OPTIONS FOR EXTENDING THE NORTH SEA SHIPPING EMISSIONS CONTROL AREA

A Report for the Department for Transport

Technical Annexes

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Authors:
Eoin O'Keeffe (UMAS), Elena Hauerhof (UMAS); Dr Tristan Smith (UMAS); Hugh van Niekerk (Frontier Economics); and Kat Deyes (Frontier Economics).

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This is a slightly updated version of a report that was produced in 2019. The cost-benefit analysis in the report was completed in 2019. It therefore reflects the evidence that was available, and the appraisal guidance that was in place, at the time the analysis was completed. The policy options assessed in the report are purely illustrative and do not represent current Government policy.

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Department for Transport

Great Minster House

33 Horseferry Road

London SW1P 4DR

Telephone 0300 330 3000

General enquiries https://forms.dft.gov.uk

Website www.gov.uk/dft

CONTENTS

GLOSSARY

AIS	Automatic identification systems
AIS coverage	% of AIS observations captured annually
At sea speed	Operating speed of a vessel when sailing at sea
Bulk carrier	A bulk carrier, bulk freighter, or colloquially, bulker is a merchant ship specially designed to transport unpackaged bulk cargo, such as grains, coal, ore, and cement, in its cargo holds
Cargo capacity	Amount of space that a ship will hold in its cargo areas
cbm	cubic meters
Chemical tanker	A type of tanker ship designed to transport chemicals in bulk
Class A AIS	Vessels with fitted Class A AIS transceiver. The regulation requires Class A AIS transceiver to be fitted aboard all ships of 300 gross tonnage and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size[1].
CO_2	Carbon dioxide
Container vessel	A ship which is designed to carry goods stored in containers
Cruise	A large ship that carries people on voyages for pleasure
Design speed	maximum operating speed of a vessel
Dwt	deadweight tonnes
EEDI	Energy Efficiency Design Index
Emissions species	Different types of emissions CO_2, CH_4, N_2O, SO_2, NO_x, $PM_{2.5}$
EMS	Equivalent market size
Ferry-pax only	Ferries designed for the transportation of passengers only
Ferry-RoPax	A ro-ro vessel built for transportation of vehicles and passengers
Fuel-related operating cost	Fuel costs due to a voyage
General cargo	A merchant ship that carries cargo, goods, and materials from one port to another
GIS polygon	An area of interest on a map defined in geographic information system (GIS) framework
GloTraM	Global Shipping Transport Model
GT	Gross tonnage
HFO	Heavy fuel oil
Installed Power	Power of the engines installed in a ship
kWh	kilowatt hour
Liquefied gas tanker	A ship designed to transport LPG, LNG or liquefied chemical gases in bulk

[1] http://www.imo.org/en/OurWork/Safety/Navigation/Pages/AIS.aspx

LNG	Liquid natural gas
LSHFO	Low sulphur heavy fuel oil
Main engine	A device on a ship that provides energy for propulsion
MDO	Marine diesel oil
Miscellaneous - fishing	Various fishing vessels
MMSI	Maritime mobile service identity is a unique 9-digit number that is assigned to an AIS unit.
NO_x	Nitrogen oxides
Offshore	Ships that specifically serve operational purposes such as oil exploration and construction work at the high seas
Oil tanker	A ship designed to carry oil in bulk
Operational emissions	Emissions associated with the fuel combustion on board of a ship during the operation of a ship.
'Other' vessel type	'Other' vessels comprise the non-modelled in GloTraM vessel types that include chemical tankers, general cargo vessels, liquefied gas tankers, other liquids tankers, refrigerated bulk carriers, vehicle carriers, yachts and miscellaneous – fishing vessels
Other liquids tankers	A ship designed to transport miscellanies liquids in bulk. This term is specific to FUSE platform while in the main report it is referred as other liquids bulk transport.
PM	Particular matter
$PM_{2.5}$	Atmospheric particulate matter (PM) that have a diameter of less than 2.5 micrometres
Ro-Ro	Roll-on/Roll-off also called RORO, these are conventional ferries that can let vehicles easily leave
SCR	Selective catalytic reduction
Service - other	Other service vessels
Service - tug	A vessel that manoeuvres other vessels by pushing or pulling them either by direct contact or by means of a tow line
SO_x	Sulphur oxides
TEU	Twenty-Foot Equivalent Unit
tnm	tonne-nautical-mile
Vehicle carrier	A vessel built for transportation of vehicles

INTRODUCTION

This document provides the technical annexes to the report “Options for Extending the North Sea Shipping Emissions Control Area”.

Technical detail relating to the modelling undertaken is first presented, followed by a description of the cost-benefit analysis.

1 TECHNICAL MODELLING

1.1 Modelling modules

The modelling involves an application of the following products:

- Fuel Use Statistics and Emissions module, or FUSE, is a cloud-based platform developed to produce a new generation of ship-based reports. FUSE reports deliver detailed estimates of a ship's speed, fuel consumption, carbon dioxide (CO_2), nitrogen oxides (NO_x) sulphur oxides (SO_x) and particular matter (PM) emissions, transport activity and operational efficiency using satellite and terrestrial AIS data coupled with global fleet's technical specifications database.
- The global transport model (GloTraM) of the maritime transportation system is designed to develop a comprehensive analysis of maritime, environmental and economic interactions. It simulates the evolution of a fleet under different economic and regulatory scenarios.

1.2 Data sources

Data sources used are:

- Technical specification database (Vessel Tracker[2]): this data provides the technical basis on which one can identify vessel type and size, estimate power use and emissions. It is a list of international vessels (Class A vessels) including main engine specification and vessel dimensions.
- Combined satellite and terrestrial Automatic Identification System (AIS) data (ExactEarth[3]): This data is vessel location information including longitude, latitude, speed and draught captured at intermittent intervals. Intermittency is due particularly to coverage of receivers and density of reporting. As a result of this lack of completeness and also data quality issues this data requires significant pre-processing and infilling using the FUSE platform.
- Ports database (Internally collated by UMAS[4]): Global database of port locations including longitude and latitude coordinates.
- Aggregated operational statistics (operational speed, days at sea, fuel consumption) per vessel type and size category for the year of 2016. The data is derived using FUSE module and used as an input to GloTraM module.

1.3 Methodology

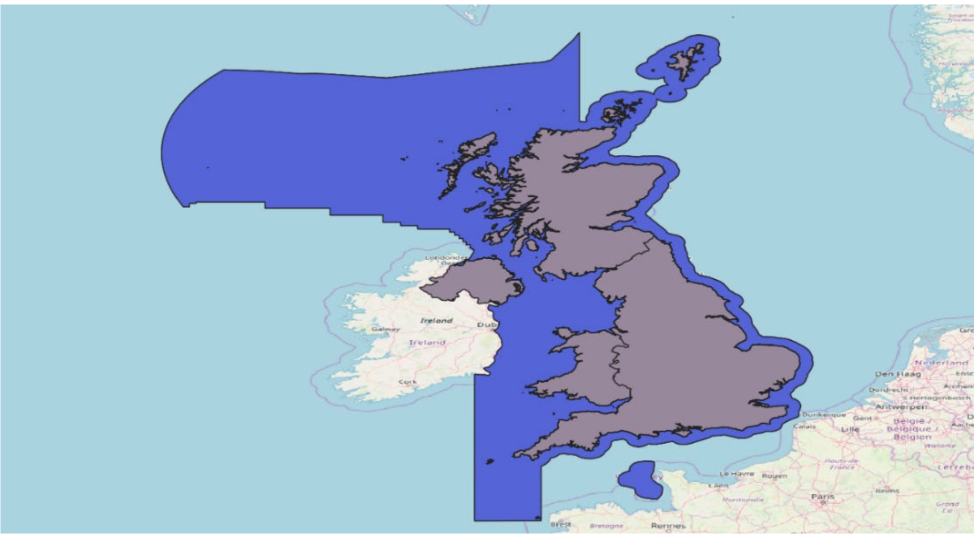
The following steps were undertaken for this work:

1. The first step was to identify vessels from the combined satellite and terrestrial AIS raw data that operate within the area of interest. A unitised GIS polygon

[2] https://www.vesseltracker.com/
[3] https://www.exactearth.com/
[4] https://u-mas.co.uk/

that defines the largest geographical area of interest was created as shown in Figure 1. This area comprises UK territorial waters boundaries, a belt of coastal waters extending at most 12 nautical miles from the baseline of a coastal state, combined with an additional area covering the Irish Sea and down to the English Channel as per the definition of the ECA extension option 3 assessed in this project. At this stage, the described geographical polygon also includes the UK coastline already compliant with the current ECA regulations. This inclusion is important when comparing the overall number of vessels that operate in UK waters with existing studies at the quality assurance stage.

Figure 1 Geographical area of interest, including the current Emission Control Area



Source: *UMAS*

In AIS data, vessels are uniquely identified based on a maritime mobile service identity (MMSI) number. For each MMSI number, active in a base year of 2016, each AIS longitude and latitude coordinate was checked against the GIS polygon defined in Figure 1. Where at least one observation was identified within the polygon, that vessel was considered in scope at this stage. In total, there were 30,855 Class A MMSIs identified at this stage. This classification includes all cargo vessels over 300 gross tonnage involved in international voyages, all passenger ships irrespective of size and fishing vessels with overall length greater than 15 meters as per definition of Class A vessels[5].

2. Each identified vessel was matched with the vessel technical specification database by vessel's identification number (IMO or MMSI). The Vessel Tracker database was used as a primary source. However, some vessels that were missing from the Vessel Tracker database were either matched to the technical specifications used in Ricardo et al. (2017)[6] for Class A vessels or assumed to be one of the vessels types identified in accordance with vessel operational activity. As such, 5 different allocation types were defined and described in section 1.4.1.

[5] http://www.imo.org/en/OurWork/Safety/Navigation/Pages/AIS.aspx

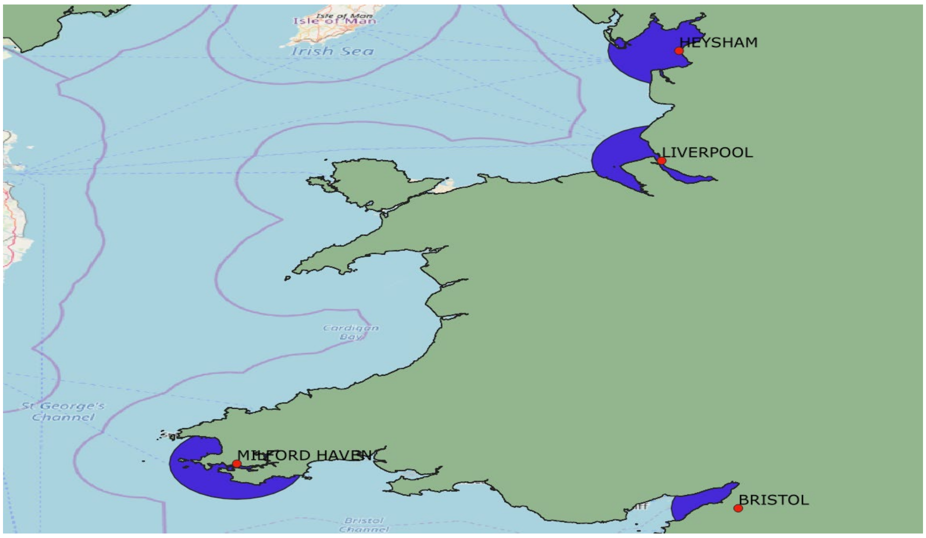
[6] Scarbrough, T. *et al. A review of the NAEI shipping emissions methodology*. (2017).

3. The AIS observations were then cleaned and resampled to 15-minute intervals for each vessel with speed and draft estimated for periods that have no AIS reports for the vessel. Vessel positions were not estimated for periods where the data is missing, and the vessel's last known location was assumed to persist until a new AIS observation is available.
4. Using FUSE modules coupled with the global ports database, port stops and associated voyages were then identified based on geographical activity captured via AIS. This algorithm uses a supervised learning model that accounts for vessel speed and port proximity at each observation. This model has been trained and tested on actual voyage data.
5. Each voyage was then classified as domestic, international or in transit.
   - Domestic shipping is shipping activity that begins and ends at a UK port
   - International shipping is defined as the fleet servicing UK international trade flows (imports and exports). This is identified from the specifics of the voyage: international shipping is shipping services provided by any ship arriving at a UK port immediately after leaving a non-UK port, or arriving at a non-UK port after leaving a UK port. The international shipping emissions within the ECA are the total of those voyages associated with both inbound to UK and outbound away from UK shipping activity.
   - In-transit shipping is those voyages that in transit, passing through the ECA areas without calling at the UK.
6. For each of the voyage groups (domestic, international and in transit) and by ship type and size, operations were aggregated into total transport work. The total transport work in this case is defined as equivalent market size (EMS) represented as a ratio between total voyage hours for each type/size/voyage type and average days at sea for that size/type. This ratio represents the equivalent number of vessels required to serve this transport demand. The purpose of this step is to account for vessels that are involved in mixed operations. For example, in case two vessels spend half the year operating domestically, and then the other half of the year operating internationally, the EMS would be one domestic vessel and one international vessel.
7. Using the same principle described in step 1, vessels operating within the geographical areas covered by each of the ECA extension policy options were identified.

   The three options are:

   - Policy Option 1: Extending the North Sea ECA to include all major ports in England not covered by the ECA from 1st January 2021. The map of the area is shown in Figure 2.
   - Policy Option 2: Extending the North Sea ECA to include all of UK territorial waters from 1st January 2021. The map of the area is shown in Figure 3.
   - Policy Option 3: Extending the North Sea ECA to include the Irish Sea and down to the English Channel (including the isle of Ouessant but not going South to the Biscay Bay) from 1st January 2026. The map of the area is shown in Figure 4.

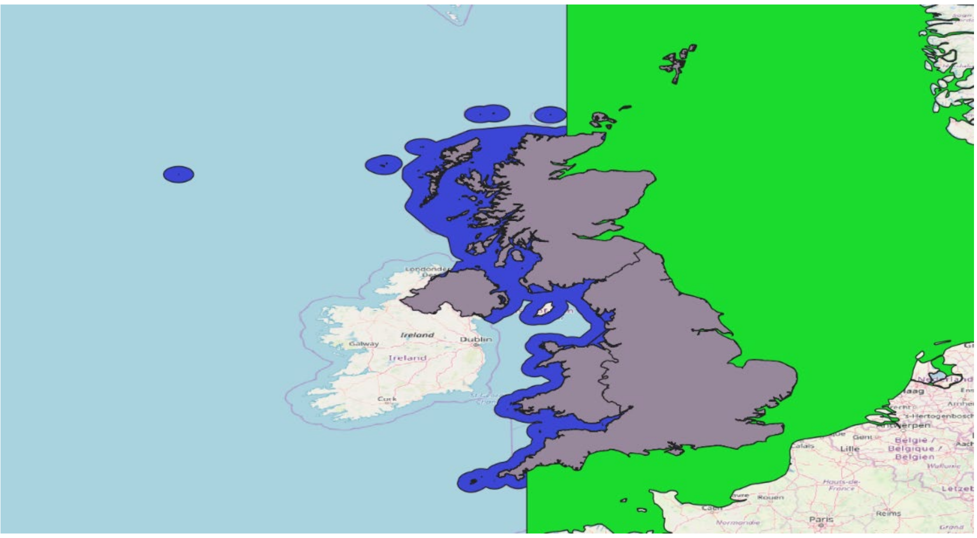
Figure 2 Emission Control Area extension option 1



Source: *UMAS*

Note: *Policy Option 1 is assumed to apply to shipping activity within a 12 nm radius around each of the ports of interest. The ports of interest are Heysham, Liverpool, Milford Heaven and Bristol.*

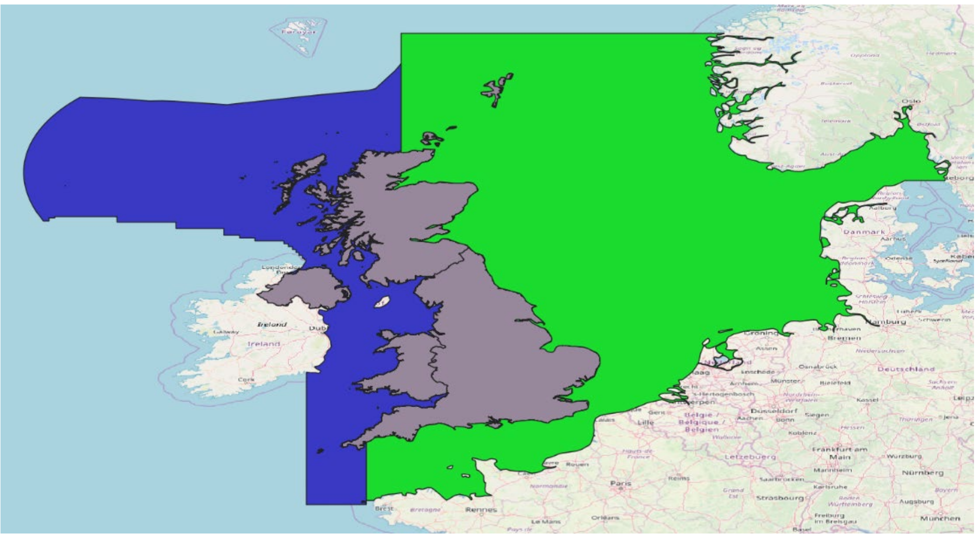
Figure 3 Emission Control Area extension option 2



Source: *UMAS*

Note: *The current ECA is shown in green, the extension option 2 is shown in blue*

Figure 4 Emission Control Area extension option 3



Source: UMAS

Note: Emission Control Area extension option 3 is shown in blue. The current North Sea Emissions Control Area is shown in green.

8. The options have all been assessed against the outcomes that would be likely in the absence of the interventions. The latter case is referred to as the 'business as usual' (BAU) case.

   For the purposes of this analysis, the BAU is defined as follows:

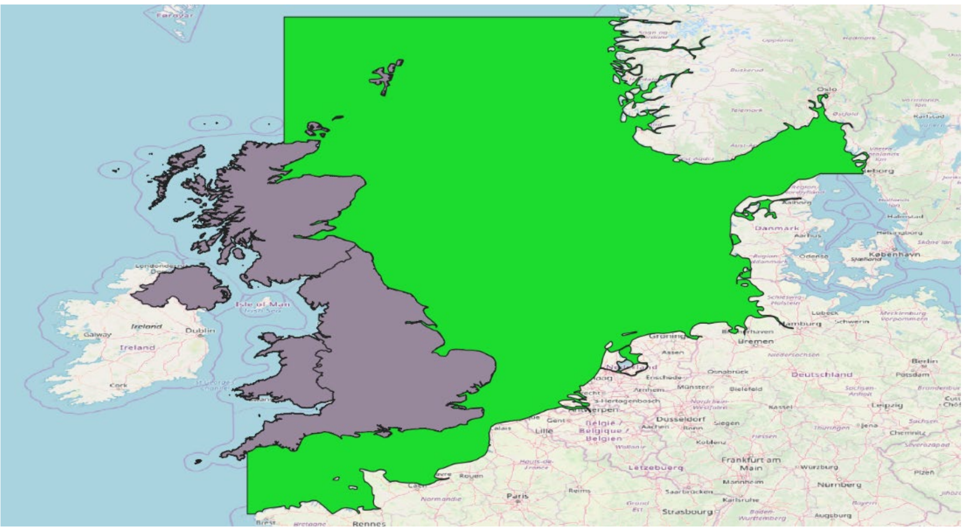
   - the ECA as shown in Figure 5 is in operation, controlling NO_x and SO_x emissions in line with the requirements of Figure 6 and Figure 7.
   - the requirements of the existing regulation 21 of MARPOL Annex VI will be met. The regulation 21 of MARPOL Annex VI that entered into force in January 2013, requires the attained Energy Efficiency Design Index (EEDI)[7] of certain categories of new ships not to exceed the required EEDI[8] with the main objective of reducing international shipping's GHG emissions via improved ship design.
   - port traffic demand is considered to grow in line with DfT's UK Port Freight Traffic Forecasts (DfT, 2019)[9].

[7] The EEDI is an index that indicates the energy efficiency of a ship in terms of gCO_2 (generated) / tonne mile (cargo carried); calculated for a specific reference ship operational condition. Source: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Air%20pollution/M2%20EE%20regulations%20and%20guidelines%20final.pdf

[8] For more information please refer to section 6.4.3 in Frontier, UMAS, CE Delft and E4tech: Reducing the UK Maritime Sector's Contribution to Climate Change and Air Pollution: Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs - Technical Annex

[9] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/771852/port-freight-forecasts.pdf

Figure 5 Current North Sea Emissions Control Area



Source : UMAS

Figure 6 MARPOL Annex VI NO_x emission limits

Tier	Year	NO_x limit g/kWh		
		$n < 130$	$130 \le n < 2000$	$n \ge 2000$
Tier I	2000	17.0	$45\ n^{-0.2}$	9.8
Tier II (outside ECAs)	2011	14.4	$44\ n^{-0.23}$	7.7
Tier III (NOx ECAs)	2021[10]	3.4	$9\ n^{-0.2}$	1.96

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

NO_x emission limits are set for diesel engines depending on the engine maximum operating speed (n, rpm), as shown in *Figure 6.* Tier I and Tier II limits are global, while the Tier III standards apply only in NO_x Emission Control Areas.

Figure 7 MARPOL Annex VI fuel sulphur limits

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

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

It should be noted that the options differ in terms of both the spatial scale of their coverage, and the time period over which they are assumed to be in operation. For these reasons, the business as usual scenario is specific to each policy option and only ships operating within the spatial areas of the respective ECA extensions of each policy option are considered.

Starting from 2016, BAU projected changes in fleet size based on DfT's UK Port Freight Traffic Forecasts (DfT, 2019)[11] for each cohort, namely vessel type, size category and a voyage group (domestic, international or in transit)

[10] Note that in the North American ECA, this date was 2016.

[11] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/771852/port-freight-forecasts.pdf

were applied. The growth rates for each commodity type from DfT's UK Port Freight Traffic Forecasts (2019) were applied where appropriate. Each category of cargo (or commodity type) has been mapped to the relevant ship types . In effect, it is assumed that the routes that vessels operate on will remain constant over time (but the number of vessels on those routes will vary over time).

9. Based on the AIS geographical coordinates, each voyage was assessed in terms of hours spent in each of the ECA extension option and the current ECA. The obtained ECA hours were then aggregated into ECA ratios for each of the cohorts by vessel type, size category and a voyage group (domestic, international or in transit). The ECA ratios represent the proportion of time each of the cohorts spent in the ECA. These ratios were then applied to the total energy demand associated with each of the cohorts to allocate an appropriate fuel type used in and outside of the ECA as explained in the next step. The resulted ECA ratios for each of the ECA extension policy option and BAU (referred as counterfactual) along with a relevant number of vessels expressed as equivalent market size (EMS) are listed in section 1.7.3.

10. The aggregated operational statistics, defined in section 1.4.4 by vessel type and size for the base year of 2016 (derived from FUSE), were used as an input to the GloTraM model to estimate emissions in both BAU and ECA extension policy options scenarios. In GloTraM, for each of these scenarios, the operational profiles were scaled by the number of vessels (EMS) in each of the voyage groups (international, domestic and in transit) over the full 10-year period of interest for each policy option. It is also assumed that under the BAU scenario, shipowners and operators will introduce different technologies, behaviours and fuels in order to comply with existing regulations whilst maximising profit. As such, the resulting energy demand for each cohort was adjusted in GloTraM to account for an appropriate mix of energy efficiency technologies and devices.[12].

11. Then, for each cohort, the energy demand was disaggregated by fuel type in accordance with assumptions listed in Figure 8. The fuel consumption values of each fuel type were estimated by applying the ECA ratios (explained in step 9) which represent the time spent inside the ECA for each of the ECA extension policy options and the BAU scenario. This is to ensure compliance with SO_x and NO_x regulations when operating inside and outside of the ECA.

    NO_x compliance is only required for newbuild ships that are required to meet the Tier III NO_x limit (e.g. ships built after 2021). It is assumed, given expectations of interoperability between coasts of the UK, that ships that need to be Tier III compliant will already have a Selective Catalytic Reduction system (or equivalent Tier III compliant machinery) fitted under the business as usual case. They will therefore just be required to operate it in the extended ECA.

[12] For more information read Chapter 4 in Frontier, UMAS, CE Delft and E4tech (2019): Reducing the UK Maritime Sector's Contribution to Air Pollution and Climate Change: Scenario Analysis - Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs.

Figure 8 Fuel type assumptions inside and outside of ECA (from 2021 onwards)

Fuel type	Outside ECA	Inside ECA
Heavy fuel oil (HFO)	HFO + Scrubber 0.5% sulphur limit	HFO + Scrubber 0.1% sulphur limit
Low sulphur fuel oil (LSFO)	LSHFO	MDO
Marine diesel oil (MDO)	MDO	MDO
Liquified natural gas (LNG)	LNG	LNG

The greenhouse gas (CO_2, CH_4 and N_2O) and air pollutant (SO_2, NO_x and $PM_{2.5}$) operational emissions were then estimated by applying the emissions factors listed in section 1.4.2. For the instances where a scrubber is installed, the $PM_{2.5}$ emissions were corrected by applying the 80% reduction (the figure is based on the works by Fridell, Erik & Salo, Kent. (2014)[13] and Lack, D. A. and Corbett (2012)[14]) to the estimated $PM_{2.5}$ emissions to account for the reduction of $PM_{2.5}$ emissions due to a scrubber. It is important to emphasise that the correction is equally applied regardless of whether the vessel is operating in an ECA as it is assumed that a scrubber is actively operating within and outside of the ECA to comply with the regulations.

It should be noted that estimates for the counterfactual and the policy options are provided for those vessels that will be affected by an ECA extension under each policy option, and not for all vessels operating in UK territorial waters. Because of this, each policy option has different business as usual (BAU) results.

12. Fuel operating costs associated with each ECA extension policy option and the counterfactual BAU scenario were estimated with the assumptions described in section 1.4.5. Only the operating costs were covered in this study because it is assumed that the fleet operating in the ECA extension area would be built to a specification that would also enable operation in the current ECA area (e.g. if a newbuild ship built after 2021 it would be fitted with a SCR). Separate estimates were derived for each year over the full 10-year period of interest for each policy option.
13. The GHG emissions and operational costs were corrected for the use of scrubbers and SCR. The methodology is described in section 1.4.6. This is because the change in behaviour that would be required for compliance has the effect of increasing operating costs and greenhouse gas emissions for the ship owner. For example, if the SCR is already fitted on the ship, switching it on when travelling through an ECA extension lowers the fuel efficiency of the vessel. When a scrubber is installed, the correction represents an additional fuel consumption associated with the intensified level of operation due to

[13] Fridell, Erik & Salo, Kent. (2014). Measurements of abatement of particles and exhaust gases in a marine gas scrubber. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment. 230.

[14] *Lack, D. A. and Corbett, J. J.: Black carbon from ships: a review of the effects of ship speed, fuel quality and exhaust gas scrubbing, Atmos. Chem. Phys., 12, 3985-4000, https://doi.org/10.5194/acp-12-3985-2012, 2012.*

switching from 0.5% to 0.1% sulphur level to comply with the ECA requirements.

14. Since the GloTraM model is limited to 10 major vessel types[15], the emissions and costs estimates were additionally corrected to account for the remaining non-modelled in GloTraM UK fleet[16] by scaling up the results using ratios listed in Figure 9. The ratios were derived from data on the annual operational energy demand for modelled and non-modelled ships that operate in the geographical areas covered by the ECA options. The operational energy demand information is from 2016 AIS data in FUSE. To obtain the total results (i.e. the sum of both modelled and non-modelled ships), the modelling results have been scaled up by those ratios. For example, projected CO_2 operational emissions from UK domestic shipping for modelled ships that operate in the geographical areas covered by the ECA extension policy option 1 in 2021 under counterfactual BAU scenario are 0.92 $MtCO_2$ (i.e. for modelled ships only) so these are scaled up to 1.25$MtCO_2e$ to represent the projected emissions in that year for all UK domestic shipping (modelled and non-modelled vessel types) that operate in the geographical areas covered by the ECA extension policy option 1 under counterfactual BAU scenario, which is 26.8% higher (reflecting the 0.268 factor used). The same methodology is applied for the 'with policy' case for each of the ECA extension policy options.

