for estimating emissions at the level of broad categories of ship types, which is what it was designed to do. It was not designed to produce individual ship level estimates and the estimates should not be used at that level.

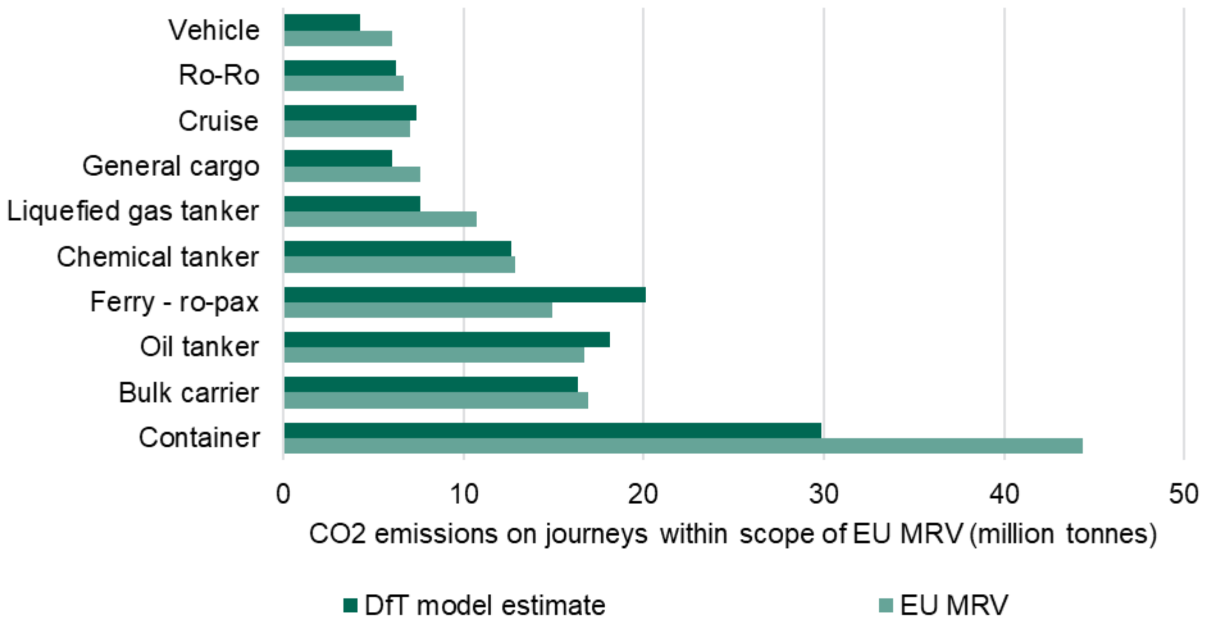

Chart 2 Comparison of EU MRV reported CO_2 emissions and DfT model estimates for the ten largest ship types

NAEI estimates

4.15 The official estimates of TtW maritime emissions are the NAEI estimates. These are the estimates used within DfT environment statistics[12]. For coastal shipping and fishing, these estimates are based on the same methodology as the maritime emissions model, but used data for 2014 and some different assumptions[13]. They are scaled based on activity data to provide estimates up to the present.

4.16 The table below shows that the DfT maritime emissions model estimates that UK domestic coastal shipping and fishing emissions totalled 5.9 million tonnes of CO_2e during 2019. The NAEI estimate this figure to be 5.0 Mt CO_2e.

Operational phase	NAEI CO_2e (% of Total CO_2e)	Emissions Model CO_2e (% of Total CO_2e)
At berth	0.5 (10%)	2.7 (45%)
At sea	4.5 (90%)	3.2 (55%)
Total	5.0	5.9

Table 9 Comparison of NAEI and DfT estimates of UK domestic coastal shipping and fishing GHG emissions ($MtCO_2e$)

4.17 The DfT emissions model estimates that at berth emissions account for a much higher proportion (45%) of total UK domestic maritime emissions than the NAEI estimates (10%).

4.18 One potential explanation for the discrepancy in at berth and overall emissions is the assumption in the NAEI estimates called the "berth day gap". This assumes that if a ship is at berth for more than 24 hours, the engines will be switched off. We have not implemented this assumption in our estimates as, even when at berth for extended periods, vessels will use their engines to power on board services. This assumption is supported by the validation results shown above. In particular, the largest

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[12] https://www.gov.uk/government/collections/energy-and-environment-statistics

[13] https://naei.beis.gov.uk/reports/reports?report_id=950

contributors to at berth emissions in the DfT estimates are tankers and chart 2 shows that we are not consistently over-estimating emissions from these ship types. In the DfT estimates, vessels which had been at berth at UK ports for over 24 hours produced 1.0 Mt CO2e in 2019. This accounts for 45% of the difference between domestic at berth emissions in the NAEI estimates and the DfT emissions model.

4.19 Another potential explanation for the difference in the proportion of emissions being produced during the ‘at berth’ operational phase is the port datasets underlying the two sets of estimates. The DfT maritime emissions model uses a larger dataset of port locations. The greater number of berths in the model mean that a greater proportion of genuine at berth domestic emissions will be captured as ‘at berth’ in the DfT model.

4.20 Another important difference between the two sets of estimates is that the NAEI estimates are based on a base year of data from 2014 which has been scaled up for subsequent years, including the 2019 figures in this section. It is possible that this scaling factor does not accurately reflect how domestic maritime emissions may have changed over this period. The DfT emissions model uses a base year of data from 2019 and includes more recent assumptions, meaning that the DfT emissions model estimates are likely to be more accurate when looking at 2019 UK domestic emissions.

Backcasting to 2008

4.21 We have produced total UK domestic WtW GHG emission figures back to 2008 by backcasting the 2019 estimates. This was done by using an activity index for each ship type to scale the 2019 emissions, shown in the table below. Emissions factors were assumed to remain constant.

4.22 In future work, we will be producing more detailed backcasting to 1990 for all types of emissions, as well as UK international emissions. This more detailed backcasting will take into account changes in fuel content and the introduction of ECAs.

Ship type	Activity index source	Activity index
Bulk carrier	DfT port freight statistics - table PORT0201	All dry bulk (tonnes)
Chemical tanker	DfT port freight statistics - table PORT0201	Other liquid bulk products (tonnes)
Container	DfT port freight statistics - table PORT0201	All container traffic (tonnes)
Cruise	DfT sea passenger statistics - table SPAS0101	All International Cruise Passengers
Ferry - pax only	DfT sea passenger statistics - table SPAS0201	All Domestic Sea Passengers
Ferry - ro-pax	DfT port freight statistics - table PORT0201	All roll-on/roll-off traffic (tonnes)
General cargo	DfT port freight statistics - table PORT0201	All other general cargo traffic (tonnes)
Liquefied gas tanker	DfT port freight statistics - table PORT0201	Liquefied gas (tonnes)
Miscellaneous - fishing	MMO UK sea fisheries statistics - tables 2.4 and 2.7	Total Landings into the UK by UK and foreign vessels (tonnes)
Miscellaneous - other	DfT port freight statistics - table PORT0201	All port traffic (tonnes)
Offshore	DESNZ Digest of UK Energy Statistics (DUKES) - table F.1	Total crude oil and natural gas liquids production
Oil tanker	DfT port freight statistics - table PORT0201	Total oil (tonnes)
Other liquid tanker	DfT port freight statistics - table PORT0201	Other liquid bulk products (tonnes)
Refrigerated cargo	DfT port freight statistics - table PORT0201	Other dry bulk (tonnes)
Ro-Ro	DfT port freight statistics - table PORT0201	Unaccompanied road goods trailers (tonnes)

Ship type	Activity index source	Activity index
Service - other	DfT port freight statistics - table PORT0201	All port traffic (tonnes)
Service - tug	DfT port freight statistics - table PORT0201	All port traffic (tonnes)
Vehicle	DfT port freight statistics - table PORT0201	Import/Export motor vehicles (tonnes)

Table 10 Activity indices used to backcast domestic emissions estimates

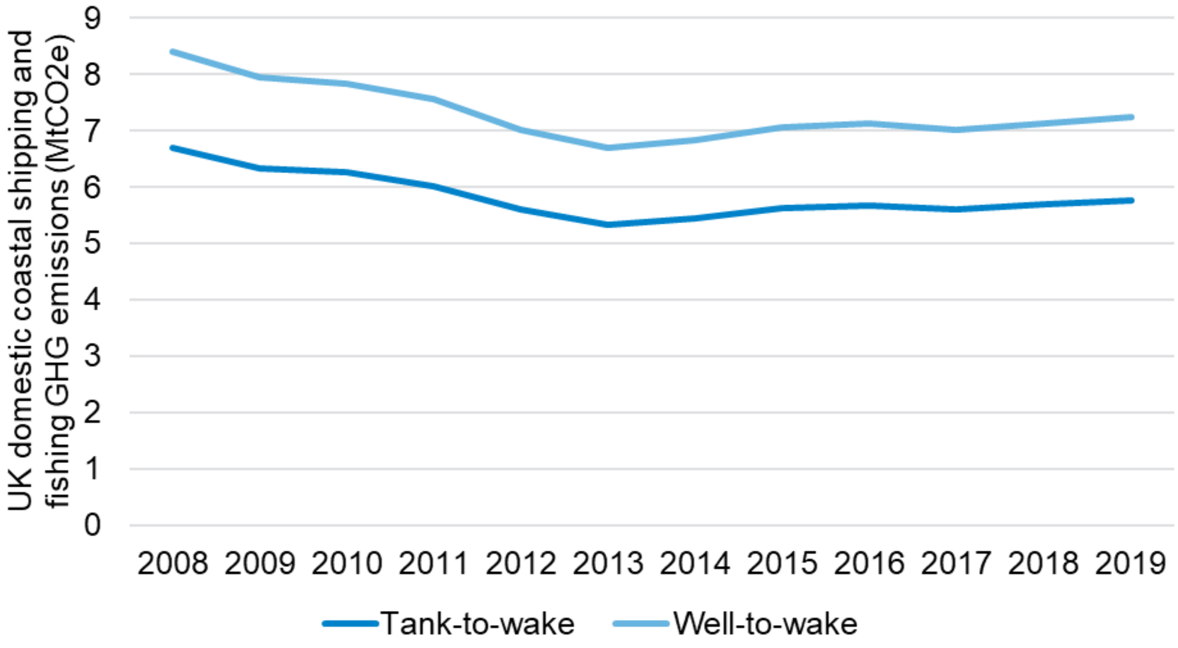

Chart 3 Backcasted UK domestic coastal shipping and fishing GHG emissions

Limitations

4.23 There are a number of limitations which should be considered when using the estimates.

4.24 As noted in the methodology, inland waterways and leisure craft are not included in these estimates. They may also only provide partial coverage of smaller ships (those below 300GT). We are exploring what data is available for these ships and will look into developing estimates for them in the future.

