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## Consideration of How to Progress the Matter of Reduction of GHG Emissions from Ships

Document submitted to the ISWG-GHG of the International Maritime Organization by Belgium, Denmark, France, Germany, the Marshall Islands, the Netherlands, Solomon Islands, Tonga and Tuvalu

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INTERSESSIONAL MEETING OF THE
WORKING GROUP ON REDUCTION OF
GHG EMISSIONS FROM SHIPS
1st session
Agenda item 2

ISWG-GHG 1/INF.2
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# CONSIDERATION OF HOW TO PROGRESS THE MATTER OF REDUCTION OF GHG EMISSIONS FROM SHIPS

## A scientific study on possible reduction targets and their associated pathways

**Submitted by Belgium, Denmark, France, Germany, the Marshall Islands, the Netherlands, Solomon Islands, Tonga and Tuvalu**

### SUMMARY

| | |
|---|---|
| *Executive summary:* | This document is submitted in support to document MEPC 71/7/7 (Possible emissions scenarios, and a method for quantifying an emissions pathway for shipping) and provides the full study "$CO_2$ emissions from international shipping – possible reduction targets and their associated pathways" |
| *Strategic direction:* | 7.3 |
| *High-level action:* | 7.3.2 |
| *Output:* | 7.3.2.1 |
| *Action to be taken:* | Paragraph 2 |
| *Related documents:* | MEPC 68/5/1; MEPC 69/7/2; MEPC 70/7/6, MEPC 70/7/13, MEPC 70/18/Add.1; MEPC 71/7/7 and MEPC 71/INF.35 |

## Introduction

1 This document provides the full study "$CO_2$ emissions from international shipping – possible reduction targets and their associated pathways", which has been carried out for the Danish Shipowners' Association by UMAS[1] and presented in November 2016.

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[1] UMAS is a sector focused commercial advisory service that draws upon the world leading expertise of the UCL Shipping Team combined with the advisory and management system expertise of MATRANS. In combination, UCLC, UCL Energy Institute and MATRANS operate under the branding of the entity UMAS.

## Action requested of the Working Group

2 The Working Group is invited to note the information provided in the annex to this document.

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ANNEX

# CO2 Emissions from International Shipping

## Possible reduction targets and their associated pathways

21-Oct-16

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## Preface

This report has been written by a team of experts from UMAS, UCL and LR for DSA.

## Acknowledgements

This study builds on work undertaken in the Low Carbon Shipping (LCS) and Shipping in Changing Climates (SCC) projects. SSC is a £4m multi-university and cross-industry research project funded for 3.5 years by the UK Engineering and Physical Sciences Research Council (EPSRC). The SCC project uses a whole systems approach to understand the scope for greater energy efficiency of the supply side, understand the demand side drivers and to understand the supply and demand interactions and potential future evolution in shipping.

## About UMAS

UMAS is a sector focused commercial advisory service that draws upon the world leading shipping expertise of the UCL Energy Institute, combined with the advisory and management system expertise of MATRANS. In combination, UCLC, UCL Energy Institute and MATRANS operate under the branding of the entity UMAS. For more details visit www.u-mas.co.uk

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# Executive Summary

The study "*$CO_2$ emissions from international shipping – possible reduction targets and their associated pathways*" focuses on understanding the potential pathways and scenarios for the future of international shipping, in the context of wider global decarbonisation consistent with the Paris Agreement.

The study derived targets ranging from the most ambitious, achieving zero emissions by around 2035 (temperature stabilization 1.5 degrees above pre-industrial levels), to the least ambitious, approximately keeping $CO_2$ emissions from shipping constant at their current levels (a target representative of the average developing country's Nationally Determined Contribution). Corresponding to each target, a set of simulated pathways, each exploring the details of how the shipping industry would meet the specified target, were produced.

This study was undertaken using a series of models and selections of assumptions, to simulate how the shipping sector might evolve to meet different constraints on its total $CO_2$ emissions.

The simulations are run from 2010 to 2050. The modelling is initiated in the baseline year 2010 using data obtained that characterises the different sectors of international shipping (broken down into ship type (e.g. dry bulk carrier, container ships) and size (e.g. Panamax, 8000TEU) at that point in time. The model then simulates the evolving decisions made by shipping owners and operators in the management and operation of their fleets (including the specification of new builds, decisions to retrofit, switch fuel or change average operating speed).

To investigate how different ships perform using different mixes of technologies and operational interventions a model underpinned by detailed engineering assumptions and relationships is used. This generates many ship design options with different design, technology, fuel and operational specifications.

In order to meet a given target for $CO_2$ emissions, the model uses a carbon price. The price is set for each year of the simulation, such that it enables a sufficient change within shipping (e.g. selection of appropriate low carbon technology, operation, fuel), or purchase of offsets, so that the overall net emissions from shipping follow the required trajectory. Varying constraints are placed on the amount of $CO_2$ emissions that can be offset out of sector.

The model is run for ten different scenarios. The scenarios correspond both to different $CO_2$ targets, and different input assumptions and allow the sensitivity of the results to variations in assumptions to be explored. All assumptions used were sourced from existing literature. The assumptions used are listed in the report, along with extensive data on the performance and costs of different energy efficiency interventions.

A key assumption and important uncertainty in the work, is the evolution of transport demand to 2050. In light of both recent trends in world trade, and suggestions from DSA members, all the study's ten scenarios use the Third IMO GHG Study 2014 demand scenarios which are broadly consistent with 2 degree temperature stabilisation and so projects declining demand for the transport of fossil commodities, coal and oil, whilst driven by increasing population and wealth, increasing demand for some bulk commodities and container shipping's services (approximately growth in demand of 4% per annum for container shipping, growth for dry bulk of 2.5% per annum, and a halving of demand for oil tankers over the period – driven by the increasing decarbonisation of the global economy.

## Results

The study proposes a target for shipping that ensures reductions consistent with the overall ambition of the Paris Agreement. There are a number of different ways to achieve this, but the study recommends that to allow a gradual transition, net emissions will need to peak in 2025, with absolute emission reductions amounting to approximately 400 million tonnes in net emissions, by 2050. Consistent with the Paris Agreement, emissions will then need to reduce to zero during the second half of the 21st century.

Regarding different possible pathways, the results from the simulations show, consistent with the Third IMO GHG Study, that with no further policy, expectations are that $CO_2$ emissions from international shipping will rise. The results also show that a number of decarbonisation pathways in which emissions from international shipping peak and then reduce, are also foreseeable. Exploring the details of the results reveals a number of key findings:

- In each decarbonisation pathway, there are different relative contributions from technical and operational interventions on energy efficiency (both more efficient newbuilds and retrofitting to existing fleet), use of alternative fuels, and the purchasing of $CO_2$ emissions offsets.
- In order to achieve absolute emissions reductions, whilst accommodating an increase in transport demand, shipping will need to reduce its average carbon intensity (the amount of $CO_2$ emitted per tonne of goods moved) by more than can be achieved through energy efficiency interventions alone. Whilst there are different ways this can be achieved, the scenario results show that in addition to the use of a number of energy efficiency interventions, alternative (low carbon) fuels such as biofuel and hydrogen become preferable to the use of extremely low operational speeds in combination with fossil fuels.
- Because the study did not exhaustively test all the different potential fuels, the study's finding that hydrogen could have an important role in the future of international shipping is not evidence that hydrogen is the most suitable. But it does indicate the potential for fuels like hydrogen generally, as a means to convert energy (e.g. from surplus renewable energy in the electricity grid) into a store of energy for use in ships. In this respect hydrogen is similar to batteries and depending on how technology develops in both of these areas will determine which could be the better solution for different future ship designs in the future.
- Costs, both for energy efficiency technologies, and fuels, are of high uncertainty. One scenario explores the consequences of dramatic cost reductions both for machinery (main engines), and energy efficiency technologies. The results show that in this scenario whilst there is a reduced cost for international shipping, the pathway that the sector follows is in practice very similar to the equivalent standard cost scenario.
- The role of offsetting is explored, assuming that a reliable and robust method for offsetting is available. Offsets purchased at an estimated 'global carbon price' appear in earlier decades (2020's and 2030's) to be a cost-effective means to manage shipping's carbon emissions. However, they become more expensive with time (as the low-hanging fruit for decarbonising the wider economy get's used up) and in later years offsets in many scenarios give way to increasing amounts of $CO_2$ emission reduction within shipping. This indicates it could be dangerous to assume that shipping's decarbonisation can be managed wholly using $CO_2$ emission offsetting.

# 1 Introduction

The overall aim of this project is to provide DSA with support and evidence so that it can establish specific, ambitious, achievable and time dependent reduction targets for $CO_2$ emissions for the future of international shipping. Those reduction targets must:

- be in form of specific reduction percentages in relation to a baseline year 2010;
- be based on thorough and comprehensive research;
- take into consideration that the fleet is diversified in size and type of operation.

# 2 Approach

## 2.1 Scenarios method overview

We carry out a scenario approach using an existing suite of data and models, and wherever possible leveraging the substantive work that has already been undertaken to develop rigorous, robust and appropriately detailed tools to describe the possible scenarios for the evolution of the shipping industry over the next decades, and the details of the sector's air pollution and GHG emissions.

The model used is called GloTraM, which performs a holistic analysis of the global shipping system for investigation of how shipping might change in response to developments in fuel prices and environmental regulation (on emissions of $SO_x$, $NO_x$, PM, $CO_2$). Areas of particular focus are the possible trajectories of the $CO_2$ emissions from the shipping industry, and what the costs and impacts of substantial emission reduction of the shipping industry might be. The period covered by the modelling is 2010-2050 with a validation scenario which runs from 2008-2015.

A conceptualisation of the modelling framework can be seen in Figure 1. Each box describes a component within the shipping 'system'. The feedbacks and interconnections are complex and only a few are displayed on this diagram for the sake of clarity. This conceptualisation allows us to break down the shipping system into manageable analysis tasks, ensure that the analysis and any algorithms are robust, and then connect everything together in order to consider the dynamics at a 'whole system' level.

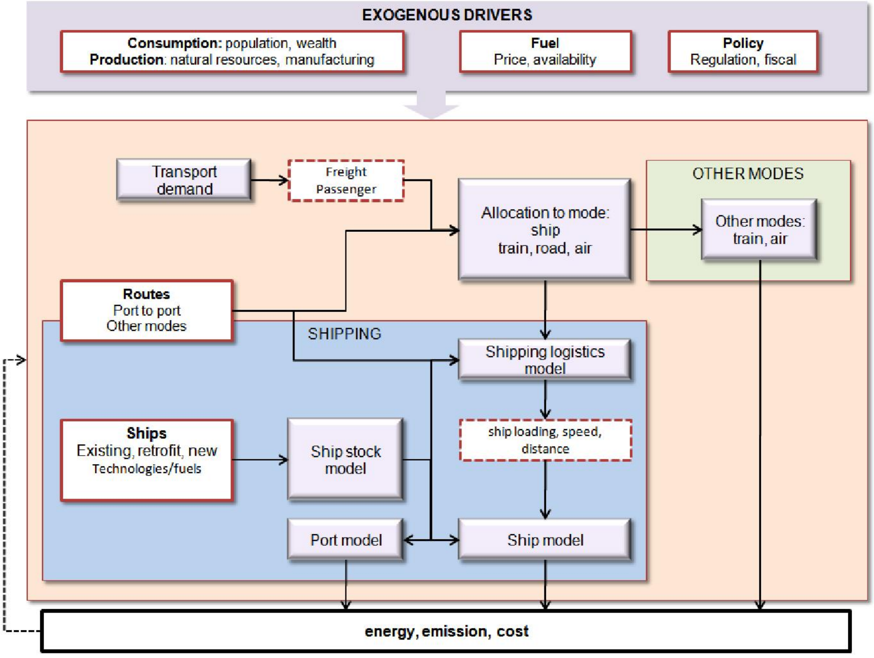

**Figure 1: Conceptualisation of the shipping system**

GloTraM and its input data and assumptions are based on a simulation of the shipping industry. The model is initiated in a baseline year using data obtained that characterises the shipping industry at that point in time, then the model time-steps forwards simulating the decisions made by shipping owners and operators in the management and operation of their fleets. The model deploys a 'profit maximising' approach, assuming that individual owners / operators make decisions to maximise their profit, and the model includes the representation of known market barriers and failures (e.g. the charterer/owner split incentive) in order to generate scenarios of technology and operational change that match actual observed behaviour as closely as possible. For a detailed model methodology documentation the interested reader is referred to Smith et al. (2013)[1] and "Global Marine Fuel Trends" in collaboration with Lloyd's Register (2014).

To investigate what might be the appropriate mix of technologies and operational approaches for future ship designs the Whole Ship Model (WSM) was developed, which is a holistic ship design tool, primarily developed at UCL, that can generate many ship design options with different design, technology and fuel combinations. The Whole Ship model can be used to explore different arrangements and uses of energy efficiency measures on container ships, bulk carriers and tankers evaluating their performance over an operating profile. Figure 2 shows an overview of the inputs that the WSM can utilise. Ship design and operational assumptions can be combined in order to examine how a ship performs over an operating profile at an early design stage. The WSM can compare technologies, different design variants of the same ship specification or examine the performance of shipping fleets, depending on the preference of the designer or decision-maker[2].

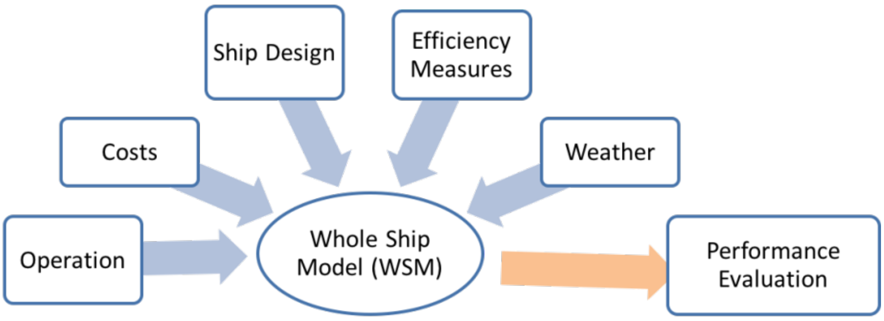

**Figure 2: Overview of Whole Ship Model**

The WSM has an iterative design process for both design and in service operating conditions that includes the effects of different technologies, operational measures, fuel types, regulations, speeds and weather; leading to a numerically balanced design option. The design process establishes and fixes the main characteristics of the ship (e.g. capacity and installed power). The operational assessment process uses the ship specification created by the design process and calculates its performance at different ship speeds, weather conditions and in regulatory regions like for example in Emission Control Areas (ECA). It is important to note that the WSM calculates the ship performance in a series of steady-state conditions. The use of time-domain approaches is being considered for future development to allow full voyage modelling.

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[1] Smith, T., O'Keefe, E. & Haji, S., 2013a. *GloTraM method.* London, UCL.

[2] Calleya, J.; Gasper H.M.; Pawling, R.; Ryan, C. (2016), *Using Data Driven Documents (D3) to Explore a Whole Ship Model*, SoSE, Kongsberg, Norway

## 2.2 Ship types included

### 2.2.1 Specific ship type and sizes

Table 1 lists the ship types and size categories that are considered in the study.

**Table 1: Ship type and size categories considered in this study, including the number of DSA member owned and operated ships corresponding to the categories**

| | | dwt | | DSA number of ships included |
|---|---|---|---|---|
| 1 | Dry bulk | > | =< | |
| | | 0 | 9,999 | 0 |
| | | 10,000 | 34,999 | 95 |
| | | 35,000 | 59,999 | 57 |
| | | 60,000 | 99,999 | 97 |
| | | 100,000 | 199,999 | 17 |
| | | 200,000 | + | 0 |
| 3 | Product and chemical carrier | dwt | | |
| | | > | =< | |
| | | 0 | 4,999 | 32 |
| | | 5,000 | 9,999 | 49 |
| | | 10,000 | 19,999 | 77 |
| | | 20,000 | + | 315 |
| 4 | Containership | TEU | | |
| | | > | =< | |
| | | 0 | 999 | 0 |
| | | 1,000 | 1,999 | 33 |
| | | 2,000 | 2,999 | 56 |
| | | 3,000 | 4,999 | 91 |
| | | 5,000 | 7,999 | 62 |
| | | 8,000 | 11,999 | 97 |
| | | 12,000 | 14,499 | 13 |
| | | 14,500 | + | 28 |
| 5 | General Cargo | dwt | | |
| | | 0 | 4999 | 50 |
| | | 5000 | 9999 | 18 |
| | | 10000 | + | 62 |
| 6 | Gas | cbm | | |
| | | > | =< | |
| | | 0 | 14,999 | 62 |
| | | 15,000 | 39,999 | 6 |
| | | 40,000 | 99,999 | 3 |
| | | 100,000 | + | 0 |
| 7 | Oil tanker | dwt | | |
| | | > | =< | |
| | | 0 | 4,999 | 0 |
| | | 5,000 | 9,999 | 0 |
| | | 10,000 | 19,999 | 0 |
| | | 20,000 | 59,999 | 11 |
| | | 60,000 | 79,999 | 0 |
| | | 80,000 | 119,000 | 18 |
| | | 120,000 | 199,000 | 0 |
| | | 200,000 | + | 2 |

### 2.2.2 Representative ships

In order to avoid including plots and tables for every ship type and size category listed in Table 1, case studies are undertaken in Section 3 on a number of specific ship specifications. Including:

- Panamax dry bulk carrier (Max size 32.31m x 294m)
- MR tanker

- Medium container (~4500 TEU)
- VL container (~13000 TEU)

## 2.3 Scenarios

Table 2 provides a summary of the scenarios with the description of the key parameters that are changed in each scenario. An explanation for the different assumptions used and justification for the variations can be found in Appendix A.

The model is run for ten different scenarios. The scenarios correspond both to different $CO_2$ targets, and different input assumptions. All assumptions used were sourced from a combination of existing literature, and discussed with DSA and its members.

There are four options for the $CO_2$ budget which correspond to 18, 23, 33 and 79 Gt of cumulative $CO_2$ emissions during the period 2010 to 2100. Scenario 4, 5, and 10 have respectively a carbon budget of 18, 23, and 79 Gt, while scenarios 6 to 9 have a carbon budget of 33 Gt.

An MBM regulation is introduced in the modelling simulations. The start year can vary; in the majority of the scenarios the start year is 2025, except for scenarios 6 and 7 in which the start year is 2030.

Only a percentage of the total revenue derived from a carbon pricing can be used to purchase $CO_2$ offsets. The percentage can be 0%, 20%, 50%, and 80% and it varies among the scenarios as shown in Table 2.

There is a single transport demand projection used for all scenarios called 2 degree SSP3. It reflects the projections described in the Third IMO GHG Study 2014 driven by the curves RCPs 2.6 and SSP3. The curve RCPs 2.6 is broadly consistent with 2 degree temperature stabilisation and so projects declining demand for the transport of fossil commodities, coal and oil. The curve SSP3 is driven by increasing population and wealth, increasing demand for some bulk commodities and container shipping's services (approximately growth in demand of 4% per annum for container shipping, growth for dry bulk of 2.5% per annum, and a halving of demand for oil tankers over the period – driven by the increasing decarbonisation of the global economy).

There is single fuel price projection called "2 degrees price", which is obtained using the output of the model TIAM-UCL. The only variation is for scenario 9 and 10, in which a modification is applied to the LNG price; it remains stable from 2035. This variant of the fuel price projections is called "LNG low". There are three options for the level of bioenergy availability. These are: lower bound (1 EJ), mid-range (4 EJ), and upper bound (11 EJ). The bioenergy availability varies among the scenarios as shown in Table 2.

There are also three options for the slow steaming constraint. Due to the relationship speed and power, this constraint is simulated by applying a limit to the minimum powering. In practice the operational speed is assumed to be set according to market conditions, however a bound is introduced for the reduction of installed power to represent different potential machinery limits. The three options are: very limited, limited, and relaxed, which reflects respectively a limit to reduction of installed power to minimums of 40%, 20% and 1% of the total installed power. For example, the case with limited slow steaming constraint means that the minimum power output is limited to reduction to 20% of installed power.

To estimate the profitability of a given selection of energy technologies, a value of 3 years for the return of investment period is used in all scenarios, except for scenario 10, in which a value of 5 years is used.

There are two options for the barrier of market parameter: 50%, and 80%. This parameter indicates the % share of the fuel savings gained by technology investment that is passed to the ship owner and is a representation of some of the market barriers that can exist between owners and charterers (such as the split incentive).

A central set of assumptions for the costs of technology (energy efficiency technologies and main machinery technologies) is used in all scenarios, except for scenario 7, in which a value of 25% of the full price is used.