Figure 9 FUSE derived ratios to account for non-modelled in GloTraM vessel types

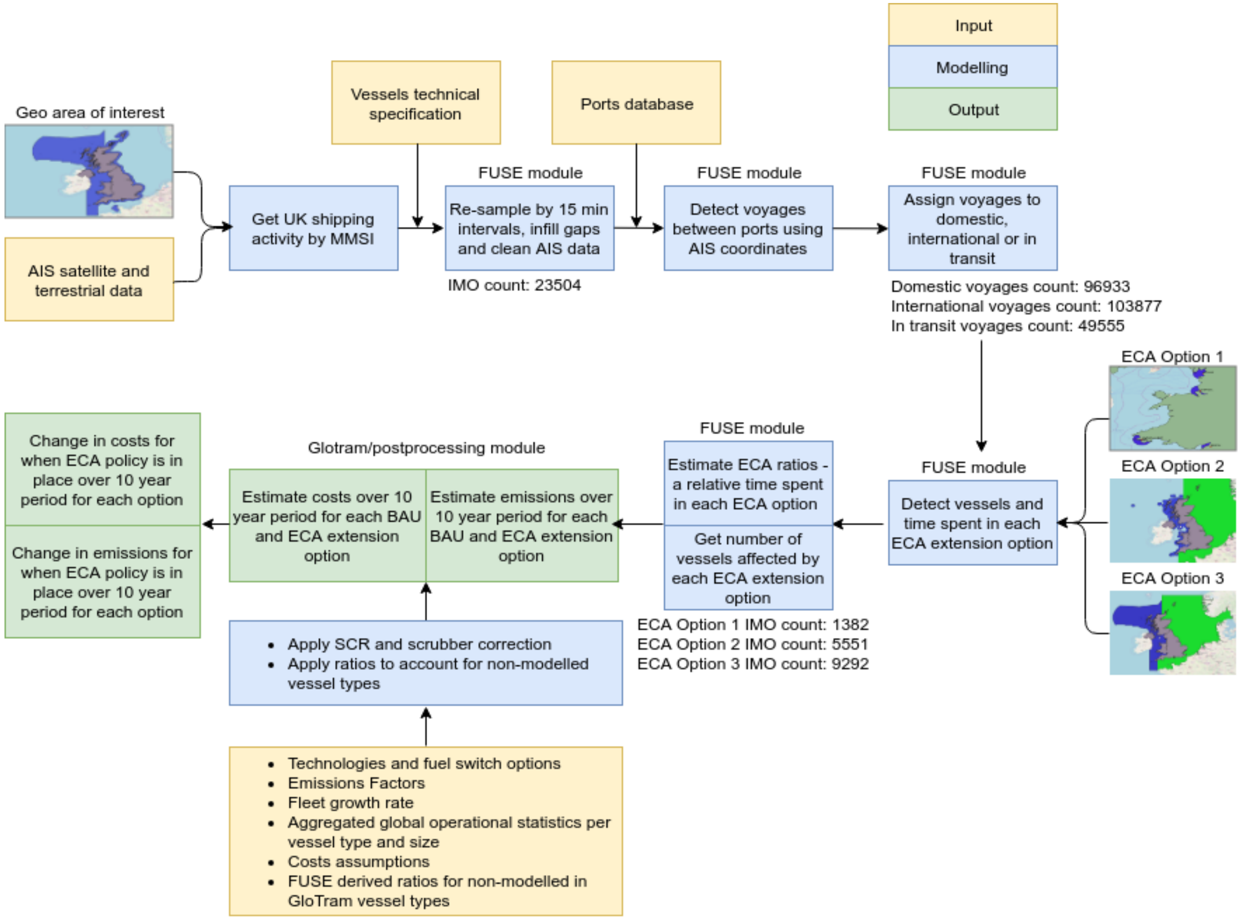
	Domestic	International	In transit
ECA option 1	0.268	0.573	0.484
ECA option 2	0.347	0.473	0.365
ECA option 3	0.335	0.355	0.324

15. The change in greenhouse gas and air pollutant emissions for each ECA extension policy option was estimated by subtracting estimates for an associated counterfactual BAU scenario from the relevant estimates in the ECA extensions policy option scenario.

[15] The vessel types included in GloTraM are passenger ferries, offshore, cruise vessels, bulk carriers, roll on/roll-off passenger ferries, service vessels, tugs, container ships, roll-on/roll-off ferries and oil tankers.

[16] The non-modelled in GloTraM vessel types considered in this study by applying relevant ratios are chemical tanker, general cargo, liquified gas tanker, other liquids tanker, refrigerated bulk, vehicle carriers, yachts, fishing vessels, miscellaneous other.

Figure 10 Overview of the modelling approach



Source: UMAS

Note: all counts in this figure are associated with 2016

1.4 Key assumptions

1.4.1 Vessel technical specifications matching principles

Figure 11 Key principles used to match AIS vessels with technical specifications

Type	Description
1	Vessel match by IMO number with Vessels Tracked database
2	Vessel match by IMO number with Vessels Tracked database where some specifications were infilled by applying multilinear regression in accordance with vessel's type and size category
3	Vessel matched with technical specifications used in Ricardo et al. (2017)[17] by IMO number
4	Vessel matched with technical specifications used in Ricardo et al. (2017) by MMSI
5	Vessel was assigned to one of the assumed types identified based on captured activity

Source: UMAS

Some vessels had no entry in the vessel technical specification database and no AIS reported features such as length or beam which could be used to indicate vessel type. To allocate these vessels, a nearest neighbour classification model was developed, trained and tested on correctly allocated vessels with the achieved accuracy score of 63%. The classification allocated on the basis of speed at sea, standard deviation of speed at sea and the number of voyages that the vessel undertook in a year. The described procedure is associated with the allocation type 5.

Figure 12 Vessel types used to allocate tech specs under type 5

Vessel type	Size category	Capacity unit
Bulk carrier	0-9999	deadweight tonnes
Chemical tanker	0-4999	deadweight tonnes
Container	0-999	TEU
Ferry-pax only	0-1999	gross tonnage
Ro-Ro	0-4999	deadweight tonnes
Ro-Ro	5000-+	deadweight tonnes
Miscellaneous - fishing	0-+	-

Source: UMAS

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

1.4.2 Emissions factors

The emission factors used in this analysis are shown in Figure 13. Data are based on the analysis undertaken in Lloyd's Register and UMAS 2019[18], Gilbert at al. (2018)[19] and own datasets based on the work done under SCC[20].

Figure 13 Operational emissions factors

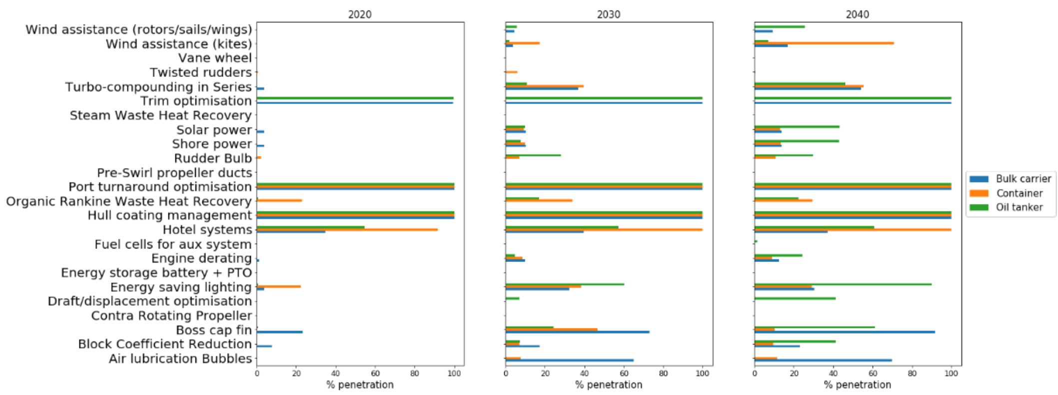
	CO_2	CH_4	N_2O	SO_2	NO_x	$PM_{2.5}$	Unit
HFO	3.02	0.0001	0.00016	0.06650	0.09300	0.00728	tonne of emissions / tonne fuel consumed
MDO	3.08	0.0001	0.00015	0.00190	0.08725	0.00097	
LSHFO	3.08	0.0001	0.00016	0.0105	0.09300	0.0024	
LNG	2.75	0.0512	0.00011	0.00002	0.0078	0.00018	

Note : LSHFO emissions factors are associated with 0.5% of sulphur content in fuel

1.4.3 Technology uptake under the business as usual scenario

Ship owners and operators are assumed to take up different technologies, behaviours and fuels in line with meeting current regulations (e.g. regulation 21 of MARPOL Annex VI), and their profit maximising behaviour. This is because of the incentives provided by the desire to minimise operating costs, namely fuel costs, over time.

Figure 14 Uptake of energy efficiency devices for bulk carriers, container ships and oil tankers by 2020, 2030 and 2040 under the business as usual scenario for UK shipping (domestic and international)



Source: UMAS modelling taken from the business as usual scenario (scenario A) which is described in detail in Frontier, UMAS, CE Delft and E4tech (2019) Reducing the UK maritime sector's contribution to climate change and air pollution: Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs.

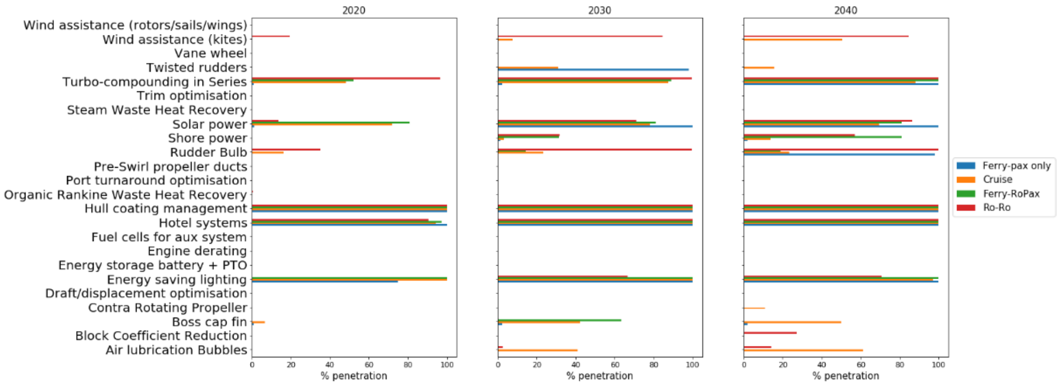
Note: '% penetration' represents the percentage of the size and age categories for each ship type that is estimated to have taken up each of the options.

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

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

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

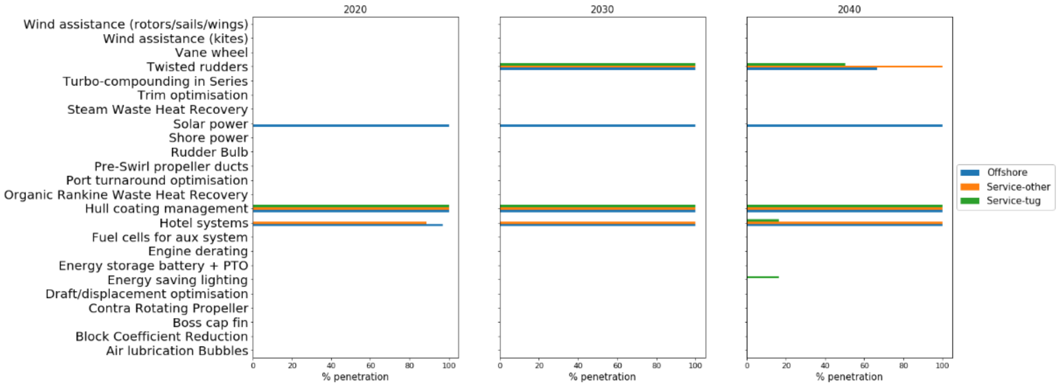
Figure 15 Uptake of energy efficiency devices for cruise, ferry-RoPax, ferry-pax only and ro-ro ships by 2020, 2030 and 2040 under the business as usual scenario for UK shipping (domestic and international)



Source: UMAS modelling taken from the business as usual scenario (scenario A) which is described in detail in Frontier, UMAS, CE Delft and E4tech (2019) Reducing the UK maritime sector's contribution to climate change and air pollution: Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs.

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

Figure 16 Uptake of energy efficiency devices for offshore, service-other and service-tug ships by 2020, 2030 and 2040 under business as usual for UK shipping (domestic and international)



Source: UMAS modelling taken from the business as usual scenario (scenario A) which is described in detail in Frontier, UMAS, CE Delft and E4tech (2019) Reducing the UK maritime sector's contribution to climate change and air pollution: Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs.

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

1.4.4 World fleet operational statistics

World fleet operational statistics were derived from AIS data for 2016 using the FUSE model. These statistics act as one of the inputs to GloTraM model necessary to estimate emissions in this study.

Figure 17 World fleet aggregated operational statistics in 2016

Ship type	Size category	Capacity unit	Total number of ships observed in AIS	Average AIS coverage	Average capacity (deadweight tonnes)	Average installed power kW	Average design speed knots	Average at sea days per annum	Average at sea speed knots	Average annual fuel consumption in main engine tonnes	Average annual fuel consumption in auxiliary engine tonnes	Average annual fuel consumption in boiler tonnes	Total fuel consumption (all engines/boilers) tonnes
Bulk carrier	0-9999	dwt	623	0.49	5113	2546	12.4	165.5	9.4	1058	489	83	1016168
Bulk carrier	10000-34999	dwt	1983	0.61	27175	6200	14.1	171.9	11.2	2763	477	75	6573306
Bulk carrier	35000-59999	dwt	3210	0.64	49840	8413	14.5	180.5	11.5	3704	655	143	14455573
Bulk carrier	60000-99999	dwt	2968	0.68	76869	9936	14.6	212.1	11.5	4888	1032	242	18290501
Bulk carrier	100000-199999	dwt	1264	0.64	168787	16762	15.0	243.6	11.1	7508	1018	213	11046001
Bulk carrier	200000-+	dwt	425	0.67	248586	19901	15.0	259.8	11.9	11682	987	174	5458443
Chemical tanker	0-4999	dwt	795	0.60	2956	1964	12.5	163.9	9.7	969	248	202	1127424
Chemical tanker	5000-9999	dwt	786	0.59	7230	3187	13.2	175.9	10.2	1546	728	381	2086884
Chemical tanker	10000-19999	dwt	951	0.64	15229	5183	14.1	182.0	11.5	2744	717	359	3632107
Chemical tanker	20000-+	dwt	1651	0.68	43323	9091	14.8	194.8	12.3	4893	1717	335	11465407
Container	0-999	TEU	888	0.64	8829	6314	16.4	189.7	12.2	2761	667	177	3200901
Container	1000-1999	TEU	1197	0.64	19410	12457	19.2	204.7	13.6	4974	1526	408	8268389
Container	2000-2999	TEU	658	0.67	34969	21708	21.6	213.7	14.2	7000	2285	546	6468662
Container	3000-4999	TEU	905	0.70	53374	36713	23.7	237.3	14.8	11457	3033	685	13733723
Container	5000-7999	TEU	663	0.71	77369	54929	24.9	244.3	15.6	17703	3175	668	14284872

Container	8000-11999	TEU	501	0.75	111102	66078	25.1	251.0	16.3	22536	3401	690	13339939
Container	12000-14500	TEU	169	0.73	149370	69890	24.6	253.5	16.5	27070	3970	754	5373166
Container	14500-+	TEU	56	0.75	185905	65727	23.6	258.1	17.3	33722	4283	751	2170316
General cargo	0-4999	dwt	4171	0.51	2843	1702	11.5	168.0	8.5	717	185	0	3762184
General cargo	5000-9999	dwt	2235	0.53	6962	3249	13.2	174.0	9.7	1293	512	120	4302336
General cargo	10000-+	dwt	1764	0.62	22925	7330	15.0	190.8	11.7	3513	1440	140	8984561
Liquefied gas tanker	0-49999	cbm	986	0.61	8038	3999	14.4	176.8	11.8	2228	483	1511	4161952
Liquefied gas tanker	50000-199999	cbm	570	0.64	68982	21485	18.8	248.7	14.4	12297	3608	1557	9953240
Liquefied gas tanker	200000-+	cbm	45	0.68	121284	30810	19.5	232.9	16.1	18555	3551	3417	1148523
Oil tanker	0-4999	dwt	1409	0.55	2860	1736	11.5	119.5	8.1	595	507	919	2847334
Oil tanker	5000-9999	dwt	541	0.59	6726	2725	12.1	125.7	8.4	790	773	1343	1572231
Oil tanker	10000-19999	dwt	165	0.58	14653	4486	12.9	126.7	9.5	1393	1270	2212	804441
Oil tanker	20000-59999	dwt	661	0.64	43614	8761	14.8	160.2	11.5	3423	1568	2421	4898936
Oil tanker	60000-79999	dwt	387	0.68	72643	12074	15.0	190.6	12.1	5652	1561	2118	3611237
Oil tanker	80000-119999	dwt	908	0.63	108275	13498	14.9	187.7	11.5	5561	2093	2861	9547052
Oil tanker	120000-199999	dwt	494	0.68	155471	17890	15.2	210.8	11.7	7812	2641	3196	6742912
Oil tanker	200000-+	dwt	645	0.61	307919	27041	15.8	242.6	12.4	14275	3161	3228	13328523
Other liquids tankers	0-+	dwt	446	0.56	11266	3841	13.4	183.9	10.5	2306	1019	1470	2138758
Ferry-pax only	0-1999	GT	801	0.44	130	2543	26.2	106.8	16.9	618	364	0	786141
Ferry-pax only	2000-+	GT	67	0.59	1873	5914	15.8	168.9	11.2	2818	1036	0	258223
Cruise	0-1999	GT	70	0.59	229	1577	12.6	108.4	8.3	352	889	532	124084
Cruise	2000-9999	GT	56	0.71	949	4785	15.6	162.3	10.0	1590	926	463	166802
Cruise	10000-59999	GT	95	0.72	3928	18906	19.6	214.8	13.5	8692	7591	1390	1678980
Cruise	60000-99999	GT	95	0.72	8244	44808	22.2	256.6	15.2	22351	24377	574	4493734

Cruise	100000-+	GT	62	0.67	11200	57814	22.4	266.1	16.3	34010	24068	498	3631743
Ferry-RoPax	0-1999	GT	1029	0.50	551	1653	12.5	121.0	8.5	490	205	0	715240
Ferry-RoPax	2000-+	GT	992	0.70	3225	15716	21.0	166.1	15.2	6633	1403	0	7971630
Refrigerated bulk	0-1999	dwt	602	0.65	6626	5859	16.9	167.9	13.0	2966	2216	425	3375302
Ro-Ro	0-4999	dwt	162	0.59	2784	3753	14.3	135.7	9.8	1261	1659	397	537399
Ro-Ro	5000-+	dwt	308	0.73	10897	11866	18.3	207.5	14.1	6654	2396	399	2910283
Vehicle	0-3999	vehicle	340	0.71	9681	9813	18.6	216.9	14.6	5739	1291	327	2501414
Vehicle	4000-+	vehicle	627	0.71	19623	13850	20.0	255.9	15.4	8600	1277	255	6353005
Yacht	0-+	-	1507	0.52	238	2667	18.4	63.9	12.3	367	257	0	939580
Service – tug	0-+	-	5415	0.63	325	2912	12.2	67.2	6.7	260	99	0	1943161
Miscellaneous - fishing	0-+	-	3383	0.56	960	2322	12.9	151.0	8.0	530	395	0	3129585
Offshore	0-+	-	4200	0.57	3918	5046	13.7	70.5	8.0	514	632	0	4816170
Service – other	0-+	-	3936	0.57	3700	3680	12.9	80.1	7.8	537	435	0	3826983

Source: UMAS

1.4.5 Key costs assumptions

Vessels are assumed to keep their machinery arrangements, operational fuel and abatement technologies under each of the ECA extension policy options the same as under the BAU scenario. For example, in order to comply with the current ECA requirements under the BAU scenario, a vessel would need to switch from LSHFO to MDO. The same principle would apply in the case of the ECA extension policy options. However, the difference between the ECA extension policy options and BAU scenario is the proportion of each fuel (LSHFO and MDO) that the vessel has consumed. Hence, the key costs that affect the adoption of the ECA extension policy options are related to the additional fuel consumed either by switching fuel (LSHFO/MDO) or due to increased scrubber and/or SCR use while operating in the ECA. These fuel costs per tonne are detailed in Figure 18.

Figure 18 Fuel prices used in each year over the period 2021 to 2036 (2017 prices)

	HFO	MDO	LSHFO	LNG
date	£/tonne	£/tonne	£/tonne	£/tonne
2021	235.5	388.6	280.3	471.4
2022	247.5	408.3	294.5	482.1
2023	255.4	421.5	289.6	492.0
2024	263.4	434.7	298.6	508.0
2025	275.4	454.4	312.2	517.9
2026	283.4	467.6	321.2	533.9
2027	291.4	480.8	330.3	544.5
2028	299.3	493.9	339.3	554.4
2029	311.3	513.7	352.9	570.4
2030	319.3	526.9	362.0	570.4
2031	319.3	526.9	362.0	570.4
2032	319.3	526.9	362.0	570.4
2033	319.3	526.9	362.0	570.4
2034	319.3	526.9	362.0	570.4
2035	319.3	526.9	362.0	570.4
2036	319.3	526.9	362.0	570.4

Source: Based on Frontier, UMAS, CE Delft and E4tech (2019) Reducing the UK Maritime Sector's Contribution to Climate Change and Air Pollution: Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs.

1.4.6 Approach to estimating additional GHG emissions and voyage costs for use of scrubber or SCR

Estimation of additional GHG emissions.

GloTraM does not estimate the additional powering required to run a scrubber or SCR when a vessel is in the ECA. Rather, it assumes the scrubber/SCR, if installed, is constantly in use. However, a requirement of this work is to provide a complete and robust estimate of the additional costs due to each ECA extension option. Therefore, the following models are deployed in a post-processing stage on the data to estimate the impacts of this additional powering. The consequence of any additional powering is to increase fuel consumption and associated emissions. This study uses an additional powering requirement due to scrubber[21] or SCR[22] of 2% for each technology (i.e. when both are installed the increase is 4.04%).

When HFO is used together with a scrubber, the scrubber is assumed to operate not only inside the ECA but also outside the ECA to comply with the 2020 global sulphur limit (0.5%). In this case the 2% increase[23] in costs and emissions represent an additional fuel consumption associated with the intensified level of operation due to switching from 0.5% to 0.1% sulphur level to comply with the ECA requirements. The change is only applied to CH_4 and CO_2 as N_2O was not deemed to be material (as a proportion of GHG emissions).

In the case of SCR, the correction represents the additional GHG emissions both relating to the reactions between exhaust species and urea, and some increase due to the additional back-pressure on the engine due to the presence of the SCR system in the exhaust.[24] The approach is as follows:

- If a scrubber and SCR is installed, the following formula was applied:

$$GHG_{new} = GHG_{org} + GHG_{org} * \Delta ECA_{time} * 4.04/100$$

Where ΔECA_{time} is the change in the proportion of time that a vessel is in an ECA (this will be between 0 and 1).

- If just scrubber (or just SCR) is installed, the following formula was applied:

$$GHG_{new} = GHG_{org} + GHG_{org} * \Delta ECA_{time} * 2/100$$

Estimation of additional voyage costs

As alluded to in the section above, there is an additional powering requirement when using a scrubber or SCR. The additional required fuel to service this will not only increase GHG emissions but also increase voyages costs. The additional voyage costs were estimated similarly to the additional GHGs model discussed in

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[21] The use of scrubbers comes typically with a fuel penalty of up to 2% https://cdn.aseminfoboard.org/documents/Air-Emissions-from-Shipping-In.pdf

[22] C R Bedick, N N Clark, D R Johnson, T H Balon Jr, P J Moynihan & M J Bradley (2011) Demonstration and evaluation of a retrofit urea-SCR after-treatment system for NOx reduction in marine diesels, Journal of Marine Engineering & Technology, 10:1, 3-13, DOI: 10.1080/20464177.2011.11020239

[23] Based on expert judgements

[24] C R Bedick, N N Clark, D R Johnson, T H Balon Jr, P J Moynihan & M J Bradley (2011) Demonstration and evaluation of a retrofit urea-SCR after-treatment system for NOx reduction in marine diesels, Journal of Marine Engineering & Technology, 10:1, 3-13, DOI: 10.1080/20464177.2011.11020239

the previous section. If a scrubber and SCR is installed, the following formula was applied:

$$voyage\ cost_{new} = voyage\ cost_{org} + fuel\ consumption_{org} * \Delta ECA_{time} * fuel\ price * \ 4.04/100$$

- If just scrubber (or just SCR) is installed, the following formula was applied:

$$voyage\ cost_{new} = voyage\ cost_{org} + fuel\ consumption_{org} * \Delta ECA_{time} * fuel\ price * \ 2/100$$

1.5 Limitations

The following limitations were recognised:

- Gaps in AIS data - average AIS coverage in 2016 is approximately 65%. Better coverage could be achieved by integrating the Maritime and Coastguard Agency (MCA) AIS data which was not available in time for this project.

  The remaining operational statistics such as speed over ground and draught observations were infilled by applying the FUSE extrapolation model. However, the vessel positions were not estimated for periods where the data is missing, and the vessels last known location was assumed to persist until a new AIS observation is available.
- The consequences of this could potentially include a misallocation of a vessel's position to within (outside) the ECA when in fact it was outside (inside) the ECA or missing some of the voyages that took place during the AIS gap. The latter could lead to slightly underestimated transport demand (i.e. number of vessels) figures that serve each fleet category and hence the associated emissions.
- This study is restricted to AIS Class A vessels. Class B vessels were excluded from the scope of this study because no technical specifications for Class B ships were available. Class B vessels mostly comprise small domestic ships and boats. Hence, the inclusion of Class B vessels would most likely increase the absolute domestic emissions figures by approximately 6% as highlighted in Ricardo et al. (2017)[25]. However, Class B vessels would have a minimal effect on the change in emissions due to ECA extension policy options. This is because most Class B vessels are fuelled with marine diesel oil (MDO) and already compliant with the ECA requirements.
- Vessel type allocation – in some cases in the AIS data the MMSI/IMO identification was missing or incorrect. The missing vessels were allocated in accordance with the modelling principles described in paragraph 1.4.1. However, there is still some possibility of vessels being allocated to an incorrect vessel type category affecting the vessel counts distribution across type categories but unlikely the total number of vessels captured and emissions figures.
- Vessel size categorisation used in this study is being quite broad, particularly on the smallest size category. It is expected that the domestic voyages within each size category to have a lower mean vessel size than vessels involved in international or in transit operations. Since smaller vessels are typically emit less amounts of emissions, this could lead to a slight overestimation of the domestic emissions figures.
- ECA time ratios for each policy option are based on equivalent market size (EMS) rather than a per vessel basis. Since a real vessel could be involved in mixed operations rather than e.g. having purely domestic or international voyages, the economic choice of the shipowner on whether to use a scrubber or fuel switch in ECA areas could be different.

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

- A scenario based approach has been applied in this study which is naturally limiting due to various modelling assumptions being made. For example,
  - GloTraM emissions were estimated based on an aggregation of the operational statistics across groups of vessels from the global fleet and not specific to UK vessels.
  - Distribution of vessel operational activity, namely a nature of voyages that a vessel annually undertakes, remains constant from base year and grows linearly with increase in UK wide transport demand.
  - Assumptions associated with the future technology uptake, transport demand and changing fuel prices were used.
  - To account for non-modelled vessels a simple percentage increase is applied across all years assuming that the fleet mix, although generally growing with increasing transport demand, remains proportionally stable.

  Considering time constraints and resource limitations associated with this research project, no deep sensitivity analyses were performed to identify the underlying key drivers of emissions fluctuations. With sensitivity analysis it would have been possible to identify the implications and measure the uncertainty associated with changing assumptions in transport demand for different vessel types and sizes, quantifying the deviations in resulted costs changes from applying different fuel price scenarios or technology mix combinations.

  However, the approach taken is not highly innovative and incorporates techno-economic modelling techniques used across the energy and transport modelling domains and there is no evidence that would have produced any significant differences in the results or conclusions.

- There are also limitations associated with the availability of data sources for the validation. Considering the unique scope of this research, the total emissions estimates are not directly comparable with the other similar studies.

  Moreover, no validation datasets, such as continuous monitoring or noon reports, were available to compare this study's emission estimates with the actual performance on a per vessel basis.

  In the quality assurance QA section, a comparison of vessel calls to all UK ports for dry bulk vessels have been provided. However, the uncertainty at a port or regional level is unknown. It would be helpful to understand any bias in the voyages generated in this study, in respect of the different ECA options tested. For example, this study may be undercounting the number of voyages to the ports in scope for Option 1 which requires a port by port comparison with Eurostat (2018)[26] and Port freight statistics (2018)[27].

[26] Eurostat, 2018. Available at https://ec.europa.eu/eurostat/data/database

[27] Port Freight Statistics for 2016 are available at https://www.gov.uk/government/statistics/port-freight-statistics-2017-final-figures

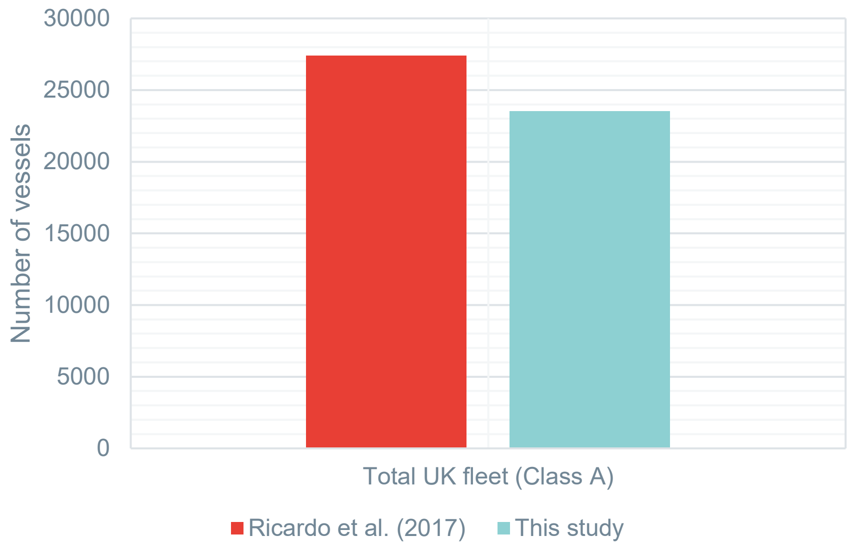
1.6 Quality assurance (QA)

1.6.1 Specification of the UK fleet

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

Quality assurance of the estimated UK fleet was established by comparing this study's bottom-up vessel counts estimation identified using AIS data against the equivalent data from Ricardo et al. (2017)[28]. The comparison of the total number of vessels that operate within the relevant study areas is shown in Figure 19 and was found to be generally within reasonable margins in total.

Figure 19 Number of vessels captured in Ricardo et al. (2017) and this study



Discrepancies can be explained by the different year of interest as Ricardo is based on 2014 and this study is based on 2016. Moreover, the UK fleet definition is different in two studies. Unlike in Ricardo where the UK fleet is defined using the full extent of MCA geographical coverage, in this study the UK fleet is limited to an area of interest specifically designed for the purposes of this research and comprises UK territorial waters boundaries, a belt of coastal waters extending at most 12 nautical miles from the baseline of a coastal state, combined with additional area covering the Irish Sea and down to the English Channel as per the definition of the ECA extension option 3 assessed in this project.