4.25 Validation of the model results used data for ships of 5000GT and above. It has not been possible to conduct validation on the estimates for ships below this size.

4.26 The purpose of the model is to produce estimates for broad categories of ships and, as shown by the validation results, the accuracy of the estimates is low at an individual ship level. In particular, estimates of non-propulsion sources of emissions (auxiliary engines and boilers) rely on a limited evidence base and do not reflect all of the variations across ships. Therefore, results for any small number of ships should be treated with caution.

5. Forecasting Methodology

5.1 The forecasts are based on modelling the development of the fleet over time. There are three key assumptions that underly this methodology.

- Firstly, we assume that ships are removed from the fleet when they reach the end of their lifespan (the current lifespan assumption for all ship types in the model is 25 years).
- Secondly, we assume that the number of ships in the fleet is kept at a sufficient level to meet demand for shipping. This means adding new ships to the fleet when their numbers drop below the amount required to undertake the work demanded.
- Finally, we assume that ship owners act to minimise costs (capital, operating, and fuel) as much as possible, while complying with regulations. This means that options such as technologies, fuels and operational measures are selected based on the lowest cost, as long as they are sufficient to comply with regulations.

5.2 The core part of the forecasting methodology is an agent-based simulation model of the fleet (the fleet model). This manages a simulated fleet over the years 2020-2050, adding and removing ships as necessary.

5.3 In addition, there is a cost model. For a given ship, this calculates the costs of the different technology, operational and fuel options and identifies the lowest cost combination of options that comply with regulations.

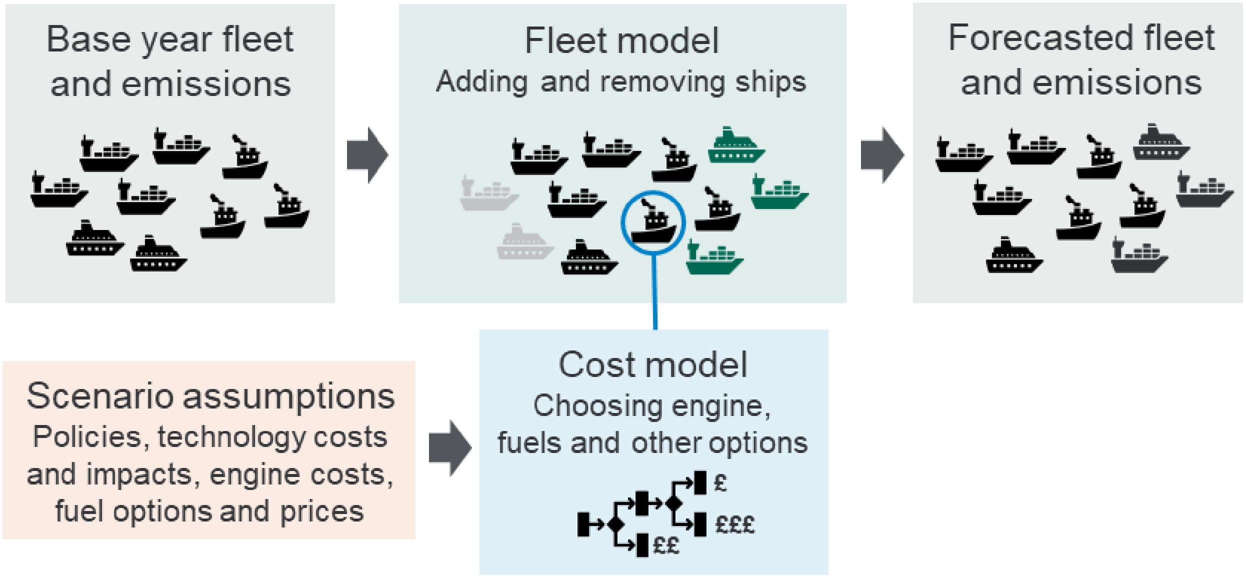

Figure 3 Diagram of fleet and cost models

Fleet model

Inputs

5.4 The **2019 emissions estimates**, as described in Section 2, are aggregated to ship level. This data is the starting point of the fleet model and each ship in this data is simulated over time. This data provides:

- Ship details (type, size, age, engine);
- Mileage and amount of transport work done (size multiplied by mileage);
- Fuel consumption by fuel type and operational mode, split into main engine primary fuel, main engine pilot fuel and auxiliary engines / boilers;
- Emissions by emission type and operational mode, split into main engine primary fuel, main engine pilot fuel and auxiliary engines / boilers;
- UK domestic operating profile (either all activity is UK domestic, some activity is UK domestic, or no activity is UK domestic);
- UK-EU operating profile (all activity is UK-EU journeys, some activity is UK-EU journeys, or no activity is UK-EU journeys);
- UK-RoW (rest of world, any country that is not EU or UK) operating profile (all activity is UK-RoW journeys, some activity is UK-RoW journeys, or no activity is UK-RoW journeys);
- EU operating profile (all activity within the EU, some activity within the EU, or no activity within the EU);
- Proportion of emissions that are UK domestic;

- Proportion of emissions that are on UK-EU journeys;
- Proportion of emissions that are on UK-RoW journeys;
- Proportion of emissions that will be covered by the EU's extension of the ETS to shipping.

5.5 **Transport demand forecasts** are an index for each ship type starting in 2019. Details on these forecasts are provided in Section 7. The fleet model defines the amount of work undertaken by the fleet as the sum of size multiplied by mileage, using the size units shown in the table below. The fleet model uses the total work undertaken in the base year by each ship type as the starting point for the demand forecast and applies the indices to these totals.

Ship type	Size Unit
Bulk carrier	DWT
Chemical tanker	DWT
Container	TEU
Cruise	GT
Ferry - pax only	GT
Ferry - ro-pax	GT
General cargo	DWT
Liquefied gas tanker	DWT
Miscellaneous - fishing	GT
Miscellaneous - other	GT
Offshore	GT
Oil tanker	DWT
Other liquids tanker	DWT
Refrigerated cargo	DWT
Ro-Ro	DWT
Service - other	GT
Service - tug	GT
Vehicle	GT
Ship type	Unit
Bulk carrier	DWT

Table 11 Size units used to calculate the amount of work each ship undertakes

5.6 **Size distribution forecasts** for each ship type provide the expected distribution of ships across the size categories (see assumptions table A.3) in each year from 2020 to 2050. Detail on the assumptions used in these forecasts is provided in Section 7.

5.7 The model uses a fixed **lifespan** by ship type. This is currently 25 years for all ship types, based on the standard assumption that ships become uneconomical to operate after 20-30 years[14].

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[14] Timeseries of average ages at demolition for tankers, bulk carriers and container ships were accessed through Clarksons Research's Shipping Intelligence Network. These showed that the average demolition age is normally within the 20-30 years range.

Modelling assumptions

5.8 Ships are only retired when reaching the end of lifespan. This means that ships are not retired if supply exceeds demand. If supply does exceed demand, then the model reduces the amount of work each ship does proportionally. For example, if demand is equal to 95% of supply, then the mileage of each ship is reduced by 5%.

5.9 In the 2019 data there are ships older than 25 years, the fixed lifespan within the model. To avoid having a large number of ships retired in the first year and consequently a large number of new ships in that year, the retirement of these ships is spread over the first five years. Each ship's retirement is determined by its build year, and they are retired only when their age is a multiple of 5. For example, if a ship was 32 years old in 2019, it would be retired in 2022 when it is 35 years old.

5.10 Similarly, we only allow a ship to change their chosen package of technology, operational measures, and engine every five years (although fuels can be selected for each individual year as long as they are compatible with the installed engine). This is also conducted based on build year with the first chance for this happening at the construction of the ship. This assumption reflects the fact that shipowners will not be making significant changes to their ship every year. In addition, it spreads the adoption of technologies and engines over multiple years, avoiding an unrealistic sudden take-up of a technology or engine within one year when it becomes economically viable for a large group of ships.

5.11 When new ships are required to meet demand, they are added to the fleet immediately. This assumes that the ships were ordered in advance of the demand arising.

Annual process

5.12 The model runs through the years 2020-2050 for each ship type individually – there is no interaction between ship types.

5.13 In each year, the model follows this process:

1. Ships that have reached the end of their lifespan are removed from the fleet.

2. Ships that are due to have their engines, technologies and operational measures reassessed are passed to the cost model to determine the most cost-effective options.

3. The amount of work supplied by the fleet (the sum of size multiplied by mileage) is calculated, taking into account any operational measures that reduce the amount of work a ship can do (i.e. speed reductions). This is then compared to the transport demand forecast (calculated using the indexed forecast and the amount of work in 2019).

4. If supply exceeds demand, then the mileage of each ship is reduced.

5. If demand exceeds supply, then new ships are added to the fleet until demand is met.

Adding new ships

5.14 When a new ship is added to the fleet, the model needs to calculate a full set of characteristics for that ship. These are generated based on distributions and averages in the 2019 data for the relevant segment of ships.

5.15 The characteristics are generated in this order:

1. **Size category**: Calculated based on the size distribution forecast by minimising the gap between the forecasted distribution and the simulated fleet's distribution in the year being modelled.

2. **Size subcategory**: Each size category is split into ten subcategories[15]. Ships are allocated to a subcategory based on minimising the gap between the distribution in the base year within the size category and the simulated fleet's current distribution.

3. **Size**: The average gross tonnage and deadweight tonnage for the size subcategory is used when a specific size is needed, for example when there are size thresholds for regulations.

4. **Fuel and engine type**: As an initial condition, each ship is allocated a fuel and engine type based on the most common fuel and engine type for that ship type and size subcategory in the base year. The main engine power and design speed is based on the averages for the ship type and size subcategory.

5. **UK domestic, UK-EU, UK-RoW and EU operating profile**: Operating profiles, including proportion of emissions covered by each category, are generated based on the distribution of ships of the same type and size subcategory in the base year.