**Table 2: Scenario descriptions**

| | Regulation scenario (Sec.3 App. A) | | | Demand (Sec. 4 App. A) | Techno economic (Sections 5 to 7, Appendix A) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fair share derived $CO_2$ budget (2010-2100) | MBM start year | Out-sector offsets | Trade scenario | Fuels option | Fuel price | Bio availability scenario | Slow Steaming constraint | NPV year | b.tc | Technology cost |
| Scenario 1 - Validation run | - | - | - | 2 degree SSP3 | All fuels excluding H2 | 2-degree price | Lower bound | Very limited | 3 | 50% | Full |
| Scenario 2 -BAU | - | - | - | 2 degree SSP3 | All fuels excluding H2 | 2-degree price | Lower bound | Very limited | 3 | 50% | Full |
| Scenario 3 - BAU no EEDI | - | - | - | 2 degree SSP3 | All fuels excluding H2 | 2-degree price | Lower bound | Very limited | 3 | 50% | Full |
| Scenario 4 | 18 Gt | 2025 | 0% | 2 degree SSP3 | All fuels | 2-degree price | Mid-range | Relaxed | 3 | 50% | Full |
| Scenario 5 | 23 Gt | 2025 | 20% | 2 degree SSP3 | All fuels | 2-degree price | Mid-range | Limited | 3 | 50% | Full |
| Scenario 6 | 33 Gt | 2030 | 20% | 2 degree SSP3 | All fuels | 2-degree price | Lower bound | Limited | 3 | 50% | Full |
| Scenario 7 | 33 Gt | 2030 | 20% | 2 degree SSP3 | All fuels | 2-degree price | Lower bound | Limited | 3 | 50% | 25% of full price |
| Scenario 8 | 33 Gt | 2025 | 20% | 2 degree SSP3 | All fuels | 2-degree price | Mid-range | Limited | 3 | 50% | Full |
| Scenario 9 | 33 Gt | 2025 | 50% | 2 degree SSP3 | All fuels excluding H2 | LNG low | Mid-range | Limited | 3 | 50% | Full |
| Scenario 10 | 79 Gt | 2025 | 80% | 2 degree SSP3 | All fuels | LNG low | Higher bound | Relaxed | 5 | 80% | Full |

# 3 Summary of results

This section explores results generated from two different approaches:

- Section 3.1 presents the results generated using the Whole Ship Model only. This shows what is achievable as a reduction on 2010 carbon intensities, using different combinations of energy efficiency technology, fuel and operational change (speed)
- Section 3.2, 3.3 and 3.4 present and explore the results simulated for the 10 scenarios defined in Table 2.

The two sets of results cannot be easily cross-referenced. The results from the Whole Ship Model in Section 3.1 are not inclusive of considerations of the cost/revenue implications of the different solutions, but focus only on how the magnitude of carbon intensity could be changed. This contrasts with the approach taken in Section 3.2, 3.3 and 3.4, which is informed by a matrix of newbuild and retrofit options generated by the Whole Ship Model, and which then explores results from GloTraM which applies an objective function in the form of a $CO_2$ emissions target, and then allows the model to select the combination of technology, operational intervention and offsetting which meets the objective function whilst maximising a shipowner's profits.

## 3.1 How could different levels of carbon intensity reduction can be achieved through combining technical and operational measures

The Whole Ship Model used in this study enables ship designs to be generated that combine a number of technical and operational measures. The model represents major key naval architecture and marine engineering interactions and relationships, in order to estimate whole system impacts of a change in technical or operating specification. An explanation of how the predecessor of the whole ship model represents technical and operational measures is given in Calleya et al. (2015)[3], with a more recent description of the new whole ship model described briefly in Calleya et al., (2016)[4] and Appendix 2. A set of technologies was defined that represents a maximum specification that could be applied:

- Contra rotating propeller
- Air lubrication
- Main engine Turbo compounding parallel
- Aux turbo compounding series
- Organic Rankine Cycle WHRS
- Flettner rotors (not applicable to the container ship)
- Kites
- Engine derating
- Speed control of pumps and fans
- Block coefficient improvement

From Table 3 it is possible to observe that there are different pathways to achieve a lower EEOI: speed reduction, alternative fuels, technology mixture or a combination of them. However, to achieve a reduction of 70% or more from the baseline EEOI, and in particular for the MR tanker and 5000 TEU container ship, it is only achievable by combining speed reduction, change of fuel and energy saving

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[3] Calleya, J.; Pawling, R.; Greig, A., *Ship Impact Model for Technical Assessment and Selection of Carbon Dioxide Reducing Technologies (CRTs)*, Journal of Ocean Engineering, Elsevier, Vol. 97, March 2015, pages 82-89, ISSN 0029-8018, http://dx.doi.org/10.1016/j.oceaneng.2014.12.014

[4] Calleya, J.; Gaspar, H.M.; Pawling, R.; Ryan, C., Using Data Driven Documents (D3) to Explore a Whole Ship Model, SoSE, Kongsberg, Norway, 2016

technologies. On the case of the Panamax bulk carrier, speed reduction could well achieve the 70% EEOI reduction but it is important to highlight that the operating speed needs to reduce by about 60% (i.e. 4.5 kt). Careful attention is needed to ensure the safety and manoeuvrability of any ship designed with such low operating speeds.

It is important to mention that the stated set of technologies (in the above list) is not as exhaustive as the list contained in Appendix 2 and should be treated as an example of a technological combination on board a ship. In practice, energy efficiency measures and their integration are designed with the specific ship and the customer requirements that are being considered. It is recognised that the management of human factors and their interaction with both the ship's systems and fuel efficient technologies will help to extract optimal performance from any ship design. Monitoring and analysis, decision making and coordinating the operational performance from on board or at shore are some examples of soft interventions that can be used to optimise the performance of the vessel. The Whole Ship Model studies and describes just a few of these options, not because they are not relevant but mainly to the difficulty of generating a robust and reliable model which can adapt to different hardware design combinations (e.g. ship type, fuel, etc.).

Two steps are shown for the increase in technology, one with all the technologies except wind assistance and block coefficient improvement, and a second step that included both wind assistance (where applicable), and block coefficient changes. In addition to these changes, variations in operating speed were considered. All results, shown in Table 3, are compared to a baseline ship specification (none of the technologies listed above are applied), and a reference EEOI which is based on the average 2010 operating speed (taken from the Third IMO GHG Study). No variations in capacity utilisation (t.nm/dwt.nm) were considered, any improvement in capacity utilisation has a linear relationship on carbon intensity - doubling the capacity utilisation will halve the carbon intensity.

Two different levels of fuel decarbonisation are also applied, both a 50% and 75% reduction in fuel carbon factor. No wider system impacts are applied to represent these fuel decarbonisations, they are therefore indicative of an increase in bio or synthetic fuel being used rather than a larger system change that might be expected with the use of a fuel such as hydrogen. This assumes that the Bio-fuel mixture has the same thermal efficiency as current oil fuels and assuming that the carbon factor can be reduced due to less emissions over the full lifecycle of the fuel. The results are presented with two different colour filters:

- Green shows greater than 70% reduction in carbon intensity (on the baseline 2010 specification)
- Yellow shows between 30% and 70% reduction in carbon intensity (on the baseline 2010 specification)

**Table 3: EEOI value indexed to the baseline, 2010 specification, calculated using the Whole Ship Model by taking into account potential impacts due to technology, operation and fuel change**

| | Operating speed (knots) | Baseline | Max. technology but no wind assistance/block | Max. technology and wind assistance/block | Max. technology, wind assistance/block and 50% carbon factor ($C_f$) reduction | Max. technology, wind assistance /block and 75% carbon factor ($C_f$) reduction |
|---|---|---|---|---|---|---|
| MR tanker | 4.5 | 46% | 49% | 34% | 17% | 9% |
| | 6.0 | 46% | 46% | 31% | 16% | 8% |
| | 8.9 | 59% | 56% | 38% | 19% | 9% |
| | 9.7 | 66% | 61% | 42% | 21% | 10% |
| | 11.3 | 80% | 73% | 50% | 25% | 13% |
| | 11.7 | 85% | 77% | 53% | 27% | 13% |
| | 11.9 | 87% | 79% | 55% | 27% | 14% |
| | 12.0 | 89% | 80% | 55% | 28% | 14% |
| | **12.8** | **100%** | 89% | 61% | 31% | 15% |
| | 14.3 | 131% | 110% | 75% | 38% | 19% |
| | 15.0 | 153% | 126% | 85% | 43% | 21% |
| Panamax bulk carrier | 4.5 | 25% | 29% | 19% | 10% | 5% |
| | 6.0 | 31% | 32% | 21% | 10% | 5% |
| | 8.9 | 52% | 49% | 33% | 16% | 8% |
| | 9.7 | 60% | 55% | 38% | 19% | 9% |
| | 11.3 | 77% | 69% | 49% | 24% | 12% |
| | 11.7 | 83% | 74% | 52% | 26% | 13% |
| | 11.9 | 86% | 76% | 54% | 27% | 14% |
| | 12.0 | 88% | 78% | 55% | 27% | 14% |
| | **12.8** | **100%** | 87% | 62% | 31% | 15% |
| | 14.3 | 134% | 110% | 78% | 39% | 19% |
| | 15.0 | 158% | 127% | 88% | 44% | 22% |
| 5000 TEU container ship | 6.9 | 34% | 33% | 34% | 17% | 8% |
| | 9.2 | 38% | 36% | 36% | 18% | 9% |
| | 13.6 | 59% | 53% | 51% | 26% | 13% |
| | 14.9 | 68% | 60% | 58% | 29% | 14% |
| | 17.3 | 88% | 76% | 72% | 36% | 18% |
| | 17.9 | 94% | 82% | 76% | 38% | 19% |
| | 18.2 | 98% | 84% | 78% | 39% | 20% |
| | **18.4** | **100%** | 86% | 80% | 40% | 20% |
| | 19.6 | 114% | 97% | 88% | 44% | 22% |
| | 21.9 | 149% | 121% | 106% | 53% | 27% |
| | 23.0 | 172% | 137% | 118% | 59% | 29% |

## 3.2 Scenario results

The total operational $CO_2$ emission trajectories of the five ship types analysed are presented alongside the shipping share of $CO_2$ emissions in Figure 3. The net emissions, which include the effect of offsetting are shown alongside the target trajectories that were defined for the simulations, in Figure 4.

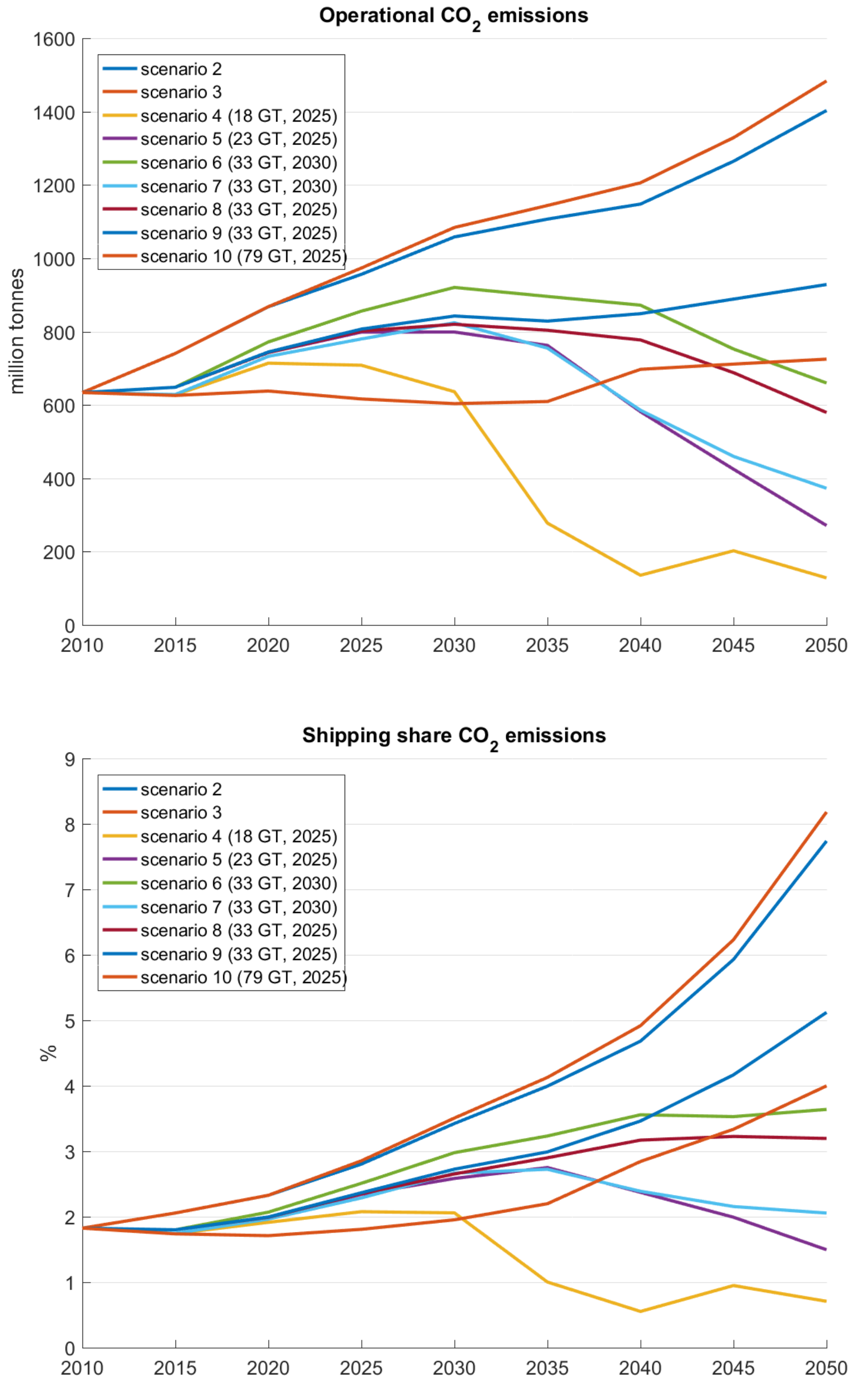


**Figure 3: $CO_2$ operational emissions trajectories net of offsets, for all scenarios, for the 5 ship types considered in this study (~80% of the total emissions of international shipping)**

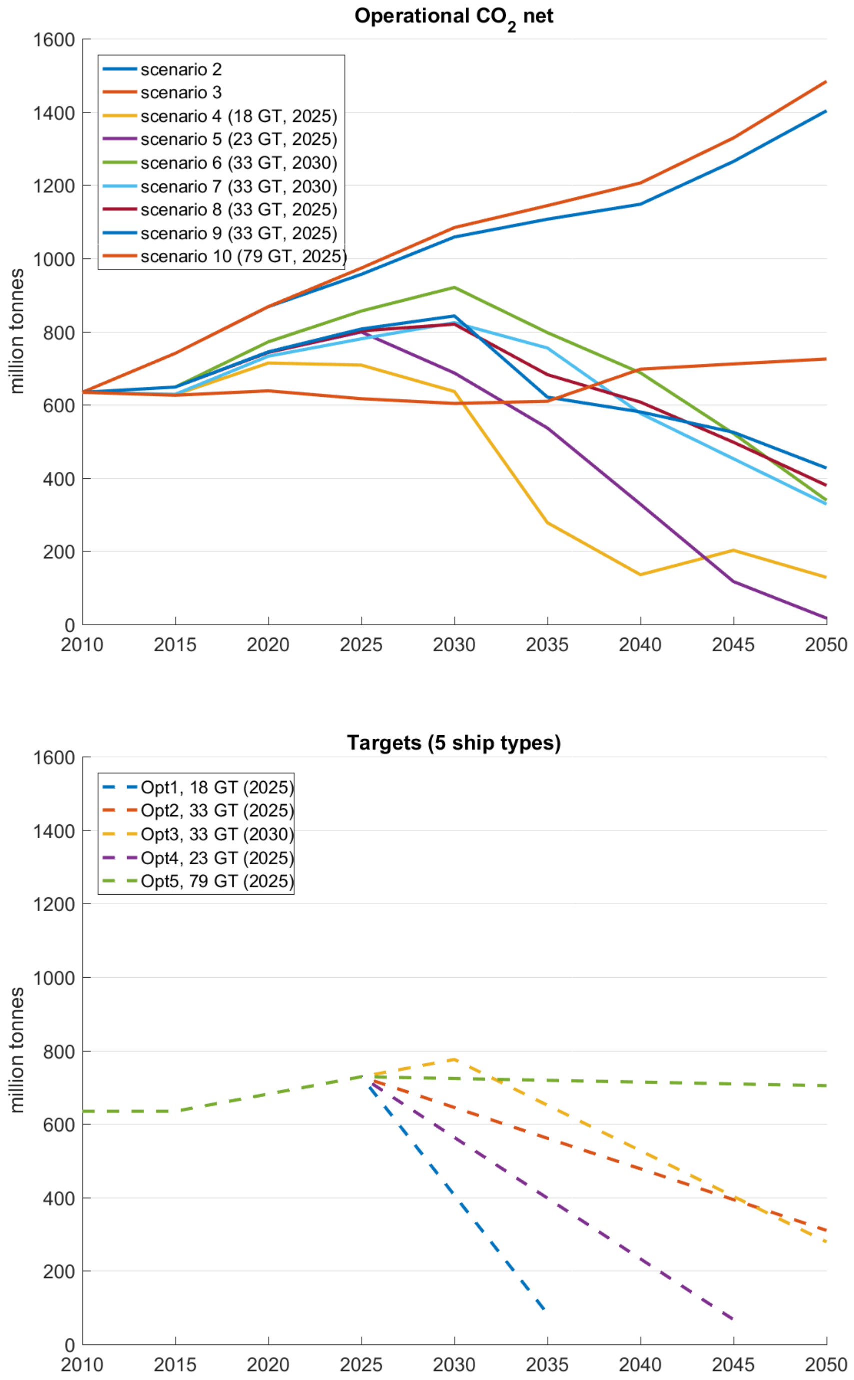


**Figure 4: $CO_2$ emissions trajectories net of offsets, and targets for all scenarios**

The fleet considered in this study represents the $CO_2$ emissions of approximately 82% of the total international shipping $CO_2$ emissions (according to comparison with the Third IMO GHG Study). We observed that:

- In scenarios 2 and 3 shipping operational emissions increase by 121-134% from 634 to 1403-1483 million tonnes $CO_2$ per year.
- In scenario 4 (18 Gt), shipping net emissions decrease by 79% from 634 to 128 million tonnes $CO_2$ per year.

- In scenario 5 (23 Gt), shipping net emissions decrease by 89% from 634 to 70 million tonnes $CO_2$ per year.
- In scenarios from 6 to 9 (33 GT), shipping net emissions decrease by a range of 32 to 48% from 634 to 427 – 328 million tonnes $CO_2$ per year. Scenario 7 presents the highest reduction (48%), while scenario 9 the lowest (32%).
- In scenario 10 (79 GT), increase by 14% from 634 to 725 million tonnes $CO_2$ per year.

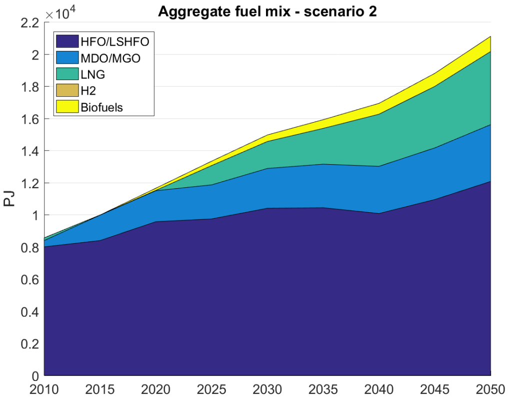
The aggregate fuel mix for all scenarios are presented in Figure 5. These illustrate that depending on both the emissions target and assumptions for the scenario, a number of different fuel mixes can arise. Scenarios 4, 5, 6, 7 and 8 all see some take up of hydrogen as a marine fuel, starting in small quantities in 2030 and growing out to 2050. In these scenarios, the decrease in operational emissions is highly dependent on a fuel shift from fossil fuels to a zero carbon at point of combustion fuel such as hydrogen. Other future fuels with low or zero carbon content could be considered instead of hydrogen. Nevertheless, the take up of hydrogen indicates that there is potential for fuels like hydrogen that similar to batteries is just an energy vector (for storing and transporting energy ready for release as needed). The rate of growth for this fuel is fastest in scenario 4 and 5, scenarios which combine a stringent $CO_2$ budget (18-23Gt) with moderate bioenergy availability and low offsetting, therefore restricting the choices for the sector's decarbonisation.