1.6.2 Total energy demand

Given the unique nature of this study, the total energy demand of the ECA extension policy options is difficult to compare with that of other studies. As described in the methodology (section 1.3), the results were estimated using GloTraM. For the purpose of this study, the GloTraM model was chosen over the

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

FUSE platform because it allows account to be taken of an appropriate mix of energy efficiency technologies and devices while allowing to simulate the operational profile of fleets in accordance with a time frame of interest.

FUSE is directly connected with GloTraM as GloTraM uses fleet performance statistics derived from FUSE (section 1.4.4). The main difference between FUSE and GloTraM is that GloTraM is based on an average vessel performance per size/type/generation cohort while FUSE estimates are based on the performance of individual vessels. Furthermore, the approach used to handle the manoeuvring and anchoring operations is different. For example, in FUSE, the manoeuvring/anchoring operations are considered separate from “at sea” and “at port/berth” operations (the approach is based on Third IMO GHG study[29]). In GloTraM, the manoeuvring/anchoring operations are combined with “at sea” operations.

For quality assurance purposes, first, the energy demand estimates modelled in GloTraM were compared with the AIS-based energy demand estimates derived from FUSE for each of the ECA extension policy options.

Secondly, the AIS-based domestic total energy demand derived from FUSE was compared with the annual UK domestic shipping energy demand in the Ricardo (2017)[30] study.

The results of these comparisons are shown in Figure 20 – Figure 24.

The only outstanding discrepancy is observed when comparing the GloTraM-derived domestic estimates with the AIS-based domestic energy demand (derived from FUSE) for all the options. This discrepancy can be explained by the fact that the GloTraM energy demand was estimated based on an aggregation of the operational statistics across groups of vessels from the global fleet and not specific to UK vessels; unlike FUSE. Moreover, as already highlighted in section 1.5, the vessel size categorisation used in this study is broad, particularly for the smallest size category. Therefore, the domestic estimates appear to be higher than the FUSE-derived results because in domestic operations, vessels generally have a lower mean size than vessels involved in international or in transit operations.

[29] Third IMO GHG Study 2014; International Maritime Organization (IMO) London, UK

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

Figure 20 Comparison of total annual energy demand (PJ) from UK domestic shipping operations from GloTraM and FUSE in 2016

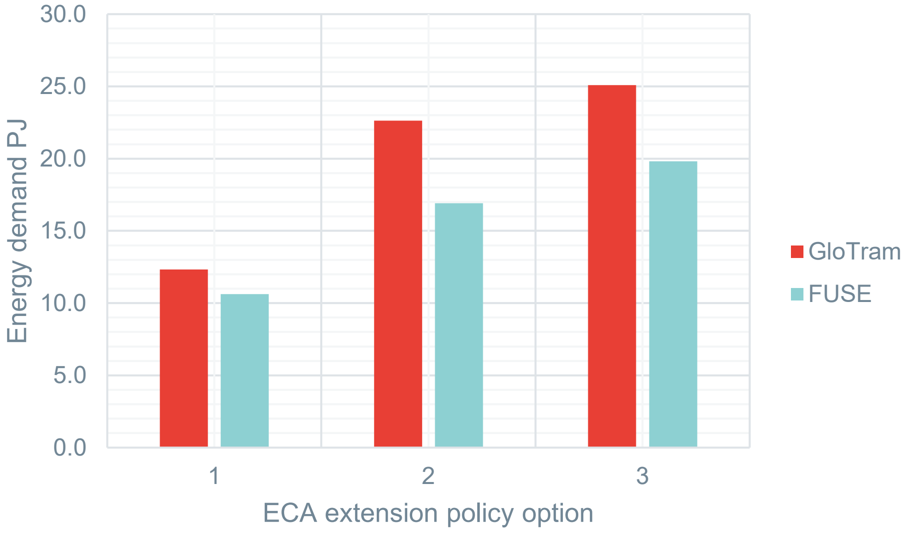


Figure 21 Comparison of total annual energy demand (PJ) estimates from UK international shipping operations from GloTraM and FUSE in 2016

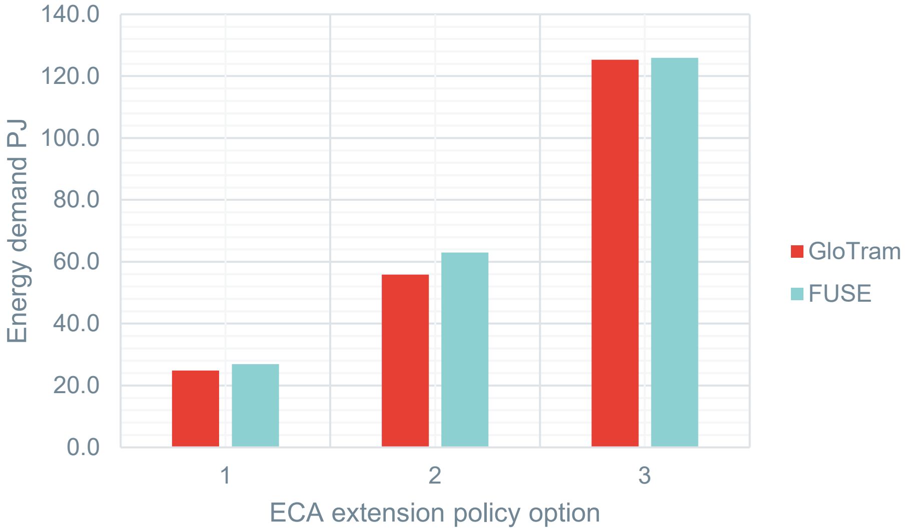


Figure 22 Comparison of total annual energy demand (PJ) estimates from in transit shipping operations from GloTraM and FUSE in 2016 for ECA extension policy option 1

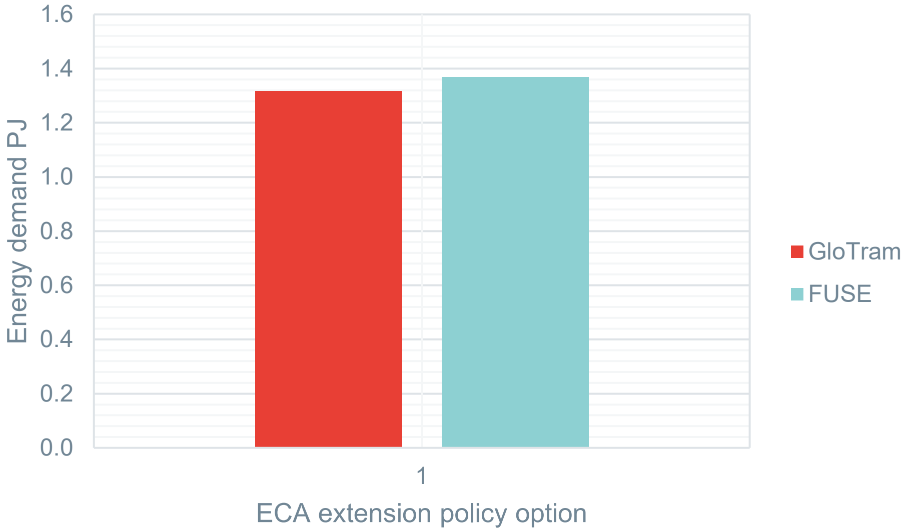


Figure 23 Comparison of total annual energy demand (PJ) estimates from in transit shipping operations from GloTraM and FUSE in 2016 for ECA extension policy option 2 and option 3

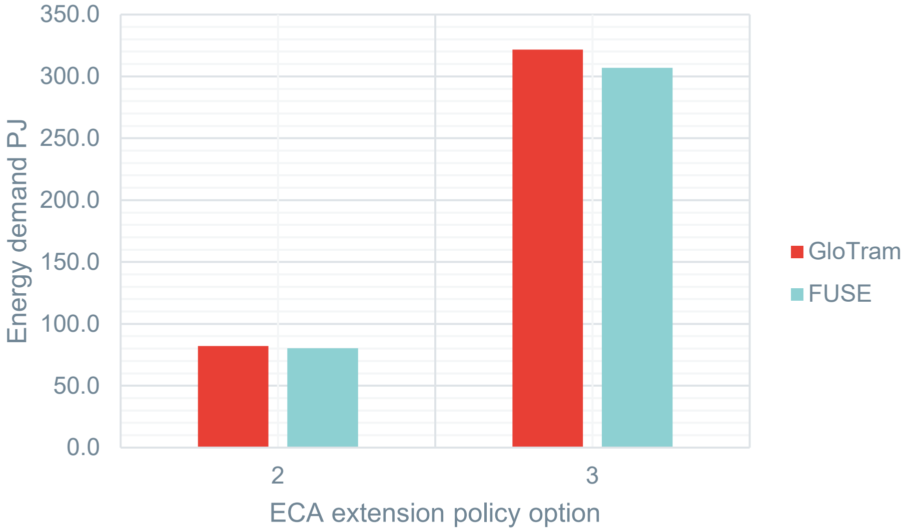
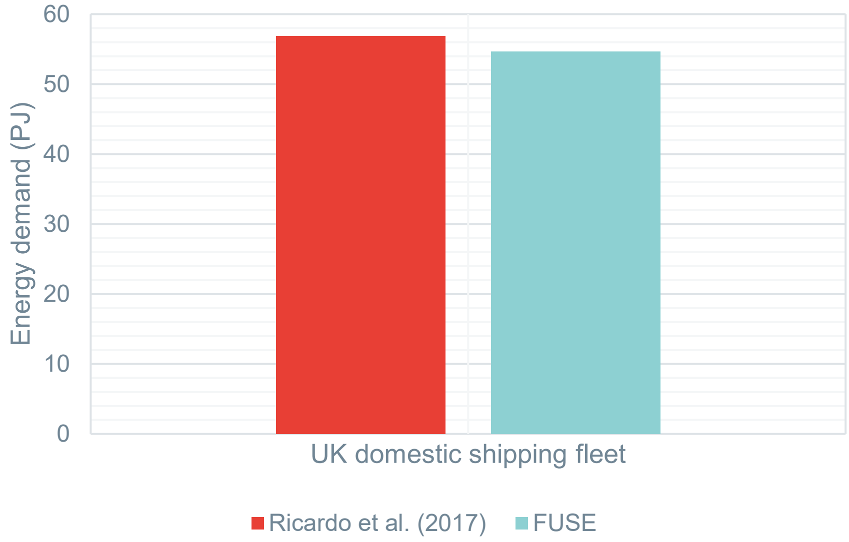


Figure 24 Comparison of total annual energy demand (PJ) from UK domestic shipping operations from Ricardo (2014) and FUSE (2016)



1.6.3 Voyage calls to selected ports

Eurostat[31] reports the number of vessel calls to each port aggregated to ship type and size (gross tonnage). The Eurostat database does not indicate whether the vessel calls are domestic, international or both. This data has been aggregated to the UK level.

The total vessel calls to the UK in 2016 according to this dataset is 2889 for dry bulk vessels below 10,000GT (assumed to be equivalent to dry bulk size 1)[32]. In this study, a total of 7124 port calls that belong to the dry bulk size 1 category was estimated for both UK domestic and UK international fleets. When focussing on international voyages, this figure reduces to 1310 vessel calls. There are a number of reasons to explain this discrepancy:

- In this study, there may be an over allocation of voyages to the domestic fleet. This could be due to close geographical proximity of some domestic ports[33], resulting in the greater total number of domestic voyage calls than the actual.

[31] Eurostat, 2018. Available at https://ec.europa.eu/eurostat/data/database

[32] As highlighted in the main body, the vessel size disaggregation from Eurostat 2016 are not consistent with those used in this study. A comparison across all types would have required a significant amount of work that is beyond the scope of this study. Therefore, the analysis is limited to dry bulk vessels only because these vessels are a significant contributor to emissions. In addition, there are notable differences between the number of vessels in size 1 category identified in this study as compared with Ricardo (2017).

[33] As discussed in section 1.3, the voyages are assigned based on proximity to ports (as well as other factors such as vessel speed). As AIS observations can be sparse around port areas, the algorithm is tuned to assign a port stop if a vessel exhibits characteristics that indicate that it has stopped. For example, if there was an AIS observation showing a vessel near a port at low speed, then there was a gap in the AIS data of a day, with the next AIS observation showing the vessel sailing away from the port with a change in draft. This would indicate that the vessel most likely stopped at that port. This model is sensitive to local conditions both geographic (e.g. multiple ports located nearby) and local vessel operations. In the specific case of over counting voyages, an area near a port may be an anchorage area for vessels awaiting instruction. The algorithm in some instances may allocate this as a port stop, when in fact the vessel did not enter port.

- Incorrect allocation of some vessels to dry bulk size 1. This is counter to what the comparison with Ricardo (2017) in the previous section shows however.

If we additionally compare between dry bulk size 3 and vessels in Eurostat between 40,000 and 50,000 GT, we see 857 vessel calls from our study and 423 from Eurostat. However, there are also some vessels in the 30,000GT to 39,999 range that would count as size 3 vessels. The vessel calls in this size range are 639. Including this as an upper bound, the vessel calls from this study, 857, fits within the vessel count range of 423 to 1062. However, this is far from conclusive.

Overall, it's not clear from this comparison whether we are undercounting or overcounting the vessel calls. Given the proximity of domestic traffic to shore, it is likely that we are overcounting voyages, however, this should not have an adverse effect on the study as we include all domestic voyages in the study and therefore counting 1 voyage as multiple voyages will only have the effect of assigning a port call where in fact the vessel is anchored but not have an effect on the total at sea time of the vessel.

1.6.4 Baseline emissions factors

As highlighted in previous sections, for the scope of this work the results are derived from GloTraM. FUSE is directly connected with GloTraM as GloTraM uses aggregated operational profiles derived from FUSE. For the validation purposes, Aether[34] compared emissions per vessel at berth and at sea from a Port of London emissions inventory[35] to FUSE.

The comparison showed that CO_2 and NO_x emissions were similar. There were some differences in SO_2 and PM emissions, which is likely to be driven by several factors. For SO_2, differences existed in assumptions around compliance rates for regulations on the sulphur content of fuels[36]. For both SO_2 and PM there were also differences in underpinning emission factors (with FUSE using the Third IMO GHG study) as well as general uncertainty in the comparison of vessel types in relation to the size distribution of vessels.

1.6.5 Robustness of the Analysis

The team undertaking the research includes a number of individuals with PhD level qualifications in subjects related to shipping emissions modelling. The team has professional experience in delivering a number of studies that have been used at the highest levels internationally (including the industry's and the IMO's evidence base, both on GHG emissions and air pollution). This is therefore a highly qualified team capable of minimising the risks of error and maximising the robustness of the analysis.

[34] https://www.aether-uk.com/

[35] https://www.pla.co.uk/assets/finalplaportwideinventoryoutputsreportv10.2publication.pdf

[36] In the Port of London inventory 100% compliance with the relevant standards at sea and for inland navigation has been assumed. However, surveys in the Netherlands, undertaken since the fuel quality regulations were introduced (including SECA), have shown that ships at berth were, on average, 90% compliant. Therefore, it has been assumed that 10% of seagoing ships at berth use 1% sulphur fuel for their auxiliary operations. https://www.pla.co.uk/assets/finalplaportwideinventoryoutputsreportv10.2publication.pdf

The outputs produced by the UMAS team have been reviewed within the UMAS team and then subject to challenge by the Frontier team for use in the cost-benefit analysis. This has ensured close scrutiny of the core modelling outputs of the project and adds a level of independent quality control. In combination with the experience of the team in leading similar work previously, and in spite of the complexity of the modelling, the overall risk of error is appropriately managed and the robustness is high.

1.7 Detailed results

In this section, all references to domestic shipping are referring to "UK domestic shipping" and all references to international shipping are referring to "UK international shipping".

1.7.1 Vessels affected by ECA extension options

The Figures below show the actual number of vessels captured via AIS in the geographical area covered by each of the ECA extension policy options. Columns referring to Type 1-5 relate to the IMO/MMSI allocation type applied as described in the section 1.4.1.

Figure 25 Vessels affected by ECA extension option 1 in 2016

Vessel type	Type 1	Type 2	Type 4	Type 5	Grand Total
Bulk carrier	175	42			217
Chemical tanker	243	61			304
Container	103	2		6	111
General cargo	113	20			133
Liquefied gas tanker	42	12			54
Oil tanker	197	19			216
Other liquids tankers	8				8
Ferry-pax only		1			1
Cruise	25	2			27
Ferry-RoPax	14	2			16
Ro-Ro	13			29	42
Vehicle	163	25			188
Service - tug	14	2	2		18
Miscellaneous - fishing			3		3
Offshore	10	12			22
Service - other	13	9			22
Grand Total	1133	209	5	35	1382

Figure 26 Vessels affected by ECA extension option 2 in 2016

Vessel type	Type 1	Type 2	Type 3	Type 4	Type 5	Grand Total
Bulk carrier	904	284	1	5		1194
Chemical tanker	601	131				732
Container	616	63			39	718
General cargo	548	62	1			611
Liquefied gas tanker	110	41				151
Oil tanker	434	57				491
Other liquids tankers	15	1				16
Ferry-pax only	1	4		1		6
Cruise	68	17				85
Ferry-RoPax	68	4				72
Refrigerated bulk	88					88
Ro-Ro	101	4			221	326
Vehicle	344	65				409
Yacht	5	4				9
Service - tug	75	13		4		92
Miscellaneous - fishing	63	35		18		116
Offshore	236	98		1		335
Service - other	72	28				100
Grand Total	4349	911	2	29	260	5551

Figure 27 Vessels affected by ECA extension option 3 in 2016

Vessel type	Type 1	Type 2	Type 3	Type 4	Type 5	Grand Total
Bulk carrier	2014	623	1	2		2640
Chemical tanker	1044	274				1318
Container	906	98			44	1048
General cargo	1017	110		1		1128
Liquefied gas tanker	235	81				316
Oil tanker	941	160				1101
Other liquids tankers	23	4				27
Ferry-pax only		2				2
Cruise	79	20				99
Ferry-RoPax	49	7				56
Refrigerated bulk	189					189
Ro-Ro	87	6			119	212
Vehicle	409	69				478
Yacht	9	17				26
Service - tug	53	14		2		69
Miscellaneous - fishing	97	44		21		162
Offshore	192	82		1		275
Service - other	112	34				146
Grand Total	7456	1645	1	27	163	9292

1.7.2 Number of voyages by vessel type and size

Below is the total number of voyages identified from AIS data using FUSE voyage counts in 2016 within the area of interest as shown in Figure 1. This includes the additional area reserved for the ECA extension policy option 3 as well as the current ECA.

Figure 28 Number of voyages in the area of interest by vessel type and size in 2016

Vessel type	Size category	Domestic	International	In transit
Bulk carrier	0-9999	5814	1310	1037
Bulk carrier	10000-34999	224	918	1228
Bulk carrier	35000-59999	204	653	1432
Bulk carrier	60000-99999	180	710	1581
Bulk carrier	100000-199999	113	372	595
Bulk carrier	200000-+	1	20	67
Chemical tanker	0-4999	3852	2667	1149
Chemical tanker	5000-9999	937	2565	1274
Chemical tanker	10000-19999	1287	2632	1097
Chemical tanker	20000-+	456	1613	2331
Container	0-999	2301	6089	2217
Container	1000-1999	147	1048	631
Container	2000-2999	93	881	714

Container	3000-4999	118	1551	1201
Container	5000-7999	58	920	707
Container	8000-11999	54	1082	552
Container	12000-14500	30	783	566
Container	14500-+	3	437	234
General cargo	0-4999	6421	16856	6076
General cargo	5000-9999	779	3386	3162
General cargo	10000-+	200	1262	2168
Liquefied gas tanker	0-49999	663	3485	1210
Liquefied gas tanker	50000-199999	28	99	174
Liquefied gas tanker	200000-+	2	117	21
Oil tanker	0-4999	1422	476	72
Oil tanker	5000-9999	157	83	46
Oil tanker	10000-19999	12	96	26
Oil tanker	20000-59999	137	542	584
Oil tanker	60000-79999	75	213	386
Oil tanker	80000-119999	790	1075	795
Oil tanker	120000-199999	206	448	340
Oil tanker	200000-+	69	115	160
Other liquids tankers	0-+	83	519	199
Ferry-pax only	0-1999	4839	191	179
Ferry-pax only	2000-+	61	12	3
Cruise	0-1999	141	34	26
Cruise	2000-9999	229	125	32
Cruise	10000-59999	301	766	129
Cruise	60000-99999	33	353	44
Cruise	100000-+	42	505	42
Ferry-RoPax	0-1999	1231	16	6
Ferry-RoPax	2000-+	3778	8709	1139
Refrigerated bulk	0-1999	36	933	1089
Ro-Ro	0-4999	554	767	296
Ro-Ro	5000-+	3769	15525	1212
Vehicle	0-+	175	2651	616
Vehicle	4000-+	146	2659	1064
Yacht	0-+	1193	1168	850
Service - tug	0-+	2788	772	281
Miscellaneous - fishing	0-+	34473	8813	7597
Offshore	0-+	8388	2611	293
Service - other	0-+	7416	2241	581
Miscellaneous – other	0-+	424	3	44

1.7.3 Detailed results of areas and periods of activity of vessels in 2016

ECA ratios corresponding to the metrics of interest for the purposes of modelling, split by vessel type and size and by a voyage type were developed for each ECA extension policy option and corresponding BAU scenario. The equivalent market size (EMS) values were are also generated for each ECA option.

Figure 29 Description of the ratios informing the analysis of time in ECA for the illustrative options

Column	Description
ECA Option 1(and 2 and 3)	Ratios represent the proportion of time spent in the ECA with the ECA extension policy options in action
Option 1(and 2 and 3) BAU (Counterfactual)	Ratios represent the proportion of time spent in the ECA with the ECA extension policy options **not** in action (i.e. under BAU where the ECA is referred to as the current North Sea ECA)
EMS Option 1(and 2 and 3)	Equivalent market size (number of vessels) for each of the ECA extension policy options

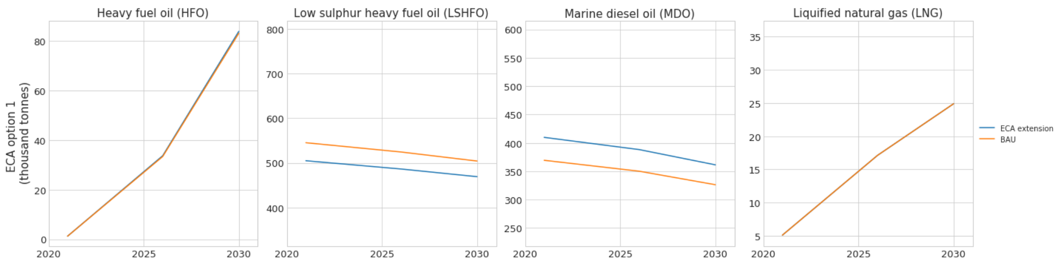
These ratios were then applied to the total energy demand of each of the cohorts to allocate an appropriate fuel type used inside and outside of the ECA.

1.7.4 Fuel consumption profile under BAU and ECA extension policy options

The results shown in Figure 30 relate to the geographical areas covered by each of the ECA extension policy options.

There is a noticeable trend indicating an increasing interest in switching to HFO coupled with a scrubber in- and outside of the ECA areas. The growing demand for HFO with a scrubber in turn affects the demand for MDO/LSHFO fuels (a combination of MDO/LSHFO or solely MDO for when operating inside and outside of the ECA) which is decreasing slightly over time for vessels operating within the geographical area covered by option 1 and option 2 while staying at mostly constant levels for vessels operating within the geographical area covered by option 3.

Figure 30 Annual total operational fuel consumption profile under BAU and ECA extension policy options

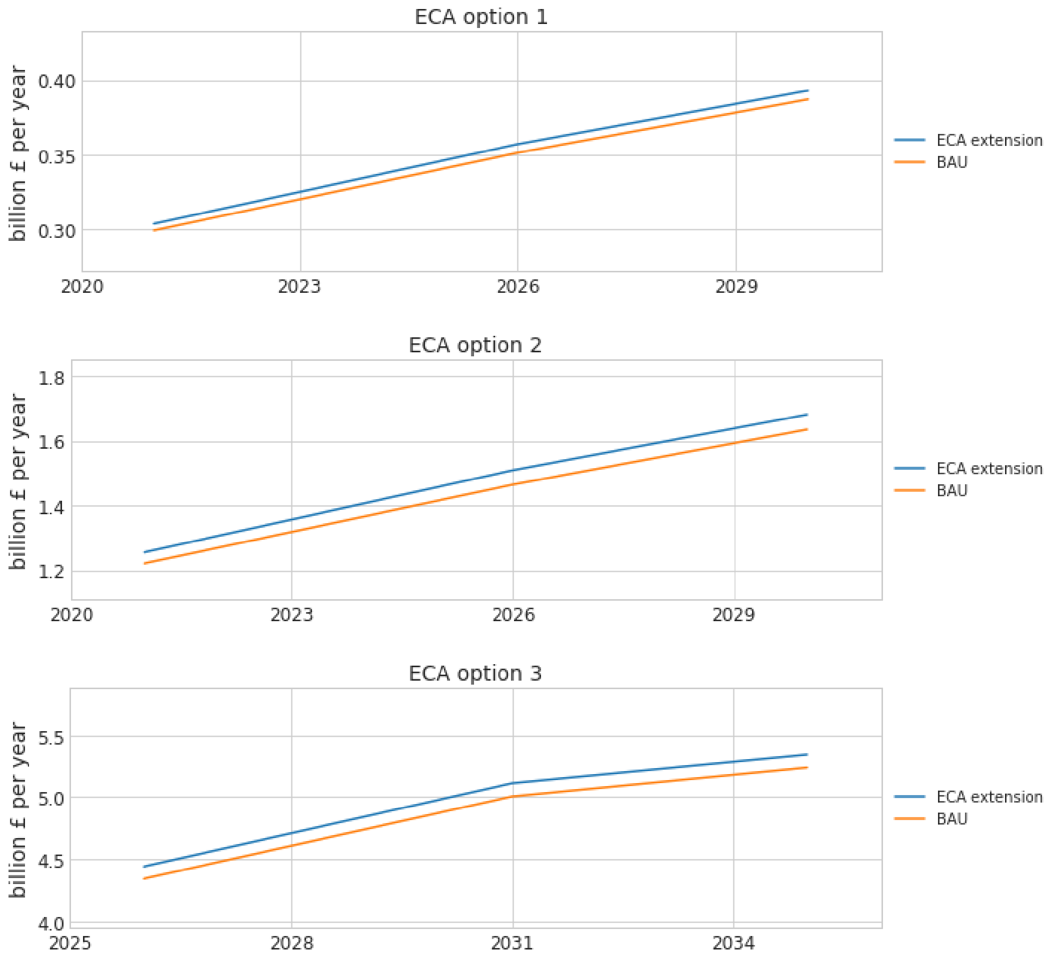



Heavy fuel oil (HFO)
Low sulphur heavy fuel oil (LSHFO)
Marine diesel oil (MDO)
Liquified natural gas (LNG)
ECA option 2 (thousand tonnes)
ECA option 3 (thousand tonnes)
ECA extension
BAU

1.7.5 Fuel operational costs profile under BAU and ECA extension policy options

The results shown in Figure 31 relate to the geographical areas covered by each of the ECA extension policy options.

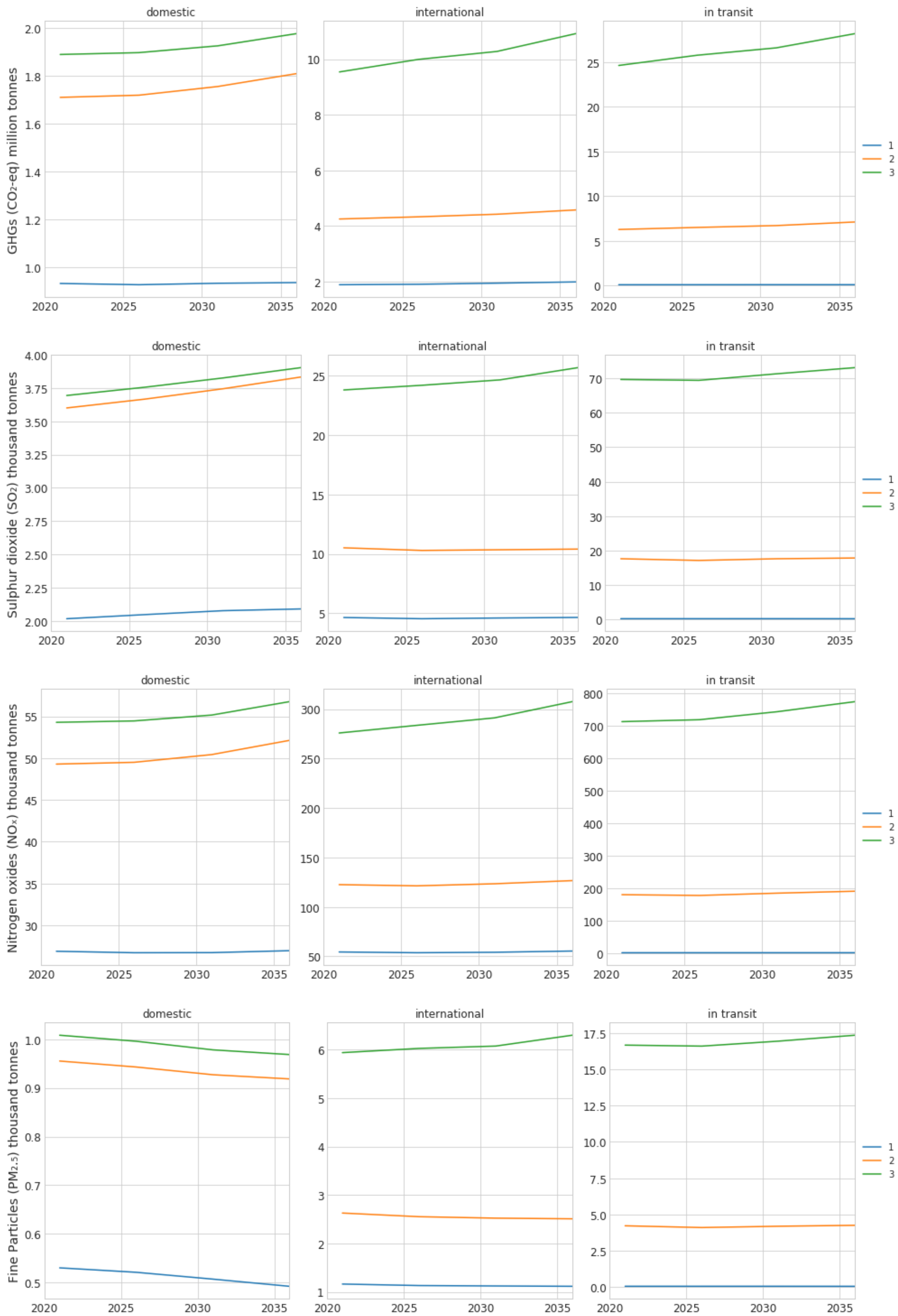
Figure 31 Annual total fuel operational costs under BAU and ECA extension options (undiscounted real 2017 prices)



1.7.6 Operational emissions profile under the business as usual scenario

The results shown in Figure 32 relate to the geographical areas covered by each of the ECA extension policy options.