6. **Mileage, fuel consumption and emissions**: These are based on the average values by ship type, size subcategory, fuel type, and UK/EU operating profile.

5.16 After these characteristics have been generated, new ships are then passed to the cost model. This identifies if a different engine type and fuel should be chosen based on costs and regulations in the year being modelled, as well as any technologies or operational measures that should be added.

Cost model

5.17 The cost model is used to determine the take up of fuels, technologies, and operational measures for an individual ship.

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[15] The subcategories are generated using the Jenks natural breaks classification method, a type of data clustering analysis.

Options considered

5.18 The cost model considers a range of abatement options for a ship. Full details on these options and their assumptions are given in Sections 6 and 7.

5.19 The technologies and operational measures are binary measures e.g. whether or not to install a technology. Each has an assumed impact on fuel consumption and emissions as a percentage of total fuel and emissions. These measures are restricted to ship types based on their assessed viability and the model also takes into account incompatibility between some measures.

5.20 There are a range of engines considered. These are either newbuild options or retrofit options. Each engine has a set of compatible fuels (or fuel blends). The model considers each fuel option for each engine, as well as an option selecting the cheapest compatible fuel in each year and the lowest CO_2 compatible fuel in each year.

Cost calculation

5.21 The costs of each option are calculated using a net present value approach. This puts more weight on short term costs. This calculation captures the additional costs for each option, which allows them to be compared, but does not calculate the full costs of a ship.

5.22 The cost is calculated using:

- Capital costs: The cost of installing a technology or engine. For engines, this also includes a fuel storage systems cost to account for the higher storage costs associated with some fuels.

- Operational costs: Any additional operating costs associated with the option (excluding fuel costs).

- Fuel costs / change in fuel costs: For engine and fuel combinations, this is the total cost of the fuel consumed. For technologies and operational measures which change the amount of fuel consumed, this is the change in fuel costs due to the technology / operational measure.

- Emissions Trading Scheme (ETS) costs[16] or carbon prices: For engine and fuel combinations, this is the total ETS or carbon cost of the fuel consumed. For technologies and operational measures, this is the change in the cost relating to the change in the amount of fuel consumed caused by the take-up of the measure.

5.23 For newbuild ships, the costs are calculated over the next 15 years. For existing ships, the costs are calculated over the next 5 years. A discount rate of 10% is

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[16] Emissions trading schemes set a cap on the total amount of certain GHGs that can be emitted by sectors covered by the scheme. Within this cap, participants receive free allowances and/or buy emission allowances at auction or on the secondary market. In the context of the model, ships must buy allowances for their GHG emissions if they are covered by an ETS. This translates into a cost per tonne of fuel calculated from the ETS price and the GHG content of the fuel.

applied. These were chosen as relatively conservative assumptions, with a high amount of short-term thinking and a large weight on upfront capex costs, which reduces the impact of potential policies.

5.24 Ships are often owned by one company and then leased to others to operate them (charterers). This means that the owner does not directly benefit from some of the options, such as improving energy efficiency, as the charterer pays for fuel, but does have to pay the capital costs. The owner may be able to accrue some of the savings through an increased charter rate, but studies show that this is limited[17]. There is also uncertainty around the level of savings these technologies would achieve, which may reduce their weight in the decision-making process. To account for this, when calculating the total cost of energy efficiency technologies, the model only considers 50% of the fuel cost and ETS / carbon price savings. This barrier is only applied to technologies and not operational changes, as operational changes would be decided by the operator who directly benefits from the reduced fuel consumption.

Selection of options

5.25 The cost model aims to select the lowest cost combination of options which complies with any regulations, such as energy efficiency measures and fuel standards. However, it is not possible to test every combination of options due to the computational time required and therefore a heuristic optimisation approach is used. This means that the cost model produces a good combination of options, but it may not be the best possible combination.

5.26 The algorithm adds options based on cost and compliance with two types of IMO regulation:

- The Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI) regulations require a minimum energy efficiency level per capacity mile for different ship type and size segments.
- The Carbon Intensity Indicator (CII) is an annual rating of a ship's operational carbon intensity (carbon per capacity mile) on an A-E scale and ships must implement a plan of corrective action if they are rated D for three consecutive years or E for one year.

5.27 Other policy measures are factored into the algorithm either as part of the cost (for example, carbon pricing) or by restricting the options available (for example, fuel standards). See Section 7 for more information on how the policy measures and IMO regulations are modelled.

5.28 The heuristic optimisation algorithm is as follows:

1. If EEDI or EEXI regulations apply to the ship, the model estimates the ship's energy efficiency. If the ship's energy efficiency falls below the level required over the time period being considered (15 years for newbuild, 5 years for existing ships), then the model adds the option with lowest cost per improvement in energy efficiency. It keeps adding options until the EEDI or EEXI requirements are met.

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[17] www.sciencedirect.com/science/article/pii/S0965856414001189

2. If CII regulations apply to the ship, the model estimates the ship's CII. As a conservative assumption on compliance, if the ship has 10 years or less remaining, then the model assumes it will aim for a D rating. Otherwise, the ship aims for a C rating. If the ship scores below the desired rating at any point over the time period being considered (15 years for newbuild, 5 years for existing ships), then the model adds the option with the lowest cost per carbon reduction. It keeps adding options until the desired rating is achieved in every year.

3. If there are any options that reduce costs without worsening the CII / EEDI / EEXI results, then the model adds the option with the largest cost saving. It keeps adding options until there are no cost savings left.

4. It is possible by the end that the model may have overshot the CII / EEDI / EEXI. For example, it may select a very cheap abatement option with a small impact first then have to select a more expensive option with a large impact that can meet a CII requirement by itself. To correct this, at the end the model looks at all technologies and operational measures which have been selected, from highest cost to lowest cost, and removes any that can be removed while still meeting CII / EEDI / EEXI requirements.

Limitations

5.29 There are several limitations to the modelling approach.

5.30 The fleet model uses distributions and averages from the base year fleet to generate many of the characteristics for new ships, including their areas of operation. This means that we do not assume any significant changes in the make-up of the fleet or where ships operate, beyond the high-level size distribution.

5.31 In terms of the way options are assessed within the cost model:

- When deciding on options, the model considers costs and regulation, but there are other factors that can be important in ship owner and operator decision making. These include fuel availability, safety procedures, customer perceptions, and labour supply. However, engagement with industry did highlight cost and regulations as the two most important factors.

- Ship owners and operators do not necessarily assess costs on a net present value basis. There is some evidence from ship owners and operators that the most often used investment appraisal tool is payback periods. However, actual decisions do not always reflect this. For example, energy saving lighting has a high take-up despite its long payback period.[18] This may be due to the other factors that influence these decisions.

- The time period ship owners and operators consider and the weight they put on short-term costs will vary depending on the nature of their operations. Engagement with industry highlighted that some operators have more certainty about the routes they operate on (such as ferry operators) and therefore can make longer term plans, including on decisions such as fuel. Other operators may operate with greater

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[18] www.sciencedirect.com/science/article/pii/S0029801817302160

uncertainty about their future areas of operation and revenue and may require short payback periods for any investment. The model uses relatively conservative assumptions with more short-term thinking. We have also conducted sensitivity analysis on the time period and discount rate assumptions, and these do not significantly change the results.

6. Fuels, Technologies, and Operational Measures

6.1 The model includes a set of fuel and engine options, as well as technologies and operational measures that can reduce emissions.

Fuels

6.2 The model includes 13 core fuels covering fossil fuels, biofuels, and hydrogen / hydrogen-derived fuels (synthetic fuels), plus battery electric. All hydrogen in the model is assumed to be liquid hydrogen, although compressed hydrogen could be used by some sectors.

Fossil fuels	Biofuels	Synthetic fuels
LSFO	LSFO	Hydrogen
MDO	MDO	Ammonia
LNG	LNG	MDO
Methanol	Methanol	LNG
		Methanol

Table 12 Core fuels included in the model

6.3 These are included by themselves and as combinations. These represent both blends of fuels, but also switching between fuels within a year. For example, a 75% MDO / 25% synMDO combination could be a ship operating on a blend composed of 75% MDO and 25% synMDO, or it could be running entirely on MDO 75% of the time and entirely on synMDO the rest of the time. These are treated the same within the model.

6.4 The combinations included in the model are:

- Fossil / biofuel mix: Blends of fossil and biofuels of the same type (e.g. MDO and bioMDO). The model includes 10%, 20% and 30% biofuel blends.

- Fossil / synthetic fuel mix: Combinations of fossil fuels and a synthetic version of the same fuel (e.g. MDO and synthetic MDO). The model includes 25%, 50%, 75% and 90% synthetic fuel options.

- Dual fuel mix: Combinations of Ammonia or Methanol with MDO, representing the flexibility that dual fuel engines have in using either their primary fuel or MDO. The model includes 10%, 25%, and 50% MDO options.

6.5 Detailed below is a short summary of each category of fuel included in the maritime emissions model.

Biofuels

6.6 Biofuels have very similar properties to regular diesel and therefore can be used by the same technologies and engines that use diesel to power a vessel. Biofuels can be produced from a range of biomass feedstocks (materials of biological origin) such as plant oils, animal fat or waste biomass and can be categorised into 3 generations: first, second and third. These generations differ in the sustainability of the feedstock used to produce the fuel. A first-generation fuel is produced using edible vegetables oil or animal fats that are otherwise used for food. A second-generation fuel is produced from lignocellulosic biomass or waste streams such as agricultural residues and used cooking oil. Whereas a third-generation biofuel is produced using non-food feedstocks that have a high yield and rapid growth rate, for example algae, and is therefore considered more sustainable.

6.7 Currently, the emissions model does not consider the specific source of biofuel and instead categorises them by the fossil fuel that they would replace: MDO, LSFO, LNG or methanol.

Hydrogen

6.8 Hydrogen can be used as a fuel either in fuel cells or hydrogen combustion engines. Hydrogen fuels can be produced using two main methods. Blue hydrogen is produced by separating hydrogen from natural gas using steam methane reforming, with subsequent capture and storage of the CO_2 produced. Alternatively, green hydrogen is produced by using renewable energy to separate hydrogen from water. Green hydrogen has the potential to be a zero-carbon fuel from Well to Wake (WtW) when produced using renewable energy.