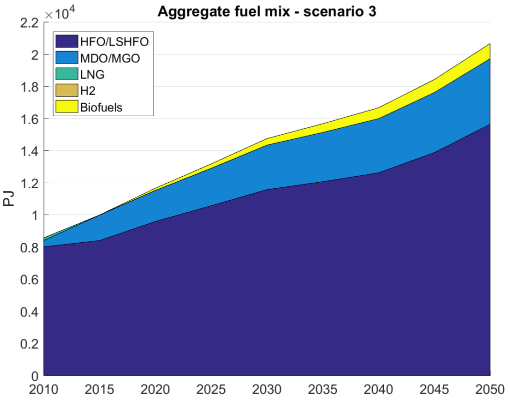
The take up of biofuels varies among the scenarios based on the assumption used on bioenergy availability. Scenario 10, has the largest take up of biofuels in accordance with the high bioenergy available in this scenario. In this case biofuels reaches about 35% of the total fuel supply in 2050. The take up of biofuels is also significant in scenarios 4, 5, 8 and 9 in which it reaches about 10 - 13% of the total shipping energy demand in 2050. The gap between the price of biofuels and conventional marine fuels is not modelled here (they are set at the same price as their fossil fuel equivalents) because it is assumed that it will become small, therefore, the key parameter is their availability. One of the consequences of this demonstrated potential significance of the role of biofuels in shipping's decarbonisation is that it raises the importance of shipping increasing its involvement and awareness in the debates around bioenergy's availability, use and wider impacts (e.g. issues associated with land-use and life cycle emissions).

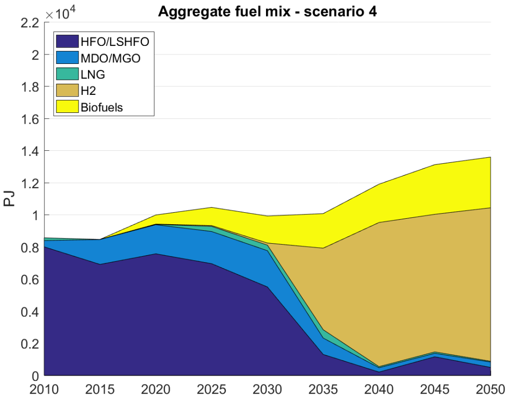
Scenario 7, which involves the largest rate of take-up of LNG, demonstrates the consequence of lower capital costs (both for alternative main engine machinery (LNG and hydrogen main machinery and storage technology), and energy efficiency equipment). The scenario can be contrasted with Scenario 6 which has all the same input assumptions, except on capital costs for which the default assumptions are used. The main difference between the scenarios is that LNG gains a larger market share in 7, because it is the machinery of choice from 2015 onwards (whereas in Scenario 6, there are still newbuilds specified with oil derivative fuels). The start year and rate of take up of hydrogen is similar in both Scenario 6 and 7, even though the lower capital costs enable greater take up of energy efficiency technology in Scenario 6 (the total PJ energy demand is slightly lower).

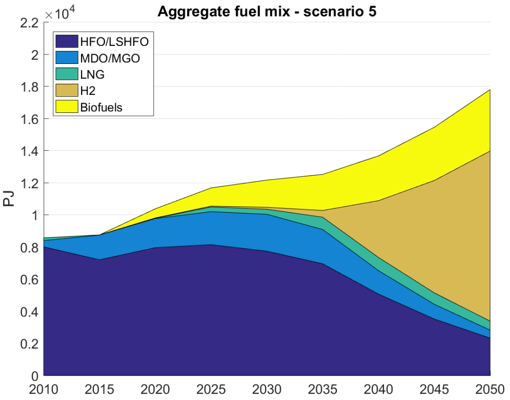
The rate of growth of the total energy demand also varies among the scenarios. The highest rate is observed in the BAU scenarios 2 and 3 reaching about 21000 PJ in 2050 (141- 146 % of increasing relative to the base year 2010). Among the scenarios with a decarbonisation trajectory, scenario 4 presents the lowest increases of total energy demand (59%), while scenario 10 presents the highest increases (121%), reaching 14000 and 19000 PJ in 2050, respectively.

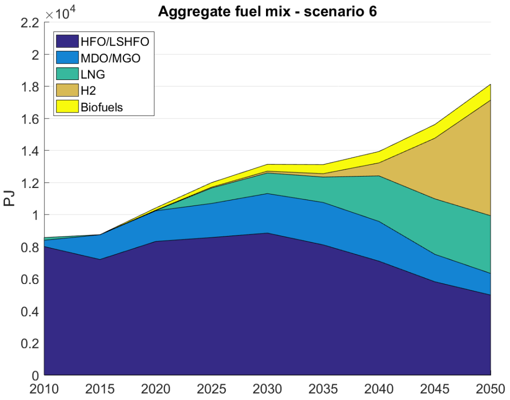
The drastic switch to more efficient engines (fuel cells) in scenario 4 can explains the relatively low growth of energy demand, while in the rest of the scenarios the growth of energy demand appears similar, varying between 91% (scenario 7) and 121% (scenario 10).

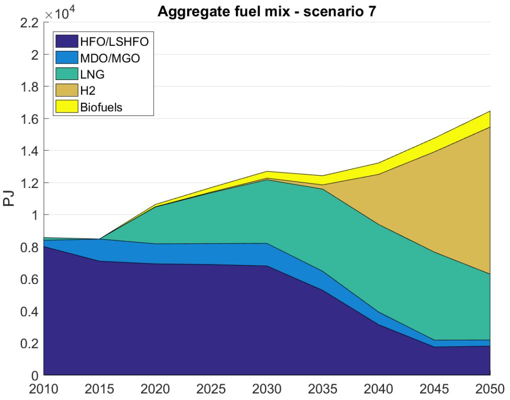

Aggregate fuel mix - scenario 2
×10^4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
PJ
HFO/LSHFO
MDO/MGO
LNG
H2
Biofuels
2010
2015
2020
2025
2030
2035
2040
2045
2050


Aggregate fuel mix - scenario 3
×10^4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
PJ
HFO/LSHFO
MDO/MGO
LNG
H2
Biofuels
2010
2015
2020
2025
2030
2035
2040
2045
2050


Aggregate fuel mix - scenario 4
×10^4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
PJ
HFO/LSHFO
MDO/MGO
LNG
H2
Biofuels
2010
2015
2020
2025
2030
2035
2040
2045
2050


Aggregate fuel mix - scenario 5
×10^4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
PJ
HFO/LSHFO
MDO/MGO
LNG
H2
Biofuels
2010
2015
2020
2025
2030
2035
2040
2045
2050


Aggregate fuel mix - scenario 6
×10^4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
PJ
HFO/LSHFO
MDO/MGO
LNG
H2
Biofuels
2010
2015
2020
2025
2030
2035
2040
2045
2050


Aggregate fuel mix - scenario 7
×10^4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
PJ
HFO/LSHFO
MDO/MGO
LNG
H2
Biofuels
2010
2015
2020
2025
2030
2035
2040
2045
2050

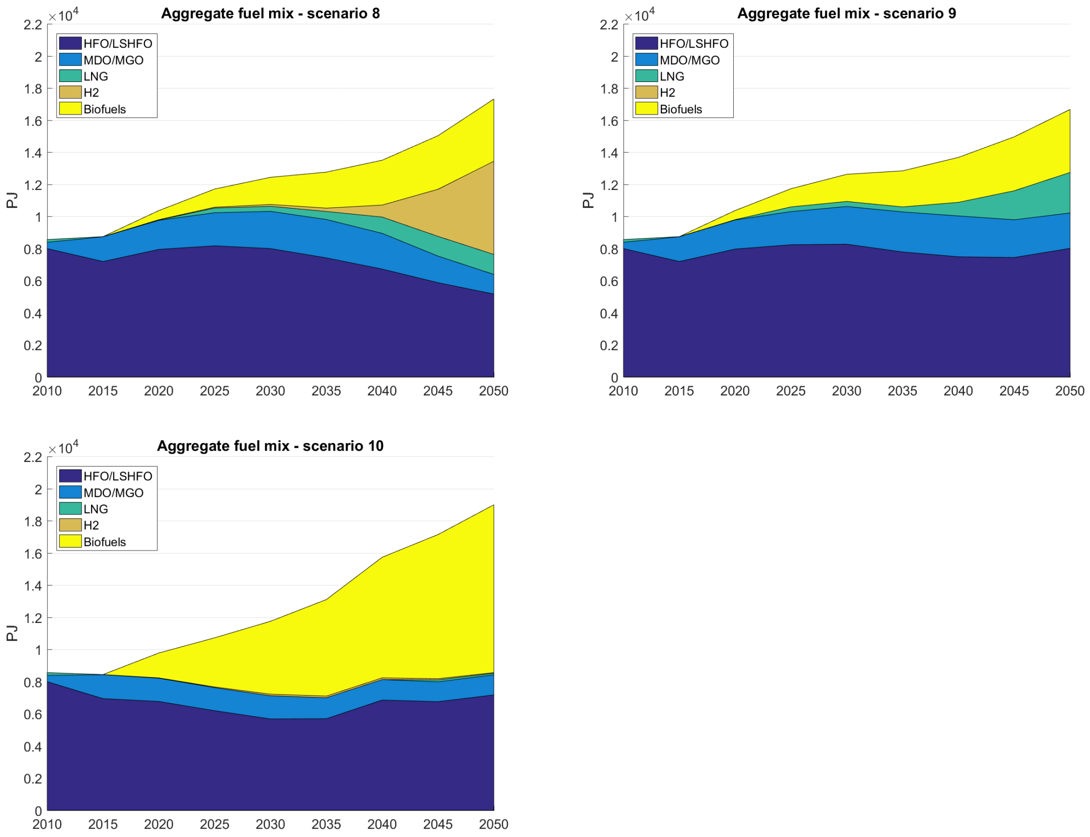


**Figure 5: Aggregate fuel mix for all scenarios**

Figure 6, Figure 7 and Figure 8 present the various trends in energy efficiency and carbon intensity indicators. EEDI and EEOI are both carbon intensity indicators and so aggregate the modifications to carbon factor of the fuels (e.g. through the use of bio or synthetic fuel), with the take up of energy efficiency technology and operational measures. Therefore, contrasting energy efficiency in J/t.nm helps to separate out the drivers of EEDI and EEOI. All figures are calculated as fleet average values for a given ship type, aggregating across the ship size categories modelled. In both instances a lower value indicates a relative improvement (in carbon intensity or energy efficiency).

Generally, the lowest levels of energy efficiency and carbon intensity occur in the two baseline scenarios with Scenarios 4 to 10 describing more ambitious trajectories. There is some commonality across all indicators between 2010 and 2030, with greater variation occurring in the period 2030 and 2050, as different stringencies of carbon intensity reduction and the different mechanisms (offsetting, alternative fuel use and varying take up of technical and operational energy efficiency options) are employed.

The graphs show that the use of low carbon fuels can enable reductions in energy efficiency. For example, Scenarios 4, 5 and 6, show deteriorating energy efficiency across all ship types between 2035 and 2050 whilst the carbon intensity improves. This is because the use of an increasing quantity of low carbon fuel (in this instance hydrogen) enables operating speeds to increase as lowering speed as an energy efficiency improvement is no longer required as the mechanism to achieve a given $CO_2$ emissions trajectory.

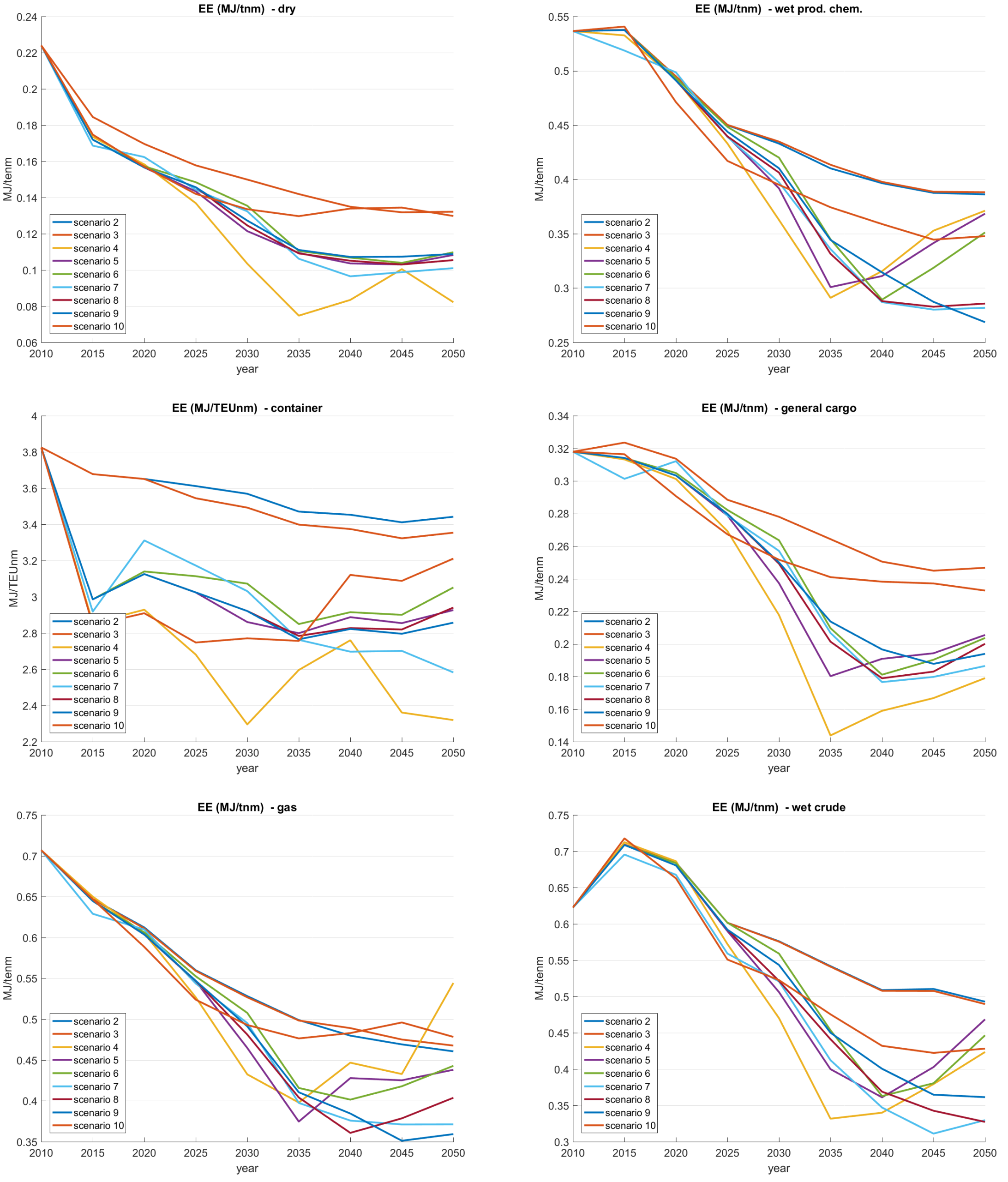


Figure 6: EE (J/t.nm) trends for all scenarios

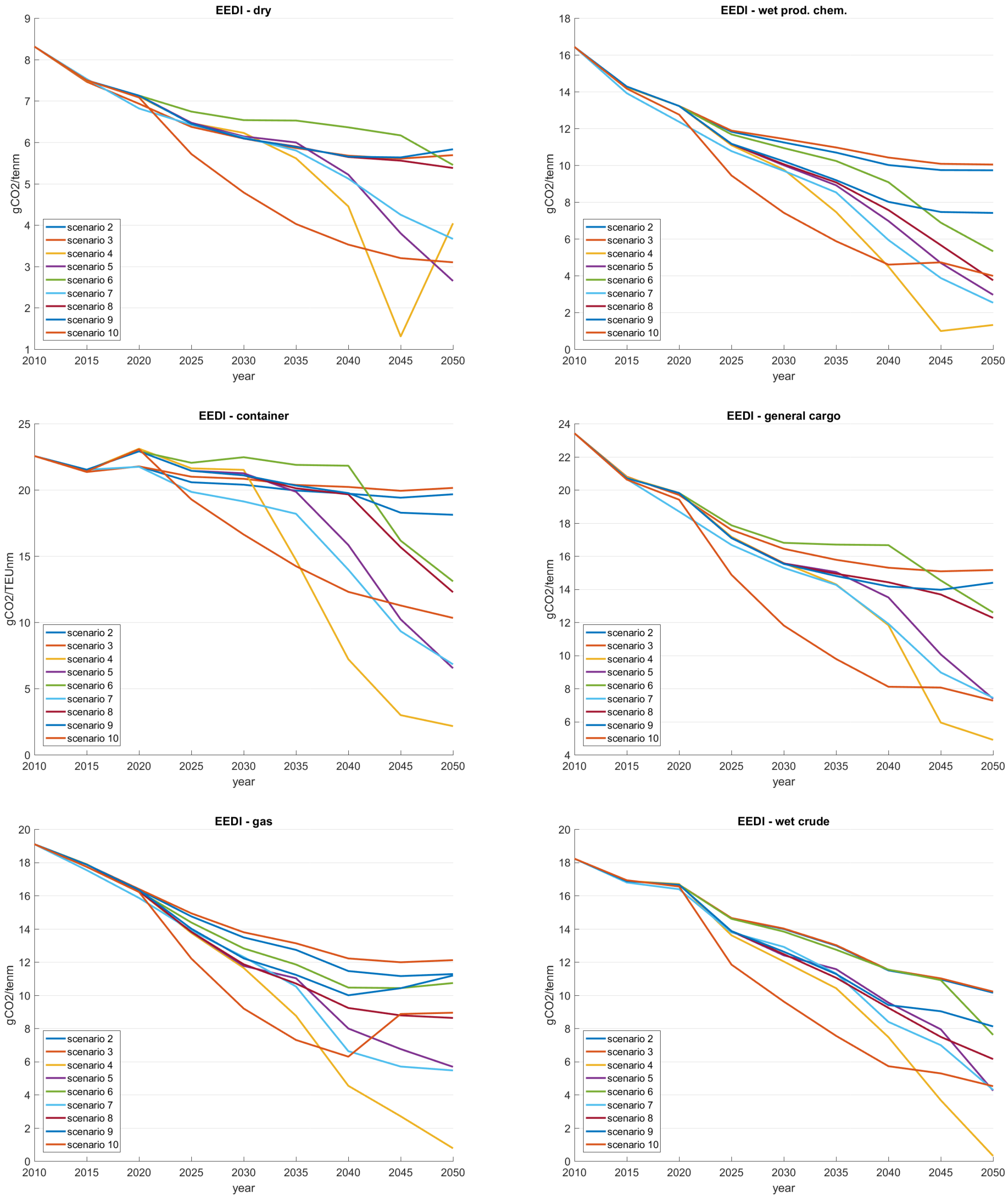


Figure 7: EEDI trends for all scenarios

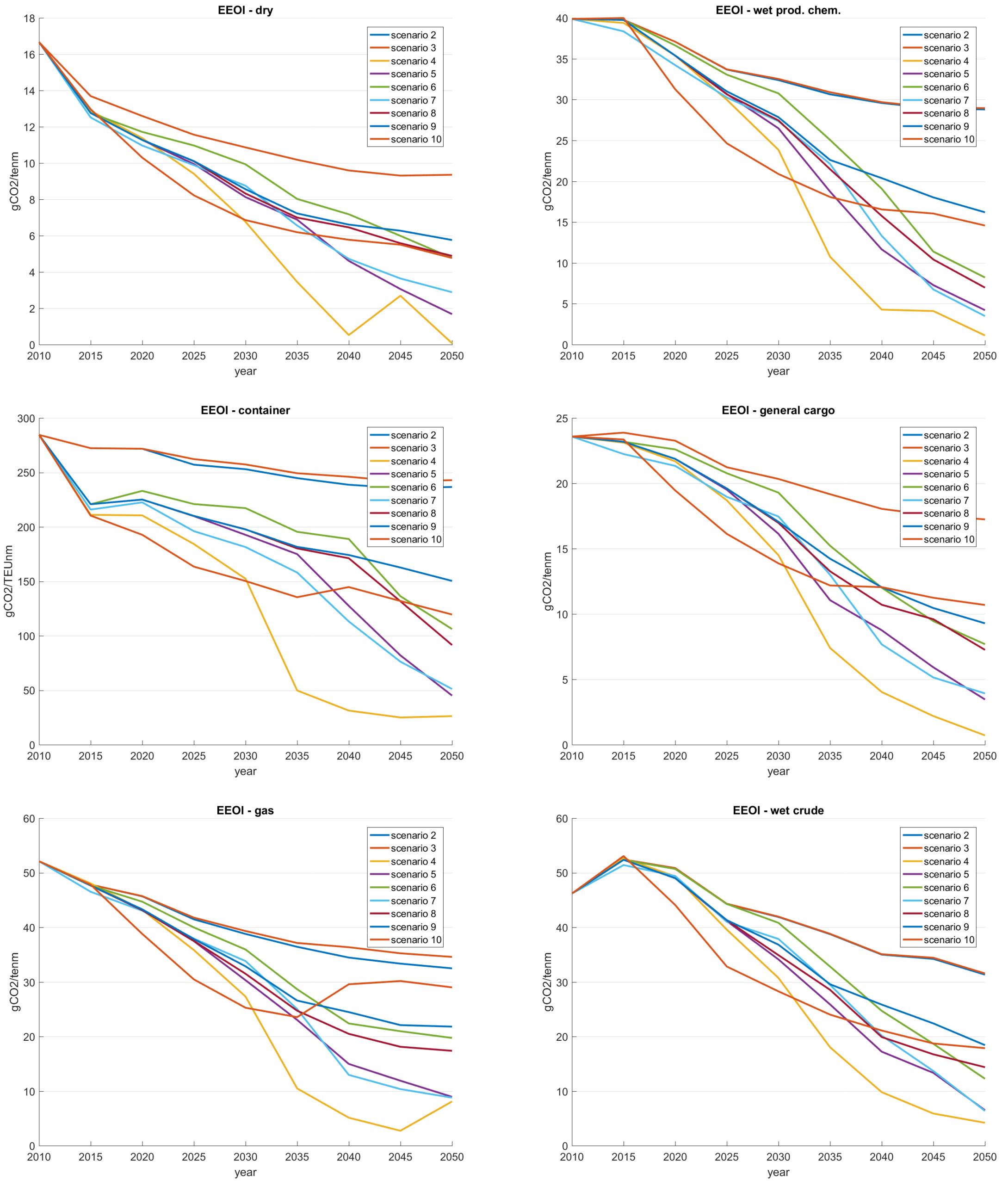


**Figure 8: EEOI trends for all scenarios**

## 3.3 Technology roadmaps

Table 4 to Table 11 describe the trajectories in newbuild specifications (including the use of energy efficiency technology), output by GloTraM and associated with the fleet aggregate trends in efficiency and carbon intensity shown in Figure 2.