Figure 32 Annual operational emissions profile under BAU for ECA extension policy options



1.7.7 Change in operational emissions and costs due to ECA extension option 1

The results shown in Figure 33 relate to the geographical area covered by ECA extension policy option 1. The charts show only the difference between the ‘with policy’ case and the BAU. The negative values in Figure 33 represent a reduction in emissions when the ECA extension policy option is in action. On the other hand, the positive values in Figure 33 represent an increase in emissions when the ECA extension policy option is in action.

Figure 33 Annual change in operational emissions compared to BAU due to ECA extension option 1

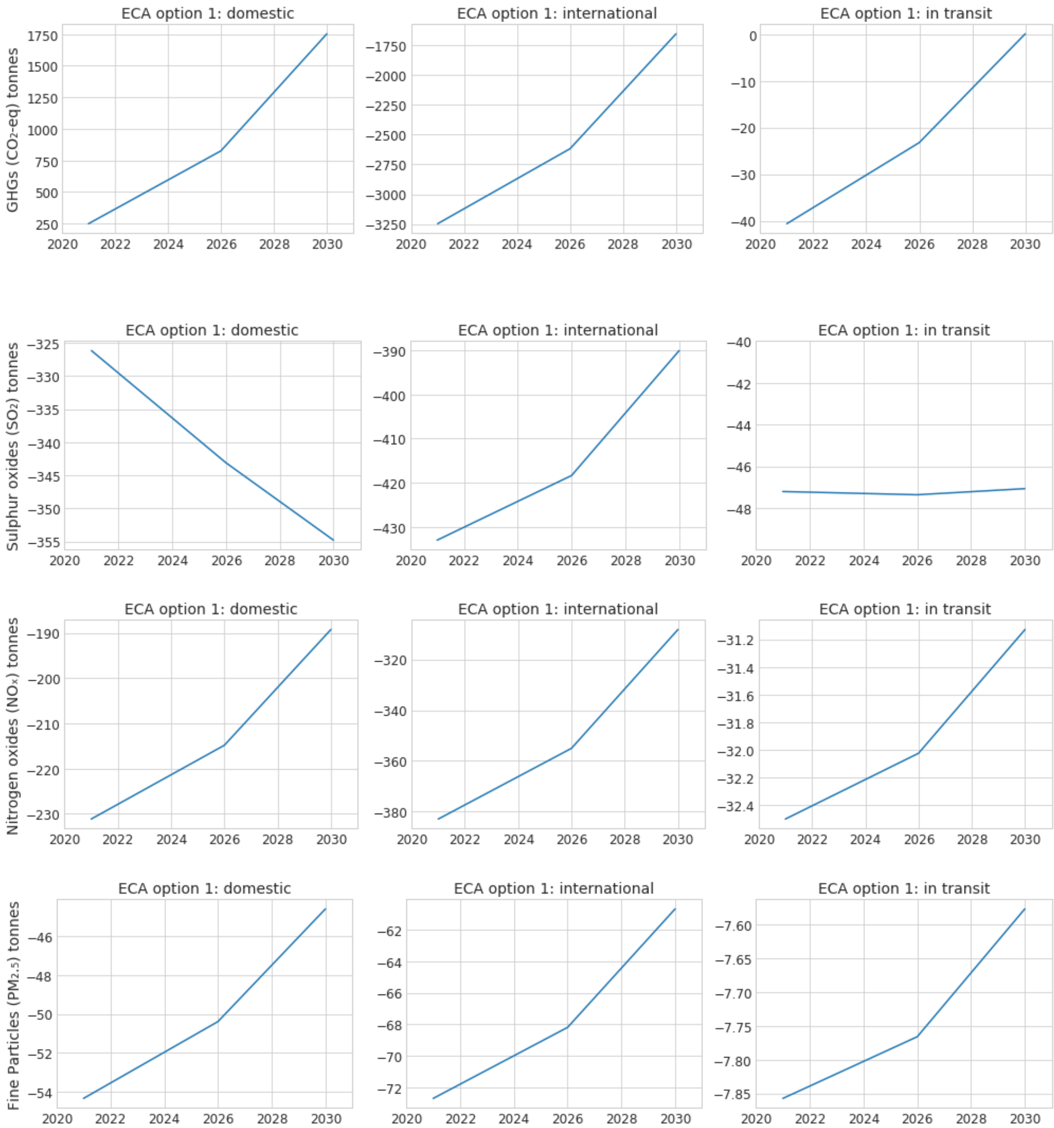
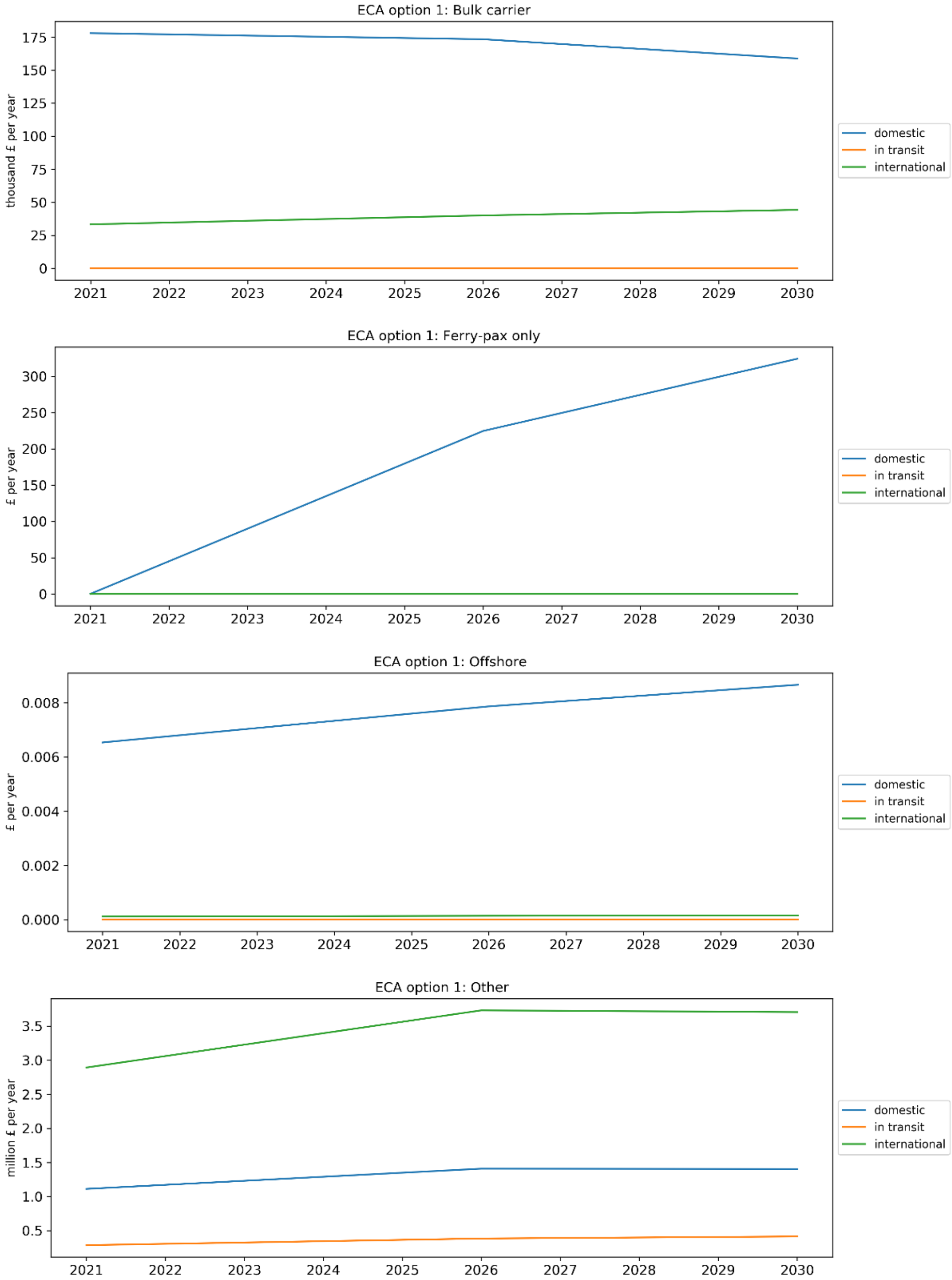
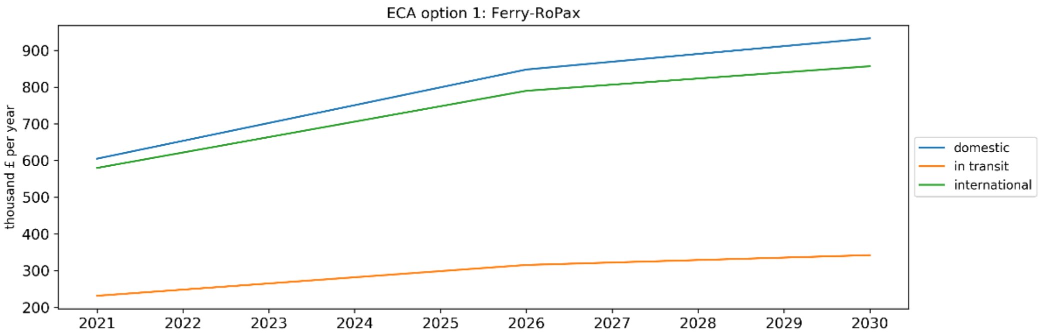
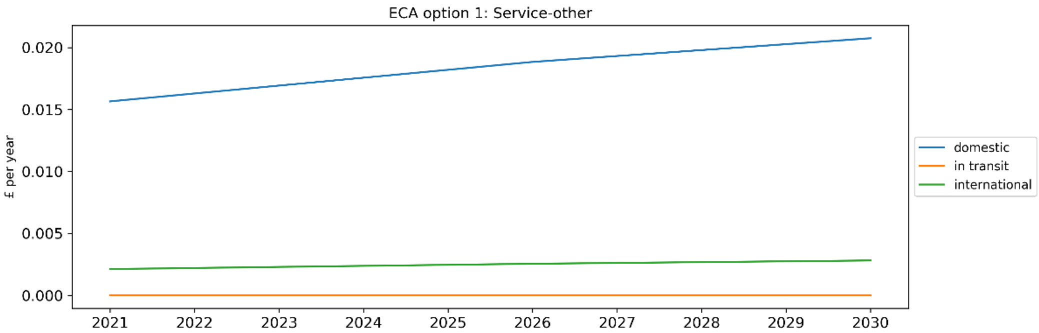
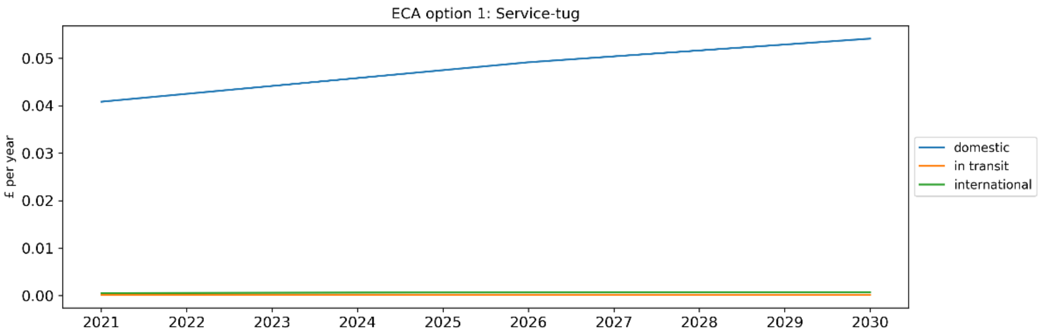


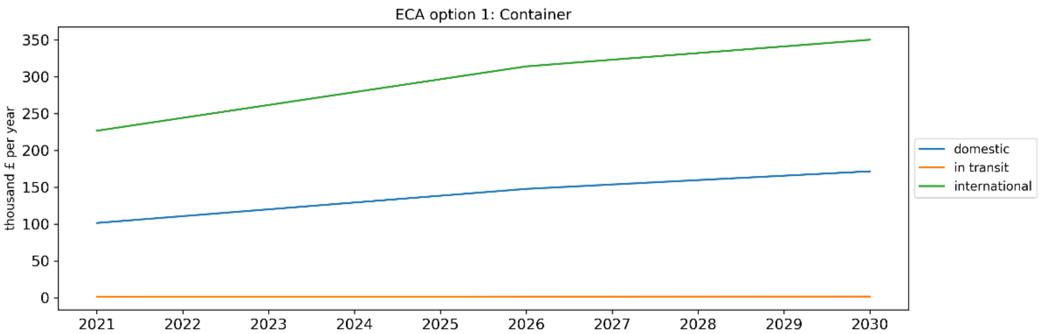
Figure 34 Annual change in fuel operating costs compared to BAU due to Option 1 (undiscounted real 2017 prices)

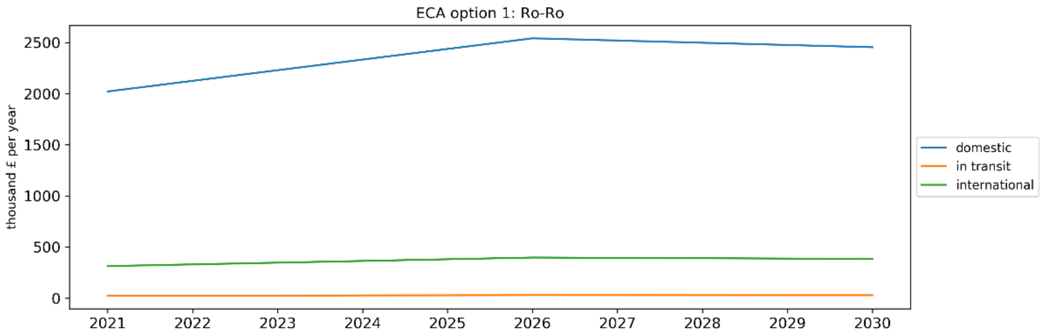


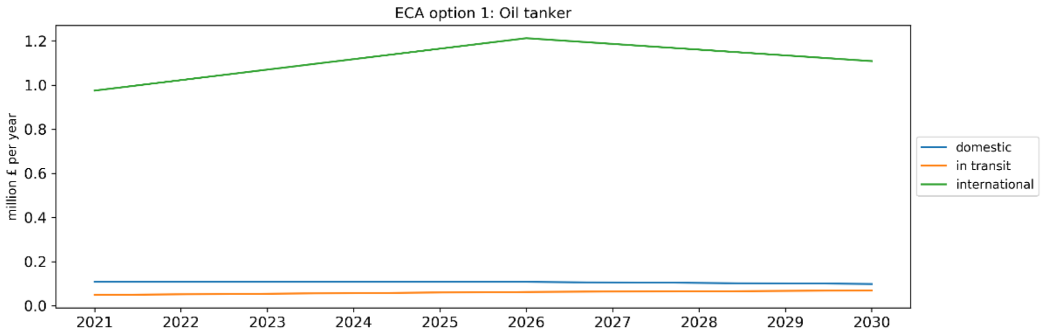

ECA option 1: Ferry-RoPax
thousand £ per year
900
800
700
600
500
400
300
200
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
domestic
in transit
international


ECA option 1: Service-other
£ per year
0.020
0.015
0.010
0.005
0.000
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
domestic
in transit
international


ECA option 1: Service-tug
£ per year
0.05
0.04
0.03
0.02
0.01
0.00
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
domestic
in transit
international


ECA option 1: Container
thousand £ per year
350
300
250
200
150
100
50
0
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
domestic
in transit
international

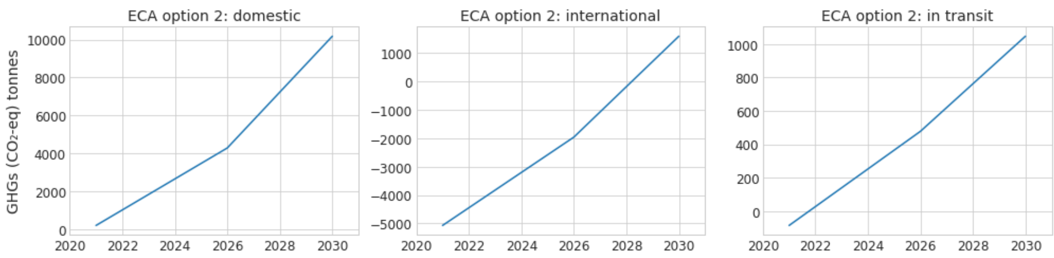




1.7.8 Change in operational emissions and costs due to ECA extension option 2

The results shown in Figure 35 relate to the geographical areas covered by ECA extension option 2. The charts show only the difference between the 'with policy' case and the BAU. The negative values in Figure 35 represent a reduction in emissions when the ECA extension policy option is in action. On the other hand, the positive values in Figure 35 represent an increase in emissions when the ECA extension policy option is in action.

Figure 35 Annual change in operational emissions compared to BAU due to ECA extension policy option 2



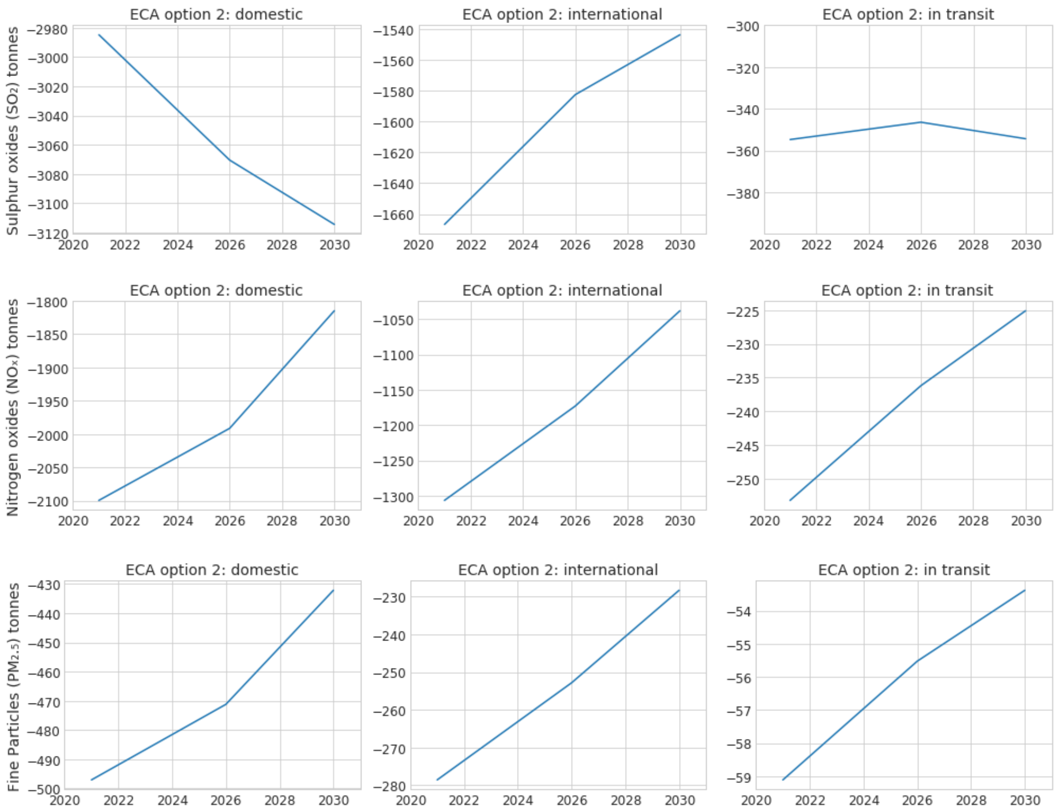
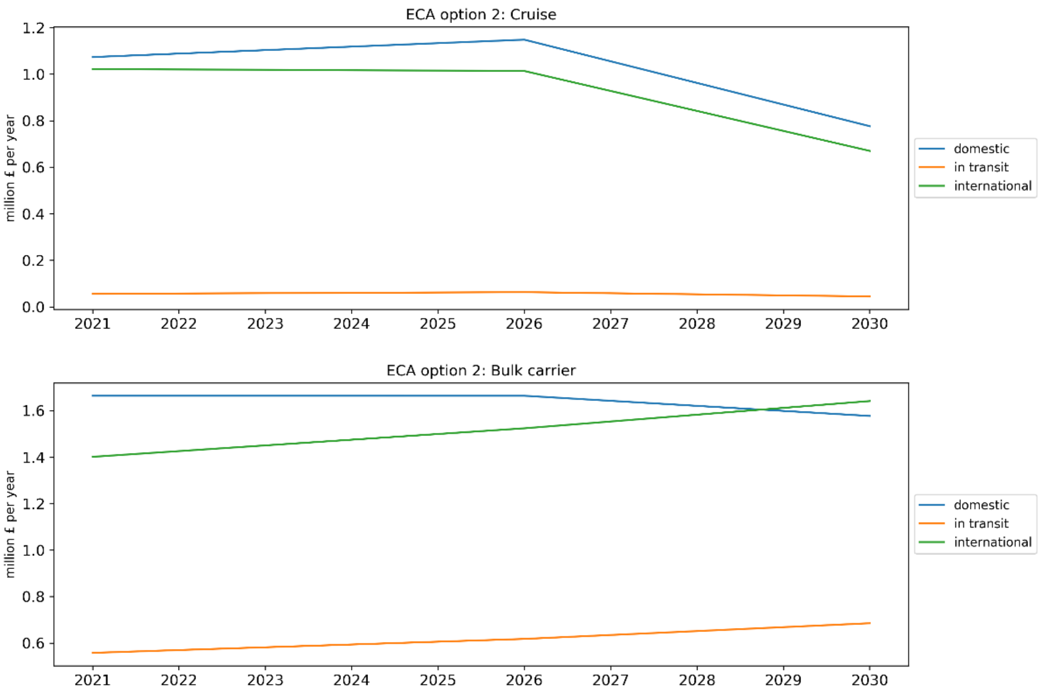
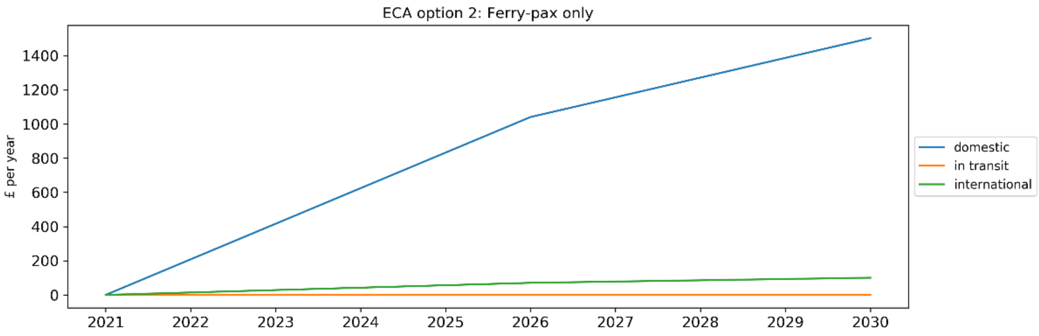
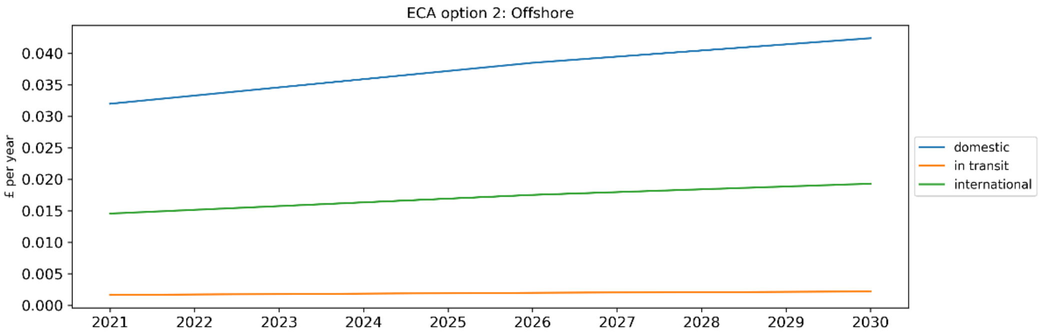
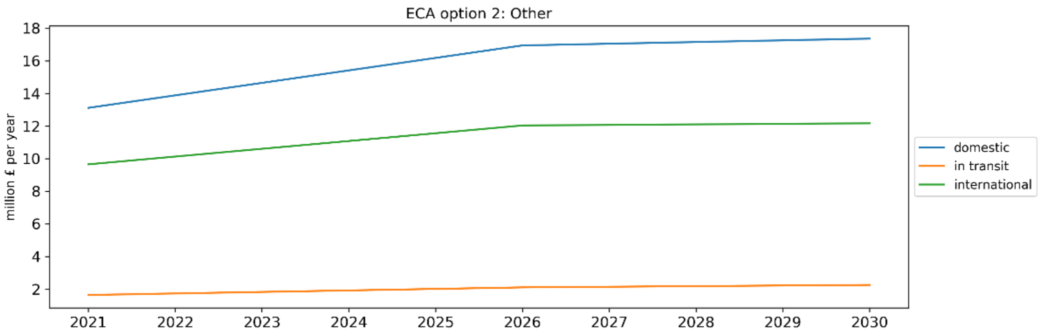


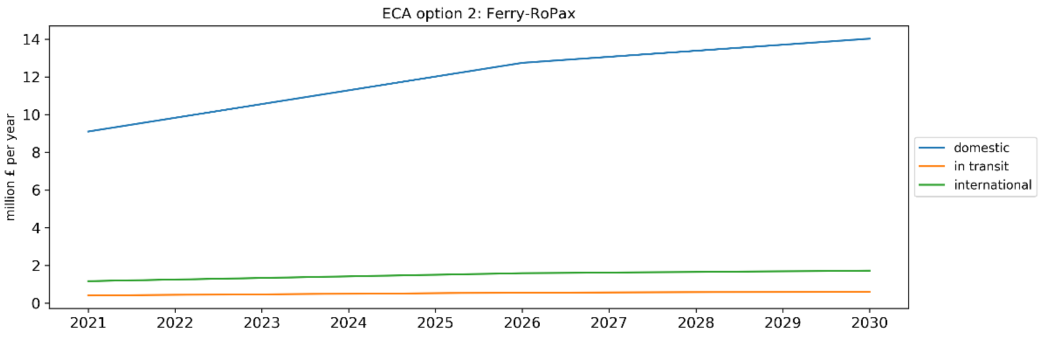
Figure 36 Annual change in fuel operating costs compared to BAU due to Option 2 (undiscounted real 2017 prices)

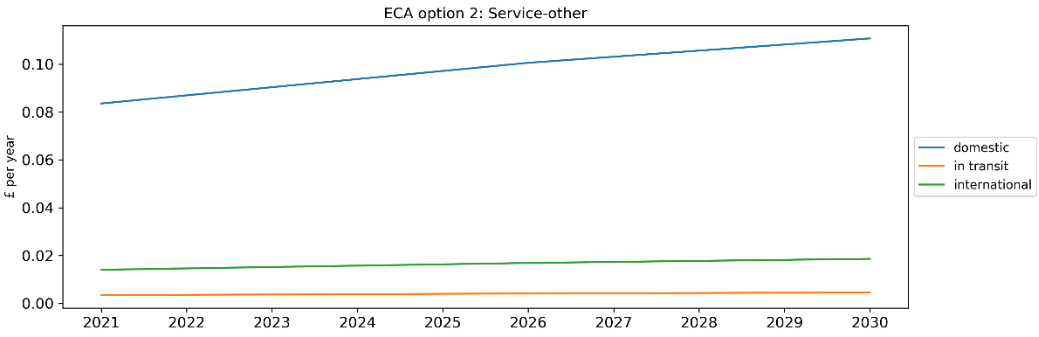


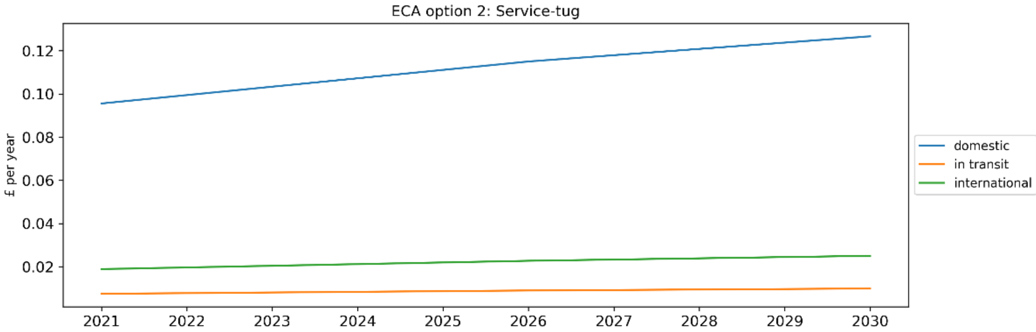

ECA option 2: Ferry-pax only
£ per year
0
200
400
600
800
1000
1200
1400
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
domestic
in transit
international