Ammonia

6.9 Ammonia has significant potential as an alternative maritime fuel to help aid decarbonisation. Ammonia can be produced using two different methods. Blue ammonia is produced by reacting nitrogen gas, obtained from the atmosphere through air separation, with hydrogen gas, obtained through the separation of natural gas where the CO_2 is captured by carbon capture and storage (CCS). Green ammonia, also referred to as e-ammonia, is produced using renewable energy to separate water from hydrogen from water and reacting this with nitrogen gas.

Synthetic fuels

6.10 In addition to ammonia, the model includes other hydrogen derived or synthetic fuels. These electro-fuels (also known as power-to-liquid/gas) are fuels produced from combining blue or green hydrogen with a carbon source to form synthetic versions of conventional fossil fuels i.e. e-diesel, e-methanol and e-methane. These fuels can have net zero CO_2 emissions assuming the carbon source is taken from the atmosphere or as part of a sustainable cycle, although they may still produce small amounts of other GHGs that are not offset by their production.

6.11 As with biofuels, these have the advantage of being ‘drop in’ fuels which are compatible with existing maritime infrastructure. The model includes ‘drop in’ synthetic fuels for MDO, LNG and methanol.

Electric

6.12 Rechargeable batteries stored on ships can allow for electricity to be used as a fuel for propulsion and other activities. If the batteries are charged using renewable energy, then electric ships could be a zero-carbon solution. There are several examples of batteries that have been suggested as potential solution, including lithium or sodium ion batteries.

6.13 Within the model, only fully electric options are considered. Hybrid battery options have not been considered at this stage, but we will explore these in future model development.

Engines

6.14 The model includes a range of engines:

- Conventional compression ignition engines using MDO or LSFO.
- Dual fuel engines for LNG, methanol, ammonia, and hydrogen. These use MDO as a pilot fuel.
- Spark ignition engines for methanol, ammonia, and hydrogen.
- Solid oxide fuel cells (SOFC) and proton-exchange membrane (PEM) fuel cells using either direct hydrogen or indirect hydrogen using LNG, methanol, or ammonia.
- Battery electric propulsion.

Other abatement options

6.15 The model considers a range of technologies and operational measures, which can improve energy efficiency and reduce emissions.

Technology / operational measure	Description	Technology readiness level (TRL)[19]
Air Lubrication Bubbles	Introduction of air bubbles under the ship's hull to reduce friction and improve energy efficiency.	Early adoption stage: technically ready but for a limited number of vessels
Wind assistance (kites, rotors, sails, or wings)	Use of wind-powered devices to assist ship propulsion and reduce fuel consumption.	Demonstration/Early adoption stage: Some technology is technically ready but for a limited number of vessels
Waste Heat Recovery Systems	Use of waste heat from a ship's engine to power an alternator or electricity for auxiliary power.	Early adoption stage: technically ready but for a limited number of vessels
Rudder Bulbs	A bulbous protrusion fitted to the rudder of a ship designed to improve hydrodynamics by reducing flow separation and drag.	Mature: Proof of stability reached
Pre-swirl propeller ducts	A device fitted around the propeller designed to increase the inflow velocity, leading to increased propulsive efficiency.	Mature: Proof of stability reached
Vane Wheel	A rotating disc fitted to the stern of a ship designed to increase propulsive efficiency by reducing rotational losses.	Mature: Proof of stability reached
Contra rotating propeller	A system in which two propellers rotate in opposite directions on a single shaft, increasing propulsion efficiency.	Mature: Proof of stability reached
Twisted rudders	Rudder design that is twisted along its length to improve manoeuvrability and reduce drag.	Mature: Proof of stability reached
Boss cap fins	A small fin mounted on the hull near the propeller, used to reduce turbulence and increase propulsive efficiency.	Mature: Proof of stability reached
Turbo compounding in series	A system in which waste heat from the engine is used to drive a turbine, which then powers a generator to produce electricity.	Development: Prototype system built and tested in a simulated environment
Solar power	The conversion of sunlight into electricity using photovoltaic (PV) cells or panels stored onboard a vessel.	Demonstration: Prototype system built and validated in a marine operational environment
Energy saving lighting	The use of energy-efficient lighting systems to reduce energy consumption and operating costs.	Mature: Proof of stability reached
Energy derating	The reduction of engine power to improve fuel efficiency and reduce emissions.	Mature: Proof of stability reached
Energy Storage Battery and PTO	A system that uses batteries to store electrical energy use it to power the propeller shaft (as a hybrid vessel) or for auxiliary purposes.	Early adoption: solution available commercially but needs further integration efforts to achieve full potential
Hull coating management	Management of the ship's hull coating to prevent corrosion and reduce biofouling.	Early adoption: solution available commercially but needs further integration efforts to achieve full potential
Trim optimisation	Adjusting the angle of a ship's hull to achieve the most efficient balance between speed, fuel consumption, and stability.	Early adoption: solution available commercially but needs further integration efforts to achieve full potential
Draft/displacement optimisation	Adjusting the weight and balance of a ship to achieve the most efficient draft and displacement, improving speed, fuel consumption, and stability	Early adoption: solution available commercially but needs further integration efforts to achieve full potential
Speed optimisation	The reduction of ship speed to reduce fuel consumption and emissions.	Mature: Proof of stability reached

Table 13 Technologies and operational measures included in the model

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[19] A measure of the maturity of a technology commonly used by researchers, engineers and funding agencies to assess the feasibility and potential impact of a technology.

Options not included

6.16 There are other potential measures that are not currently included in our modelling. These include:

- Onboard Carbon Capture and Storage (OCCS)
- Nuclear power
- Exhaust treatment technologies
- Hybrid battery electric
- Shore power
- Fuels with negative WtW GHG emissions

6.17 It has not been possible to include these in the model at this stage of development. For some this is due to a lack of evidence and early state of the technology. For others, such as shore power and hybrid battery electric, this is because these are more complex to model than other options and will require further stages of model development.

6.18 In addition, this initial model development stage has focussed on modelling greenhouse gas emissions. As a result, emissions capture technology that focuses on reducing air pollutants has not been modelled at this stage.

7. Forecasting Assumptions

7.1 This section sets out how we produced the assumptions used in the forecasts and the sources we used for this. Published alongside this document is a spreadsheet containing the detailed figures for all assumptions (tables A-H).

7.2 As part of the development of the model, we commissioned research to review existing evidence and provide recommendations for a range of assumptions required within the model. This research included a series of stakeholder interviews with a mixture of academics, engine manufacturers, fuel suppliers, vessel classification societies and technology providers, to identify evidence and data that could be used to produce input assumptions. This research was the main source for most of the assumptions. There is more information on this research in Section 3.

7.3 We also held industry workshops where stakeholders provided feedback on the methodology, key assumptions, and draft results. We made several updates to the assumptions in response to this feedback.

7.4 Many of the assumptions on future engines, fuels and technologies have limited evidence, reflecting the early stage of development. We will keep these assumptions under review and update them as the evidence develops. We would welcome any feedback and particularly any evidence that supports alternative assumptions.

Uncertainty

7.5 There is significant uncertainty surrounding many of the assumptions used within the forecasts. We have considered low, central, and high assumptions for the model inputs. We have the flexibility within the model to consider different combinations of these and we have conducted uncertainty analysis using these ranges.

7.6 For general uses, we have combined the key assumptions into best- and worst-case scenarios for emissions as shown in the table below.

Uncertainty factors	Best case for emissions	Worst case for emissions
Freight demand	Low	High
Non-freight demand	Flat	Growing
Technology costs	Low	High

Uncertainty factors	Best case for emissions	Worst case for emissions
Technology effectiveness	High	Low
Emissions prices	High	Low
Fuel prices	Low hydrogen and hydrogen-derived fuel prices, high fossil fuel prices	Low fossil fuel prices, high hydrogen and hydrogen-derived fuel prices

Table 14 Assumptions used in best- and worst-case scenarios

7.7 There is also significant uncertainty about future fuels. We have produced five fuel mix scenarios in the model, which involve limiting biofuels, restricting ammonia engines to certain ship types, and using low and central battery cost assumptions. These fuel mixes are designed to reflect a wide range of possible outcomes and are not an indication of government policy.

Fuel mix scenario	Ammonia assumption	Battery assumption	Biofuel assumption
Balanced mix	Only allowed for freight ships	Central battery costs	Max 30% blend allowed, other than for pilot fuels
More ammonia	Only allowed for freight ships and large passenger ships	Central battery costs	Max 30% blend allowed, other than for pilot fuels
No ammonia	Not allowed for any ships	Central battery costs	Max 30% blend allowed, other than for pilot fuels
More battery electric propulsion	Only allowed for freight ships	Low battery costs	Max 30% blend allowed, other than for pilot fuels
More biofuel	Only allowed for freight ships	Central battery costs	100% biofuel use allowed

Table 15 Fuel mix scenarios and associated assumptions

7.8 In combination, these two sets of scenarios cover the key sources of uncertainty. We will continue to review these as the evidence for the assumptions develops and we may explore other scenarios in the future.

Fuel assumptions

7.9 The fuels and fuel blends / combinations included in the model are shown in assumptions table B.1.

Blue / green profile

7.10 The synthetic fuels included in the model can be produced using blue or green methods. The blue and green versions of fuels have different upstream emissions and prices.

7.11 The model uses a fixed blend of blue and green fuels in each year to simplify the options. The current assumption used in the model is that 100% of synthetic fuels are produced using blue process in 2020, with the green proportion growing until it reaches 100% in 2050. This is shown in assumptions table B.2. This simplistic assumption is used to simplify the fuel choices. In practice, the blue / green proportion of fuel will vary depending on where ships are refuelling, which is not currently modelled.

Prices

7.12 We produced a price for each fuel type in 2020 based on a combination of evidence sources. These base prices and their sources are in assumptions table B.3.

7.13 The synLNG prices used in the model are the same for blue and green sources. This was due to a lack of evidence that distinguished between the two. We will work to improve this assumption but, given the low take-up of synLNG in the model, this is unlikely to have a significant impact on the results.

7.14 We were unable to identify sources for prices for bioLSFO, blue synMethanol, and blue synMDO. We produced 2020 prices for these using simplistic assumptions by scaling other prices.