Different scenarios with their different fuel and carbon prices, incentivise different levels of technology take-up and in combination with operational (speed) and fuel choices result in differences in how parameters like installed power and design speed change over time for the different ship types.

As alluded to in Table 3 as a potential technology for improving energy efficiency, several ship types see the take up of wind assistance technology (kites, sails), from the year it first becomes available in 2025. This may be challenging, considering the current level of maturity, but as with all specific results it should be viewed in the context of the assumptions made about the cost and performance of these technologies (provided in Appendix B). There are some results which are counter-intuitive. It is surprising that comparatively low cost technologies like trim and draft optimisation do not see take up that frequently. Inspection of the detailed results suggests this is to do with how savings for this option vary with ship's operating parameters.

Scenario 7 sees consistently greater take up of technology, driven by the reduced capital costs for equipment in this scenario. However, there are also examples of scenarios in which higher take up of technology could be expected (e.g. Scenario 4 a high mitigation scenario with only 18Gt budget), for which there are fewer technologies taken up. This can be explained by the use of a dominant technology (e.g. contra-rotating propellers), that can become viable and both prevent other technologies from being viable because of incompatibility, and because the marginal fuel savings, and therefore the cost-benefit achievable, have been reduced.

### Table 4: Newbuild specifications of panamax dry bulk carrier, size 3 (35000-59999 dwt), in each scenario

| | | Scenario 2 | | | | Scenario 3 | | | | Scenario 4 | | | | Scenario 5 | | | | Scenario 6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameter[5] | Unit | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| dwt | te | 53888 | 53888 | 53888 | 53888 | 53888 | 53888 | 53888 | 53888 | 53888 | 53888 | 53438 | 53433 | 53888 | 53888 | 53729 | 53433 | 53888 | 53888 | 53714 | 53433 |
| P_me[6] | kW | 7207 | 7207 | 7207 | 7207 | 7207 | 7207 | 7207 | 7207 | 7207 | 7207 | 5626 | 5686 | 7207 | 7207 | 5686 | 5686 | 7207 | 7207 | 6308 | 5686 |
| P_ae | kW | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 |
| fi_me[7] | # | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 5 | 5 | 3 | 3 | 4 | 5 | 3 | 3 | 4 | 5 |
| fi_ae | # | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 5 | 2 | 2 | 4 | 5 | 2 | 2 | 4 | 5 |
| V_des | kt | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| V_op_load | kt | 11 | 13 | 13 | 13 | 11 | 13 | 13 | 13 | 11 | 11 | 13 | 10 | 11 | 12 | 10 | 10 | 11 | 13 | 10 | 10 |
| sox_spec[8] | # | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| nox_spec | # | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 |
| sfc_me | g/kWh | 193 | 204 | 204 | 204 | 193 | 204 | 204 | 204 | 193 | 221 | 78 | 84 | 193 | 212 | 199 | 84 | 193 | 204 | 205 | 84 |
| sfc_ae | g/kWh | 210 | 210 | 210 | 210 | 210 | 210 | 210 | 210 | 210 | 210 | 65 | 65 | 210 | 210 | 177 | 65 | 210 | 210 | 172 | 65 |
| me_spec[9] | # | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 5 | 5 | 1 | 1 | 4 | 5 | 1 | 1 | 4 | 5 |
| eedi | gCO$_2$/tenm | 4.6 | 4.7 | 4.5 | 4.4 | 4.6 | 4.7 | 4.5 | 4.4 | 4.6 | 4.3 | 0.0 | 0.0 | 4.6 | 4.3 | 3.1 | 0.0 | 4.6 | 4.7 | 3.6 | 0.0 |

| | | Scenario 7 | | | | Scenario 8 | | | | Scenario 9 | | | | Scenario 10 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Unit | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| dwt | te | 53719 | 53729 | 53695 | 53461 | 53888 | 53888 | 53888 | 53788 | 53888 | 53888 | 53830 | 53729 | 53888 | 53888 | 53886 | 53886 |
| P_me | kW | 6061 | 5686 | 5232 | 5345 | 7207 | 7207 | 7207 | 5926 | 7207 | 7207 | 6231 | 5686 | 7207 | 7207 | 7941 | 8026 |
| P_ae | kW | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 | 450 |
| fi_me | # | 4 | 4 | 4 | 5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 1 | 1 |
| fi_ae | # | 4 | 4 | 4 | 5 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 2 | 2 | 2 | 2 |
| V_des | kt | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 14 | 14 |
| V_op_load | kt | 12 | 14 | 10 | 11 | 11 | 12 | 10 | 10 | 11 | 12 | 10 | 10 | 11 | 13 | 16 | 15 |
| sox_spec | # | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 |
| nox_spec | # | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 2 | 2 | 2 |
| sfc_me | g/kWh | 170 | 179 | 198 | 77 | 193 | 212 | 222 | 240 | 193 | 212 | 244 | 199 | 193 | 204 | 202 | 203 |
| sfc_ae | g/kWh | 176 | 177 | 212 | 65 | 210 | 210 | 210 | 252 | 210 | 210 | 216 | 177 | 210 | 210 | 217 | 217 |

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[5] All parameters in the table represents the average for a specific ship type and size category

[6] P_me and P_ae indicate the installed power

[7] fuel type (fi_me and fi_ae) key: 1=HFO; 2=MDO; 3=LSHFO (0.5%); 4=LNG; 5= H2

[8] sox spec and nox spec key: 0 = no scrubber; 1 = with scrubber only in Emission Controlled Areas (ECA); 2 = with scrubber globally. The consequence of both SOx and NOx scrubbers is to decrease the efficiency of the main engine, which is simulated as an increase in power output.

[9] me spec key: 1=2 stroke diesel; 2=4 stroke diesel; 3=diesel electric; 4=LNG compatible IC engine; 5=Fuel Cell+H2; 7=Fuel Cell+LNG

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| me_spec | # | 4 | 4 | 4 | 5 | 1 | 1 | 1 | 3 | 1 | 1 | 3 | 4 | 1 | 1 | 1 | 1 |
| eedi | gCO$_2$/tenm | 3.4 | 3.3 | 3.0 | 0.0 | 4.6 | 4.3 | 3.9 | 3.4 | 4.6 | 4.3 | 3.9 | 3.0 | 4.6 | 3.4 | 2.8 | 2.3 |

**Table 5: Technology take up for panamax dry bulk carrier, size 3 (35000-59999 dwt), in each scenario**

| | Scenario 2 | | | | | | | | Scenario 3 | | | | | | | | Scenario 4 | | | | | | | | Scenario 5 | | | | | | | | Scenario 6 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| Air Lubrication | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Autopilot Upgrade | | | | | | | | | | | | | | | | | | | | | | ■ | | | | | | | | | | | | | | | ■ | | | |
| Biocide Hull Coating | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Common Rail | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Contra-rotating Propeller | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engine Derating | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | | ■ | |
| Future Hull Coating | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | ■ | | | | | | ■ | ■ | ■ | | | | | | | ■ | ■ |
| Hull Cleaning | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Kite | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Sails | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ |
| Solar power | | | | | | | | | | | | | | | | | | | | | | | ■ | | | | | | | | | | | | | | | | | |
| Trim and Draught Optimisation | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | ■ | | | | | | ■ | ■ | ■ | | | | | ■ | | ■ | ■ |
| Turbocompound Parallel | | | | | | | | | | | | | | | | | | | | | ■ | | | | | | | | | | | | | | | | ■ | | | |

| | Scenario 7 | | | | | | | | Scenario 8 | | | | | | | | Scenario 9 | | | | | | | | Scenario 10 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| Air Lubrication | | | | | | | ■ | | | | | | | | | | | | | | | | | | | | | | | | | |
| Autopilot Upgrade | | ■ | | | | | | | | | | | ■ | | | | | | | | ■ | ■ | | | | | | | | ■ | | |
| Biocide Hull Coating | | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Common Rail | | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Contra-rotating Propeller | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | | |
| Engine Derating | ■ | ■ | ■ | ■ | | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Future Hull Coating | | | | ■ | ■ | ■ | ■ | ■ | | | | | | | ■ | ■ | | | | | | | | ■ | | | | | | | | |
| Hull Cleaning | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Kite | | | | | | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Sails | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ |
| Solar power | | | | | | ■ | | | | | | | | | | ■ | | | | | | | | | | | | | | | | |
| Trim and Draught Optimisation | | ■ | | ■ | | ■ | ■ | | | | | | ■ | | ■ | | | | | | ■ | ■ | | ■ | | | | | | ■ | | ■ |
| Turbocompound Parallel | | ■ | | ■ | | ■ | | | | | | | ■ | | ■ | | | | | | ■ | ■ | | ■ | | | | | | ■ | | ■ |

**Table 6: Newbuild specifications for MR tanker, size 3 (35000-59999 dwt), in each scenario**

| | | Scenario 2 | | | | Scenario 3 | | | | Scenario 4 | | | | Scenario 5 | | | | Scenario 6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| dwt | te | 46931 | 46933 | 46927 | 46927 | 46931 | 46933 | 46927 | 46927 | 46931 | 46955 | 46807 | 46807 | 46931 | 46955 | 46807 | 46807 | 46931 | 46931 | 46807 | 46807 |
| P_me | kW | 4958 | 4958 | 5615 | 5615 | 4958 | 4958 | 5615 | 5615 | 4958 | 2412 | 2176 | 2176 | 4958 | 2412 | 2176 | 2176 | 4958 | 5166 | 2176 | 2176 |
| P_ae | kW | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 |
| fi_me | # | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 5 | 5 | 3 | 3 | 5 | 5 | 3 | 3 | 5 | 5 |
| fi_ae | # | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 5 | 2 | 2 | 5 | 5 | 2 | 2 | 5 | 5 |
| V_des | kt | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| V_op_load | kt | 12 | 12 | 11 | 11 | 12 | 12 | 11 | 11 | 12 | 13 | 13 | 13 | 12 | 13 | 13 | 13 | 12 | 11 | 13 | 13 |
| sox_spec | # | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| nox_spec | # | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 |
| sfc_me | g/kWh | 202 | 202 | 216 | 216 | 202 | 202 | 216 | 216 | 202 | 212 | 63 | 62 | 202 | 216 | 63 | 63 | 202 | 211 | 63 | 63 |
| sfc_ae | g/kWh | 213 | 210 | 210 | 210 | 213 | 210 | 210 | 210 | 213 | 210 | 65 | 65 | 213 | 210 | 65 | 65 | 213 | 210 | 65 | 65 |
| me_spec | # | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 5 | 5 | 3 | 3 | 5 | 5 | 3 | 3 | 5 | 5 |
| eedi | $gCO_2$/tenm | 4.1 | 4.0 | 4.4 | 4.1 | 4.1 | 4.0 | 4.4 | 4.0 | 4.1 | 2.1 | 0.0 | 0.0 | 4.1 | 2.1 | 0.0 | 0.0 | 4.1 | 4.3 | 0.0 | 0.0 |

| | | Scenario 7 | | | | Scenario 8 | | | | Scenario 9 | | | | Scenario 10 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| dwt | te | 46902 | 46954 | 46807 | 46807 | 46931 | 46927 | 46807 | 46807 | 46931 | 46927 | 46957 | 46957 | 46955 | 46955 | 46955 | 46957 |
| P_me | kW | 2880 | 2689 | 2176 | 2176 | 4958 | 5615 | 2176 | 2176 | 4958 | 5615 | 2171 | 2219 | 2630 | 2630 | 2630 | 2171 |
| P_ae | kW | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 | 463 |
| fi_me | # | 4 | 3 | 5 | 5 | 3 | 3 | 5 | 5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| fi_ae | # | 4 | 2 | 5 | 5 | 2 | 2 | 5 | 5 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| V_des | kt | 14 | 14 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 14 | 14 | 14 | 13 |
| V_op_load | kt | 14 | 14 | 13 | 13 | 12 | 11 | 13 | 13 | 12 | 11 | 12 | 9 | 14 | 14 | 14 | 13 |
| sox_spec | # | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| nox_spec | # | 0 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| sfc_me | g/kWh | 179 | 225 | 63 | 63 | 202 | 216 | 63 | 63 | 202 | 211 | 210 | 227 | 223 | 223 | 223 | 215 |
| sfc_ae | g/kWh | 172 | 210 | 65 | 65 | 213 | 210 | 65 | 65 | 213 | 210 | 210 | 210 | 210 | 210 | 210 | 210 |
| me_spec | # | 4 | 3 | 5 | 5 | 3 | 3 | 5 | 5 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| eedi | $gCO_2$/tenm | 1.9 | 2.4 | 0.0 | 0.0 | 4.1 | 4.2 | 0.0 | 0.0 | 4.1 | 4.2 | 1.7 | 1.7 | 2.4 | 1.7 | 1.3 | 0.9 |

**Table 7: Technology take up for MR tanker, size 3 (35000-59999 dwt), in each scenario**

| | Scenario 2 | | | | | | | | Scenario 3 | | | | | | | | Scenario 4 | | | | | | | | Scenario 5 | | | | | | | | Scenario 6 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| Autopilot Upgrade | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | |
| Block Coefficient Reduction | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ | | | | | ■ | ■ | ■ | ■ |
| Bulbous Bow | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Common Rail | ■ | | | | | | | | ■ | | | | | | | | ■ | | | | | | | | ■ | | | | | | | | ■ | | | | | | | |
| Contra-rotating Propeller | | ■ | ■ | ■ | ■ | | | | | ■ | ■ | ■ | ■ | | | | | ■ | ■ | | ■ | ■ | ■ | ■ | | ■ | ■ | | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | | ■ | ■ | ■ |
| Engine Derating | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | |
| Engine Tuning | ■ | | | | | | | | ■ | | | | | | | | ■ | | | | | | | | ■ | | | | | | | | ■ | | | | | | | |
| Hull Cleaning | ■ | ■ | | ■ | | | | | ■ | ■ | ■ | ■ | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | | | | | | |
| Sails | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Trim and Draught Optimisation | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | |
| Turbocompound Parallel | ■ | ■ | | | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | | | | | | | ■ | ■ | | | | | | | ■ | ■ | | | | | | |

| | Scenario 7 | | | | | | | | Scenario 8 | | | | | | | | Scenario 9 | | | | | | | | Scenario 10 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| Autopilot Upgrade | | | | | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | |
| Block Coefficient Reduction | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | ■ | ■ | ■ | ■ | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Bulbous Bow | ■ | | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Common Rail | | | | | | | | | ■ | | | | | | | | ■ | | | | | | | | | | | | | | | |
| Contra-rotating Propeller | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | | ■ | ■ | ■ | | ■ | ■ | | | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Engine Derating | | | | | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | |
| Engine Tuning | | | | | | | | | ■ | | | | | | | | ■ | | | | | | | | | | | | | | | |
| Hull Cleaning | | | | | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | |
| Sails | | | | | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Trim and Draught Optimisation | ■ | ■ | | | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | | | ■ | ■ | | | | | | | | | |
| Turbocompound Parallel | | | | | | | | | ■ | ■ | | | | | | | ■ | ■ | ■ | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

**Table 8: Newbuild specifications for VL container, for each scenario**

| | | Scenario 2 | | | | Scenario 3 | | | | Scenario 4 | | | | Scenario 5 | | | | Scenario 6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| teu | # | 13448 | 13449 | 13448 | 13448 | 13448 | 13449 | 13448 | 13448 | 13448 | 13449 | 13279 | 13438 | 13448 | 13449 | 13279 | 13279 | 13448 | 13449 | 13449 | 13279 |
| P_me | kW | 44300 | 42686 | 44300 | 43539 | 44300 | 42686 | 44300 | 43539 | 44300 | 39702 | 39311 | 40497 | 44300 | 39702 | 39311 | 39311 | 44300 | 43539 | 40497 | 39311 |
| P_ae | kW | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 |
| fi_me | # | 1 | 3 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 3 | 5 | 1 | 1 | 3 | 5 | 5 | 1 | 1 | 1 | 5 |
| fi_ae | # | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 2 | 2 | 2 | 5 | 5 | 2 | 2 | 2 | 5 |
| V_des | kt | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 |
| V_op_load | kt | 18 | 16 | 16 | 16 | 18 | 16 | 16 | 16 | 16 | 13 | 15 | 11 | 18 | 13 | 15 | 13 | 18 | 15 | 13 | 13 |
| sox_spec | # | 2 | 0 | 2 | 2 | 2 | 0 | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 2 | 2 | 2 | 0 |
| nox_spec | # | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 0 |
| sfc_me | g/kWh | 174 | 171 | 178 | 171 | 174 | 171 | 178 | 171 | 177 | 192 | 55 | 203 | 174 | 193 | 56 | 58 | 174 | 178 | 193 | 58 |
| sfc_ae | g/kWh | 206 | 210 | 206 | 206 | 206 | 210 | 206 | 206 | 206 | 210 | 65 | 194 | 206 | 210 | 65 | 65 | 206 | 210 | 210 | 65 |
| me_spec | # | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 5 | 1 | 1 | 1 | 5 |
| eedi | gCO$_2$/tenm | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 0 | 1 | 8 | 7 | 0 | 0 | 8 | 8 | 7 | 0 |

| | | Scenario 7 | | | | Scenario 8 | | | | Scenario 9 | | | | Scenario 10 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| teu | # | 13388 | 13449 | 13286 | 13286 | 13448 | 13449 | 13449 | 13279 | 13448 | 13449 | 13449 | 13449 | 13448 | 13449 | 13449 | 13449 |
| P_me | kW | 41012 | 40098 | 37728 | 37728 | 44300 | 39702 | 40497 | 39311 | 44300 | 39702 | 40497 | 40497 | 43539 | 40497 | 40497 | 40497 |
| P_ae | kW | 3658 | 3658 | 4410 | 4410 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 | 3658 |
| fi_me | # | 4 | 3 | 5 | 5 | 1 | 3 | 1 | 5 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| fi_ae | # | 4 | 2 | 5 | 5 | 2 | 2 | 2 | 5 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| V_des | kt | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 |
| V_op_load | kt | 18 | 13 | 16 | 13 | 18 | 13 | 13 | 13 | 18 | 13 | 13 | 13 | 18 | 15 | 18 | 18 |
| sox_spec | # | 0 | 0 | 0 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 2 | 2 | 2 | 2 | 2 |
| nox_spec | # | 0 | 2 | 0 | 0 | 2 | 2 | 2 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| sfc_me | g/kWh | 141 | 200 | 47 | 51 | 174 | 193 | 193 | 58 | 174 | 193 | 193 | 193 | 167 | 183 | 173 | 173 |
| sfc_ae | g/kWh | 172 | 210 | 84 | 84 | 206 | 210 | 210 | 65 | 206 | 210 | 210 | 210 | 206 | 210 | 210 | 210 |
| me_spec | # | 4 | 1 | 5 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| eedi | gCO$_2$/tenm | 6 | 8 | 0 | 0 | 8 | 7 | 6 | 0 | 8 | 7 | 6 | 6 | 8 | 5 | 4 | 4 |