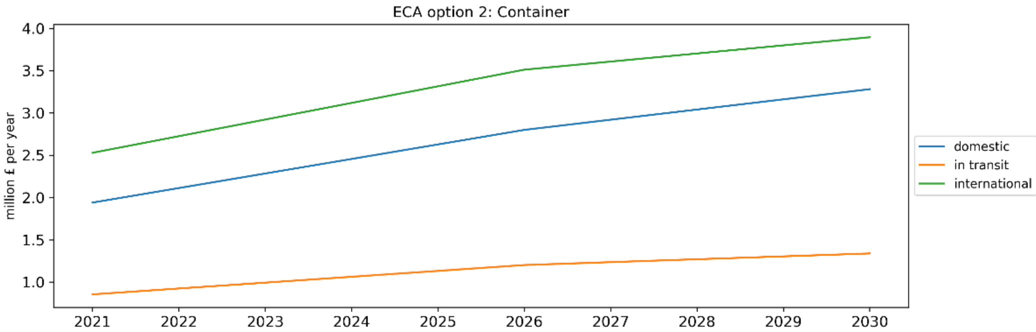

ECA option 2: Offshore
£ per year
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
domestic
in transit
international

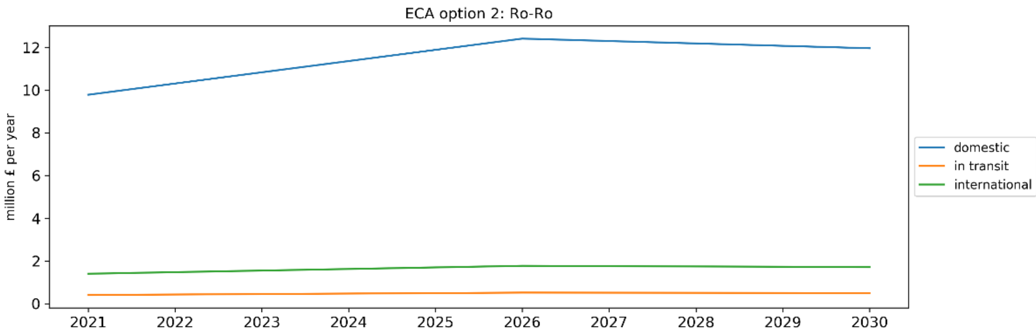

ECA option 2: Other
million £ per year
2
4
6
8
10
12
14
16
18
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
domestic
in transit
international

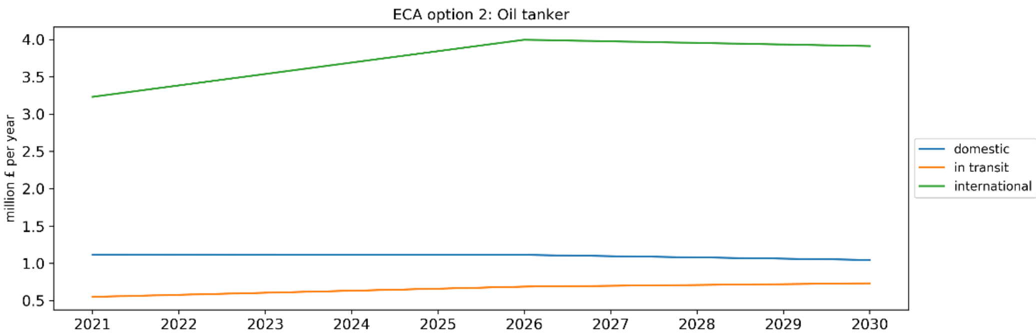

ECA option 2: Ferry-RoPax
million £ per year
0
2
4
6
8
10
12
14
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
domestic
in transit
international


ECA option 2: Service-other
£ per year
0.00
0.02
0.04
0.06
0.08
0.10
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
domestic
in transit
international









1.7.9 Change in operational emissions and costs due to ECA extension option 3

The results shown in Figure 37 relate to the geographical area covered in the ECA extension option 3. The charts show only the difference between the 'with policy' case and the BAU. The negative values in Figure 37 represent a reduction in emissions when the ECA extension policy option is in action. On the other hand, the positive values in Figure 37 represent an increase in emissions when the ECA extension policy option is in action.

Figure 37 Annual change in operational emissions compared to BAU due to ECA extension policy option 3

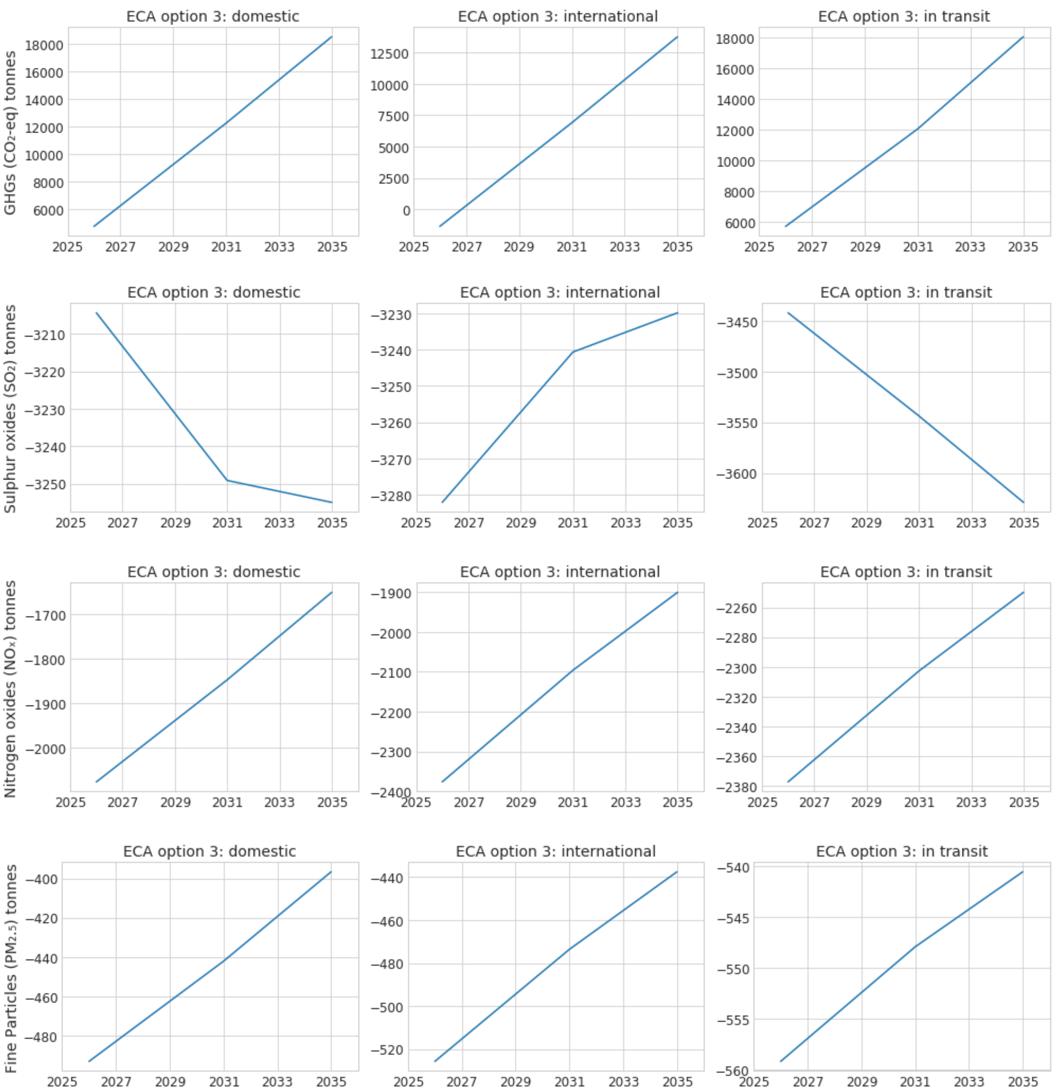
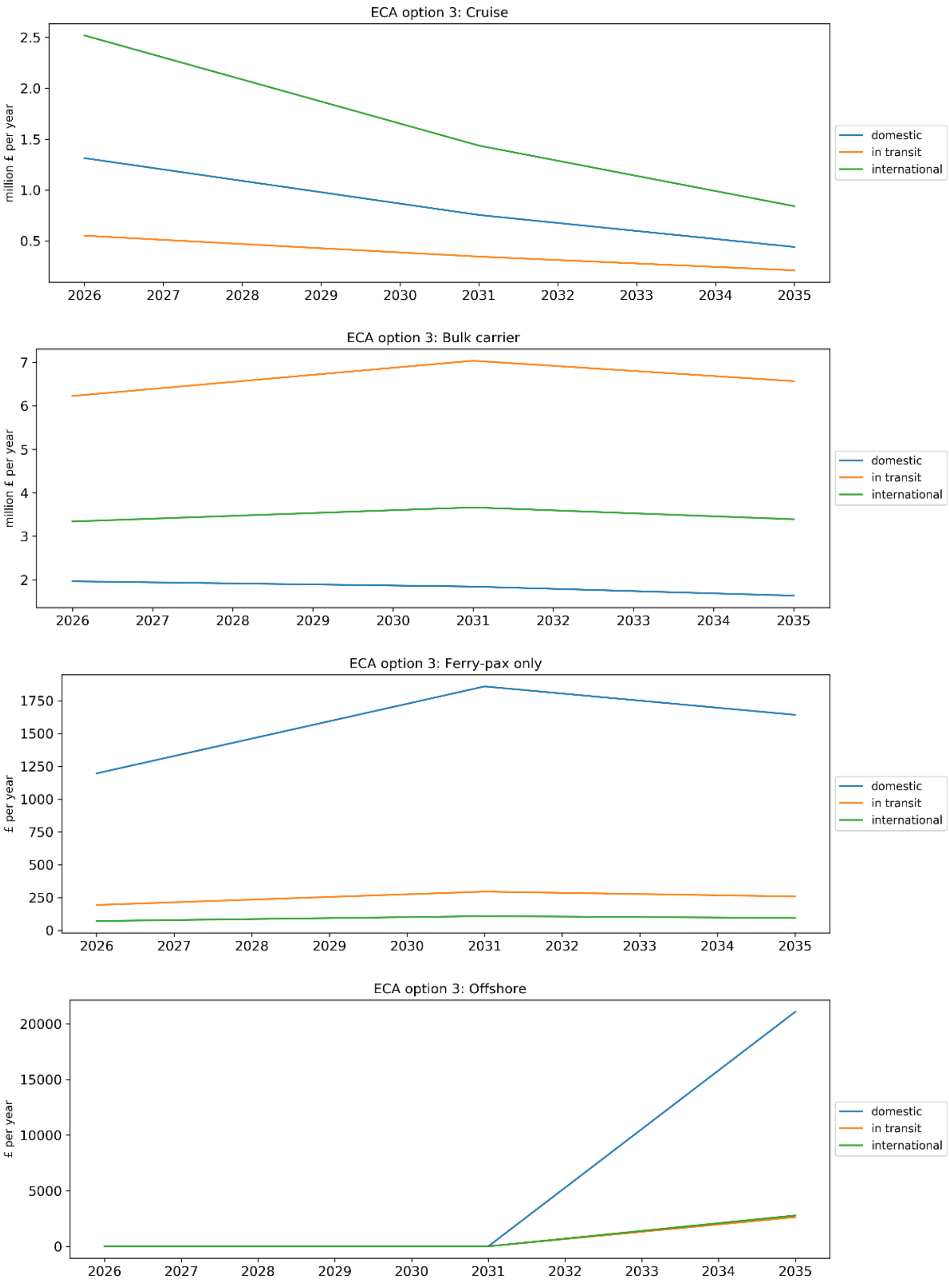
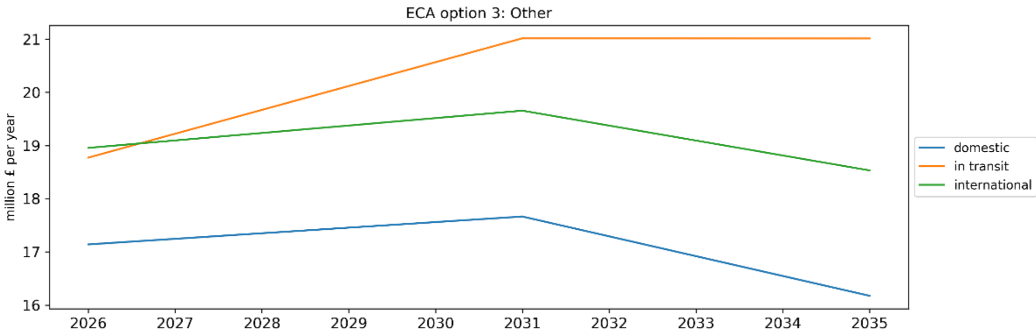
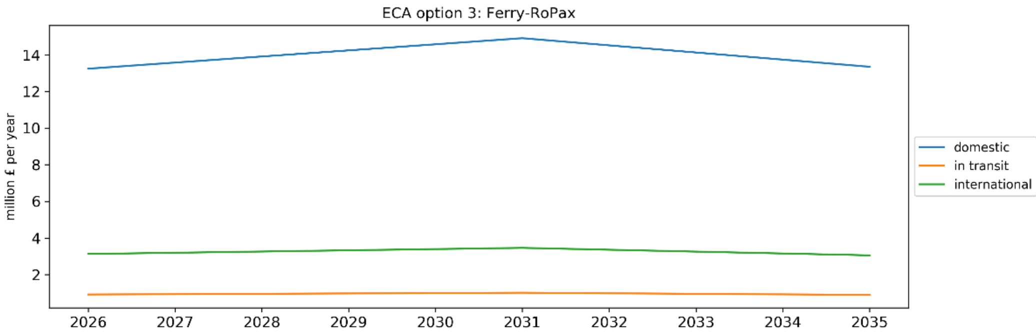
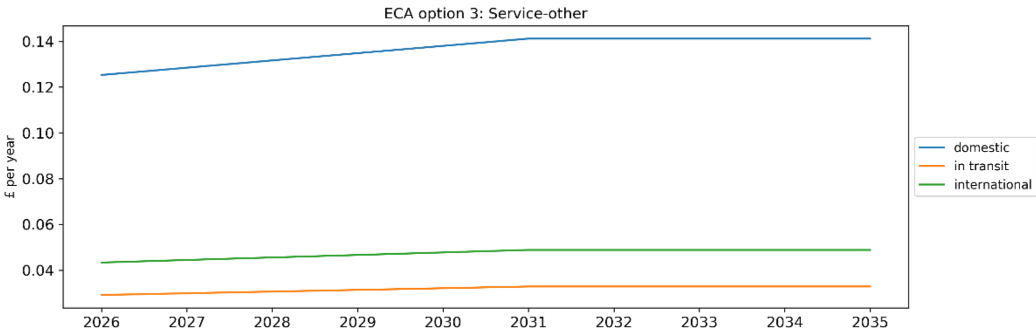


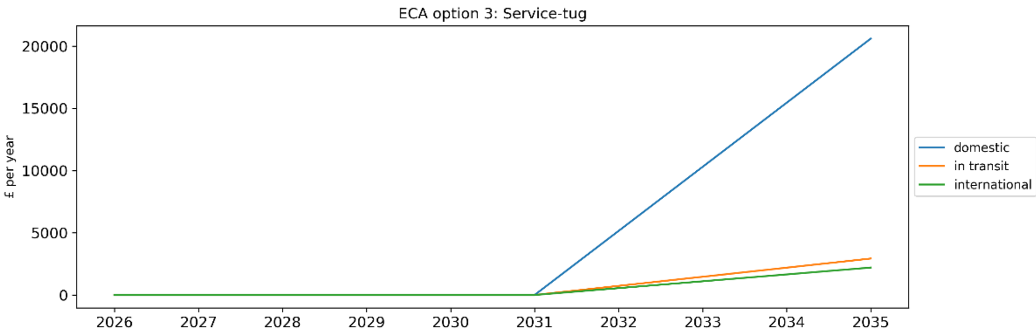
Figure 38 Annual change in fuel operating costs compared to BAU due to Option 3 (undiscounted real 2017 prices)

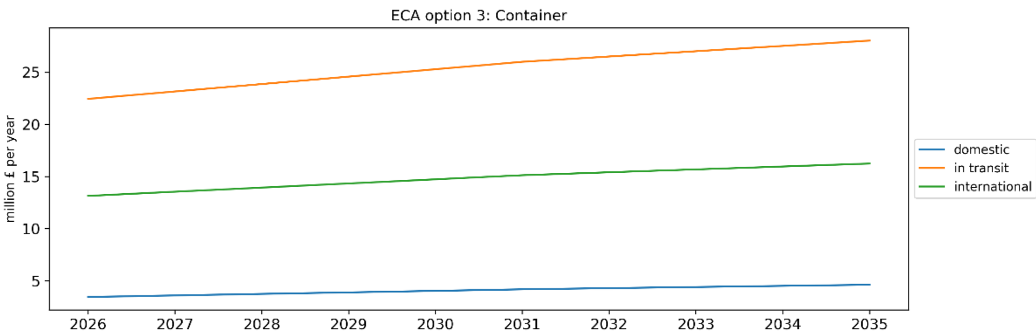


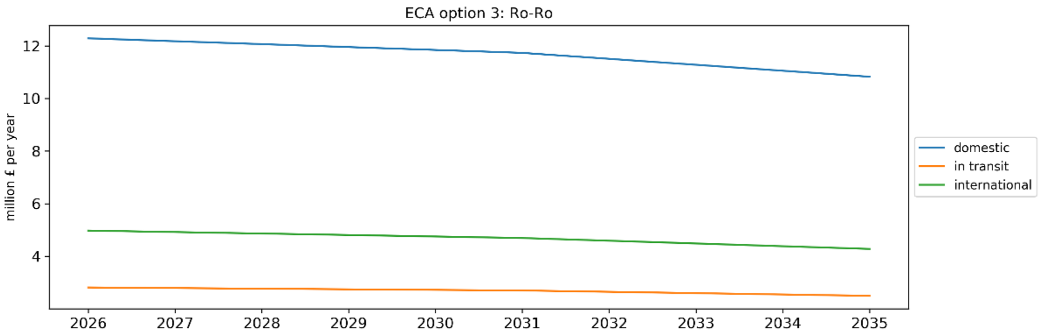

ECA option 3: Other
million £ per year
21
20
19
18
17
16
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
domestic
in transit
international

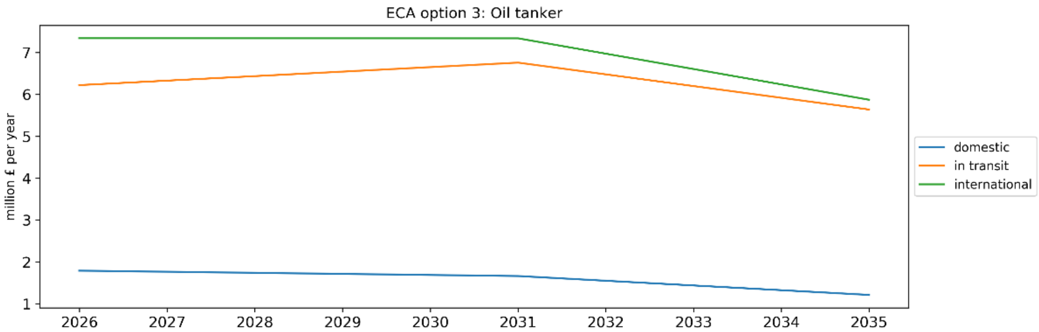

ECA option 3: Ferry-RoPax
million £ per year
14
12
10
8
6
4
2
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
domestic
in transit
international


ECA option 3: Service-other
£ per year
0.14
0.12
0.10
0.08
0.06
0.04
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
domestic
in transit
international


ECA option 3: Service-tug
£ per year
20000
15000
10000
5000
0
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
domestic
in transit
international


ECA option 3: Container
million £ per year
25
20
15
10
5
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
domestic
in transit
international


ECA option 3: Ro-Ro
million £ per year
12
10
8
6
4
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
domestic
in transit
international


ECA option 3: Oil tanker
million £ per year
7
6
5
4
3
2
1
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
domestic
in transit
international

2 COST BENEFIT ANALYSIS

2.1 Aims of the analysis

The aim of this analysis is to estimate the change in air pollution (SO_2, NO_x, $PM_{2.5}$) and greenhouse gas (GHG) emissions (CO_2, CH_4, N_2O), and associated costs and benefits due to three different illustrative options of extending the North Sea Emission Control Area (ECA) beyond its current geographical limits.

- **Option 1:** Extending the current North Sea ECA to include all major ports in England[37] not covered by the current ECA, with a time period of interest from 1 January 2021 to 31 December 2030.
- **Option 2:** Extending the current North Sea ECA to include all of the UK territorial waters with a time period of interest of from 1st January 2021 to 31st December 2030.
- **Option 3:** Extending the current North Sea ECA to include the Irish Sea and down to the English Channel (including the Isle of Ouessant but not going South to the Biscay Bay) with a time period of interest of 1st January 2026 to 31st December 2035.

This annex details the approach used for estimating the costs and benefits under the three different policy options, relative to the business as usual (BAU). In particular, it sets out the assumptions, data sources, methodology, limitations, Quality Assurance (QA) and detailed results of the cost benefit analysis (CBA).

2.2 Assumptions

Below are the various assumptions used in the CBA. This annex only includes assumptions directly related to the CBA as the technical detail of the modelling of shipping and its emissions is included in the previous section of this report. General assumptions are set out, before considering specific assumptions relating to emissions, fuel costs and charter revenues. Wider assumptions about the GloTraM modelling suite run by UMAS can be found in Section1.4.

2.2.1 General

Options available for compliance of ships with the ECA regulations

When the ECA extension options are implemented, all ships operating in that area, whether calling at a UK port or not, have to comply with the corresponding emissions regulations. There are two pollutants which are controlled in the ECA and both are assumed in the modelling to be complied with using the following two strategies.

Compliance with the ECA sulphur limit:

[37] Please note that port activity is a devolved area and therefore this option can only cover English ports plus Milford Haven in Wales – which is also reserved.

- If ships are using fuel oil and do not already have a sulphur scrubber fitted under the business as usual scenario, including if they are expected to be using 0.5% compliant low sulphur fuel oil, then when operating in the extended ECA they are expected to switch to MDO to be in compliance of the 0.1% limit. This has the impact of increasing the operating costs to the relevant ship owners and operators. For ships not using fuel oil (e.g. using MDO or LNG), these ships will already be in compliance and therefore they are assumed to continue using the same fuel when operating in the extended ECA. If the ship is specified in the business as usual case as already having a sulphur scrubber fitted, then the ship is assumed to continue to use high sulphur fuel when operating in the extended ECA, with the scrubber used to reach the compliance limit.

Compliance with the ECA NOx limit:

- Compliance is only required for newbuild ships that are required to meet the Tier III NOx limit (e.g. ships built after 2021). It is assumed, given expectations of interoperability between coasts of the UK, that ships that need to be Tier III compliant will already have a Selective Catalytic Reduction system (or equivalent Tier III compliant machinery) fitted under the business as usual case. They will therefore just be required to operate it in the extended ECA.

In both cases, the change in behaviour that would be required for compliance has the effect of increasing operating costs for the ship owner. This is because if the SCR is already fitted on the ship, switching it on when travelling through an ECA extension lowers the fuel efficiency of the vessel. Likewise, MDO is assumed to be a more expensive fuel than the fuel oil used under BAU (if it wasn't, the ship owner would already have shifted to this fuel already).

SO_2 and NOx limits

Under each policy option (for the relevant time period), the extended ECAs have the same limits on SO_2 and NO_x emissions as the current North Sea ECA will have (e.g. this includes the new limits on NO_x emissions that will apply in the current North Sea ECA after 1 January 2021).

Business as usual

The cost benefit analysis relating to each of the three policy options considers the impacts on ships that are operating within the respective ECA extension areas only. The analysis therefore focuses on the difference between the business as usual and the 'with policy' option cases for ships only in those respective areas. For this reason, each policy option has its own defined business as usual.

This is discussed in detail in Section 1.7

Scope of shipping included

The policy options are assumed to impact only on those ships and voyages that are within the ECA extension areas. Vessels are classified into three categories:

- **Domestic shipping** – shipping services that begin and end at a UK port;

- **International shipping** – shipping services provided by any ship arriving at a UK port immediately after leaving a non-UK port, or arriving at a non-UK port after leaving a UK port;
- **In transit voyage** – shipping services that pass through the ECA but do not call at a UK port.

Estimating costs and benefits to the UK

In line with HM Treasury Green Book guidance (HMT, 2018), only costs and benefits to the UK of any policy intervention should be included in the CBA. The international nature of shipping activity therefore requires that assumptions are made about which costs and benefits associated with an intervention are considered to be costs and benefits to the UK specifically. When considering the costs and benefits which accrue to the UK we adopt the following approach.

Benefits (i.e. air pollutant reductions) from domestic, international and in transit vessels are all treated as benefits to the UK. This is because all reduction in emissions to air of pollutants from shipping will benefit the UK, regardless of the origin and destination of the vessels that produce these emissions. It should be noted that in line with Defra advice, only emissions to air of pollutants that occur within a certain distance from the UK are included in the modelling (as explained in Section 1), and therefore all changes in such air pollutant emissions to air from ships are included within the CBA.

The relevant costs to the UK from changes in fuel costs are taken to be only those arising from domestic and international shipping. Fuel costs for in-transit vessels are not considered to be costs to the UK. In terms of the costs associated with increases in GHG emissions, BEIS advice at the time of drafting is that because only GHG emissions from domestic shipping are included in the UK carbon budgets, only changes in GHG emissions from domestic shipping are included in the CBA. Changes in GHGs for international and in-transit shipping are therefore excluded from the central case analysis.

Figure 39 below sets out the benefits and costs that are included in the central analysis.

Figure 39 Costs and benefits included in the central analysis across ECA policy options

	Domestic	International	In-transit
Air quality benefits	✓	✓	✓
Fuel costs	✓	✓	
GHG costs	✓		

Sensitivity tests are undertaken with alternative assumptions.

2.2.2 Emissions

The change in both GHG emissions and air pollutants are valued following the methodology expanded on below.

Valuing GHGs (expressed as CO_2 equivalent)

GHG emissions (CO_2, CH_4 and N_2O) are converted into CO_2 equivalent. This is done using Global Warming Potential (GWP) values relative to CO_2. Figure 40 below shows the assumed conversion factors for each of the GHGs.

Figure 40 Global Warming Potential (GWP)

Greenhouse Gas	Conversion factor
Carbon Dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298

Source: BEIS (2018) Valuation of Energy Use and Greenhouse Gas, table 3.1. Available at https://webarchive.nationalarchives.gov.uk/20190105013225/https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/671205/Valuation_of_energy_use_and_greenhouse_gas_emissions_for_appraisal_2017.pdf. Since undertaking this analysis, the guidance from BEIS has been updated.

Valuing changes in CO_2 equivalent emissions can be based on traded or non-traded values. For this analysis we use a 'central 'estimate of non-traded CO_2 equivalent values because shipping is not included within the EU Emissions Trading System. Sensitivities are carried out using 'low' and 'high' estimates.[38]

In line with the HMT Green Book, all emissions valuations over the period of the policy are discounted to the start of the policy (or to 2019 as an alternative) using an annual social discount factor of 3.5%[39].

Valuing air pollutants

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

- The impact pathways approach (IPA) is recommended for use where the air quality impacts are estimated to be significant (>£50 million) or where changes to air quality are the principle objective of the policy or project. This approach requires the estimation of emissions, dispersion, population exposure and outcomes.

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

[39] https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

- The damage cost approach uses a set of national impact values (£) per tonne of each relevant pollutant that have been derived using the impact pathways approach.

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

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

As advised by Defra, the specific damage costs in Table 3 of the Defra guidance[40] used to value shipping emissions are as follows:

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

As mentioned in the main report, Defra experts have advised that these damage costs can be used to value emissions from all types of shipping activity (domestic, international, and ships in-transit near to the UK). These damage costs account for the fact that some shipping emissions will be further from shore – i.e. the damage costs represent an average.

However, these damage costs are estimated based on the emissions included in the National Atmospheric Emissions Inventory (NAEI) only. In particular, the analysis is based on the mapped NAEI emissions for shipping. In this instance, the 2013 NAEI. Therefore, Defra has advised that the damage costs should not be used to value any shipping emissions beyond the geographical area that the mapped NAEI emissions from shipping covers – emissions further away are not likely to incur the average health and environmental costs to the UK that the

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

damage costs represent.[41] In line with this, the emissions from GloTraM modelling do not include emissions of air pollutants (NO_x, SO_2 and $PM_{2.5}$) that are outside of the geographical area that the mapped NAEI emissions from shipping covers.[42]

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

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

Air pollutants (NO_x, SO_2 and $PM_{2.5}$) valuations are uplifted by a factor of 2% annually (from 2017) to reflect a higher future willingness to pay for health. This is in line with Defra guidance from the air quality damage costs appraisal toolkit.

As with CO_2 equivalent, all air pollutant valuations over the period of the policy are discounted to the start of the policy (or 2019 as an alternative) using an annual social discount factor of 3.5%.

Fuel costs and charter revenue

As previously mentioned, the change in air pollutants, form the monetised benefits of the different options.

The costs comprise changes in operational fuel costs incurred by UK domestic and UK international shipping in the ECA extension areas, as well as the increase in GHG emissions from UK domestic shipping in the ECA extension areas.