7.15 To forecast prices, we produced simplistic trends which are applied to the 2020 prices. A simple approach was chosen as full modelling of fuel prices and supply is beyond the scope of the existing model. In addition, future fuel prices are highly uncertain, so a more sophisticated approach is not guaranteed to provide more accurate forecasts, and we have instead reflected the uncertainty with high and low forecasts.

7.16 These trends were designed to align with the existing research on future fuel prices. This includes:

- DESNZ fossil fuel price assumptions;[20]
- Research conducted for the department by UMAS, UCL, and E4tech (currently unpublished);
- Research by Lloyds Register and UMAS.[21]

7.17 For electricity, we used the volume weighted wholesale electricity price forecast from the DESNZ Energy and Emissions Projections[22].

7.18 As noted above, future fuel prices are highly uncertain, particularly for alternative fuels given that the production of these fuels is at an early stage of development. The prices will also be influenced by the demand for the fuels from the shipping sector and other sectors. The fuel prices have a significant impact on the results of the model, particularly the fuel mix. This is reflected in the uncertainty analysis set out above. The best- and worst-case scenarios explore the impact that higher or lower low carbon fuel prices have on the level of emissions. The fuel mix scenarios are produced mainly by restricting fuels, but the wide range of fuel mixes they capture also covers the range that could be produced by a different balance of fuel prices (for example, a higher ammonia price and lower synMethanol price would produce a fuel mix between the balanced mix and no ammonia scenarios).

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[20] www.gov.uk/government/publications/fossil-fuel-price-assumptions-2019
[21] www.lr.org/en/knowledge/research-reports/techno-economic-assessment-of-zero-carbon-fuels/
[22] www.gov.uk/government/collections/energy-and-emissions-projections

Emissions factors

7.19 The 2019 estimates used tank-to-wake emissions factors by engine type and fuel type, as set out in Section 2. For use in the forecasts, these emission factors were simplified by using average emissions factors for each fuel and ignoring the engine type (assumptions table C.2). To ensure continuity with the 2019 emission estimates, when a ship changes fuel, the emissions are scaled using the proportional difference in the emissions factors of the old fuel and the new fuel. These factors are assumed to be constant over time.

7.20 There is significant uncertainty about emissions from alternative fuels and engines. In particular, there is some evidence that hydrogen will produce some NO_x and N_2O emissions due to high temperature combustion in air[23]. But this evidence is very limited, and it was not possible to produce NO_x and N_2O emission factors for hydrogen. Therefore, we have treated these as zero in the forecasts, but we have undertaken some sensitivity analysis using the LSFO N_2O and NO_x emission factors for hydrogen as a worst-case estimate.

7.21 The well-to-tank GHG emissions factors used in the forecasts are the same as those used in the 2019 estimates (assumptions table C.3). They are assumed to decline over time, as the fuel production and transport sectors decarbonise.

7.22 We have treated biofuels and synthetic fuels as having zero CO_2 emissions as these are assumed to be offset in the production of the fuel. As noted in Section 3, under IPCC guidance on GHG inventories, biofuels can be treated as zero CO_2 on a tank-to-wake basis but reporting practices for synthetic fuels are currently undefined.

Availability

7.23 We do not model the supply of fuels and generally assume that fuels are available when required. The model does allow for fuels to be excluded from the options in each year or to be restricted to only be used as a pilot fuel. We have used this to explore scenarios where certain fuels are not available, for example by only allowing 100% biofuels to be used as pilot fuel reflecting a scenario with limited biofuel availability.

Engine costs

7.24 Assumptions on the costs of engines were produced by the consortium of consultants as part of work producing assumptions for the 2019 estimates. These are shown in assumptions tables E.1 and E.2.

Capital expenditure (CapEx)

7.25 The CapEx cost is based on buying the engine from an engine supplier. This will include the engine components themselves and the commissioning of the engine, and whether the engine be on a newbuild ship or retrofitted. This information is

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[23] For example: https://www.gov.scot/publications/nitrous-oxide-emissions-associated-100-hydrogen-boilers/

commercially sensitive with many engine manufacturers unwilling to give costing data. Engine CapEx costs are highly project specific and are normally subject to a large amount of negotiation. The CapEx costs used in the model are from a combination of academic studies, engine quotations obtained by the consultants for previous projects, and press releases.

7.26 Spark ignition engines that burn alternative fuels are in various stages of development. Methanol is currently available and is in process of being scaled up. Ammonia will follow shortly, whereas Hydrogen ICEs are still in the very early stages of development and are anticipated to be available in different sizes and powers between 2030 and 2040. Due to these factors, there is limited reliable cost data on the alternative fuel engines. Mechanically, the spark ignition engines will all operate on the same principles regardless of the fuel being burnt. The subtle difference will be in the combustion control, fuel handling and storage systems, however this is not anticipated to have a large impact on the overall price per kW installed. Therefore, the price of a spark ignition engine has been assumed as the same for all fuels but the date they will be commercially available for vessel owners is different.

Operational expenditure (OpEx)

7.27 OpEx costs are associated with routine maintenance, lubricants, spares, and maintenance person hours, and are presented as a cost per year per kW. OpEx will not be constant year on year due to aging machinery requiring more maintenance and running cost increasing as the engine gets less efficient as it gets older. However, as this decline is too variable to assess over an entire fleet, a constant rate is used.

7.28 Engines are usually subject to periodic major overhauls with the time intervals between overhauls suggested by the manufacturers and are usually based on engine running hours (typically between 30,000-45,000 hours). The cost for these major overhauls has been accounted in the average OpEx. The operational cost of running an engine is dominated by the labour cost, with spares, lubricants, tooling, etc. making up a very small proportion of the overall cost.

7.29 For all internal combustion engines in this study, a high (3%) and low (1%) estimate for OpEx is presented as a percentage of the CapEx. This corresponds to the range of operating cost found during the research phase.

7.30 Due to the emerging nature of fuel cells, there is limited long term data to inform the OpEx for a fuel cell powered vessel. For this study the same high and low estimates are assumed. This is to reflect the cost reducing over time as the technology becomes more established and the personnel become more familiar with the technology. Fuel cells are currently a specialist piece of equipment but as they become more common it is assumed that the workforce will become more familiar with the technology and the OpEx costs will reduce.

New build

7.31 New build cost has been assumed as the price of the engine plus the labour to commission engines during a newbuild programme. Drydock and other shipyard costs have not been included as these are assumed to be accounted for in the wider vessel build cost.

Retrofit

7.32 Retrofitting has been split into two categories: replacement and conversion. A replacement is when the entire engine is decommissioned, removed and a new unit installed in its place. A conversion is when the existing engine is converted from one fuel type to another (or to dual fuel).

7.33 Some engines are more suitable to replacement than conversion. For example, high speed engines tend to be smaller and easier to remove, so the labour cost for conversion would be high compared to the cost of a new engine: accordingly, owners would tend towards an engine replacement. Many high-speed engines are designed to be removed and reconditioned by the manufacturers after a set number of running hours to prolong the overall life. On the other hand, it is not feasible to replace a large 2 stroke engine due to the complexity of its removal from the vessel, so conversion is preferable. Assumptions table E.4 shows the assumptions used on the model on which engines would be replaced or converted.

7.34 The price of replacing an engine has been calculated by adding the price of a new build engine to an estimation of the dry docking and labour cost associated with removing an old engine and installing a new one. These costs have been estimated from academic papers and industry articles where available.

7.35 The prices for conversions have been taken from publicly available information from vessel conversions. Converting existing diesel engines to run on dual fuel is a growing market with several projects completed and many more in the pipeline.

Prices forecasts

7.36 Forecasting the CapEx price of engines is dependent on many factors, including demand for fuel type, raw material supply chain, inflation, shipbuilding capacity, and regulatory pressures. As a result, price forecasts contain a considerable uncertainty. The following methodology and assumptions are made for forecasting prices.

7.37 For ICEs, the “commercially available date” has been assumed to be when engine manufacturers say they will have a new product available, plus five years. This five–year interval is to account for the first of its kind being installed, trialled at sea, and commissioned, plus time to prove the engine in an operational environment. Once proven it is anticipated that more vessel owners will consider placing orders. We have assumed that it would take another 5 years after the commercially available date before there would be wide take-up in the active fleet (i.e. factoring in the time for wider ordering and the build time of the ships).

7.38 Once the demand for engines increases, the price is assumed to gradually decrease until it is comparative with a well-established technology (engines running on conventional fuel oil). This duration has been assumed as 25 years, which is the typical life cycle of a ship and therefore the time for the new technology to displace old technology. The price of well-established engine technologies that use conventional fuels is assumed not to change. There could be marginal development but nothing on the scale that will affect the price significantly.

7.39 The price of marine fuel cells has been assumed to follow the same trend as automotive fuel cells over the past 20 years. As the R&D effort increases the cost will quickly fall and then begin to level off as the production scales up. This initial fall has been around 60% in the first 10 years of development in the automotive sector. Due to the relatively smaller size of the marine fuel cell market the trend will begin to level off faster than what has been seen on in other sectors. Economies of scale will not have as large an impact with the smaller production numbers.

7.40 PEM fuel cells with onboard hydrogen production have been assumed to always be slightly more expensive in terms of CapEx due to the purchase of the methanol reformer or ammonia cracker. However, depending on the fuel availability and price, the OpEx could be lower and offset this.

7.41 Although a promising technology SOFC's are around 10 years behind the PEM fuel cell development. Their initial development has been assumed as 10% faster due to the lessons learnt and increased demand compared to initial PEM development 10+ years ago.

Limitations

7.42 Future cost data for any engine technology is difficult to predict due to the large number of variables, such as material costs, demand, economies of scale, and improvements in manufacturing processes. This is further complicated by engine technologies still being at the research and development or even theoretical stage of development. Projected costs are therefore best estimates based on the following assumptions:

- There are no significant changes to material costs other than inflationary (inflation not being included in the data provided).
- There is a demand for the technology in the future and this is sufficient to drive savings from economies of scale over a typical life cycle; and,
- Improvements in manufacturing are consistent with improvements seen in the past with the development of diesel engines.

Other engine assumptions

Main and auxiliary engine combinations

7.43 To simplify the modelling, we have assumed that new engine installations use a limited set of main and auxiliary engine combinations. These are based on an assumption that the main and auxiliary engines are likely to use the same primary fuel and that auxiliary engines are typically 4 stroke medium speed engines. These combinations are shown in assumptions table E.3.