### Table 9: Technology take up for VL container, for each scenario

| |Scenario 2||||||||Scenario 3||||||||Scenario 4||||||||Scenario 5||||||||Scenario 6||||||||
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| |15|20|25|30|35|40|45|50|15|20|25|30|35|40|45|50|15|20|25|30|35|40|45|50|15|20|25|30|35|40|45|50|15|20|25|30|35|40|45|50|
|Air Lubrication||||||||||||||||||||||||||||||||||||||||||
|Autopilot Upgrade|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■||■|■|■|■|■|■|■||||■|■|■|■|■|■|||
|Engine Derating|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■||||||■|■|■||||||■|■|■|■|||||
|Foul Release Hull Coating|||■|■|■||■|■|||■|■|■||■|■|||■|||||||||■|||||||||■|■|||||
|Future Hull Coating||||||||||||||||||||■|■|■|■|■||||■|■|■|■|■|||||■|■|■|■|
|Hull Cleaning|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|
|Hybrid Turbocharging|||||||||||||||||||||||■|■|||||||||||||||||
|Organic Rankine Cycle WHR||||||||||||||||||||||||■|||||||||||||||||
|Rudder Bulb||||||||||||||||||||||||||||||||||||||||||
|Turbocompound Parallel|■|■|■||■|■|■|■|■|■|■||■|■|■|■|■|■|■||||■|■|■|■|■||||||■|■|■||||||

| |Scenario 7||||||||Scenario 8||||||||Scenario 9||||||||Scenario 10||||||||
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| |15|20|25|30|35|40|45|50|15|20|25|30|35|40|45|50|15|20|25|30|35|40|45|50|15|20|25|30|35|40|45|50|
|Air Lubrication||||||■|■|■|||||||||||||||||||||||||||
|Autopilot Upgrade|■|■|■||||||■|■|■|■|■|■|||■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|
|Engine Derating|■|■|■||||||■|■|■||||||■|■|■||||||■|■|■||||||
|Foul Release Hull Coating|■|■|■||||||||■||||||||■||||||■|■|■||||||
|Future Hull Coating||||■|■|■|■|■||||■|■|■|■|■||||■|■|■|■|■||||■|■|■|■|■|
|Hull Cleaning|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|■|
|Hybrid Turbocharging||||||||||||||||||||||||||||||||||
|Organic Rankine Cycle WHR||||||||||||||||||||||||||||||||||
|Rudder Bulb|■|■|■||||||||||||||||||||||||■||||||
|Turbocompound Parallel|■||■||||||■|■|■||||||■|■|■||||||■|■|■||||||

**Table 10: Newbuild specifications for medium container, for each scenario**

| | | Scenario 2 | | | | Scenario 3 | | | | Scenario 4 | | | | Scenario 5 | | | | Scenario 6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| teu | # | 3464 | 3464 | 3464 | 3464 | 3464 | 3464 | 3464 | 3464 | 3464 | 3464 | 3395 | 3458 | 3464 | 3464 | 3395 | 3395 | 3464 | 3464 | 3463 | 3395 |
| dwt | te | | | | | | | | | | | | | | | | | | | | |
| P_me | kW | 18281 | 18646 | 18646 | 18646 | 18281 | 18281 | 18646 | 18646 | 18281 | 16907 | 16576 | 17245 | 18281 | 17941 | 16576 | 16576 | 18281 | 18142 | 17245 | 16576 |
| P_ae | kW | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 |
| fi_me | # | 3 | 1 | 1 | 1 | 3 | 3 | 1 | 1 | 3 | 3 | 5 | 1 | 3 | 3 | 5 | 5 | 3 | 3 | 1 | 5 |
| fi_ae | # | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 2 | 2 | 2 | 5 | 5 | 2 | 2 | 2 | 5 |
| V_des | kt | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| V_op_load | kt | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 13 | 10 | 13 | 10 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| sox_spec | # | 0 | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 |
| nox_spec | # | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 0 |
| sfc_me | g/kWh | 195 | 199 | 195 | 195 | 195 | 195 | 195 | 195 | 211 | 224 | 75 | 226 | 212 | 214 | 75 | 75 | 212 | 212 | 213 | 75 |
| sfc_ae | g/kWh | 214 | 210 | 214 | 214 | 214 | 214 | 214 | 214 | 214 | 214 | 65 | 235 | 214 | 214 | 65 | 65 | 214 | 214 | 221 | 65 |
| me_spec | # | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 5 | 1 | 1 | 1 | 5 |
| eedi | $gCO_2$/tenm | 15 | 14 | 14 | 14 | 15 | 14 | 14 | 14 | 15 | 12 | 0 | 2 | 15 | 13 | 0 | 0 | 15 | 14 | 13 | 0 |

| | | Scenario 7 | | | | Scenario 8 | | | | Scenario 9 | | | | Scenario 10 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 | 2020 | 2030 | 2040 | 2050 |
| teu | # | 3438 | 3463 | 3400 | 3400 | 3464 | 3464 | 3463 | 3395 | 3464 | 3464 | 3463 | 3463 | 3463 | 3463 | 3463 | 3463 |
| dwt | te | | | | | | | | | | | | | | | | |
| P_me | kW | 17589 | 16907 | 15250 | 15250 | 18281 | 17941 | 17245 | 16576 | 18281 | 17941 | 17245 | 17245 | 18300 | 17245 | 17245 | 17245 |
| P_ae | kW | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 | 1516 |
| fi_me | # | 4 | 3 | 5 | 5 | 3 | 3 | 1 | 5 | 3 | 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| fi_ae | # | 4 | 2 | 5 | 5 | 2 | 2 | 2 | 5 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| V_des | kt | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| V_op_load | kt | 14 | 13 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 16 | 14 | 17 | 16 |
| sox_spec | # | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 |
| nox_spec | # | 0 | 2 | 0 | 0 | 2 | 2 | 2 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| sfc_me | g/kWh | 185 | 212 | 75 | 75 | 212 | 214 | 213 | 75 | 212 | 214 | 213 | 213 | 196 | 202 | 191 | 195 |
| sfc_ae | g/kWh | 181 | 221 | 65 | 65 | 214 | 214 | 221 | 65 | 214 | 214 | 221 | 221 | 221 | 221 | 221 | 221 |
| me_spec | # | 4 | 1 | 5 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| eedi | $gCO_2$/tenm | 12 | 13 | 0 | 0 | 15 | 13 | 11 | 0 | 15 | 13 | 11 | 10 | 14 | 10 | 7 | 6 |

**Table 11: Technology take up for medium container, for each scenario**

| | Scenario 2 | | | | | | | | Scenario 3 | | | | | | | | Scenario 4 | | | | | | | | Scenario 5 | | | | | | | | Scenario 6 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| Autopilot Upgrade | | | ■ | | | | ■ | | | | | | | | ■ | | | | | | | | | | | | | | | | | | | | ■ | | | | | |
| Biocide Hull Coating | | | ■ | | | | | | | | | | | | | | | | ■ | | | | | | | | | | | | | | | | ■ | ■ | | | | |
| Common Rail | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Contra-rotating Propeller | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Engine Derating | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | |
| Future Hull Coating | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | | ■ | | | | | | | | | | | | | ■ | ■ | ■ | ■ |
| Hull Cleaning | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Hybrid Turbocharging | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | | | | | | ■ | ■ | | | | | | ■ | | |
| Kite | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Organic Rankine Cycle WHR | | | | | | | | | | | | | | | | | | | | | | | | ■ | | | | | | | | | | | | | | | | |
| Solar power | | | | | | | | | | | | | | | | | | | | | | | | ■ | | | | | | | | | | | | | | | | |
| Steam WHR | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | | | | | | | | | | | | | | | |
| Turbocompound Parallel | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | |

| | Scenario 7 | | | | | | | | Scenario 8 | | | | | | | | Scenario 9 | | | | | | | | Scenario 10 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| Autopilot Upgrade | ■ | ■ | ■ | | | | | | | | | ■ | | | | | | | | ■ | | | | | ■ | ■ | ■ | | | | | |
| Biocide Hull Coating | ■ | ■ | ■ | | | | | | | | | ■ | | | | | | | | ■ | | | | | ■ | ■ | ■ | | | | | |
| Common Rail | | | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Contra-rotating Propeller | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | | |
| Engine Derating | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Future Hull Coating | | | | ■ | ■ | ■ | ■ | ■ | | | | | ■ | ■ | ■ | ■ | | | | | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ |
| Hull Cleaning | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Hybrid Turbocharging | ■ | ■ | ■ | ■ | ■ | | | | | | | | | ■ | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Kite | | | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Organic Rankine Cycle WHR | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Solar power | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Steam WHR | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Turbocompound Parallel | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

## 3.4 Scenario summary

Table 12 shows a summary of the key results for all scenarios. The cumulative share of $CO_2$ is the share of cumulative emissions of international shipping (five ship types) out of global cumulative emissions. The lowest cumulative share of $CO_2$ in 2050 for the five ship types analysed is observed in scenario 4 (1.87%), while the greatest share is observed in scenario 9 (3.25%), beside the BAU scenarios 2 and 3 which both have a cumulative share of $CO_2$ above 4%. A similar pattern can be observed for the shipping share of total emissions in 2050, in which scenarios 4 and 9 also represents the lowest and greatest shares of the decarbonisation scenarios.

Scenario 5 and 9 have a high level of cumulative $CO_2$ offsets (4.84 and 5.46 Gt), however, scenario 5 is challenged by a more stringent carbon budget and rely on the use of offsetting as an interim step, while scenario 9 shows an increasing dependence on offsetting. Section 4.2 analyses in more detail the role that offsetting might play.

Upstream CO2e emissions are estimated to increase over time. Due to the high use of hydrogen and its associated upstream emissions in scenario 4 and 5, the cumulative upstream emissions represent 18 – 13% of the cumulative operational CO2e emissions, respectively. Section 4.4 analyses in more detail the upstream GHG and air pollution implications of the different scenarios.

**Table 12: Summary of results from all scenarios**

| **Scenario** | **Cumulative share $CO_2$ (2010-2050)**[10] | **Share of total emissions in 2050**[11] | **Cumulative $CO_2$ offset (Gt)**[12] | **Total spent on offsets (bn$)**[13] | **Cumulative upstream emissions in $CO_2$ (Gt)**[14] | **Cumulative operational emissions in $CO_2e$ (Gt)**[15] |
|---|---|---|---|---|---|---|
| 2 | 4.14% | 7.7% | N/A | N/A | 3.98 | 44 |
| 3 | 4.27% | 8.1 % | N/A | N/A | 4.01 | 42.76 |
| 4 (18 Gt) | 1.87% | 0.7% | 0 | 0 | 3.37 | 19.18 |
| 5 (23 Gt) | 2.66% | 1.5% | 4.84 | 170 | 3.51 | 27.53 |
| 6 (33 Gt) | 3.23% | 3.6% | 3.38 | 166 | 3.67 | 34.50 |
| 7 (33 Gt) | 2.68% | 2.0 % | 1.95 | 14 | 3.59 | 31.7 |
| 8 (33 Gt) | 2.99% | 3.2 % | 2.91 | 127 | 3.21 | 30.96 |
| 9 (33 Gt) | 3.25% | 5.1 % | 5.46 | 261 | 2.99 | 33.67 |
| 10 (79 Gt) | 2.63% | 4,0 % | 0 | 0 | 2.4 | 26.82 |

Table 13 shows the change in energy efficiency from 2010 to 2050. The EE values are weighted by the number of ships in each ship size category. EE is calculated for each ship type separately since there is great variation within ship types. This parameter basically quantifies the percentage improvement in efficiency achieved in 2050 compared to baseline year (2010). For example, in scenario 2, energy efficiency of dry bulk ship category in 2050 is 59% more compared to energy efficiency in 2010 and so on.

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[10] Cumulative share $CO_2$ (2010-2050):.This is calculated assuming a global cumulative emission of 1200 Gt for period 2010-2050.

[11] Share of total emissions in 2050: Assuming 18Gt of global $CO_2$ emissions in 2050 source: GTEM (Global Trade and Environmental Model126.6)

[12] Cumulative $CO_2$ offset (Gt): This is the cumulative amount of $CO_2$ offsets which are needed to meet the target

[13] Total spent on offsets (bn$): This is the total amount in dollars required to be spent on purchasing out-sector offsets

[14] Cumulative upstream emissions in CO2 (Gt): Total cumulative emissions accounted for upstream emissions.

[15] Cumulative operational emissions in CO2e (Gt): This variable is the cumulative operational $CO_2e$ emissions taking into account emissions resulting from both fossil and biofuels. $CO_2e$ is calculated for each fuel type assuming a GWP (Global Warming Potential) of 100 years using factors 34 for $CH_4$ and 298 for $N_2O$ (CMIP5).

Table 13: Energy efficiency change by ship type for each scenario

| Scenario | Energy efficiency (J/t.nm) in 2050 expressed as percentage improvement relative to baseline year (2010) | | Scenario | Energy efficiency (J/t.nm) in 2050 expressed as percentage improvement relative to baseline year (2010) | |
|---|---|---|---|---|---|
| 2 | Dry | 59.0 | 7 | Dry | 45.1 |
| | Product & Chemical | 72.0 | | Product & Chemical | 52.5 |
| | Unit | 90.0 | | Unit | 67.5 |
| | Gen cargo | 77.6 | | Gen cargo | 58.6 |
| | Gas | 65.2 | | Gas | 52.5 |
| | Crude | 79.2 | | Crude | 52.9 |
| 3 | Dry | 59.0 | 8 | Dry | 47.1 |
| | Product & Chemical | 72.4 | | Product & Chemical | 53.3 |
| | Unit | 87.7 | | Unit | 76.9 |
| | Gen cargo | 77.5 | | Gen cargo | 62.9 |
| | Gas | 66.2 | | Gas | 57.1 |
| | Crude | 78.6 | | Crude | 52.6 |
| 4 | Dry | 36.7 | 9 | Dry | 48.6 |
| | Product & Chemical | 69.2 | | Product & Chemical | 50.1 |
| | Unit | 60.6 | | Unit | 74.7 |
| | Gen cargo | 56.3 | | Gen cargo | 61.0 |
| | Gas | 77.0 | | Gas | 50.8 |
| | Crude | 68.0 | | Crude | 58.0 |
| 5 | Dry | 48.7 | 10 | Dry | 58.0 |
| | Product & Chemical | 68.6 | | Product & Chemical | 64.8 |
| | Unit | 77.9 | | Unit | 84.0 |
| | Gen cargo | 64.5 | | Gen cargo | 73.2 |
| | Gas | 62.4 | | Gas | 67.7 |
| | Crude | 74.6 | | Crude | 68.8 |
| 6 | Dry | 49.0 | | | |
| | Product & Chemical | 65.5 | | | |
| | Unit | 79.8 | | | |
| | Gen cargo | 64.1 | | | |
| | Gas | 62.7 | | | |
| | Crude | 71.7 | | | |

# 4 Specific findings

## 4.1 What will EEDI deliver?

The EEDI regulation entered into force in 2013 and sets a minimum efficiency requirement for newbuild ships entering the fleet from 2013 onwards. In practice, shipowners specifying the design of a new ship decide on what specification of ship is required to ensure competitiveness in their market, as well as ensuring that the ship will be compliant with the minimum required EEDI. This choice is reflected in the scenarios modelled in GloTraM – at each time-step, the model will select a design that satisfies the twin constraints of profit maximisation (given a market with a given fuel price and freight rate), and regulatory compliance.

Figure 9 shows the results from GloTraM in the form of total $CO_2$ emissions for two scenarios, one which applies the EEDI regulation, as it is defined in MARPOL Annex VI (Scenario 2), and another scenario where the EEDI regulation is artificially relaxed, as if it had not entered into force (Scenario 3). In both Scenario 2 and 3 the newbuild specifications, and fleet operational specifications are being selected by a combination of market forces and compliance with the requisite GHG reduction amounts. The contrast between the two results shows only a marginal difference: the total $CO_2$ difference between the two scenarios is small, with the application of the EEDI regulation showing a small reduction in total $CO_2$ during the timescale considered.

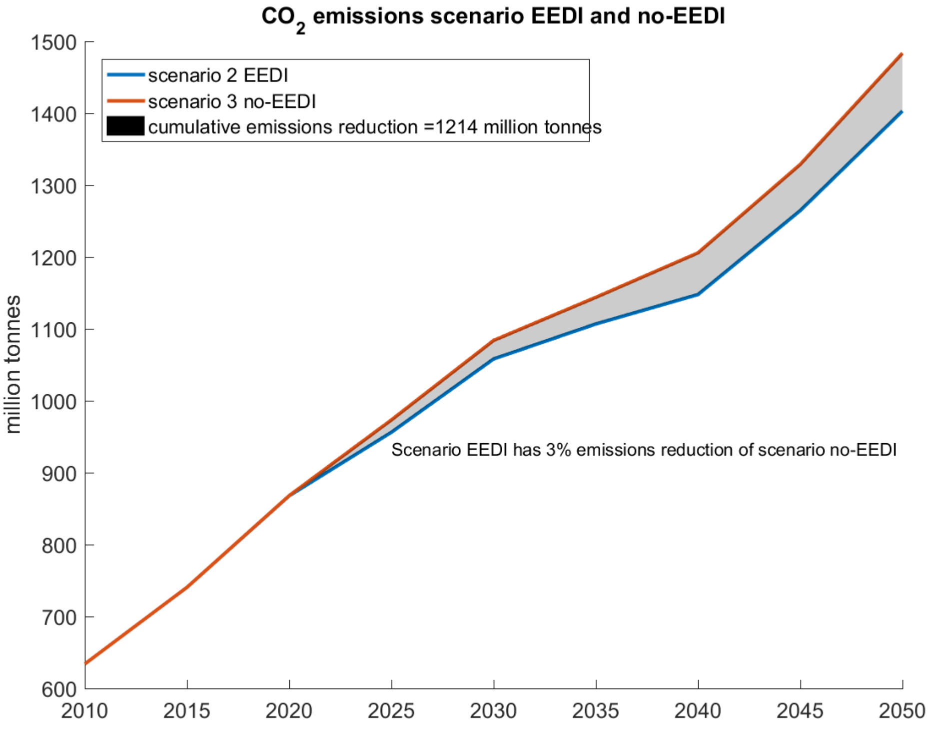

**Figure 9: $CO_2$ emissions scenario EEDI and no-EEDI**

The explanation for this result has several components:

- The EEDI regulation only affects newbuild ships' specifications, and therefore it takes time for the regulation to manifest itself in the total $CO_2$ emissions of the fleet – a fleet composed, at least out to 2040, of many ships built before the regulation entered into force.
- EEDI is required to be met at an operating point of 75% MCR of the installed power. However, ships choose operating points and speeds to suit market conditions, which in many

instances may be for average power outputs from main engines significantly different to that EEDI condition (see Figure 20 for the operating speeds selected in this instance). Given the way GloTraM selects operating points to suit market conditions, this means many technologies fitted to help achieve EEDI compliance will often be performing in conditions for which they were not designed and therefore don't necessarily achieve the savings expected based on their 75% MCR performance characteristics.

- Compliance with regulation is only one driver of technology take up; markets and fuel prices are another. In the scenario without EEDI, there is still take up of energy efficient designs enabled by the fuel price.

Further evidence to support this modelling result can be taken from a review of the ships that have entered the global fleet since the EEDI baselines were defined. Attained EEDI's of newbuild ships are consistently exceeding the Phase 0 and Phase 1 required EEDIs, and in many cases are already exceeding the Phase 3 required EEDIs (even though this would not be necessary until 2025). The fact that the attained EEDI's are so often well below the required EEDI point implies that it is not the regulation that is driving the specification, but developments in the market and newbuild design/technology that has occurred since the baselines were specified.