Administration costs related to disseminating the information and implementing the policy change have not been taken into account. Such costs are not included within the GloTraM suite and were outside of the scope of this analysis. They are however important to consider in the context of comparing policy options and would therefore benefit from separate analysis.

Valuing fuel costs and charter revenue to business

In light of the two abatement options for compliance (increased use of SCR and/or scrubber or switching to MDO fuel), cost impacts are on operational costs (fuel only) and not capital costs or non-fuel operational costs. This is because it is assumed that the fleet operating in the ECA extension area would be built to a specification that would also enable operation in the current ECA area (and newbuild ships built after 2021 would be fitted with a SCR).

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

[42] Further discussion of this approach is provided in Frontier et al (2019): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816019/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs-technical-annexes.pdf

Charter revenue is impacted by spot charter rates (which do not change as a result of the ECA extension), and the transport supply provided by the vessel. The latter changes with the speed of the vessel, which remains constant between BAU and the different options. Because both these variables remain unchanged, charter revenue is constant between BAU and different extension options. Charter revenues are therefore excluded from the CBA analysis.

GloTraM generates the changes in fuel costs directly, using 2015 US Dollars. For the CBA, fuel costs from GloTraM were converted back into 2017 UK Pound prices by applying the yearly Pound/Dollar exchange rate and then converting figures to 2017 prices using the Office for National Statistic (ONS) and the Office for Budgetary Responsibility Economic and Fiscal Outlook GDP deflator values[43].

As with the emissions valuation, to allow comparison across policy options, all fuel costs are discounted to 2019 using a social discount factor of 3.5%.

2.3 Data sources

Figure 41 below sets out the various data sources used for the CBA analysis.

[43] In line with guidance from HM Treasury (2018) Green Book.

Figure 41 Data sources

Data	Source	Link
Operating costs	GloTraM modelling suite	N/A
Emissions	GloTraM modelling suite	N/A
Global Warming Potential values	BEIS (2018) Valuation of Energy Use and Greenhouse Gas	https://webarchive.nationalarchives.gov.uk/20190105013225/https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/671205/Valuation_of_energy_use_and_greenhouse_gas_emissions_for_appraisal_2017.pdf
CO_2 equivalent valuation	BEIS (2017) Data tables 1 to 19: supporting the toolkit and the guidance	https://webarchive.nationalarchives.gov.uk/20190105010941/https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/696677/Data_tables_1-19_supporting_the_toolkit_and_the_guidance_2017__180403_.xlsx[44]
NOx, SOx, $PM_{2.5}$ valuation	Defra (2019) air quality damage costs appraisal toolkit	https://www.gov.uk/guidance/air-quality-economic-analysis#damage-costs-approach
Social discount rate	HM Treasury (2018) Green Book	https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent
UK GDP deflator	BEIS (2017) Data tables 1 to 19: supporting the toolkit and the guidance	https://webarchive.nationalarchives.gov.uk/20190105010941/https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/696677/Data_tables_1-19_supporting_the_toolkit_and_the_guidance_2017__180403_.xlsx
Pound Dollar exchange	BEIS 2017 Energy & Emissions Projections	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/670353/Annex-m-price-growth-assumptions.xls

[44] Since this analysis was undertaken, this guidance has been updated by BEIS.

2.4 Methodology

Below we set out the methodology used to calculate the costs and benefits of extending the North Sea ECA. The analysis involves three overarching sections:

1. Benefit valuation

- **Valuing changes in emissions to air of pollutants from ships**
  - Estimate the level of air pollutants (SO_2, NOx, $PM_{2.5}$) for each year of the 10-year appraisal period under the BAU, and each of the ECA extension policy options.
  - Estimate the annual difference in air pollutants between each policy option and the BAU case for each year of the 10-year appraisal periods.
  - Estimate the value of the benefits associated with the air pollutant changes each year for each policy option relative to the BAU over the 10-year appraisal period.
- **Calculate the Present Value of benefits (PV)**
  - Calculate the Present Value back to 2019 (2017 prices) of all benefits (reduced air pollutants) for each policy option relative to the counterfactual over the 10-year appraisal period by applying the social discount rate of 3.5%.

2. Cost valuation

- **Valuing fuel cost changes**
  - Estimate the level of operational fuel costs for each year of the 10-year appraisal period under the BAU, and each of the ECA extension policy options.
  - Estimate the annual difference in costs between each policy option and the BAU case for each year of the 10-year appraisal periods.
- **Valuing GHG changes**
  - Estimate the level of GHG emissions (CO_2, CH_4, N_20) for each year of the 10-year appraisal period under the counterfactual (BAU), and each of the ECA extension policy options.
  - Estimate the annual difference in GHG emissions between each policy option and the BAU case for each year of the 10-year appraisal periods.
  - Estimate the value of the costs associated with the GHG changes each year for each policy option relative to the BAU over the 10-year appraisal period.
- **Calculate the Present Value of costs (PV)**
  - Calculate the Present Value (2019) of all costs for each policy option relative to the counterfactual over the 10-year appraisal period.

3. Results, disaggregation and sensitivity analysis
   - Compare the PV benefits calculated in 1.) and the PV costs calculated in 2.) to determine whether each option is cost beneficial and which option delivers the best CBA result.
   - Repeat analysis 1.) and 2.) for each shipping type (i.e. domestic, international and in transit), and by vessel type.
   - Perform a sensitivity analysis using 'low' and 'high' valuations for GHG emissions and air pollutants.

2.4.1 Results, disaggregation and sensitivity analysis

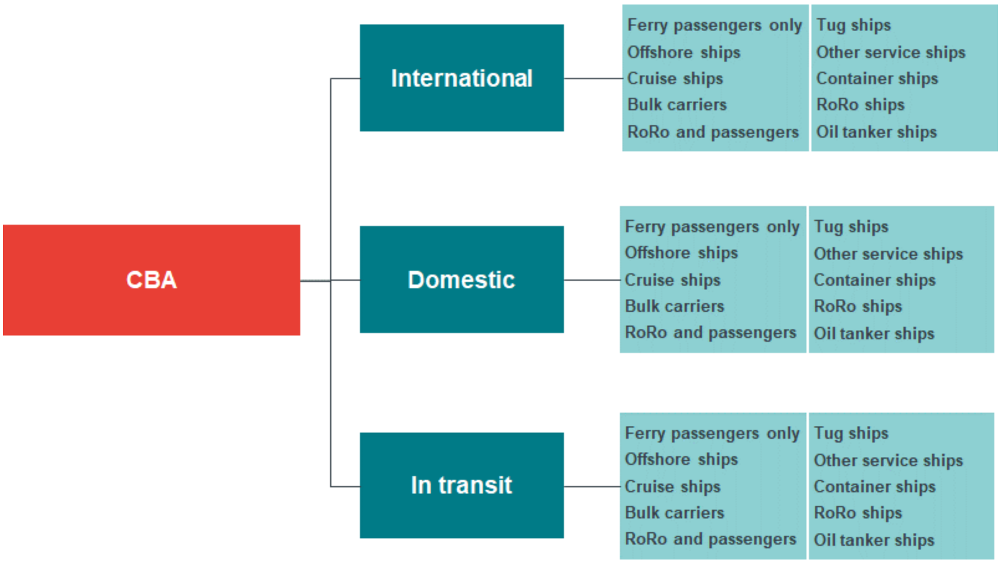
Compare the PV benefits calculated in 1.) and the PV costs calculated in 2.) to:

- Generate the net present value over the 10-year period (this shows the extent to which the present value of benefits exceeds the present value of costs) for each option; and
- Determine which option delivers the highest net present value (NPV)

Results are disaggregated by shipping type (i.e. domestic, international and in transit) and by vessel type. Figure 42 below illustrates this breakdown. The main report sets out results by shipping type.

As previously mentioned, a sensitivity analysis using the 'high' and 'low' valuations for GHG emissions and air pollutants has been undertaken. GloTraM modelling did not use any sensitivity tests on the changes in fuel costs. The fuel costs reported are therefore considered as central estimates.

Figure 42 Breakdown of CBA results*



*RoRo stands for 'roll-on roll-off'

2.5 Limitations

There are several limitations to be mindful of with the CBA. These include the limitations described below.

1.) **Constraints on using 'impact pathway' approach to value air pollutants** – The impact pathways approach (IPA) is recommended for use where the air quality impacts are estimated to be significant (>£50 million) or where changes to air quality are the principle objective of the policy or project. This approach comes with additional rigour and robustness. However, given the time and resources required to undertake this form of analysis, this approach was not considered feasible for the purposes of this particular analysis, though could be considered in future work.

2.) **No sensitivity analysis for fuel costs –** The GloTraM modelling analysis which underpins the CBA does not include sensitivity tests on the fuel costs. This could be considered as part of future work.

3.) **Outputs from GloTraM modelling –** The accuracy of the CBA rests on the reliability of outputs from the GloTraM modelling suite. This modelling carries its own assumptions (set out in Section 1).

4.) **Costs and benefits accruing to the UK –** As set out above, the core CBA analysis does not include changes in operating costs for in-transit shipping, and changes in GHGs for international and in-transit shipping. However, sensitivity analysis which has been carried out and is described in the main report, provides estimates of the additional costs accruing to international and in-transit shipping.

5.) **Long term uncertainties –** The ECA extension options all consider a relatively long time period into the future. Forecasting into the future introduces uncertainty – especially since results are dependent on how emissions are valued, and these may change going forward. However, a number of sensitivity scenarios have been undertaken to try and capture these uncertainties in a logical and proportionate way. The results are presented in the main report, this annex report and the CBA model.

2.6 Quality Assurance (QA)

This section sets out the steps taken to QA the results of the CBA. The QA process is broken down into three main steps:

1. QA of CBA inputs
2. QA of CBA setup
3. QA of CBA calculations

The underlying motive of the QA is to ensure that the analysis is reasonable, robust and reduces uncertainty surrounding the topic. It is important to ensure that any analysis produced has been thoroughly checked in an appropriate and proportionate way. The QA activities are below.

2.6.1 QA of CBA inputs and underlying assumptions

Figure 41 above sets out all the inputs and sources used for the CBA. This provides a clear trail that can be used to identify exactly where inputs originate.

Emissions and costs are inputs from the GloTraM modelling suite, and this modelling was led by UMAS. Separate QA of the modelling has been carried out and is described in Section 1.

All other inputs have been independently checked and raw numbers verified by the Frontier team.

2.6.2 QA of CBA setup

The CBA workbook as well as the calculations used, are set out in a logically coherent format which is easy to understand and navigate. This was put together by an economic consultant with past experience in creating economic models. The approach follows standard best practice.

Raw data and calculations are included in separate sheets for transparency where excel formulae are used. Where the calculation tabs use raw data, formulae link this data back to the originating raw data sheets. This enables the user to trace any numbers used in the workbook back to their source.

Two Frontier economists, not directly involved in the work, were asked to navigate the sheets independently and highlight any areas that needed clarification and refining. These comments have been taken on board and the relevant changes implemented.

2.6.3 QA of CBA calculations

The CBA analysis has undergone rigorous quality assurance by the team through three key activities:

1. The economist responsible for the model has comprehensively checked that calculations as well as the selection tools are all working as expected. This involved spot checks on raw data to ensure that the correct data is being pulled through from relevant sheets, as well as a thorough review of the model's mechanical aspects to ensure the calculations are working correctly.
2. Two Frontier economists not involved in the work were tasked with separately going through all calculations to make sure no errors had been made. A further sense check was undertaken to make sure that the disaggregated calculations broken down by vessel type and shipping type summed to the aggregated calculations.
3. Finally, the project manager performed a last check on all calculations and verified results. This involved working through the spreadsheets for each of the policy options and checking that the appropriate assumptions had been

used; that formulae had been correctly applied; that input data were appropriately picked up; and that calculations were undertaken correctly.

Results were also shared with the GloTraM modelling team to ensure that these made coherent sense. Any surprising and unexpected results were flagged and further explored to establish the underlying basis for these. Where these were being driven by idiosyncrasies in the model, they were rectified.

2.7 Detailed results

This section sets out the detailed results from the CBA. It first sets out the summary results for each ECA extension option, discounting to both:

- the start of the policy date; and
- then 2019 as the base year.

Also included in this section are results broken down by ship type.

It then considers results for each ECA extension option, across UK domestic shipping, UK international shipping and in transit shipping. For each of the options, the total costs and benefits over the period are considered. As previously mentioned, when considering total costs and benefits that would accrue to the UK, the benefits from reducing emissions to air of pollutants from all vessels (UK domestic shipping, UK international shipping and in transit)[45] are included; where as for the costs, the changes in fuel costs from UK domestic shipping and UK international shipping are included along with the costs of changes in GHG emissions from UK domestic shipping only. All future references to domestic are referring to "UK domestic shipping", and all references to international are referring to "UK international shipping".

2.7.1 Central results

The central results use the central non-traded values for CO_2 equivalent emissions and the central valuations for emissions to air of pollution from shipping. For the purposes of transparency, all costs and benefits are shown. As mentioned previously when considering the impact on the UK for the purpose of the CBA, only some of the results are relevant. Namely, all benefits from reducing emissions to air of pollutants (UK domestic shipping, UK international shipping and in-transit shipping) are included, and only UK domestic shipping and UK international shipping fuel costs, and UK domestic shipping GHG costs are included.

Summary results

In Figure 43 to Figure 45, the costs and benefits for each of the options over their respective 10 year appraisal periods are discounted to the assumed start date of the policy i.e. Options 1 and 2 are discounted to 2021 while option 3 is discounted to 2026. All prices remain in 2017 prices. All negative costs should be interpreted as benefits.

[45] Note that these are only including emissions to air from ships in the ECA extension areas that are within a certain distance of the UK.

Figure 43 PV of total benefits and total costs (over 10 years) for domestic vessels (discounted to start date of policy)

ECA extension	Domestic (£m)		
	Air quality benefits	Fuel costs	GHG costs
Option 1 (2021 PV)	44.3	41.9	0.5
Option 2 (2021 PV)	405.7	390.0	2.8
Option 3 (2026 PV)	449.1	439.9	8.9

Source: Frontier calculations
2017 prices

Figure 44 PV of total benefits and total costs (over 10 years) for international vessels (discounted to start date of policy)

ECA extension	International (£m)		
	Air quality benefits	Fuel costs	GHG costs
Option 1 (2021 PV)	58.7	51.6	-1.7
Option 2 (2021 PV)	219.2	204.6	-1.4
Option 3 (2026 PV)	470.4	463.8	4.8

Source: Frontier calculations
2017 prices

Figure 45 PV of total benefits and total costs (over 10 years) for in transit vessels (discounted to start date of policy)

ECA extension	In-transit (£m)		
	Air quality benefits	Fuel costs	GHG costs
Option 1 (2021 PV)	6.5	6.4	-0.0
Option 2 (2021 PV)	47.6	46.5	0.3
Option 3 (2026 PV)	520.9	537.2	9.0

Source: Frontier calculations
2017 prices

From this point all present value figures are discounted to 2019 to allow for comparisons across options. All prices remain in 2017 prices.

Figure 46 PV of total benefits and total costs (over 10 years) for domestic vessels (discounted to 2019)

ECA extension	Domestic (£m)		
	Air quality benefits	Fuel costs	GHG costs
Option 1 (2019 PV)	41.4	39.1	0.5
Option 2 (2019 PV)	378.7	364.0	2.6
Option 3 (2019 PV)	353.0	345.8	7.0

Source: Frontier calculations
2017 prices

Figure 47 PV of total benefits and total costs (over 10 years) for international vessels (discounted to 2019)

ECA extension	International (£m)		
	Air quality benefits	Fuel costs	GHG costs
Option 1 (2019 PV)	54.8	48.2	-1.5
Option 2 (2019 PV)	204.6	191.0	-1.3
Option 3 (2019 PV)	369.7	364.6	3.8

Source: Frontier calculations
2017 prices

Figure 48 PV of total benefits and total costs (over 10 years) for in transit vessels (discounted to 2019)

ECA extension	In-transit (£m)		
	Air quality benefits	Fuel costs	GHG costs
Option 1 (2019 PV)	6.0	5.9	-0.0
Option 2 (2019 PV)	44.5	43.4	0.3
Option 3 (2019 PV)	409.4	422.2	7.0

Source: Frontier calculations
2017 prices

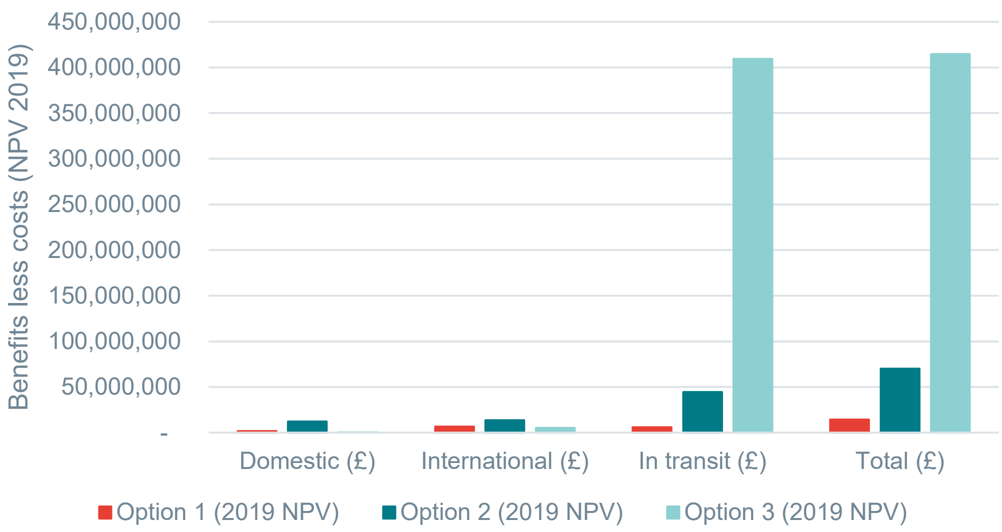
As previously mentioned, when considering total costs and benefits that would accrue to the UK, included in the estimation are the benefits (decrease in emissions to air of pollutants from ships) from all vessels (UK domestic shipping, UK international shipping and in transit shipping), and fuel costs from only UK domestic and UK international shipping, and GHG costs from only UK domestic shipping. Figure 49 and Figure 50 illustrate the results

Figure 49 NPV (over 10 years) accruing to the UK under central assumptions (discounted to 2019 in 2017 prices)

	Central case			
ECA extension	Domestic (£m)	International (£m)	In transit (£m)	Total (£m)
Option 1 (2019 NPV)	1.7	6.6	6.0	14.3
Option 2 (2019 NPV)	12.1	13.7	44.5	70.2
Option 3 (2019 NPV)	0.1	5.1	409.4	414.7

Source: *Frontier calculations*
2017 prices

Figure 50 Difference between costs and benefits accruing to the UK over 10 years i.e. NPVs (2017 prices) – central assumptions

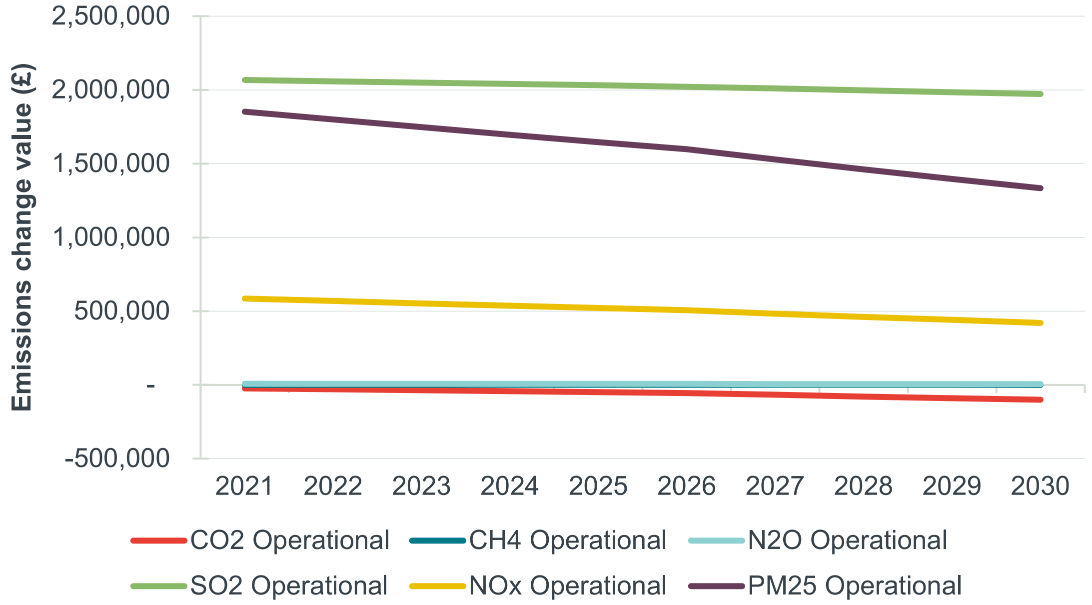


Source: *Frontier calculations*
2017 prices

Option 1

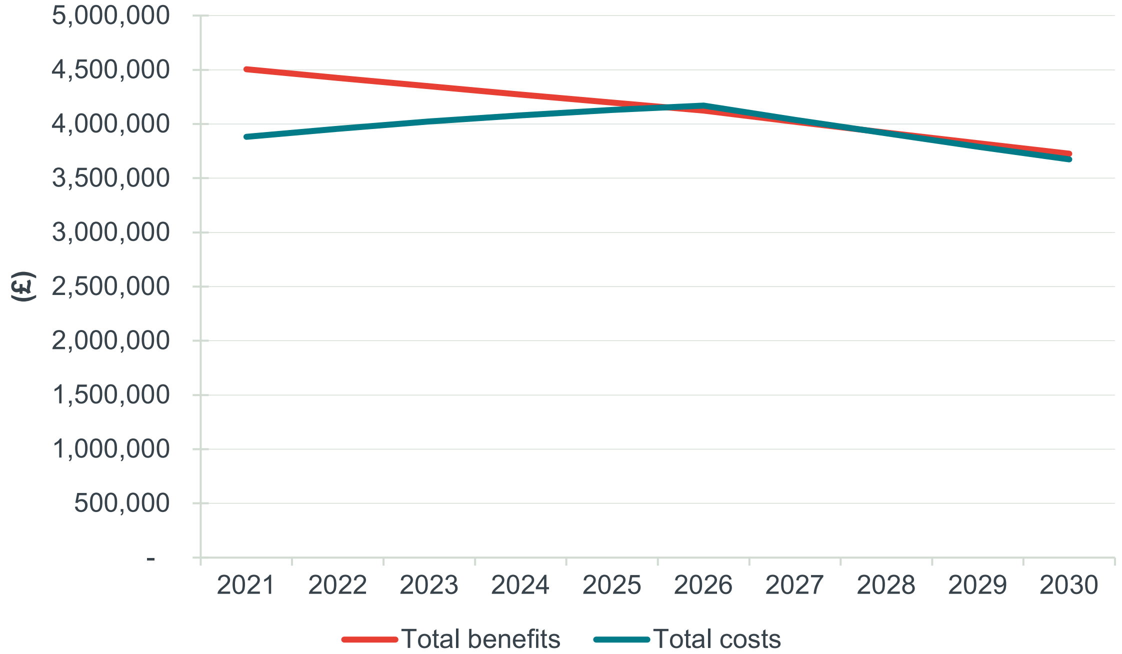
This section presents the estimates of the value of the change in emissions and the total costs and benefits over the appraisal period for Option 1. All monetary estimates are in 2017 prices and have been discounted to 2019 unless otherwise stated. Positive monetary values (in pounds) for the change in emissions indicate a **decrease** in emissions from the policy. Similarly, negative monetary values (in pounds) for the change in emissions indicate an **increase** in emissions from the policy. Total costs and benefits are only those assumed to impact the UK (i.e. benefits capture the changes in air pollutants from all shipping, while costs capture the changes in fuel costs from domestic and international shipping, and the changes in GHGs from domestic shipping).

Figure 51 Annual value of all emission changes discounted to 2019 (Option 1 domestic vessels)



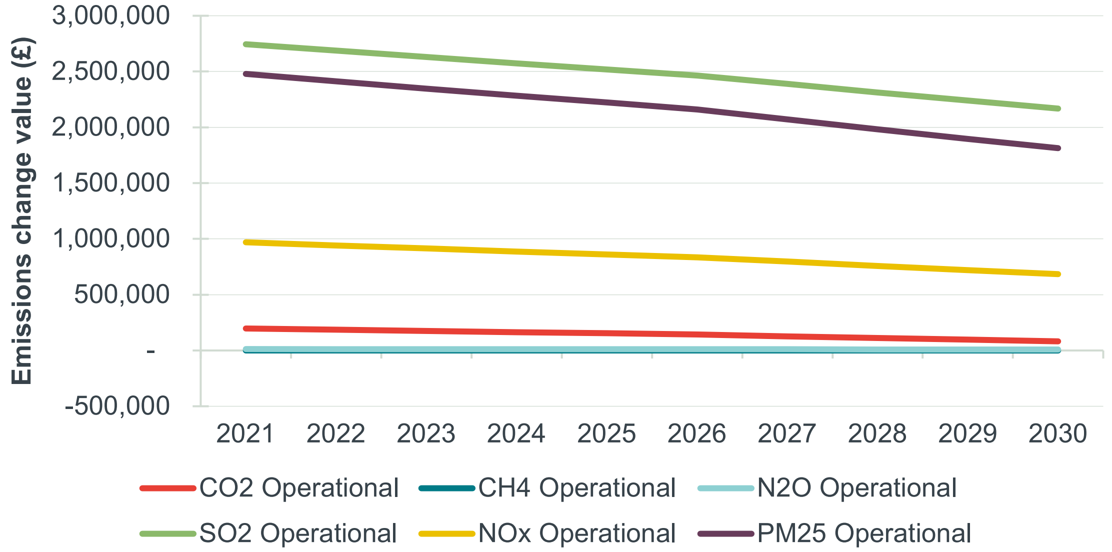
Source: Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result
2017 prices

Figure 52 Total annual costs and benefits accruing to the UK discounted to 2019 (Option 1 domestic vessels)



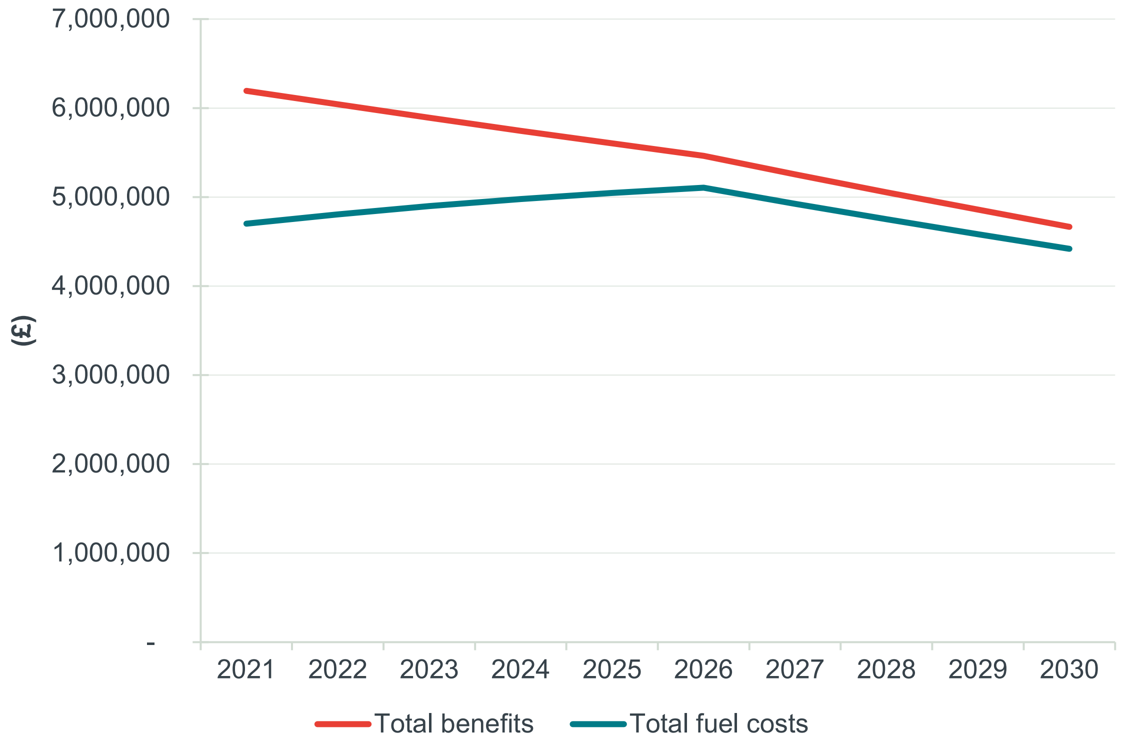
Source: Frontier calculations
2017 prices

Figure 53 Annual value of all emission changes discounted to 2019 (Option 1 international vessels)



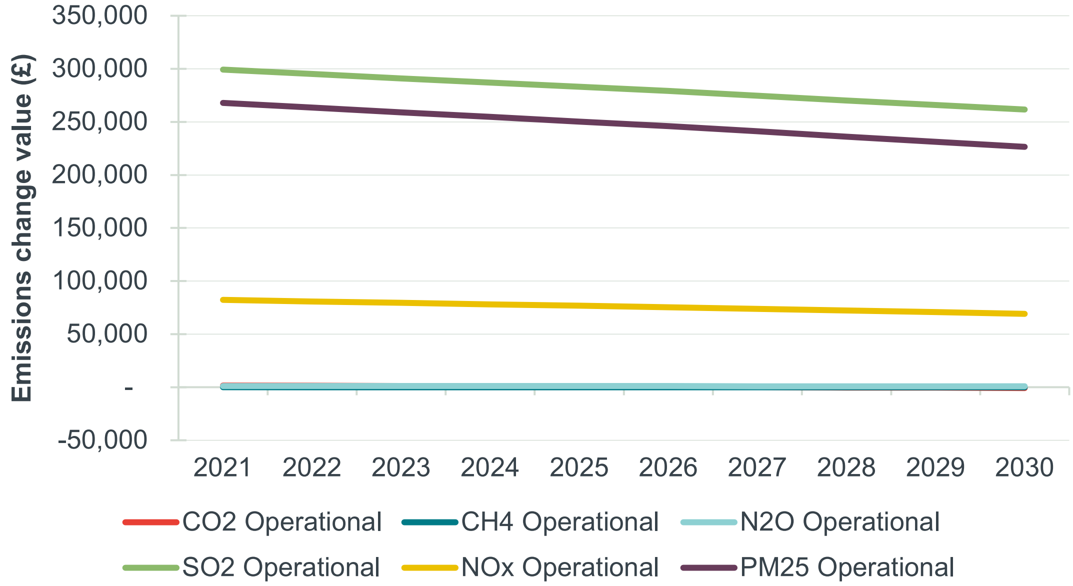
Source: Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result
2017 prices