7.44 Auxiliary engine power is used to calculate the cost of auxiliary engines and was not available for many ships in the fleet data. Therefore, we could not use averages when generating new ships, as is done for the main engines. Instead, the auxiliary engine power is calculated based on the main engine power using a ratio of main engine power to auxiliary engine power. The ratios used are shown in assumptions table E.5. These are based on two sources: the IMO 3rd GHG study (Annex table 6)[24] and a US EPA study (table 5)[25]. The figures from both sources were compared with ratios from the fleet data where auxiliary engine power was available, and judgement was used to determine which source to use for each ship type.

Fuel options

7.45 Each engine type has a set of fuels that are available. The compatibility of engines and fuels is shown in assumptions table E.8.

7.46 We have assumed that MDO or a drop-in substitute for MDO (biofuel or synthetic) is always used as pilot fuel in dual fuel engines. In addition, we currently assume that dual fuel engines use their primary fuel at least 50% of the time. We will look to refine this assumption in the future.

Fuel storage costs

7.47 In addition to the capex cost of an engine, the model considers the costs of fuel storage systems. These assumptions were produced by ship type and size category for each primary fuel. They are based on estimates of the volume of storage required and costs per cubic meter. The volume and cost figures are shown in assumptions tables E.6 and E.7.

7.48 The fleet data provided the volume of storage for conventional fuels for some ships. Averages by ship type and size category were calculated. We have converted these into volumes for alternative fuels by assuming that the total space occupied by fuel storage would be the same as conventional fuels. This is calculated by using the volumetric efficiency of fuel storage systems i.e. the ratio between the maximum fuel volume that can be carried and the total volume of the fuel storage, accounting for lost space around cylindrical tanks and excess space for boil-off.

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[24] www.imo.org/en/ourwork/environment/pages/greenhouse-gas-studies-2014.aspx

[25] www3.epa.gov/ttnchie1/conference/ei15/session1/browning.pdf

7.49 The volumetric efficiency of the liquid hydrogen, LNG and ammonia tanks was derived from a design for an LNG tank for a fishing vessel[26]. Cryogenic tanks require space for boil-off and industry standard practice is to use only 0.85 of an LNG tank's total capacity, which also means the tank is never fully empty and therefore remains at the correct temperature for refuelling. This assumption was also used for liquid hydrogen and ammonia. For methanol, we assumed the same volumetric efficiency as conventional fuels.

7.50 In addition, we have made an assumption on the proportion of fuel storage that would be primary fuel and pilot fuel. These values were based on previous research for minimum pilot fuel for reliable engine operation. In practice, operators may choose to carry much more conventional fuel so that they can operate entirely on conventional fuel with reasonable range if the primary fuel is not available. We will explore alternative assumptions in the future, as part of the work to consider greater usage of MDO fuel by dual fuel engines.

	Storage cost (£/m3)	**Volumetric efficiency of fuel store (fuel volume:total fuel store volume)**	**Primary fuel fraction by energy**
Conventional fuel	49	1	1
Liquid hydrogen	5549	0.496	0.75
Methanol	97	1	0.95
Ammonia	608	0.496	0.95
LNG	3013	0.496	0.99

Table 16 Assumptions used to calculate fuel storage costs

7.51 The costs per cubic meter were taken from various sources, with the final values selected for a representative size of ship and converted into 2023 prices:

- LNG: Costs for 86m^3 and 1,800m^3 storage systems were taken from a report by Argonne Laboratory and the US Department of Energy[27]. The value used in the assumptions is an interpolated figure for a 1,750m^3 system, which is close to the average bunker capacity for the vessel types modelled.

- Liquid hydrogen: Costs for 190 m^3 and 3300m^3 storage systems were taken from the same source used for LNG. As with LNG, the value used in the assumptions is an interpolated figure for a 1,750m^3 system.

- Ammonia: Costs were taken from a report by ABS, CE-DELFT and Arcsilea[28] for 3,500GJ and 71,300-74,600GJ tanks. As for LNG, the value used in the assumptions is an interpolated figure for a 1,750m3 system.

- Conventional fuel: A figure for LSMGO was taken from the source used for LNG and liquid hydrogen.

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[26] https://doi.org/10.1016/j.trd.2016.10.032

[27] www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-viii5-ahluwalia.pdf

[28] https://cedelft.eu/wp-content/uploads/sites/2/2022/12/CE_Delft_EMSA_210113_Ammonia-as-fuel-in-Shipping_FINAL.pdf

- Methanol: No data could be found for methanol. The main costs are a zinc-based coating in the tanks to prevent corrosion, a double-walled piping system, and an inerting system for the tanks. At scale, these are not significant costs. We have therefore used an estimate of double the cost of a conventional fuel storage system.

Battery costs

7.52 The model uses assumptions on battery costs for electric propulsion ships in a similar way to fuel storage costs. The assumptions are provided by ship type and size category. We have currently assumed that fully battery electric is only an option for passenger only ferries, offshore sector ships and other service vessels. In practice, the applicability of battery electric and the size of battery required will depend on a ship's operating pattern. Therefore, this is an assumption we want to refine in the future.

7.53 The size of batteries required was based on the average power demand in the 2019 estimates for each ship type and size category. The low, central and high assumptions are the average power demand for 3, 6 and 12 hours respectively.

7.54 Low, central and high estimates of the cost per kWh were produced as part of the work producing assumptions for technologies and operational measures detailed below. The battery size and cost figures are shown in assumptions tables E.6 and E.7.

Restrictions on take-up by ship type

7.55 In addition to the restriction on batteries, the model can also restrict other engines by ship type. We have used this to restrict the take-up of ammonia engines. Ammonia is toxic and particularly harmful to aquatic life, which may mean that installation of ammonia storage will require measures such as exclusion zones and containment mechanisms, as well as specialist training for crew. This would likely make it unsuitable for small ships. This may also pose a challenge for passenger ships and many stakeholders in the passenger industry are cautious about ammonia.

7.56 We have produced three sets of assumptions for ammonia restrictions: no ammonia, ammonia for freight ships only, ammonia for freight and large passenger ships. These are used in the fuel mix uncertainty scenarios. These aim to reflect a wide range of possible outcomes and are not an indication of government policy. The details by ship type and size category are shown in assumptions table E.9.

Technologies and operational measures

7.57 Assumptions for the modelled technologies and operational measures were produced by consultants as part of the same project that produced engine assumptions. For each of the technologies and operational measures, the following assumptions were produced:

- Technology readiness level assessment

- Current cost per key variable for each technology and operational measure
- Forecasted costs
- Viability when paired with each of the other technologies and operational measures
- Viability to the different ship types
- Impact on air pollutant emissions and fuel consumption

7.58 These assumptions were produced from a combination of academic studies, publicly available data and data gathered from stakeholder interviews. Sources were prioritised in the following way:

1. Best Data: Data obtained from recorded trials or directly from manufacturers as it was considered that this information provides the most accurate and reliable estimates for the technologies under consideration.
2. Second-Best Data: Research papers that conduct cost-benefit analyses and predict the costs of the specific technologies. These papers serve as valuable sources for estimating costs.
3. Third-Best Data: Evidence from applications of the technology outside the maritime sector.

7.59 The assumptions produced by the consultants are shown in tables G.2-G.8 and information on these is given in the sections below. These assumptions were shared with industry and academic stakeholders during model development. Based on feedback received and an internal review of the assumptions, some of these were changed. The final complete set of assumptions used in model is shown in assumptions table G.1.

Technology Readiness Level Assessment

7.60 A Technology Readiness Level (TRL) is a measure of the maturity of a technology. It is commonly used by researchers, engineers and funding agencies to assess the feasibility and potential impact of a technology.

7.61 The forecasted TRLs are shown in assumptions table G.7. These were based on the TRL scale used in an IMO study on low and zero carbon technologies[29] and range from 1 to 11, with 1 being the lowest level of readiness and 11 being the highest level of readiness.

7.62 This IMO study was the main source used to understand the TRLs for the technologies. For technologies not covered in the IMO study, TRLs were taken from

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[29] Ricardo/DNV 2023. Study On The Readiness And Availability Of Low- And Zero-Carbon Ship Technology And Marine Fuels. wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/FFT%20Project/Study%27s%20technical%20proosal_Ricardo_DNV.pdf

previous research produced for DfT[30], adapting a 1-9 scale to the IMO 1-11 scale. For technologies with no available data on their TRL score in either source, a score was assigned based on commonly understood maturity levels. For example, for widely available solutions a score of 11 is given.

Costs

7.63 For each technology, the key variable that impacts costs was identified and then current CapEx and OpEx costs per the key variable were produced, where evidence was available. The main source used for costs was the IMO's Energy Efficiency Appraisal Tool[31] which included CapEx, OpEx, and other relevant data.

7.64 Costs were forecasted using assumptions based on technology readiness levels (TRLs). As a technology progresses from a lower TRL to a higher TRL, its cost tends to decrease. This is because, as a technology is developed and tested, its design and manufacturing processes become more efficient and economies of scale may also come into play.

7.65 For each technology, percentage reductions in costs were produced for each TRL. The cost is assumed to plateau when a technology reaches a TRL of 11 of maturity. Three approaches were used to produce these percentage reductions, depending on the data available.

1. Approach one: Forecasted percentage cost reductions were obtained for that specific technology and extrapolated to provide a cost reduction from base year annually.

2. Approach two: When no forecasted data was identified for the specific technologies, the forecasted price reductions of substitute/ similar technologies have been used instead and approach one has then been followed.

3. Approach three: Where no data could be identified, a general assumption of a reduction by 15% from the current TRL up to level 7, and then a reduction by 8% per TRL as prices start to stabilise was adopted.

Viability to the different ship types

7.66 Individual technologies and operational measures are not always applicable to every ship type for a number of reasons, including operational profile, vessel characteristics, and technology characteristics. As such, a mapping of the viability for each technology against each ship type was produced, using a 0-3 scoring system, as shown in the table below. Within the model, only options with a score of 2 or 3 are considered to be viable. This mapping is shown in table G.6.