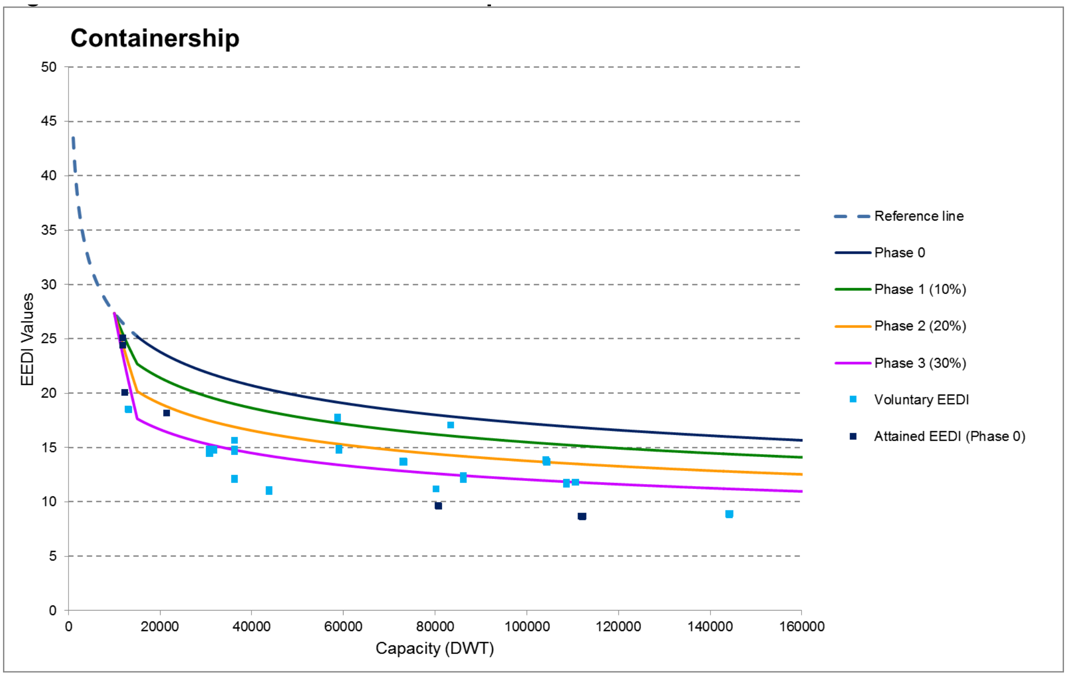

**Figure 10: Required and Attained EEDIs for newbuild containerships entering the fleet (from MEPC 68 INF.13)**

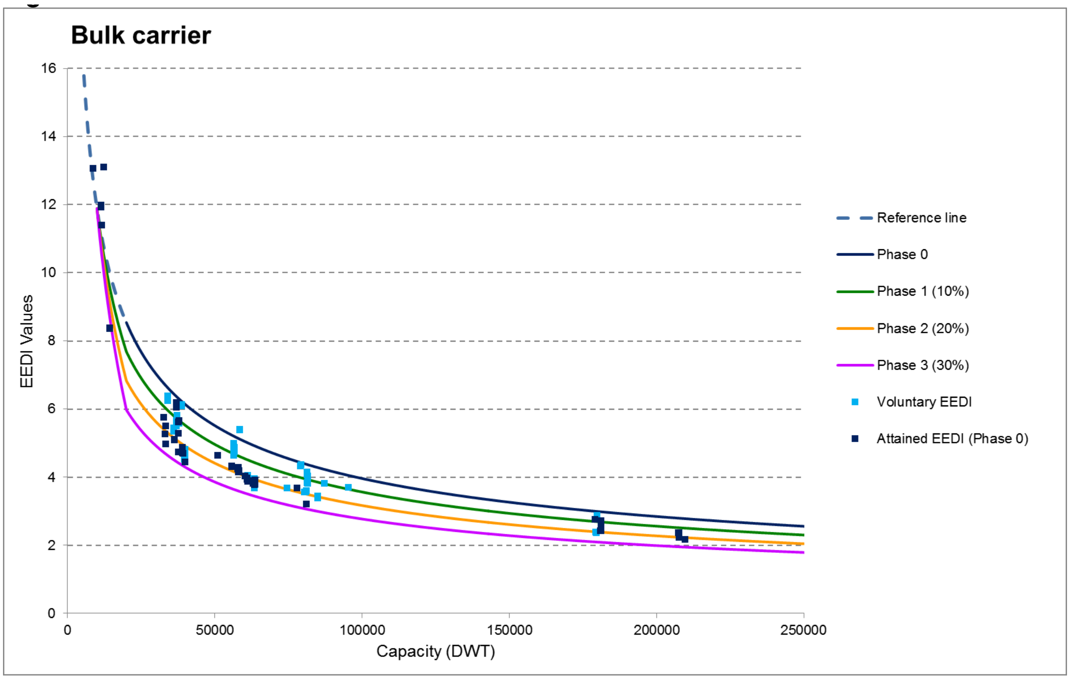

**Figure 11: Required and Attained EEDIs for newbuild bulk carriers entering the fleet (from MEPC 68 INF.13)**

A review of the IMO secretariat's publication of its EEDI database (MEPC 68 INF.13, which records information on the specifics of different ship types and sizes), reveals that in no cases (at least by 2015), were designs invoking the fourth or fifth term in the EEDI formula, which reflect the use of innovative electrical or mechanical technology. Furthermore, an analysis by CE Delft (MEPC 69 INF. 29) implies that in many cases the attained EEDIs are not being achieved by significant modifications of design speed, and should be mainly attributed to efficiency achieved through optimisation of relatively conventional machinery, hullform and propeller. Therefore, whilst attention has to be paid to the minimum design speed for safety reasons (especially for large tankers and bulk carriers), there remain a number of options still available for attained EEDIs to be reduced further.

The Phase 2 stringencies for EEDI (that are applied from 2020) are under review at present and will be discussed further at MEPC 70. It is possible that this may result in an increased stringency, for containerships in particular. If the stringency is greatly increased this may mean that EEDI as a regulation could start to drive the efficiency in advance of what is achieved by market forces alone, but this will need to be reviewed further if and when any stringency change has been defined.

However, whilst these findings suggest that EEDI as a regulation may have only a small role in shipping's decarbonisation, it should be noted that this has been assessed using a techno-economic model (GloTraM), that is less able to represent the importance of behaviour and cultural change. And it may be that significant responsibility for behaviour change, especially the focusing of attention on energy efficiency and the quantification of a ship's specific carbon intensity (gCO2/t.nm), to the regulation.

## 4.2 What role might offsetting play?

Offsetting emissions involves the purchase of emissions credits outside of the shipping sector. It relies on there being an appropriate scheme in place that enables a credit purchase to be equivalent to the mitigation of a tonne of anthropogenic $CO_2$ in another sector. The concept is often enabled through Emissions Trading Schemes such as the EU ETS which provide a market for $CO_2$ emissions credits, however a number of different structures could be designed and used in the future by the sector to enable credits to be purchased. Depending on the price of these credits relative to the cost of in-sector emission reduction, the use of offsets may present a way to achieve net emission reductions across the global economy that satisfy an overall target whilst different sectors decarbonise at different rates depending on their respective marginal costs of decarbonisation.

Offsetting mechanisms could also be used by the shipping sector to sell carbon credits – e.g. enabling other sectors to purchase credits for mitigation of emissions within shipping.

In all sectors, not just shipping, decarbonisation starts with the ‘low hanging fruit’ and as the decarbonisation stringency increases overtime towards full decarbonisation, increasingly high cost mitigation steps are required. To estimate how this might modify the cost of decarbonisation over time, this study uses TIAM UCL, a whole-economy model, to estimate a whole-economy global carbon price (Figure 12) which represents a hypothetical carbon market where sectors are allowed to buy and sell their carbon credits so that decarbonisation starts with the most cost-effective interventions and the overall carbon price is minimised. The model is set up to achieve a two degree stabilisation above pre-industrial temperatures.

Figure 13 shows the carbon price that the model calculates in each scenario in order to enable the target $CO_2$ emissions given the scenario’s assumptions. Figure 14 and Figure 15 display the different levels of offsetting in the different scenarios, and the amounts of revenue that are raised according to the assumptions defined in Appendix 1.

The use of offsetting varies, sometimes being used as an interim step (for example scenario 5), before in-sector decarbonisation can take over. In other scenarios, the sector becomes increasingly dependent on offsetting (for example scenario 9) towards 2050, relying increasingly on the assumption that there will be lower priced credits available outside of the shipping industry. In scenario 7, instead, the discounted cost for energy efficiency and main machinery makes the sector less dependent on offsetting as the operational emissions decreases at a high rate. As a consequence, the carbon price does not increase as much as in the case of the equivalent Scenario 6.

The carbon price trajectories for shipping are consistent with wider economy price trajectories, suggesting that as carbon budgets are increasingly used towards the end of this half-century, the marginal cost of technologies able to achieve the necessary levels of decarbonisation will increase. Shipping carbon prices are consistently higher than those in the wider economy suggesting it is unlikely to become a significant vendor of emissions credits. However, this could change depending on how the wider drivers of growth and decarbonisation of shipping evolve in the coming decades.

In addition, shipping carbon prices are higher than those in the wider economy because the different assumptions used to derive those projections. For example, the estimates of the global carbon prices derived from TIAM-UCL include the learning curve effect on technology costs, while the shipping model GloTraM does not include this effect on the estimates of the shipping carbon prices. In this study, therefore, the shipping carbon prices are used to derive the model’s results and not as a prediction.

In all scenarios, significant revenue is raised by the hypothetical Market Based Mechanism, which can be used in turn to both fund spend within the shipping sector (for example on infrastructure and R&D) and outside of the sector (for example on rebates, compensation and the Green Climate Fund). In the scenarios considered here, the minority of the expenditure raised through an MBM is deployed on purchasing of offsets. Figure 15, shows how the total revenue is spent. The values are indexed to the total revenue raised in 2050 assuming the global carbon price and the shipping emissions as in scenario 2. In-sector refers to the amount spent within the shipping sector (infrastructure and R&D), out-sector refers to the amount spent outside the sector (for example on rebates, compensation and the Green Climate Fund), and offsets refers the amount spent to purchase offsets of $CO_2$.

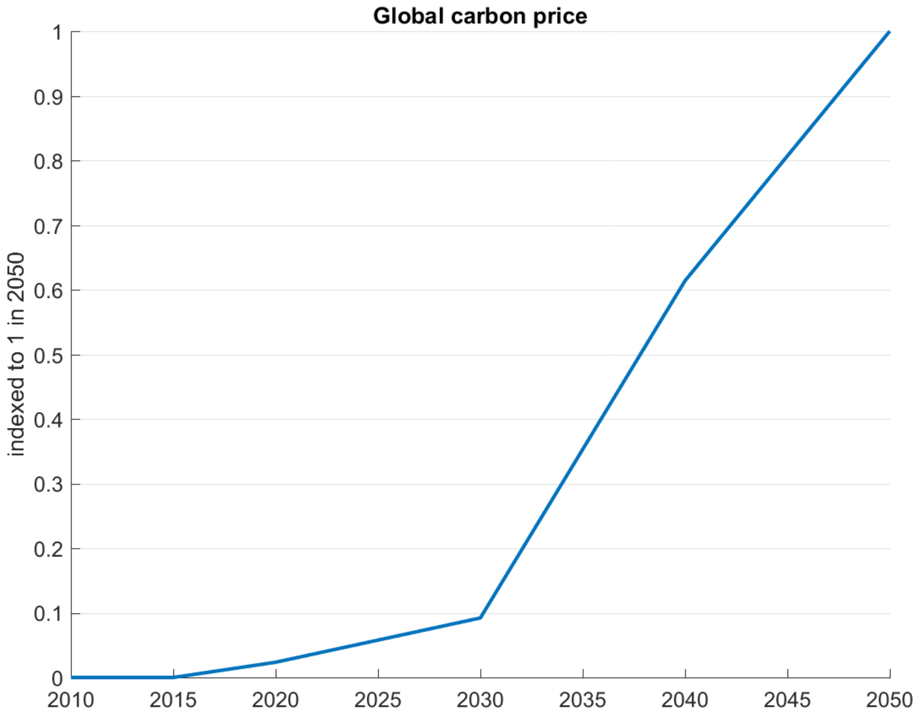

Figure 12: Global carbon price consistent with a 2 degree temperature rise target, as estimated by TIAM UCL

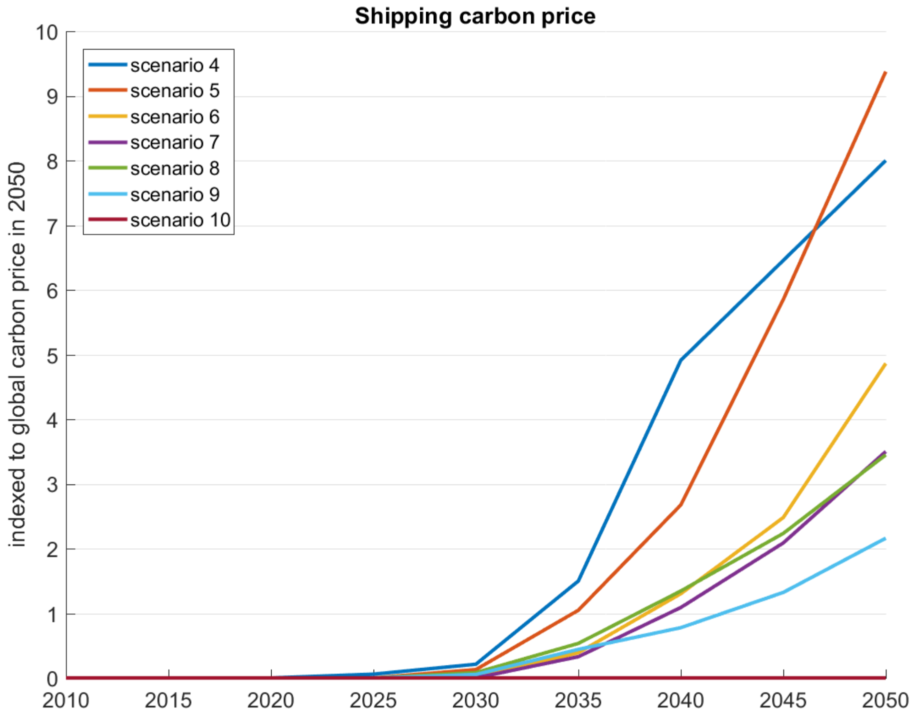

Figure 13: Shipping carbon price, as estimated by GloTraM, all indexed to the value of the global carbon price in 2050

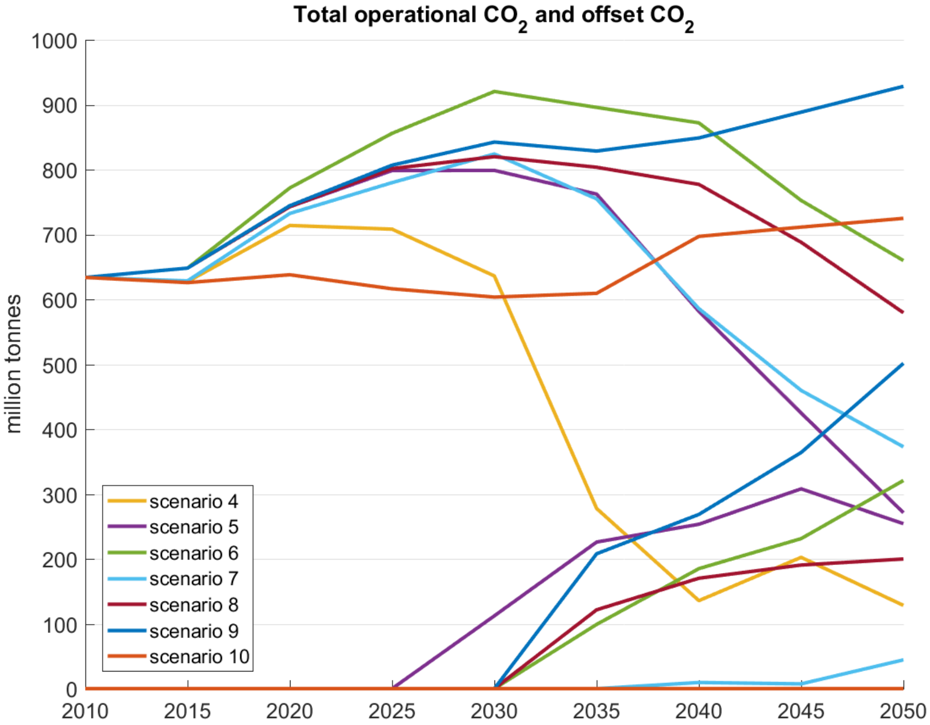

**Figure 14: Total operational $CO_2$ and offset $CO_2$, all scenarios**

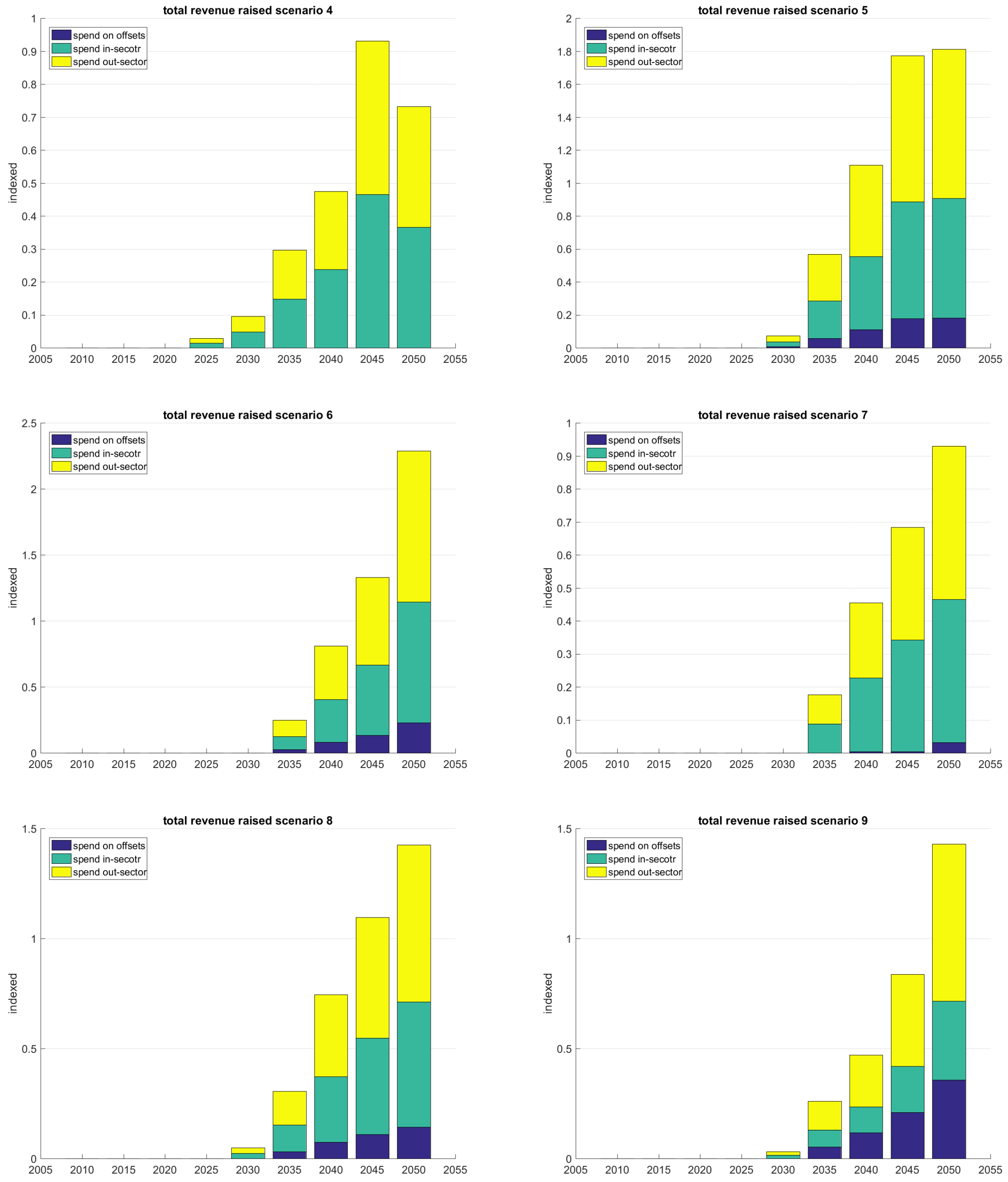

**Figure 15: Total revenue raised (indexed to the revenue raised in 2050 at a global carbon price and shipping emissions as in scenario 2)**

## 4.3 What are the respective relative and absolute targets?

Figure 16 and Table 14 provide a range of potential targets for the shipping industry, as discussed and derived in Appendix 1. These absolute targets are coherent with the values for the carbon intensity trajectories (Figure 8) calculated for each of the scenarios. Each scenario has a different carbon intensity trajectory, with the range of trajectories showing a range of plausible futures for the sector.