Figure 54 Total annual costs and benefits accruing to the UK discounted to 2019 (Option 1 international vessels)



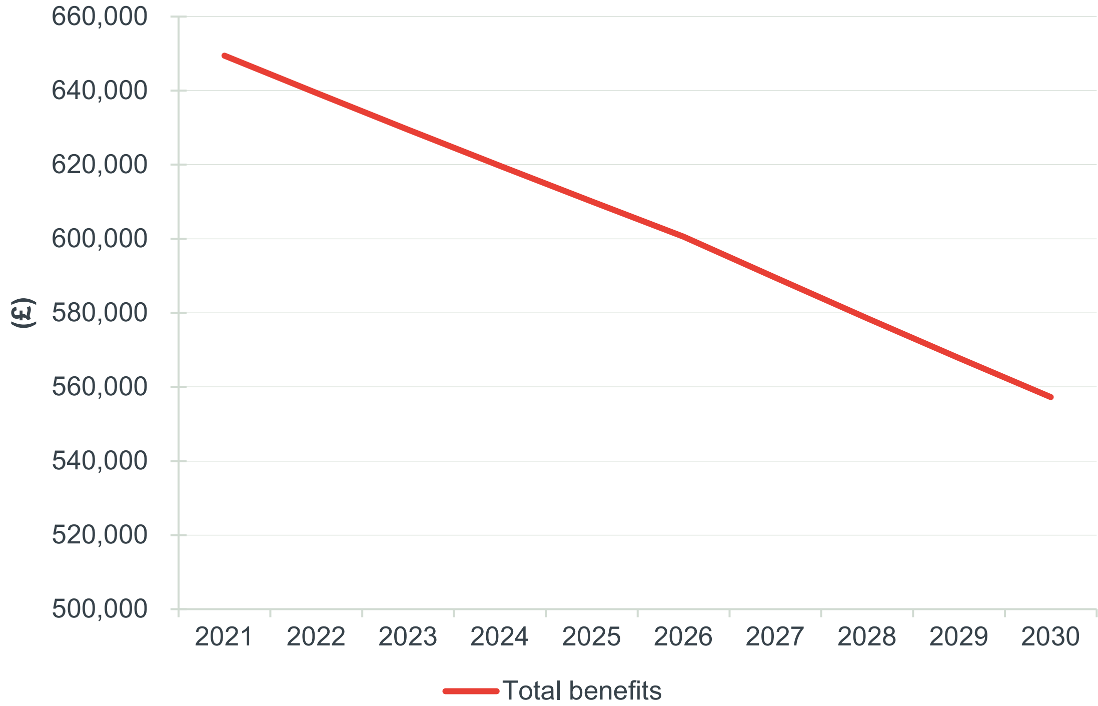
Source: Frontier calculations
2017 prices

Figure 55 Annual value of all emission changes discounted to 2019 (Option 1 in transit vessels)



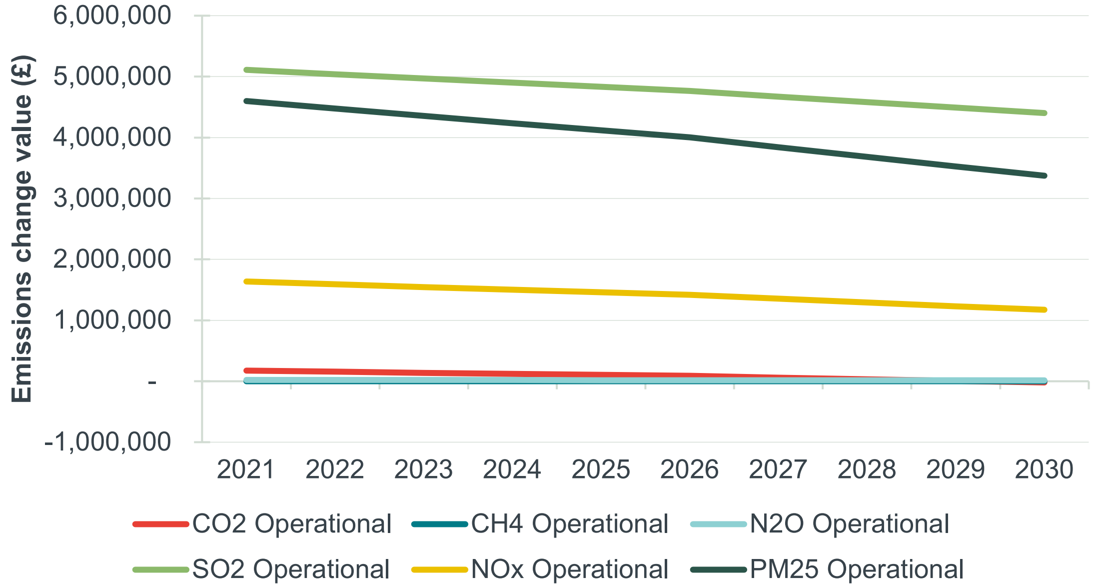
Source: *Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result*
2017 prices

Figure 56 Total annual benefits accruing to the UK discounted to 2019 (Option 1 in transit vessels)



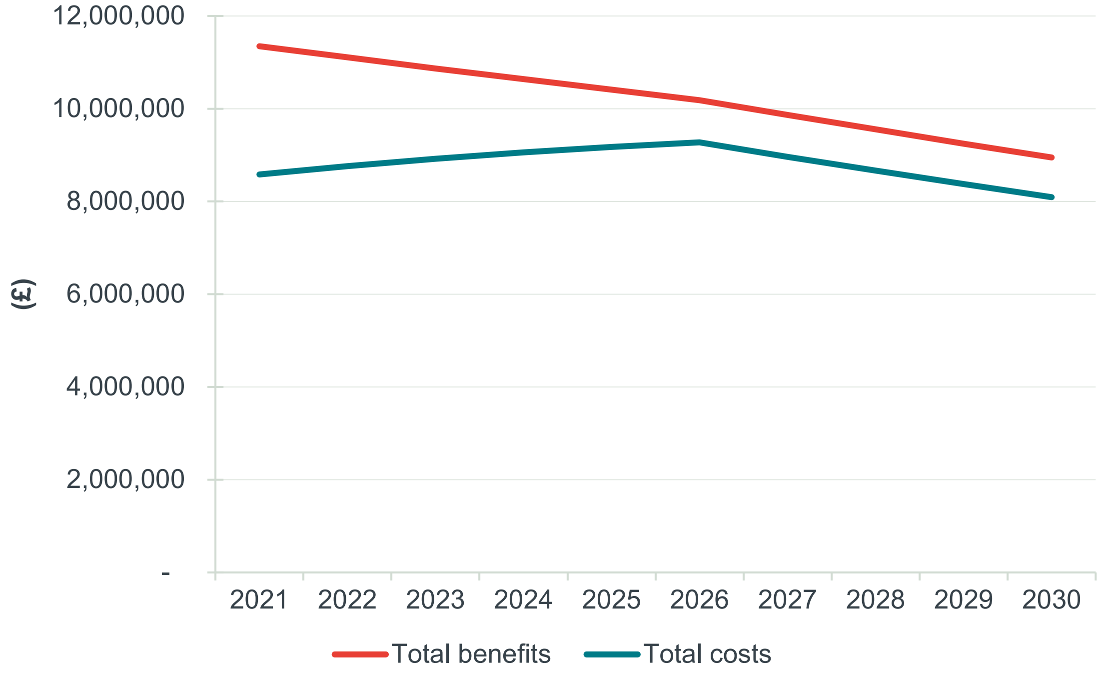
Source: *Frontier calculations*
2017 prices

Figure 57 **Annual value of all emission changes discounted to 2019 (Option 1 all vessels)**



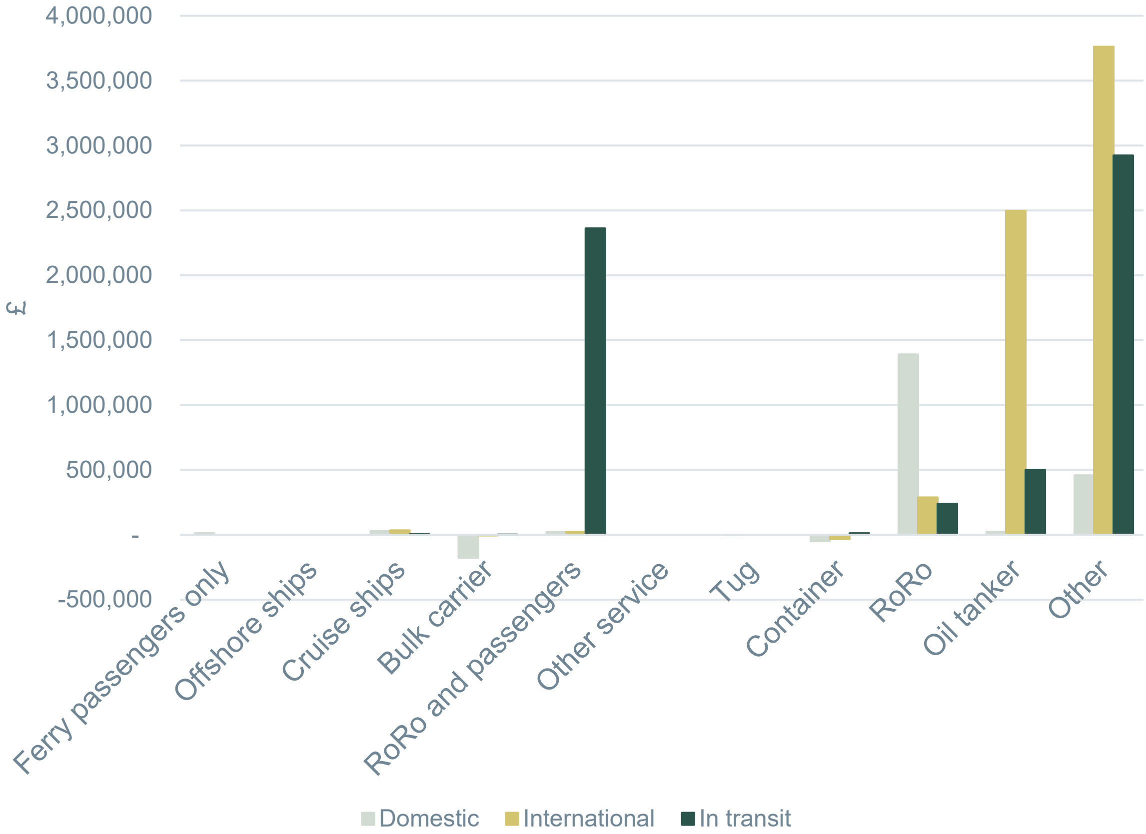
Source: Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result
2017 prices

Figure 58 **Total annual costs and benefits accruing to the UK discounted to 2019 (Option 1 all vessels)**



Source: Frontier calculations
2017 prices

Figure 59 Breakdown of NPV across vessel type and status discounted to 2019 (Option 1 over the 10 years of the policy)[46]



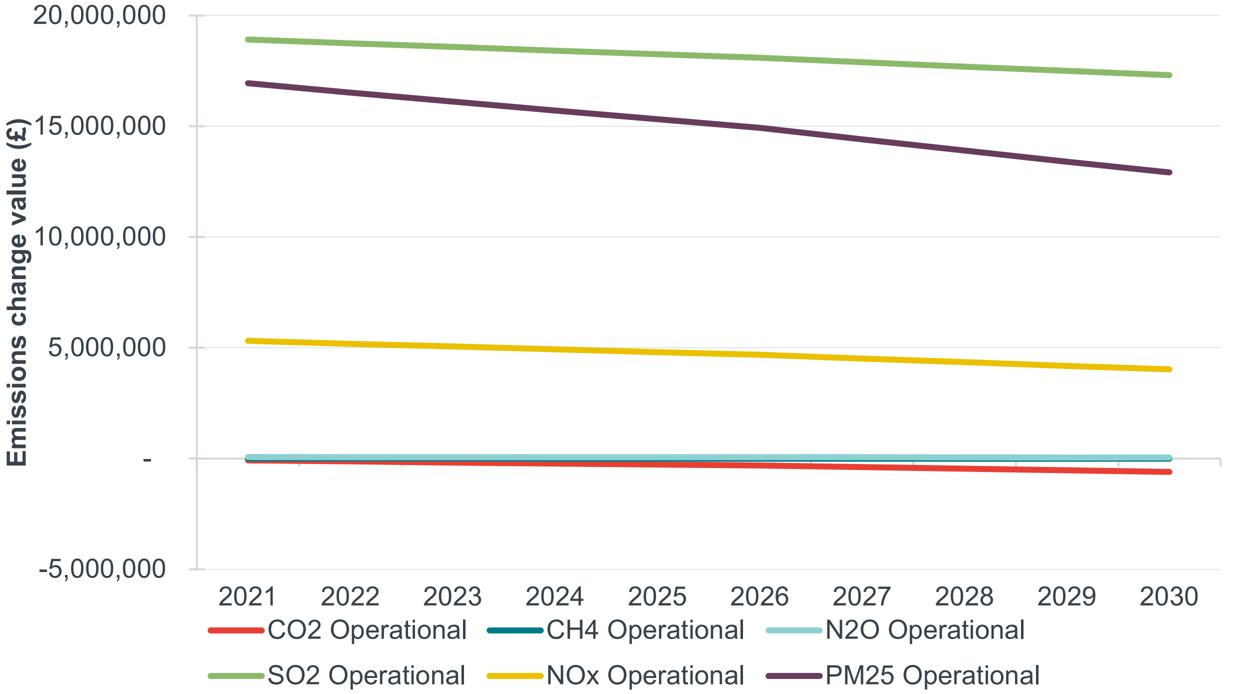
Source: Frontier Economics
2017 prices

Option 2

This section presents the estimates of the value of the change in emissions and the total costs and benefits over the appraisal period for Option 2. All monetary estimates are in 2017 prices and have been discounted to 2019 unless otherwise stated. Positive monetary values (in pounds) for the change in emissions indicate a **decrease** in emissions from the policy. Similarly, negative monetary values (in pounds) for the change in emissions indicate an **increase** in emissions from the policy. Total costs and benefits are only those assumed to impact the UK (i.e. benefits capture the changes in air pollutants from all shipping, while costs capture the changes in fuel costs from domestic and international shipping, and the changes in GHGs from domestic shipping).

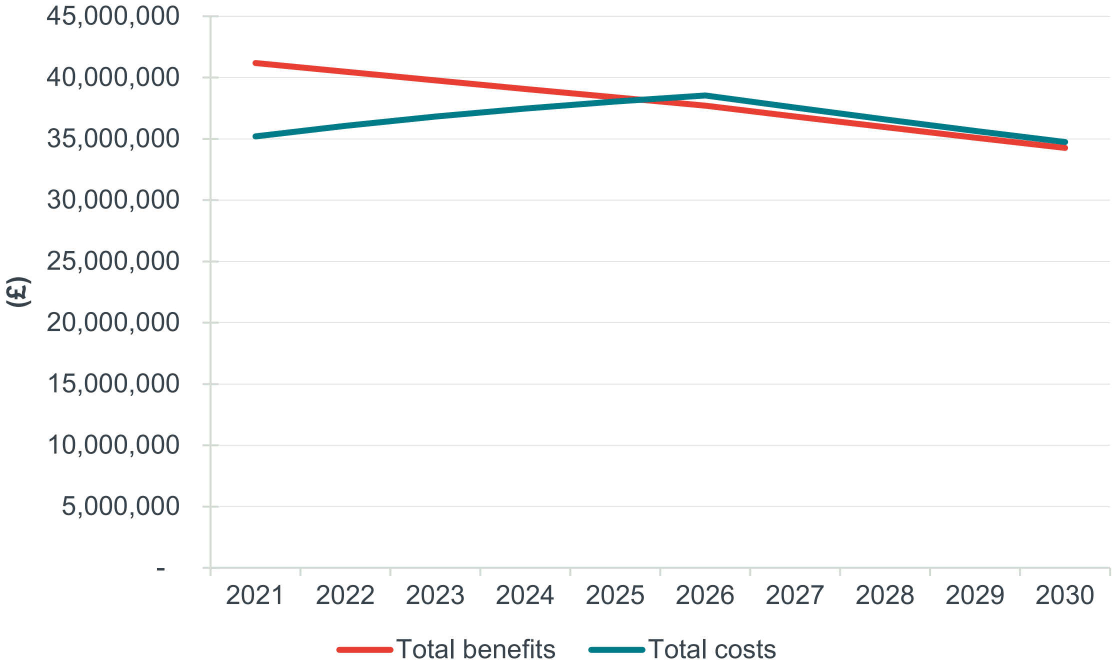
[46] Positive values indicate that for that shipping type, the policy has a positive NPV impact, while negative values indicate the opposite.

Figure 60 Annual value of all emission changes discounted to 2019 (Option 2 domestic vessels)



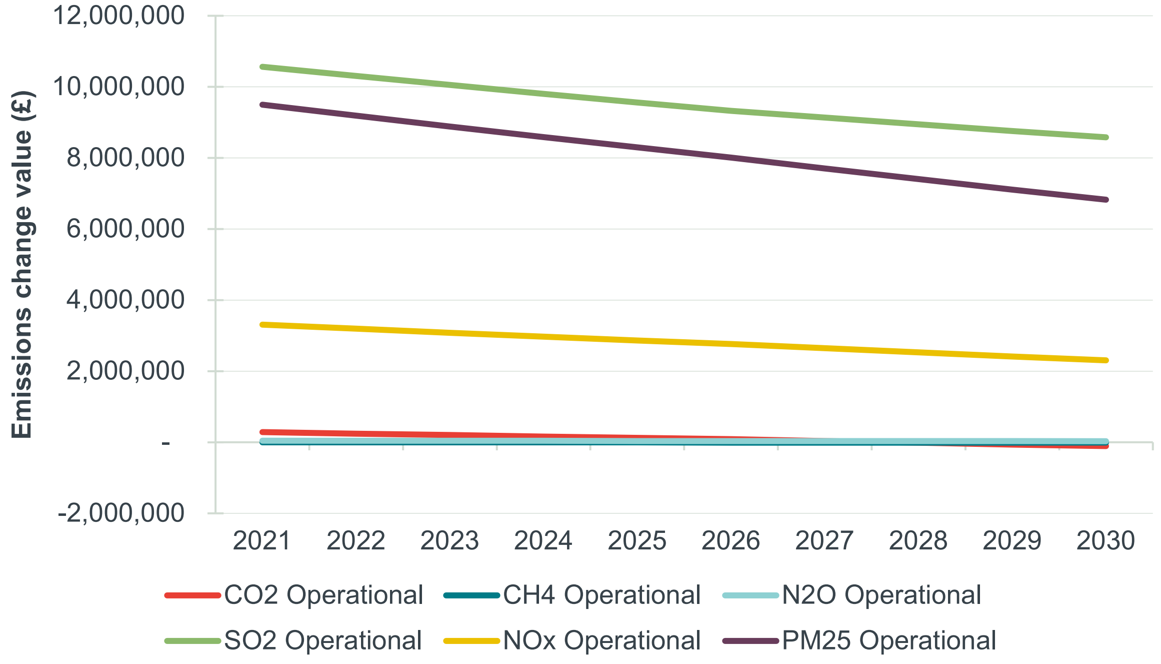
Source: Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result
2017 prices

Figure 61 Total annual costs and benefits accruing to the UK discounted to 2019 (Option 2 domestic vessels)



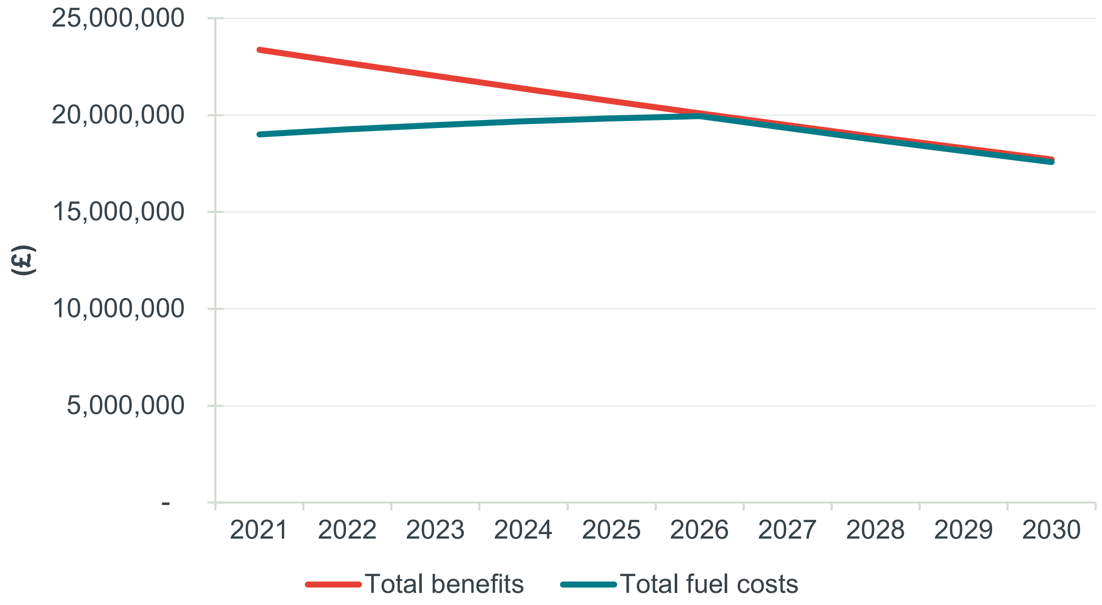
Source: Frontier calculations
2017 prices

Figure 62 Annual value of all emission changes discounted to 2019 (Option 2 international vessels)



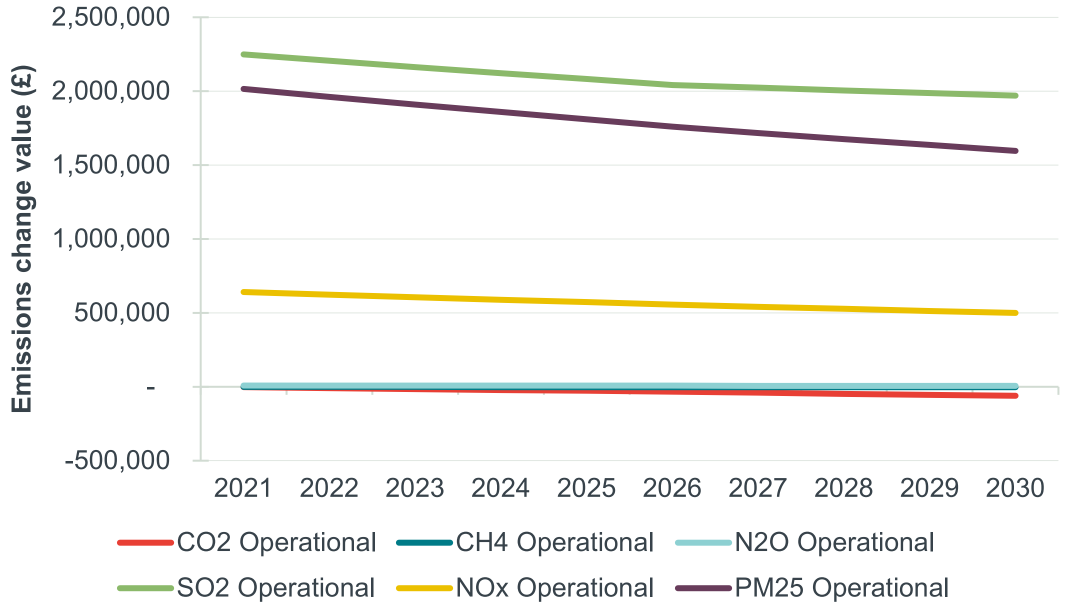
Source: Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result
2017 prices

Figure 63 Total annual costs and benefits accruing to the UK discounted to 2019 (Option 2 international vessels)



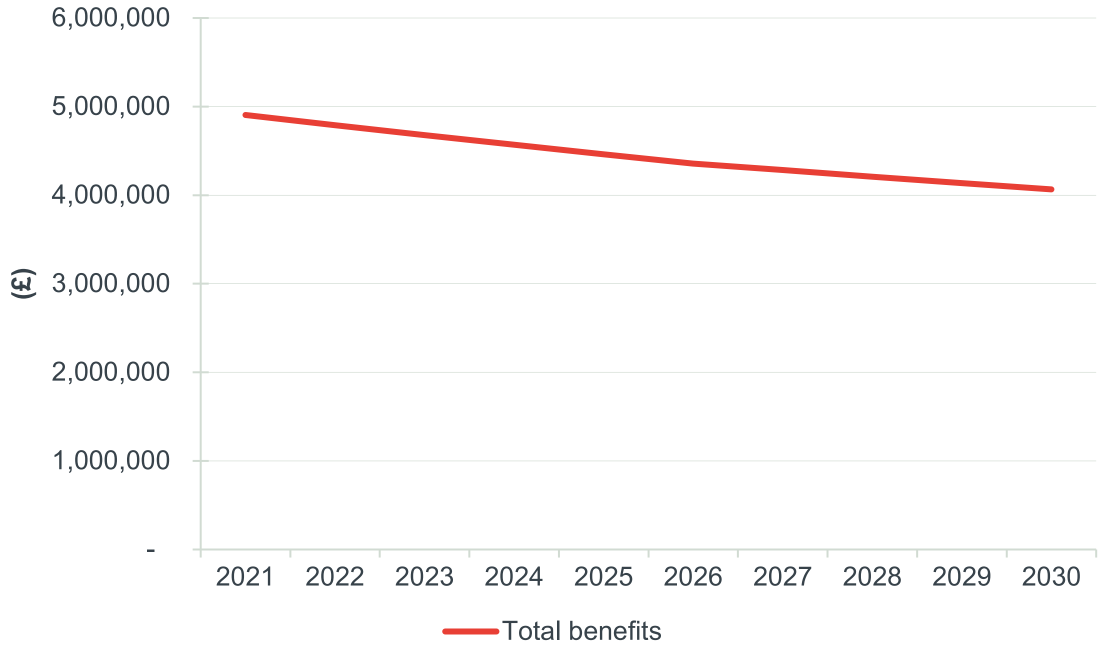
Source: Frontier calculations
2017 prices

Figure 64 Annual value of all emission changes discounted to 2019 (Option 2 in transit vessels)



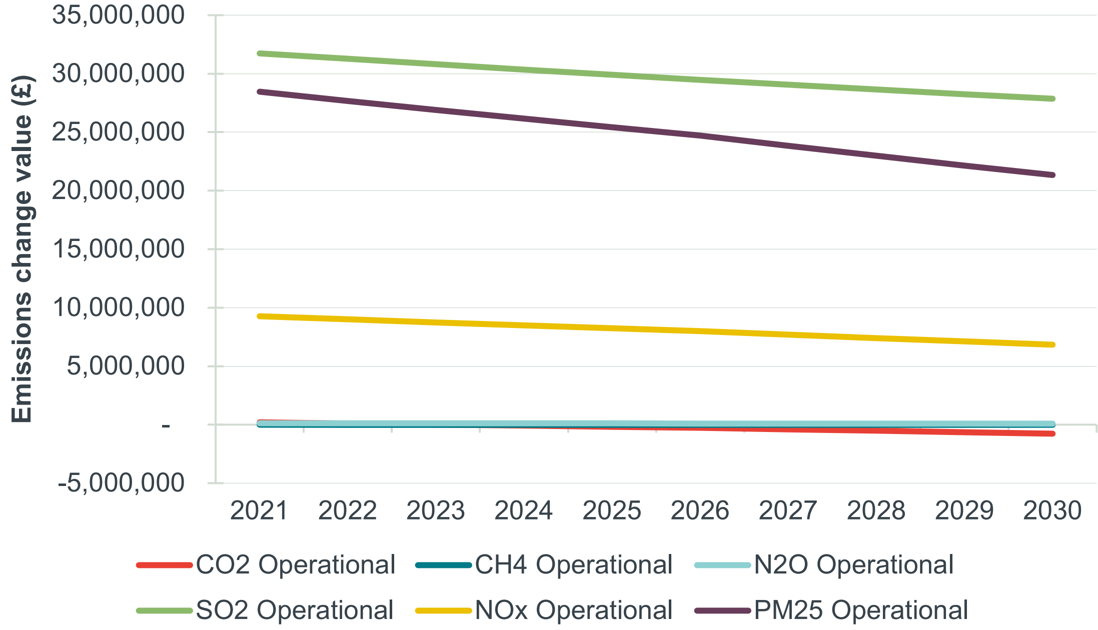
Source: Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result
2017 prices

Figure 65 Total annual benefits accruing to the UK economy discounted to 2019 (Option 2 in transit vessels)