Score	Definition
3	Clear choice

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[30] https://assets.publishing.service.gov.uk/media/5d25f1b1e5274a585d617fd5/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs.pdf

[31] www.imo.org/en/OurWork/Environment/Pages/Computer-based-model-to-appraise-the-technical-and-operational-energy-efficiency-measures-for-ships.aspx

Score	Definition
2	Relevant
1	Could be made to work but inhibits design drivers
0	Not relevant / viable or is very difficult to apply

Table 17 Compatibility scoring criteria

7.67 The mapping is underpinned by a combination of academic studies, direct data, feedback from stakeholders, and previous studies (including the Maritime and Coastguard Agency's decarbonisation pathways study). Where specific data could not be identified, proxies based on industry experience have been utilised.

7.68 Where a technology has been considered to have a significant impact on the operating profile of a vessel (resulting in a material impact on annual income), this has been scored as a zero as it is not applicable / relevant to the vessel. To evaluate a more detailed picture of the impact of annual income would require details that vary between vessels and is beyond the scope of the current model.

Viability when paired with each of the other technologies and operational measures

7.69 The technologies and operational measures are not always compatible with each other. Each technology and operational measure was mapped against the others to evaluate their compatibility. This resulted in a matrix showing the likely relationship between these pairings, shown in assumptions table G.4. The mapping reflects whether they can be fitted in the same vessel to benefit the overall operation of the vessel, using 0-5 scoring system, as shown in the table below. Within the model, only combinations with a score of 3 or higher are allowed.

Score	Definition
5	100% viable
4	Partially compatible - pairing would reduce combined effectiveness by 1-20%
3	Partially compatible - pairing would reduce combined effectiveness by 20-40%
2	Partially compatible - pairing would reduce combined effectiveness by 40-60%
1	Partially compatible - pairing would reduce combined effectiveness by 60-80%
0	Incompatible

Table 18 Scoring criteria for technology-to-technology mapping

Impact on air pollutant emissions and fuel consumption

7.70 The impacts of technologies were estimated across: the reduction of air pollution emissions (applies only to exhaust treatment technologies); propulsion power demand and fuel consumption; and auxiliary power demand and fuel consumption. These figures are shown in assumptions table G.5.

7.71 Real data points were used where available using ranges across multiple studies. The baseline conditions for emissions savings identified for each technology may vary and will not be the same for every abatement option. This is therefore a potential area for further exploration.

Applicability to new builds or retrofits or both

7.72 The project produced an indication for each technology of whether it is best applicable to new builds, retrofits, or both (assumptions table G.2). Technologies identified as only available for new builds are either due to abnormally high installation cost or based on technical insulation processes.

Limitations and constraints

7.73 A number of limitations were identified in the assumptions for technologies and operational measures:

- Data relating to costs for technologies was difficult to obtain due to commercial sensitivities. Where it was possible to identify proxies for this data these have been included.
- Cost predictions for technologies out to 2060 were challenging due to a combined lack of data in the public domain for individual technology price forecasts and the lack of data for high level assumptions on cost reduction per TRL. We have therefore developed a structure that is based on the latest data available in the sector but is flexible and can be updated as new data becomes available going forward.
- Initial results on the take-up of technologies and operational measures showed a higher take-up in the early years of the forecast (2020-2025) than has occurred[32]. This is likely due to the fact that the model only considers the costs and savings of the options and not other factors that will influence decisions. This has been mitigated in results by disallowing some options before 2025.

Transport demand forecasts

7.74 Transport demand forecasts for freight ship types are based on an unpublished 2024 update of the 2019 DfT port freight forecasts[33], with each ship type matched to relevant freight categories in the forecasts. The matching of ship types to freight categories is shown in assumptions table F.1.

7.75 Forecasts for other ship types (passenger, fishing and service vessels) were not available. We have assumed that demand for these types of shipping is constant. For sensitivity analysis, we have produced a high demand forecast where these increase by 1% of 2019 demand each year.

7.76 The central, low and high forecasts are shown in assumptions tables F.2, F.3 and F.4.

Size distribution forecasts

7.77 The fleet model uses a forecast of ship size distributions to determine the sizes of newbuild ships. These were produced as a forecasted distribution for 2050, with an

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[32] DfT analysis using Clarksons Research's Green Technology Tracker

[33] www.gov.uk/government/publications/uk-port-freight-traffic-2019-forecasts

assumed linear transition from the 2019 distribution to the forecasted 2050 distribution. The 2019 and 2050 distributions are shown in assumptions table A.3.

7.78 The 2050 distribution was produced based on reviewing the size forecasts in the IMO 4th GHG Study and historical trends in 2009-2021 fleet data held by DfT. In addition, as the DfT model currently only considers ships that called at the UK, the global fleet forecasts were adjusted to align with the 2019 size distribution of ships calling at the UK.

Policy measures

Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ships Index (EEXI)

7.79 As set out in Section 4, the cost model chooses options to meet EEDI and EEXI requirements where applicable. It is not possible for the model to calculate the full EEDI/EEXI formula as not all of the detailed information required is available within the fleet data. Instead, the model calculates an estimated EEDI/EEXI value for each ship, using a simplified formula based on the estimated index value (EIV) formula used by the IMO to produce the EEDI and EEXI reference lines[34]:

$$EIV = \frac{CF_{ME} \cdot SFC_{ME} \cdot P_{ME} \cdot f_{jRoRo} + CF_{AE} \cdot SFC_{AE} \cdot P_{AE}}{Capacity \cdot V_{ref} \cdot f_{cRoPax}}$$

Parameter	Definition
CF_{ME}	Carbon factor of the main engine's primary fuel
SFC_{ME}	Specific fuel consumption of the main engine
P_{ME}	75% of the total installed main engine power (MCR)
CF_{AE}	Carbon factor of the auxiliary engine's primary fuel
SFC_{AE}	Specific fuel consumption of the auxiliary engine
P_{AE}	Auxiliary power calculated according to paragraphs 2.2.5.6.1 and 2.2.5.6.2 of MEPC.364(79)[35]
$Capacity$	Ship capacity calculated according to section 2.2.3 of MEPC.364(79)
V_{ref}	Service speed (assumed to be 75% of MCR)
f_{jRoRo}	Ship specific design elements correction factor for RoRo and RoPax ships from paragraph 2.2.8.3 of MEPC.364(79) (set to 1 for all other ships)
f_{cRoPax}	Cubic capacity correction factor for RoPax ships with a DWT/GT ratio of less than 0.25 from paragraph 2.2.12.3 of MEPC.364(79) (set to 1 for all other ships)

Table 19 Definition of parameters used to calculate EIV

7.80 The carbon factor and specific fuel consumption values used for each engine type are given in assumptions table H.1. The RoRo correction factor (f_{jRoRo}) is applied to RoPax and RoRo ships and uses an average correction factor for the two ship types (0.34 and 0.43 respectively) calculated from average ship characteristics given in a research paper on this correction factor using IHS fleet data[36]. The cubic correction

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[34] MEPC.231(65), wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/231(65).pdf

[35] MEPC.364(79), wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/RESOLUTION%20MEPC.364(79).pdf

[36] www.researchgate.net/publication/284498793_On_the_Energy_Efficiency_Design_Index_of_Ro-Ro_passenger_and_Ro-Ro_cargo_ships (table 2)

factor for RoPax ships with a DWT/GT ratio of less than 0.25 is taken from paragraph 2.12.3 of MEPC.308(73):

$$f_{cRoPax} = \left(\frac{\left({}^{DWT}\!/_{GT}\right)}{0.25}\right)^{-0.8}$$

7.81 The RoRo and RoPax correction factors are included because validation of the estimated EEDI/EEXI against EEDI/EEXI reported in EU MRV data showed that these significantly improved the accuracy of the estimates. The estimates performed well for other ship types without the use of any correction factors.

Ship type	**Average estimated EEDI/EEXI**	**Average reported EEDI/EEXI/EIV (EU MRV)**	**Average estimate error**	**Percentage of estimates within ±50% of reported EEDI/EEXI/EIV**
Bulk carrier	5.4	5.8	-2%	99%
Container	16.7	17.6	-1%	96%
Chemical tanker	8.9	9.1	0%	98%
Oil tanker	4.2	4.8	-6%	99%
General cargo	13.8	15.3	-6%	96%
Vehicle	17.9	19.2	-4%	94%
Liquefied gas tanker	10.5	12.0	-5%	95%
Ro-Ro	13.3	14.9	0%	83%
Cruise	15.3	30.5	11%	58%
Ferry - ro-pax	33.3	52.2	116%	61%
Refrigerated cargo	20.6	22.3	-7%	100%

Table 20 Comparison of estimated EEDI/EEXI using RoRo and RoPax correction factors with EU MRV data

7.82 The required EEDI or EEXI in each year for each ship is calculated using the reference lines and the required reduction factors in each year as set out in MARPOL Annex VI[37]. Some of the ship types used in the model cover multiple EEDI/EEXI ship types. These were handled in the following ways:

- Bulk carriers in the model includes combination carriers, which have their own EEDI reference lines. The reference lines are very similar to those for bulk carriers and the required reduction factors are the same, therefore the bulk carrier reference lines and reduction factors were used for all bulk carriers in the model.

- Liquefied gas tankers in the model covers LNG carriers and gas carriers. All of those over 65,000 DWT are LNG carriers, so the LNG carrier reference line and reduction factors were used for these. The majority of those below 65,000 DWT are gas carriers, so the gas carrier reference line and reduction factors were used for these.

7.83 When assessing options, the cost model looks at the change in the EIV. For engines, this is calculated by looking at the difference between the EIV for the existing engine and the potential new engine. For technologies and operational measures, this is calculated from the existing EIV using each option's assumed percentage reduction

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[37] wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.328(76).pdf

in main and auxiliary engine power, only for options which would be factored into the calculation of EEDI or EEXI (this is shown in assumptions table G.1).

Carbon Intensity Indicator (CII)

7.84 As with EEDI and EEXI, the cost model chooses options to meet CII requirements where applicable. The CII is calculated using each ship's estimated carbon emissions and mileage. As part of the forecasting process, these are updated when a ship changes fuels, installs a technology, or takes up an operational measure. This then feeds into the forecasted CII of each ship.

7.85 Validation of the CII estimates in 2019 against reported CII in EU MRV data showed that the model appeared to be overestimating CII for some ship types. This could be due to the model missing mileage for some ship types. To correct this, the CII estimates are capped at 50% above the reference CII and correction factors are applied to RoPax ferries, oil tankers, and refrigerated cargo ships based on the average error in the validation (see assumptions table H.2).