Table 15 is an attempt to capture the range of plausible values at given points along the trajectories. All values are calculated relative to 2010.

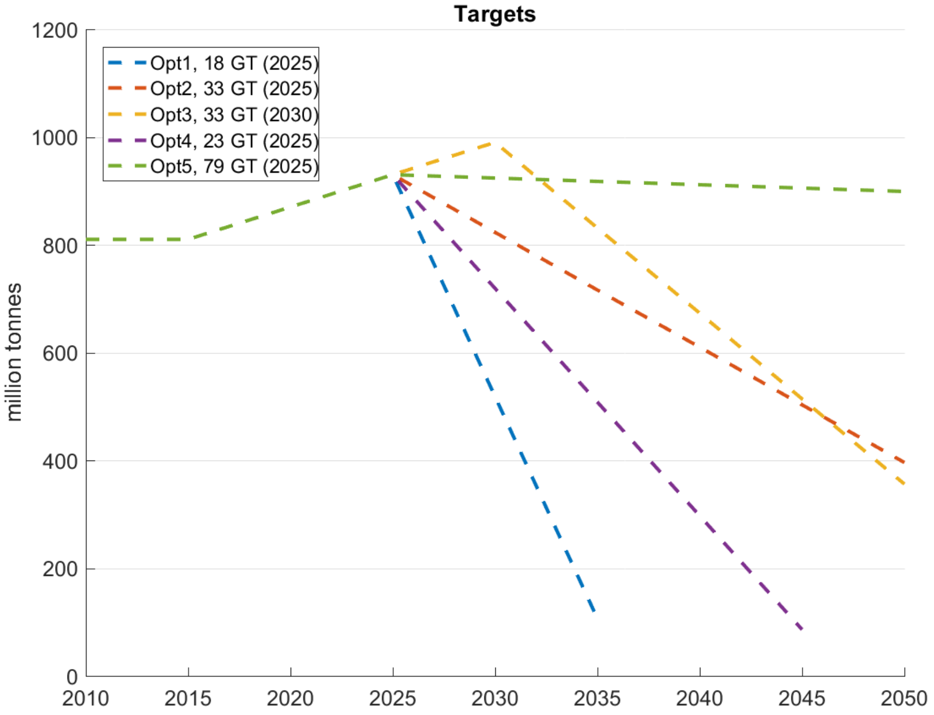

**Figure 16: $CO_2$ targets quantified**

**Table 14: Absolute $CO_2$ emissions targets for international shipping under five different target derivations (million tonnes)**

| | **2010** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|---|---|
| Opt.1 - Responsibility principle, 1.5 degrees, 18 Gt (2025) | 810 | 810 | 870 | 930 | 518 | 106 | | | |
| Opt.2 - Responsibility principle, 2 degrees, 33 Gt (2025) | 810 | 810 | 870 | 930 | 823 | 716 | 610 | 503 | 396 |
| Opt.3 - Responsibility principle, 2 degrees, 33 Gt (2030) | 810 | 810 | 870 | 930 | 990 | 831 | 673 | 514 | 356 |
| Opt.4 - Egalitarian principle, developed country based, 23 Gt (2025) | 810 | 810 | 870 | 930 | 719 | 508 | 297 | 86 | |
| Opt.5 - Egalitarian principle, developing country based 79 Gt (2025) | 810 | 810 | 870 | 930 | 924 | 917 | 911 | 905 | 898 |

**Table 15: Variability for the carbon intensity in different scenarios, for different ship types, all scenarios except ‘no policy’ scenarios (Scenario 2 and 3)**

| | | carbon intensity (EEOI in $gCO_2$/t.nm) | | | |
|---|---|---|---|---|---|
| | | high | low | average | relative to 2010 EEOI |
| bulk carrier | 2010 | 16.5 | 16.5 | 16.5 | 100% |
| | 2020 | 12 | 10.5 | 11.25 | 68% |
| | 2030 | 10 | 7 | 8.5 | 52% |
| | 2050 | 6.5 | 2 | 4.25 | 26% |
| container | 2010 | 280 | 280 | 280 | 100% |
| | 2020 | 230 | 195 | 212.5 | 76% |
| | 2030 | 220 | 150 | 185 | 66% |
| | 2050 | 160 | 50 | 105 | 38% |
| oil tanker | 2010 | 47 | 47 | 47 | 100% |
| | 2020 | 50 | 43 | 46.5 | 99% |
| | 2030 | 43 | 29 | 36 | 77% |
| | 2050 | 20 | 5 | 12.5 | 27% |

## 4.4 What are the well-to-wake emission and air pollution implications of the different scenarios?

Figure 17 shows how the total $CO_2e$ emissions might evolve both in terms of operational emissions from the sector, and upstream emissions. Figure 18 shows the emissions for a number of non-GHG air pollutants.

The results show that there are significant challenges ahead for the sector’s upstream emissions, with these growing in some scenarios which see significant reductions in operational $CO_2e$ emissions. For example, whilst in 2010 upstream $CO_2e$ emissions are estimated to be approximately 14% of operational $CO_2e$ emissions, by 2050 in scenario 5, they have reached 50%, which is predominantly due to the high use of hydrogen in scenario 5 and its associated upstream emissions. Opportunities exist for addressing these upstream emissions (for example in the case of hydrogen, alternative production technology such as electrolysis could be used). Upstream emissions will occur on land and the fuel production industry will be incorporated within the NDC framework of UNFCCC, so there is no reason for upstream emissions to be assumed to be a reason for shipping not to decarbonise. However, the results do demonstrate the importance of taking a multi-stakeholder approach to decarbonisation strategies for shipping, understanding how demand for different fuels might arise and how this might create increased pressure on NDCs and other sector’s commitments.

Operational $CO_2e$ emission broadly follow the trends in operational $CO_2$ emissions, so non-$CO_2$ emissions do not appear to be of great significance in the scenarios considered. Where differences do occur, it is commonly around methane slip from the use of LNG as a fuel, and assumptions for the extent of methane slip are uncertain and high sensitivity.

Wider air pollution impacts are generally relatively improved in scenarios where there is significant take-up of hydrogen and LNG (Scenarios 5,6 and 7), suggesting that a number of alternative fuels have the potential for combinations of GHG reduction in combination with air pollution reduction.

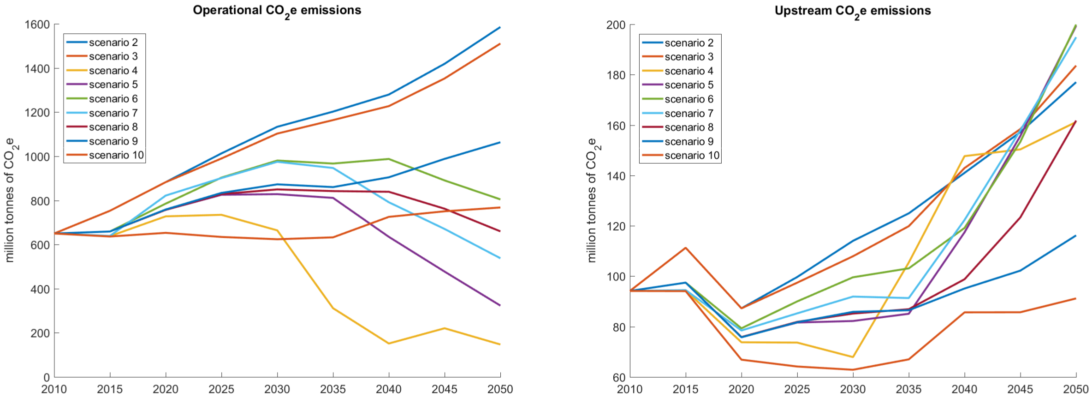

**Figure 17: Operational and upstream $CO_{2e}$ emissions all scenarios**

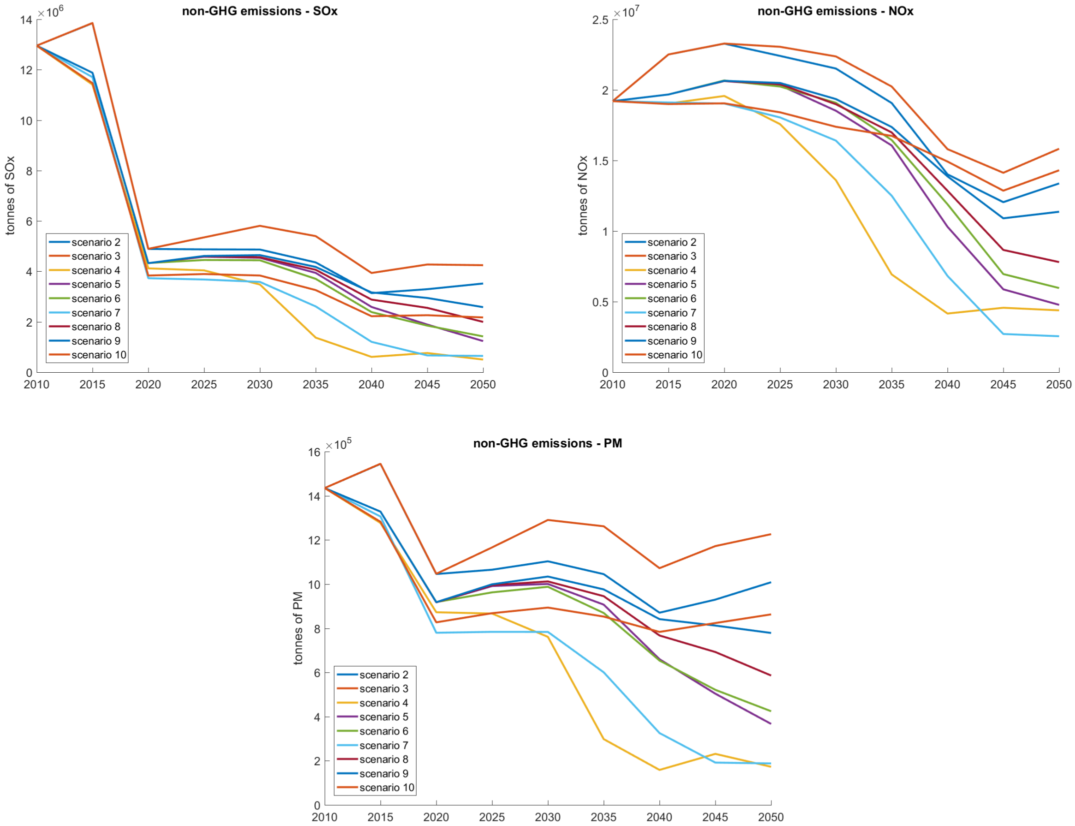

**Figure 18: Non-GHG emissions ($SO_x$, $NO_x$, PM) all scenarios**

## 4.5 What is the role of speed?

Figure 19 and Figure 21 show how different scenarios drive different trends in design and operating speed. The results are shown as average speeds across all ship sizes within a ship type. Consistently across all scenarios, design and operating speeds reduce relative to 2010, with the exception of the ‘no policy’ scenarios which show for some ship types an increase in operating speed.

Design speed changes are comparatively small and in many cases constrained by the minimum speed requirements associated with safety and manoeuvring considerations. Average operating speed reductions can be significantly greater, depending on the scenario. Increases in average operating speed can also be observed in certain scenarios, particularly following the adoption of low carbon fuels (Scenarios 4, 5 and 6). In scenario 4 the slow steaming constraint is “relaxed”, which means that the minimum powering is limited to reduction of installed power up to 1%. In this case the average operating speed reduces more drastically until 2035 in comparison with the other scenarios which have a “limited” slow steaming constraint.

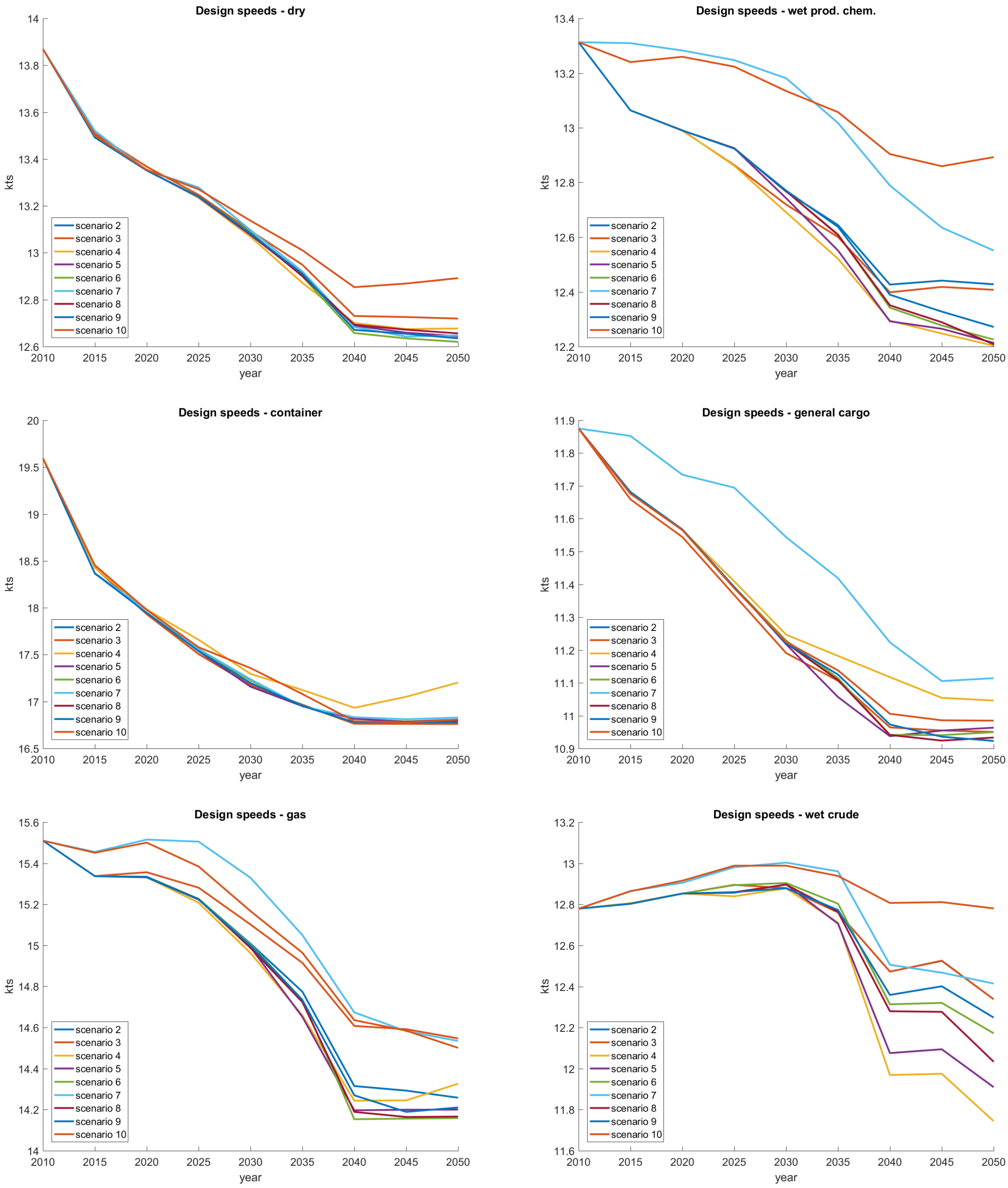

**Figure 19: Ship design speeds for all scenarios**

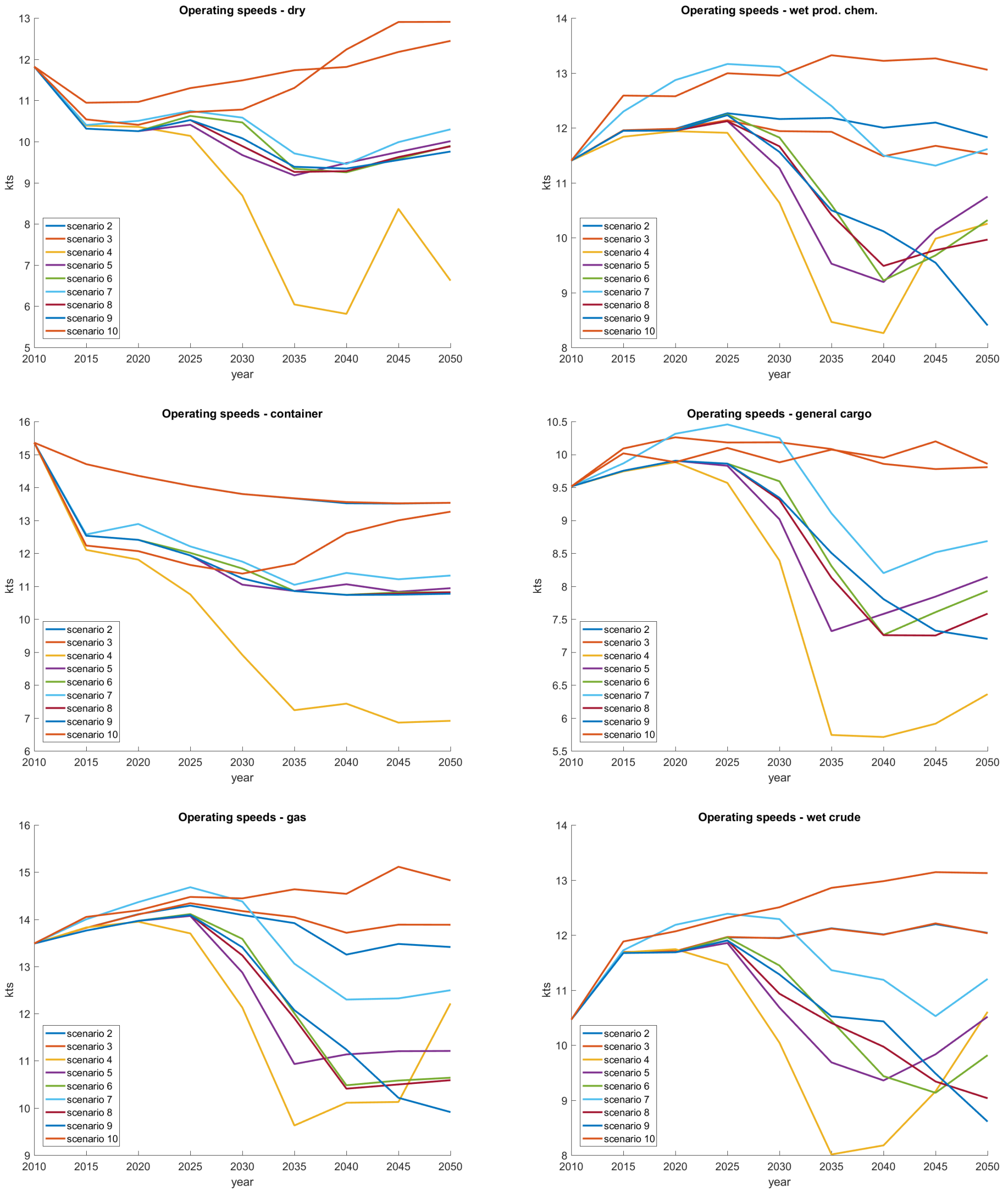

Figure 20: Ship operating speeds for all scenarios

# 5 Discussion

## 5.1 How reliable are these findings?

### 5.1.1 Key assumptions in the modelling

GloTraM, like any model, requires a number of assumptions to be made in order to simplify appropriately. In several places in the report, these assumptions are explored in some detail. This section serves as a summary of all the key assumptions and reminder to bear these assumptions in mind when reviewing the results.