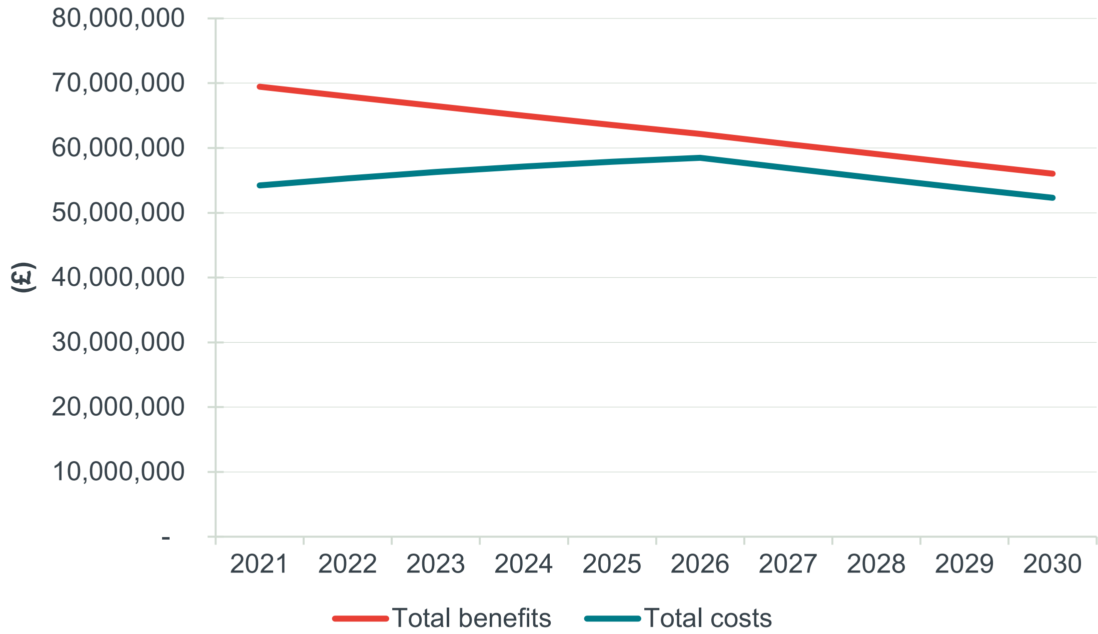
Source: Frontier calculations
2017 prices

Figure 66 Annual value of all emission changes discounted to 2019 (Option 2 all vessels)



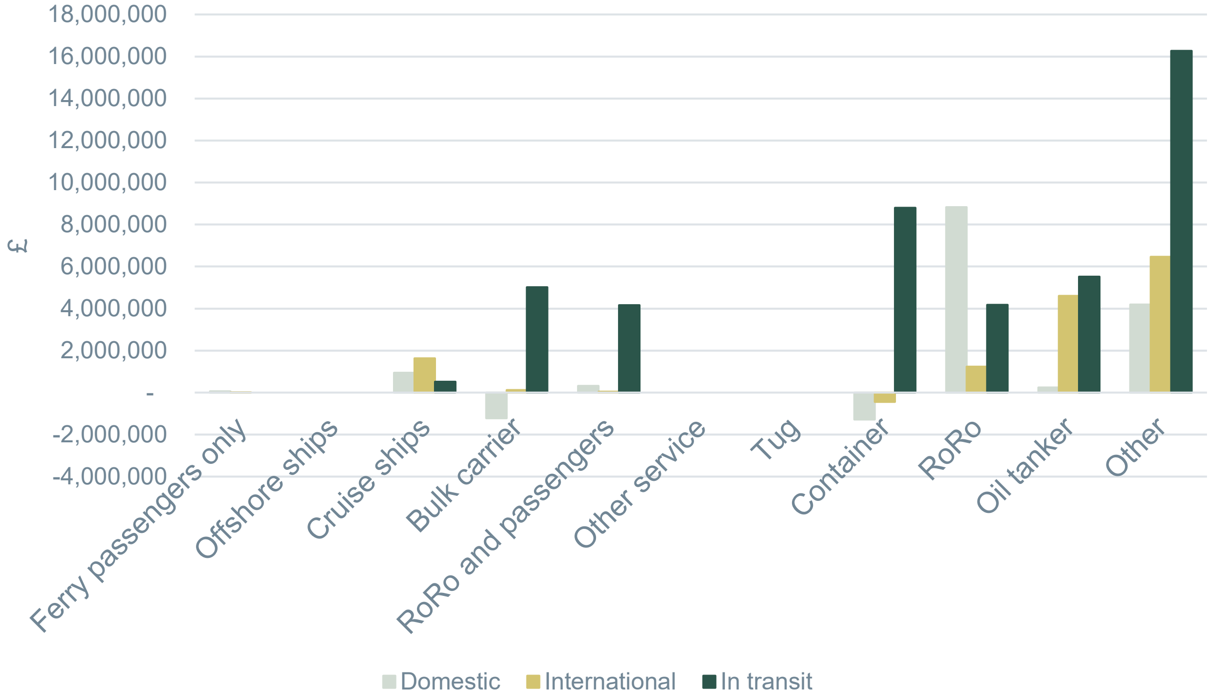
Source: Frontier calculations, some lines may be overlapping and difficult to certain emission values are very similar, and some lines may be overlapping and difficult to see as a result

Figure 67 Total annual costs and benefits accruing to the UK discounted to 2019 (Option 2 all vessels)



Source: Frontier calculations
2017 prices

Figure 68 Breakdown of NPV across vessel type and status (Option 2 over the 10 years of the policy)[47]



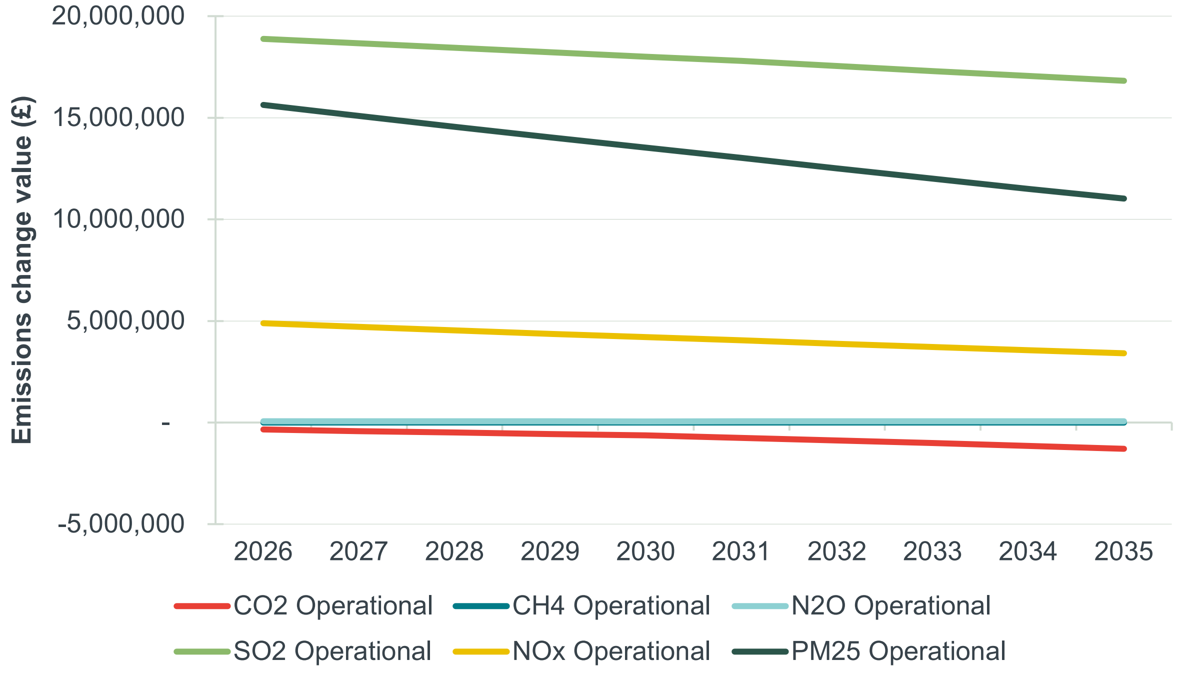
Source: Frontier Economics
2017 prices

Option 3

This section presents the estimates of the value of the change in emissions and the total costs and benefits over the appraisal period for Option 3. All monetary estimates are in 2017 prices and have been discounted to 2019 unless otherwise stated. Positive monetary values (in pounds) for the change in emissions indicate a **decrease** in emissions from the policy. Similarly, negative monetary values (in pounds) for the change in emissions indicate an **increase** in emissions from the policy. Total costs and benefits are only those assumed to impact the UK (i.e. benefits capture the changes in air pollutants from all shipping, while costs capture the changes in fuel costs from domestic and international shipping, and the changes in GHGs from domestic shipping).

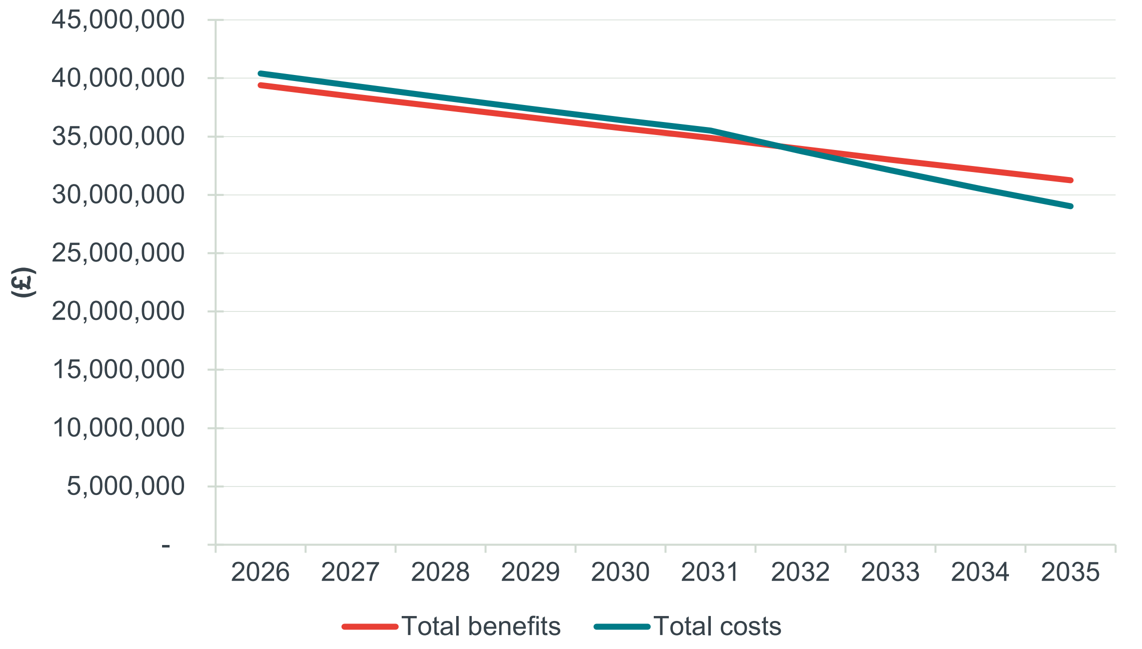
[47] Positive values indicate that for that shipping type, the policy has a positive NPV impact, while negative values indicate the opposite.

Figure 69 Annual value of all emission changes discounted to 2019 (Option 3 domestic vessels)



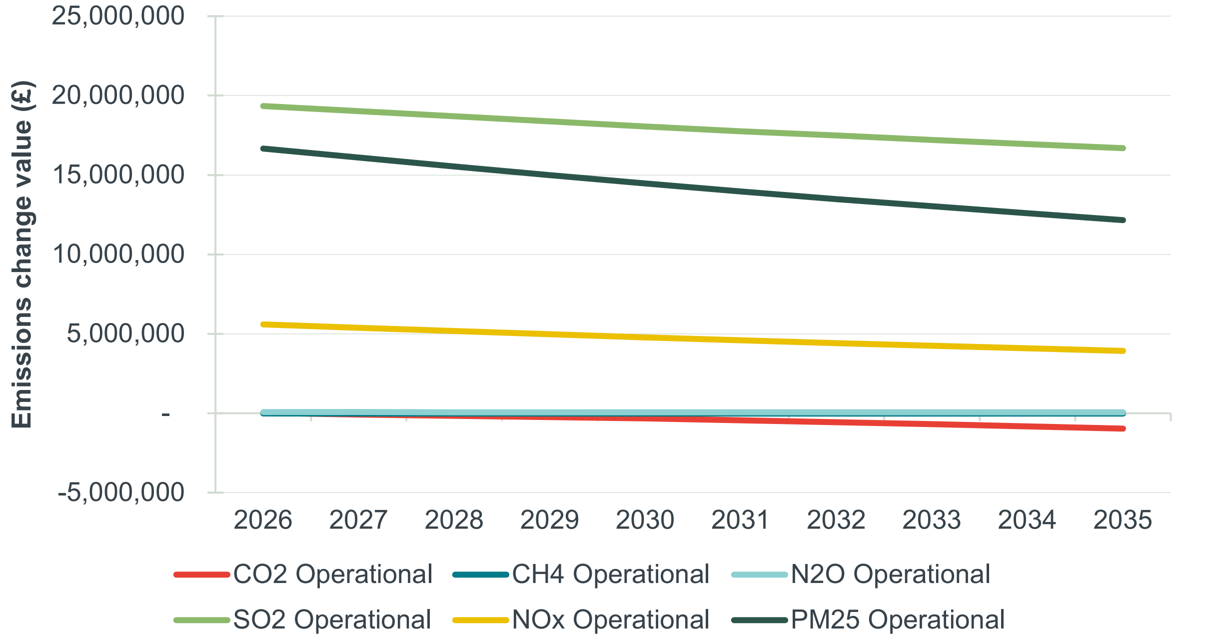
Source: Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result, 2017 prices

Figure 70 Total annual costs and benefits accruing to the UK economy discounted to 2019 (Option 3 domestic vessels)



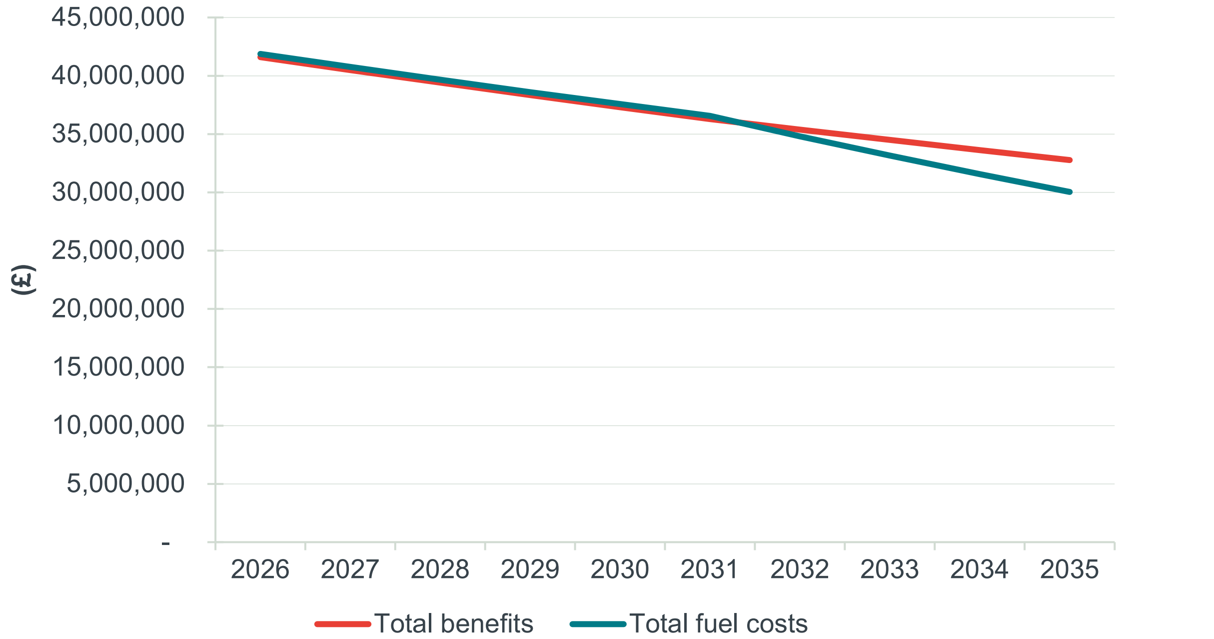
Source: Frontier calculations
2017 prices

Figure 71 Annual value of all emission changes discounted to 2019 (Option 3 international vessels)



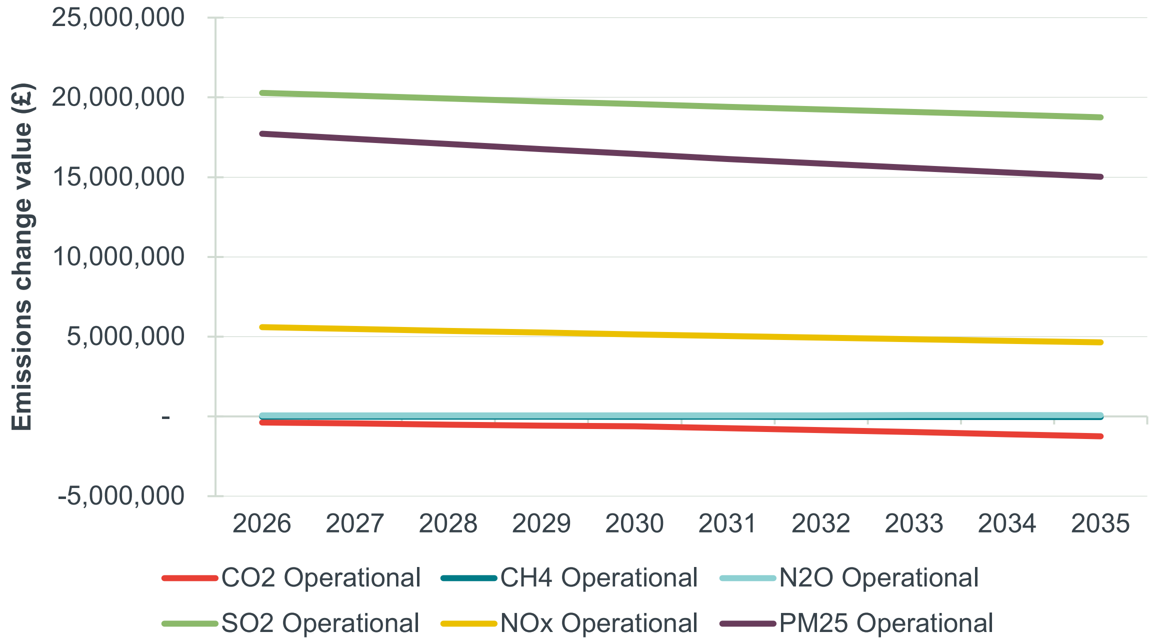
Source: Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result
2017 prices

Figure 72 Total annual costs and benefits accruing to the UK economy discounted to 2019 (Option 3 international vessels)



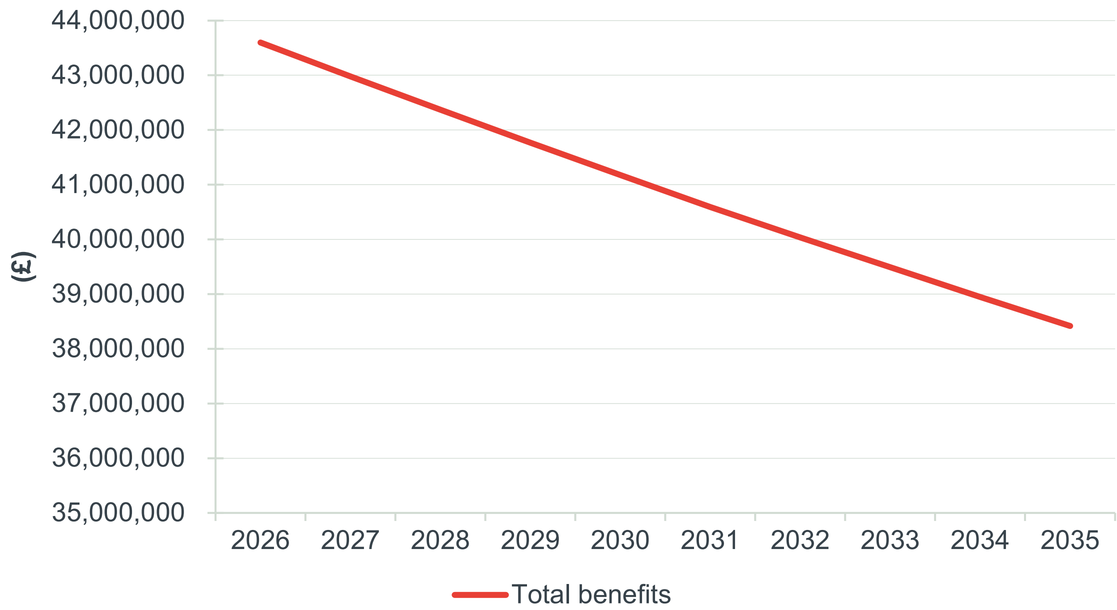
Source: Frontier calculations
2017 prices

Figure 73 Annual value of all emission changes discounted to 2019 (Option 3 in transit vessels)



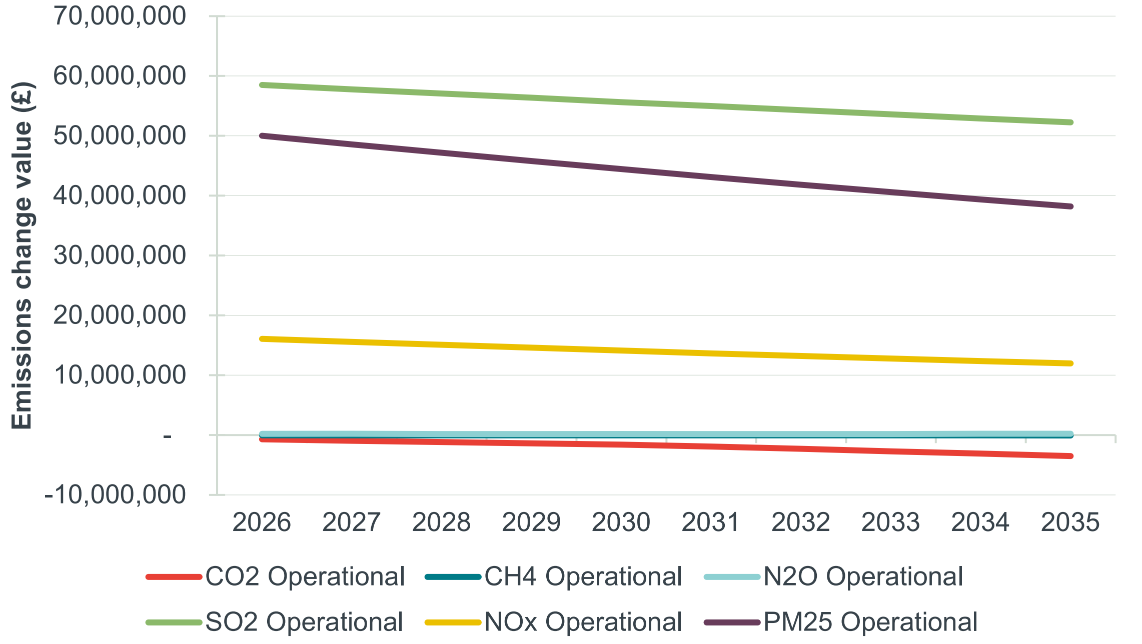
Source: *Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result*
2017 prices

Figure 74 Total annual benefits accruing to the UK economy discounted to 2019 (Option 3 in transit vessels)



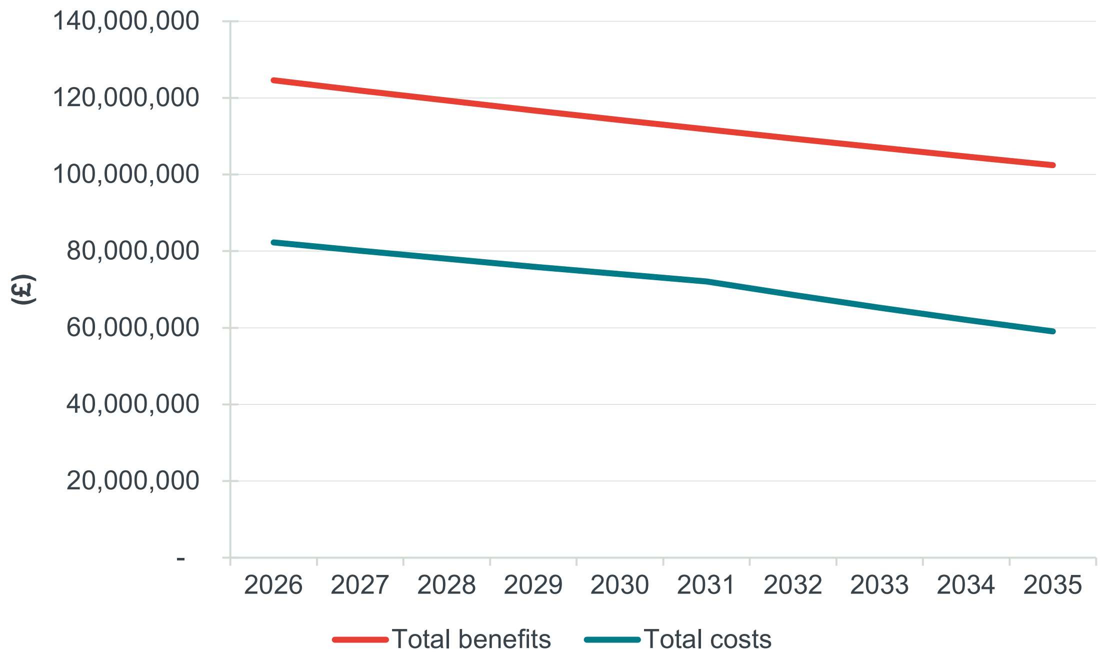
Source: *Frontier calculations*
2017 prices

Figure 75 Annual value of all emission changes discounted to 2019 (Option 3 all vessels)



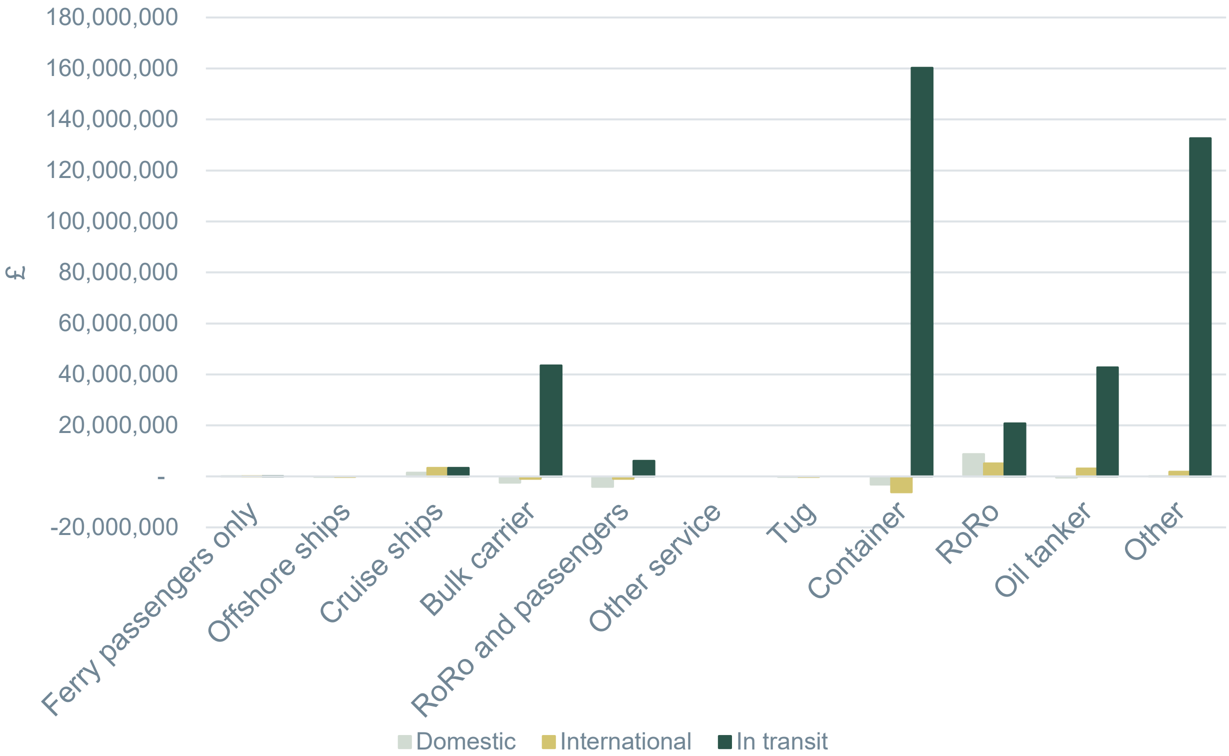
Source: Frontier calculations, certain emission values are very similar, and some lines may be overlapping and difficult to see as a result
2017 prices

Figure 76 Total annual costs and benefits accruing to the UK economy discounted to 2019 (Option 3 all vessels)



Source: Frontier calculations
2017 prices

Figure 77 Breakdown of NPV across vessel type and status (Option 3 over the 10 years of the policy)[48]



Source: Frontier Economics
2017 prices

High sensitivity

The high sensitivity results use the low non-traded values for CO_2 equivalent emissions and the high valuations for air pollution. As previously mentioned, when considering total costs and benefits that would accrue to the UK, this includes the benefits (decrease in air pollutants) from all vessels (domestic, international and in transit), and fuel costs from only domestic and international vessels, and GHG costs from only domestic vessels. These results are included in the accompanying CBA model.

[48] Positive values indicate that for that shipping type, the policy has a positive NPV impact, while negative values indicate the opposite.

Low sensitivity

The low sensitivity results use the high non-traded values for CO_2 equivalent emissions and the low valuations for air pollution. As mentioned previously when considering the impact on the UK economy, all benefits (domestic, international and in-transit) are included and only domestic and international costs are included. These results are also included in the accompanying CBA model.

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