Ship type	Average estimated CII	Average reported CII (EU MRV)	Average estimate error	Percentage of estimates within +/-50% of reported CII
Bulk carrier	5.4	6.2	-11%	98%
Container	8.5	10.9	-21%	96%
Oil tanker	5.0	6.6	3%	80%
General cargo	13.9	17.3	-4%	78%
Vehicle	5.2	6.5	-19%	97%
Liquefied gas tanker	14.1	15.2	-12%	93%
Ro-Ro	14.2	15.7	-9%	98%
Cruise	13.6	16.0	-10%	89%
Ferry - ro-pax	22.7	26.1	-13%	99%

Table 21 Comparison of estimated CII with EU MRV data where CII reported after applying corrections

7.86 The CIIs required for a C and D rating in each year for each ship are calculated using the reference lines[38], the reduction factors in each year[39], and the rating boundaries[40]. As with EEDI/EEXI, some ship types in the model cover multiple CII ship types. These were handled in the same way as EEDI/EEXI.

7.87 Currently, the reduction factors for CII are agreed out until 2026. In some scenarios, an assumed reduction factor is added for 2030 with a linear trend of reductions assumed for the years 2027-2029.

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[38] MEPC.353(78), wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.353(78).pdf

[39] MEPC.338(76), wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.338(76).pdf

[40] MEPC.354(78), wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.354(78).pdf

Fuel standards

7.88 The model includes the options of three fuel standards:

- EU fuel standard which applies to ships calling at EU ports.
- UK fuel standard which applies to ships undertaking UK domestic journeys.
- IMO fuel standard which applies to ships on international voyages that are not within the EU.

7.89 When modelling UK domestic and international emissions, every ship is covered by at least one of the fuel standards - either they will have undertaken only UK domestic journeys and be in scope of the UK fuel standard or they will have undertaken at least one international journey and be in scope of the IMO fuel standard. Ships can be in scope of multiple fuel standards; for example, if a ship undertook some UK domestic journeys, then an international journey to the EU, and finally some EU journeys, it would be in scope of all three fuel standards. Each fuel standard has an assumed size threshold that can be set by year and ships under the size threshold are exempt.

7.90 The maritime emissions model is not currently able to model the inclusion of flexibility mechanisms within the design of a fuel standard (e.g. the trading of surplus compliance between ships). These fuel standards are therefore currently modelled in a simplistic way with some limitations. For modelling purposes, they are defined as a required reduction in GHG intensity in each year from a baseline which must be met by all vessels in scope of the fuel standard. In the model, this determines which fuels are valid within each year and ships are restricted to those fuels. This means that the results of the modelling assume that each ship individually must comply with any fuel standards that apply and there are no flexibility mechanisms.

7.91 An important limitation of the model is that it does not currently allow for a vessel to change the fuels it uses within a calendar year, so ships are assumed to use the same fuel for all of their journeys within a calendar year. This means that each fuel standard impacts on all of a ship's journeys if the ship does a single journey within its scope. When forecasting the UK's maritime emissions without a UK fuel standard, this can mean that the EU fuel standard has a significant impact, which is likely an overestimate as, in reality, ships would probably switch fuels or operators would redistribute their fleets to focus their lower carbon ships on EU activities. To mitigate this, when forecasting UK maritime emissions (domestic and international), the model does not enforce the EU fuel standard on ships where less than 20% of their UK emissions were on UK-EU journeys. This results in the majority of UK-EU emissions being reduced by the EU fuel standard, but other UK activity is not impacted.

7.92 The reductions required in the GHG intensity of maritime fuels assumed within the model are shown in assumptions table H.3. The EU assumptions are taken from the FuelEU regulation[41]. The IMO assumptions are designed to meet the lower and upper ends of the indicative checkpoints to reach net-zero GHG emissions from

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[41] https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en

international shipping in the 2023 IMO GHG Strategy[42] under the low ambition and high ambition scenarios respectively. The UK assumptions are designed to meet the UK domestic maritime emission reduction goals established in the UK Maritime Decarbonisation Strategy.

7.93 Note that because they are applied simplistically, the modelling of the fuel standards results in some overcompliance. The model is currently designed to provide a high-level view of what future paths to reducing maritime emissions could look like to inform decisions on targets and the application of different policy levers in broad terms. We are not at the stage yet of modelling the detailed designs of policies such as fuel standards. Therefore, the assumptions made in the model do not reflect what the actual reductions would need to be for a fuel standard with a flexibility mechanism and should not be treated as proposed levels for potential future fuel standards.

Carbon pricing

7.94 The model includes the option of applying carbon prices to GHG emissions. These prices can be set for three different scopes of emissions:

- GHG emissions covered by the EU ETS (emissions on journeys within the EU, emissions when at berth at an EU port, and 50% of emissions on journeys between an EU and a non-EU port), with a phased introduction 2024-2026[43].
- UK domestic maritime GHG emissions, reflecting an expansion of the UK ETS to domestic maritime emissions.
- All other emissions.

7.95 These scopes are defined without any overlap. For each of these scopes, prices are set per tonne of CO_2e which are converted into a price per tonne of each fuel, using either tank-to-wake or well-to-wake emissions factors depending on the scenario. In addition, size thresholds are set for each scope in each year.

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[42] wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2015.pdf

[43] https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en

8. Summary

8.1 The Maritime Emissions Model produces historical estimates of emissions from ships in 2019 and forecasts of emissions out to 2050. The diagram below shows an overview of the model.

8.2 We have produced this model to support the development of future maritime policies, with the purpose of:

- Understanding emissions in the baseline, providing breakdowns of emissions for broad categories of ships.
- Exploring different potential future paths to reducing maritime emissions with the application of different policy levers in broad terms.

8.3 There are limitations to both the estimates (paragraph 4.23) and the forecasts (paragraph 5.29). However, the model is suitable for the intended purpose. This is supported by the results of the estimates validation (Section 4). We have also produced scenarios to capture the key sources of uncertainty in the forecasts (paragraph 7.5).

8.4 In future work, we will look to address these limitations including improving the scope of ships covered by the estimates (paragraph 2.10), adding emissions reductions options not currently included (paragraph 6.16), and improving the modelling of policies such as the fuel standard to allow more detailed analysis (paragraph 7.93).

8.5 In addition, many of the assumptions on future engines, fuels and technologies have limited evidence, reflecting the early stage of development. We will keep these assumptions under review and update them as the evidence develops.

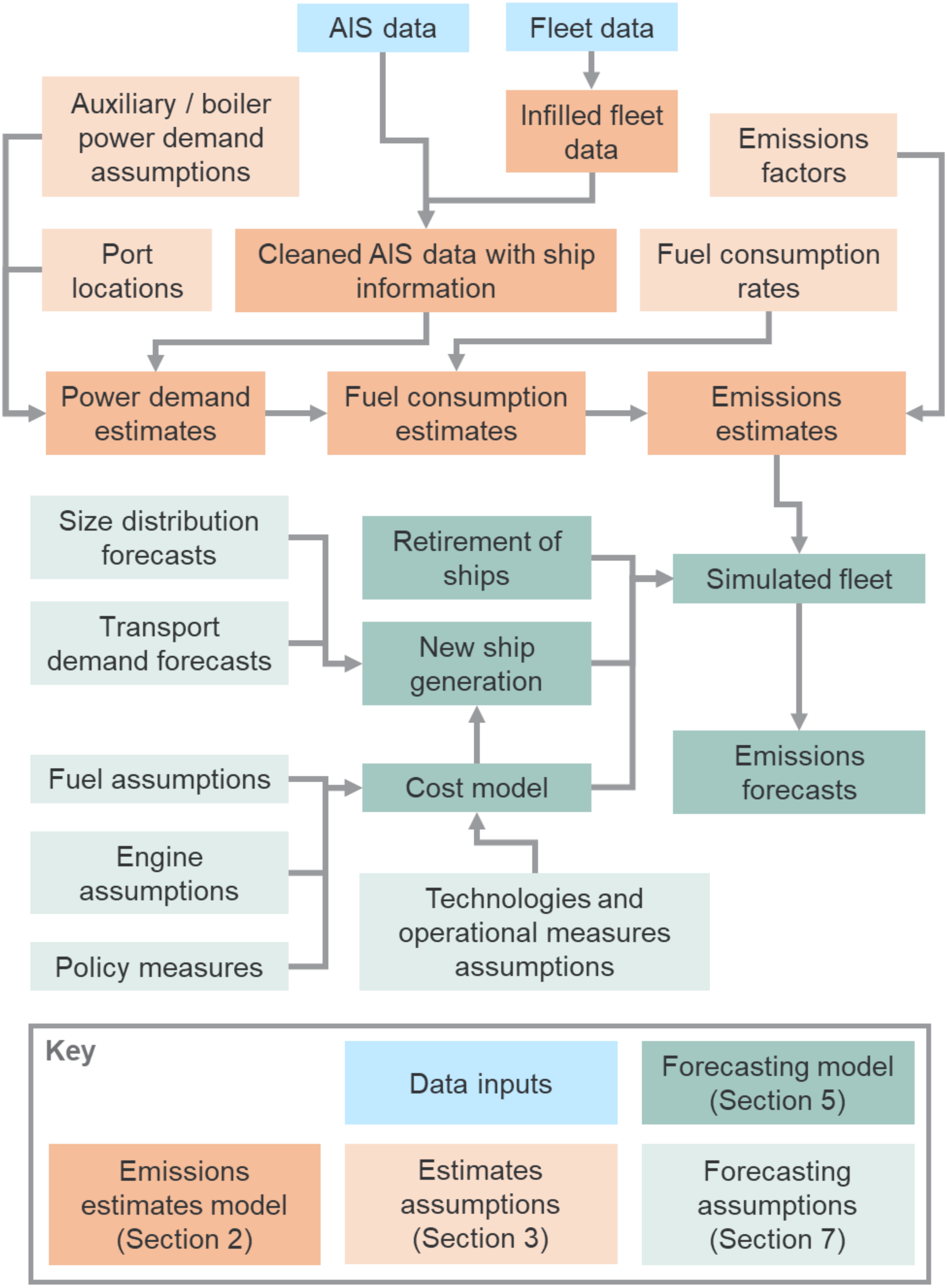

Figure 4 **Diagram of the DfT Maritime Emissions Model**