- One of the key drivers of emissions in the shipping industry is transport demand. Transport demand in this study is derived from the Third IMO GHG Study scenarios RCP 2.6, SSP 3. Whilst by historical standards this assumes a low rate of demand growth, there is uncertainty around how both demand and GDP might be related in the future and how global GDP might evolve. Small changes in annual growth of transport demand can create large changes in total demand over the 40 year period of this study, and therefore this is an important high sensitivity uncertainty.
- The amount of energy (fuels) that could be sourced from biomass in the future is highly uncertain and the results have a large sensitivity to this assumption. Two different levels have been used in this study's scenarios and show a large range of possible levels of availability. Biofuels have been considered as substitute fuels to fossil with equivalent prices, whilst uncertainty remains about the relative bio and fossil fuel prices.
- There is uncertainty about the year in which further GHG policy would be implemented in order to control GHG emissions from shipping. This modelling assumes a start year which may not be politically feasible. The later the start year, the greater the rate of decarbonisation so this is a high sensitivity parameter to the trajectory that the sector's emissions might ultimately take.
- As well as timescale, there is uncertainty about how any further GHG policy might be implemented. The scenarios studied assume a Market Based Measure that uses a price signal (on $CO_2$ emissions) as a lever to change the sectors technology, fuels and operation. Alternatives may become the favoured mechanism (for example mandatory carbon intensity standards for existing ships), and these might incentivise different choices than those shown.
- Related to the uncertainty around the use of different Market Based Measures, is the persistence of a number of market barriers and failures that would impact the carbon price needed to create a specific level of change within the sector. Key existing failures include information deficits (knowing what the relative performance and costs are for different technologies), and split-incentives (e.g. between shipyards and owners, and between owners and charterers).
- This model has centred on $CO_2$ emissions, whilst referencing the non-$CO_2$ GHG emissions and upstream emissions, so these are considered even if they are not included in the target. The control of these emissions are dependent on equipment manufacturers and fuel producers, and so high uncertainties remain for those non-$CO_2$ and upstream emissions, particularly on the future feedstocks and production methods of different marine fuels, and this could in turn have a large impact on the overall climate impacts of different pathways.
- Historically, air pollution and GHG emission regulation has interacted. Whilst MARPOL Annex VI and the associated $SO_x$ and $NO_x$ regulation has been taken into account, additional regulation may yet be developed on these and other emissions (e.g. methane, black carbon, PM), which could in turn drive differences to the optimal choices for the combined objective of compliance and profit maximisation.
- The shipping sector is assumed to be unable to store $CO_2$ emissions. Whilst CCS has become a potentially important technology for land-based emissions abatement, it is not

assumed to be viable for shipping because of the mobile nature of ships and the space constraints for storage of any exhaust emissions.

- A wide range of different technologies and operating measures have been considered in this study, and show that there are a number of different combinations that could assist. High uncertainty remains around the potential emission reduction of some technologies (for example wind assistance technologies), and the impact of production volume and learning to cost reduction for the different technologies is uncertain. All these uncertainties could impact both the cost of decarbonisation and the technology pathways for the sector.
- On the subject of fuels, the study limited analysis to a number of fossil, synthetic and bio fuels. There are different fuels (for example ammonia) that are considered in early stage research at present, which may be shown in due course to have good potential for managing the sector's climate impacts.
- A further uncertainty arises from the impact of climate change on shipping. That is, the uncertainty of how climate change over the next 35 years might influence the environment and infrastructure within which shipping operates. Examples include the effect of rising sea levels on ports and harbours, and the impact of increasing storminess and severe weather on safety and operation of ships, around both of these examples there remains significant uncertainty. The modelling carried out in this study has not included factors or effects reflecting any climate related changes because all scenarios are assumed to lie within the limits of 'dangerous' climate change. However, in the event that globally commitments fail to be sufficient to enable the avoidance of dangerous climate change, this may prove to be an increasingly important missing assumption.

### 5.1.2 The role of ship size

Carbon intensity is strongly related to ship size, if all else is equal larger ships move goods with greater efficiency because of economies of scale. Figure 21 shows this relationship for different types of ships.

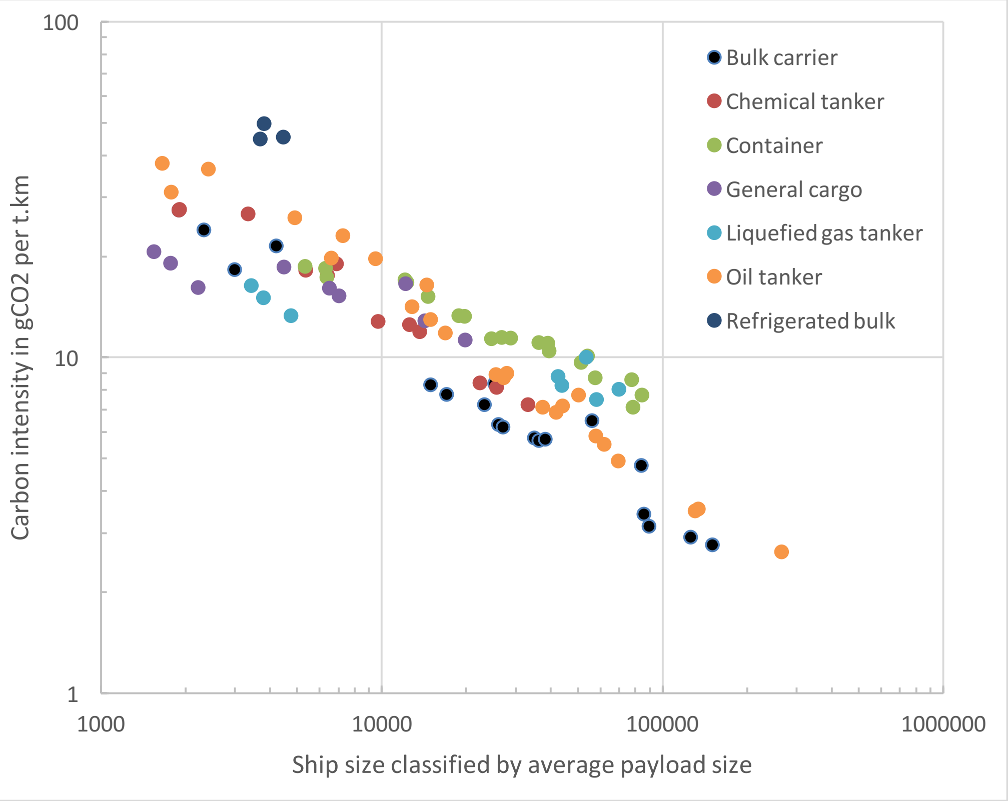

**Figure 21: Relationship between ship size and EEOI, data from MEPC 68 INF.24**

Therefore, there exists a potential for the sector's decarbonisation to be assisted by the replacement of smaller ships with larger ships.

For transparency and simplicity, the modelling assumption in GloTraM is that the ship size distribution is static with the ship size distribution in the model's baseline year of 2010. That is to say that the distribution of transport supply between the different ship size categories is constant out to 2050. This assumption is conservative and is more appropriate for the bulk fleets than the container fleets which have experienced significant growth in maximum ship size and average ship size in recent years and could continue to increase in size.

Projecting how ship size may evolve is complicated by the many factors that impinge on it, not least the size of the port, the port's infrastructure, the draught constraints on any port, the constraints on any access or canals, the volume of trade on a given route. However, it is not unreasonable to consider even taking these factors into consideration, that over the next several decades, consistent with the growth in trade behind the transport demand scenarios, average ship sizes for all ship types could increase further. To produce an estimate of how this could then impact $CO_2$ emissions, Table 16 explores two scenarios where average ship size increases and everything else is held constant. Using the data from Table 5 in MEPC 68 INF.24, the consequence of allocating transport demand up one ship size and two ship sizes is quantified in terms of the change in total $CO_2$ emitted for the equivalent total amount of transport work. For example, in the case of increasing up one ship size category, that bulk cargoes currently moved on the smallest size category (0-9999 dwt), are moved by the next size category up (10000-34999 dwt), etc.

**Table 16: Data calculated from MEPC 68 INF.24 to relate an increase in the ship size to the resultant reduction in carbon emissions**

| | number of ship size categories incremented | |
|---|---|---|
| | 1 | 2 |
| bulk carrier | 18% | 26% |
| container | 14% | 22% |
| oil tanker | 20% | 30% |

Because the variability in carbon intensity with ship size, and the distribution of carbon intensity as a function of ship size is not consistent across ship types, there are some differences. However, the emissions reductions are similar between ship types, and result in averages of approximately 17% and 26% for 1 and 2 size increments respectively.

### 5.1.3 The importance of developments of fuels and infrastructure

The scenario results show a number of different ways in which the decarbonisation of the sector can be enabled. One key finding is that most of the pathways will require a substitute to fossil fuel, because energy efficiency improvements alone will not be sufficient in the medium to longer term. Energy storage in batteries and renewable energy sources (wind and solar), will undoubtedly have an important role, but are likely to still leave a requirement for a liquid fuel source. There are two main categories of non-fossil fuels:

- Bio-derivative fuels
- Synthetic fuels

Synthetic fuels (for example hydrogen) can be bio-derived, so the main difference is that the first category refers to classical biofuels (straight vegetable oil, FAME etc.), which have been produced by a refinery of biomass into a fuel that can be used on board a ship.

Development and testing of both bio and synthetic fuels has been ongoing for many years. Hydrogen is in use on in-service submarines and a number of prototype craft, biofuels have been available for some time and are commonly used in the sector already in blends such as B10 and B20 (10 and 20% biofuel) of MDO and MGO. A firm targeting a marine bio product, Goodfuels, has developed drop-in biofuel blends of up to 50% and has a marine HFO bio variant in development.

So whilst further testing, use and dedicated systems for such alternative fuels will still be required, it is clear that even without a substantial IMO policy driver there will continue to be developments which will help to provide options for the sector in future years.

However, the practicalities of substituting the volume of fossil fuel currently in use by shipping (~300 million tonnes), with some mix of bio and synthetic fuel, in the timescales of decades required by most targets, makes any potential non-fossil fuel switch a significant undertaking. Placed in the context of the current debates around 0.5% fuel oil availability, a comparatively moderate transition for the refinery and bunkering sector, it is clear that careful planning and infrastructure development will be required.

The experience gained to date with LNG may provide some important lessons. LNG is a fuel which requires significantly different storage, handling and infrastructure and so gives rise to a number of challenges e.g.:

- the development of bunkering infrastructure,
- the containment on board,
- the development of new classification society rules,
- the supply chains for the bunker provider
- managing the uncertainty of LNG vs. HFO vs. MDO prices

Opens several questions:

1) are the current investments in LNG still viable if LNG is only used for a short period by the sector before being replaced by bio and synthetic fuels (does it make sense to continue to grow these investments or for their growth to be re-evaluated)?

2) what experiences gained from the transition to the use of LNG could be used to understand and assist a transition to bio and synthetic fuels.

Whether considered separately or as part of the above challenges, a key uncertainty remains the global production of any non-fossil shipping fuel. Dividing this in two provides

- Synthetic fuel production – The example used in these scenarios is hydrogen because it is one of the main synthetic fuels considered for the global energy system. Others certainly would need further consideration to test whether hydrogen is the most likely synthetic fuel. Production of hydrogen is currently most often from reformation of fossil natural gas. This produces a waste stream of $CO_2$, and so will require CCS. In the event that CCS is not viable or cost-effective, alternatives for its production include from biomass or electrolysis. The latter provides an opportunity for use of otherwise unwanted excess renewable supply. Hydrogen production may well be required for many other parts of the global economy (e.g. land transport), and so the shipping sector would need to consider how this might evolve, engage with other sectors that might be on the demand side as well as the entities likely to be on the production/supply side, and identify the timing for scaling up of production.
- Biofuel production – The results from the scenarios show that even with conservative assumptions about the future availability of biofuels globally (given assumptions about land use and productivity), there are circumstances in which sufficient quantities could be available for the shipping sector's use. Just as in the case of crude oil and natural gas, biomass can be

used or refined to produce many different fuels, and the optimal balance between energy density, storage, transportability, feedstock availability means that it is not as yet clear which product might be best suited for shipping. As in the case of crude oil, it may be that there is a residual product that can still be combusted effectively in a marine two stroke and that the shipping industry continues to be the user of the wider energy system's waste streams.

In addition to availability and price uncertainty, uncertainty exists around the upstream and wider operational emissions of different fuel and machinery combinations. Some possible emissions, consistent with the different scenarios simulated, have been provided and discussed in Section 5.4.

Taking all of the above into consideration, the sooner the shipping sector has a clear high-level target, and associated potential pathways for technology transitions identified, the easier these important conversations with the impinging stakeholders will be, and the sooner assumptions about any non-fossil fuel can be improved.

### 5.1.4 How does fleet lifespan affect the findings

Fleet lifespan and fleet turnover are directly related. Shorter lifespans increase turnover, which means that the fleet's specification can change faster if newbuilds are significantly different to the fleet that they are replacing. Whilst historically ship lifespans of 25-30 years were common, in the current market depressed with oversupply, there is sometimes scrappage of ships after just 10-15 years of their use. Although the driver at present might be oversupply, in the future it may increasingly be technological obsolescence depending on whether the sector is able to collectively plan ahead and manage its low carbon transition to minimise the development of technological obsolescence and stranded assets, or whether it cannot and therefore undergoes a more turbulent technological adjustment.

Many of the energy efficiency technologies considered in this study can be both retrofitted and applied to newbuilds. Applying a technology to a newbuild design will usually be possible at a lower cost, or not necessary at all (for example some propeller retrofits may not be cost-effective on a newbuild if an adequate propeller diameter and specification is chosen). Particularly in the case of alternative fuels, which require significant storage and machinery modification, application to newbuilds may be the only viable option. However, recent experience gained from retrofitting of LNG machinery and storage shows that this is certainly viable technically and can be made possible with the right economic drivers.

In spite of the evidence of LNG retrofitting, in the GloTraM scenarios applied here, the assumption is that ships are scrapped at thirty years and that hydrogen and LNG and wind are only available for newbuild ships. This conservative assumption means that in the high rate of decarbonisation scenarios (Scenarios 4 to 8), the existing fleet is decarbonised either through offsetting of emissions (if this is permitted in the scenario), or through speed, energy efficiency measures and bioenergy. Particularly where bioenergy is in low supply, this can drive up the carbon price significantly.

Therefore, in the GloTraM scenarios, reducing ship lifespan would have increased the rate of take-up of alternative energy (wind and hydrogen), and this would in turn create less reliance on offsetting and more expensive retrofit solutions, and this in turn would reduce the carbon price experienced.

The suggestion for the how the sector could address this in practice would therefore be some combination of:

- Planning for shorter economic lifespans, either by assuming the need for a faster return on investment, or factoring in at purchase a second-hand value that acknowledges the likely rate of change of technology and loss of value this implies,

- Planning for initially more capital cost and a more complicated design which is able to be easily retrofitted to suit the different technologies as they mature and become widespread (being wind, bio or synthetic fuel ‘ready’),
- Designing under circular economy principles: instead of presuming conventional scrappage at end of life, think at design about how the value of the ship could be maximised and loss minimised through a range of reuse and recycling opportunities.

#### 5.1.5 Innovation and cost-reductions

Estimating the future rate of technology change requires handling both uncertainty of the drivers of the change (policy and macroeconomics) which set the landscape for the change, but also handling the uncertainty of the technology itself and how its performance and cost may evolve in the future. Figure 22 compares the estimates by IEA of future solar PV and wind installed capacity, with the actual rate. Projections made about installed capacity only 5 years forward were consistently proved to dramatically underestimate the actual rate of capacity growth. A number of factors are thought to be responsible for this underestimation, including an underestimate in the rate of reduction of cost of the technology due to experience gained through the increasing rates of production.

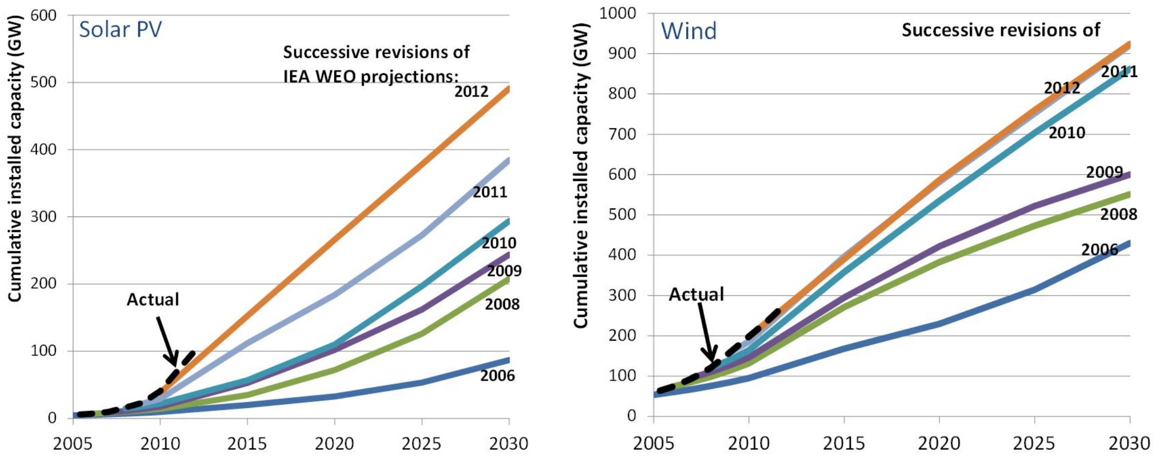

**Figure 22: Comparing IEA estimates of forecasts for installations of wind and solar with the actual rates observed (Whitworth, A (2013) On Climate Change Policy)**

This project is attempting to estimate technology change in the shipping sector over decades and will no doubt be found to have made similar errors when eventually actual change can be compared to the scenarios considered.

One example of a technology that is an important component in the GloTraM scenarios but which has a highly uncertain future cost is the hydrogen fuel cell. Figure 23 shows the trajectory of price to customer of a PEMFC technology illustrating an order of magnitude cost reduction over a single decade. Given that in many of the scenarios considered, fuel cell technology becomes a significant component of the shipping industry from 2030, the task of estimating realistic technology costs relevant to the take-up in 15 years time, is not simple.

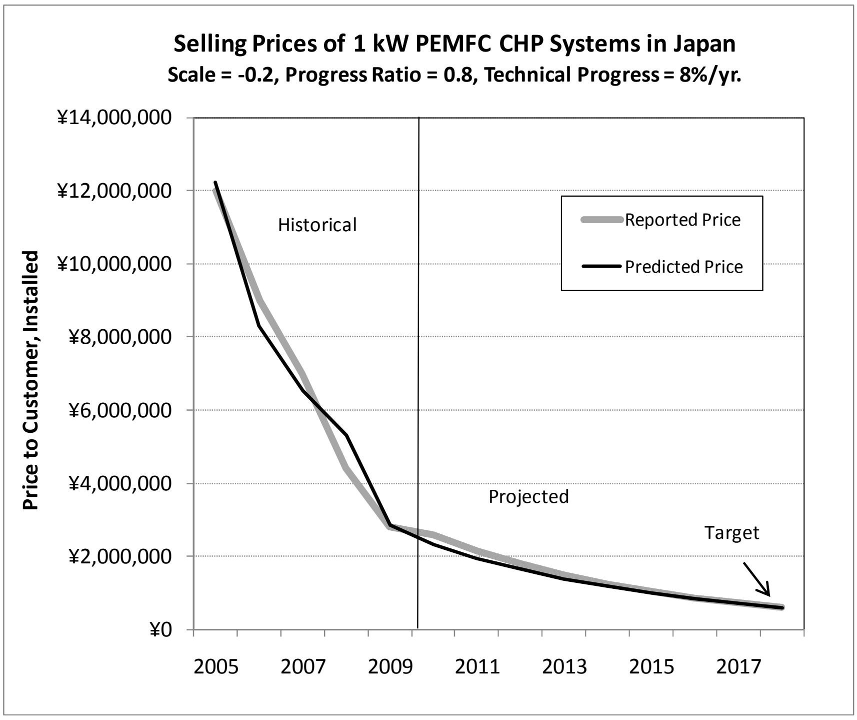

**Figure 23: Historical and projected selling price of 1kW PEMFC CHP units in Japan 2005-2018 (Greene, D.L. (2011) Status and Outlook for the US Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities)**

In addition to the fact that the cost of known technologies is uncertain (a known unknown), there is also the issue that technologies may yet evolve that have not yet been conceived for their application to the sector's GHG emission reduction (an unknown unknown).

In light of these unknowns, the approach taken is a pragmatic one: that the costs of technology that are used represent our best estimate of the long-run cost, but that these are predominantly based on evidence obtainable now (e.g. current best estimates), and that we only represent technologies that have been conceived.

These assumptions are both conservative and are therefore likely to overestimate the economic cost to the sector of decarbonisation. Shipping's decarbonisation costs will be reduced both by learning obtained from inside the sector, but also as technologies mature and are used outside of the sector (it is likely that there could be commonality in fuels and machinery with other 'heavy duty vehicles', whether bio or synthetic fuelled), which only increases the scale efficiency and learning opportunity for shipping.

There are consequence of this both for the interpretation of this report's findings and more generally for the sector:

- In the context of this report the carbon price trajectories (Figure 13), which are driven by the decarbonisation cost estimates, should be considered only as indicative relative costs, not as authoritative absolute estimates of future carbon price.
- The use of a target and a strategy are important mechanisms to signal to the equipment manufacturers and market the likely trajectory of take-up that will be required and therefore the rate of production and volume, and associated cost learning, that may be achievable. The more the users of this future technology (owners and operators) engage with the producers of it (equipment manufacturers), the better.

### 5.1.6 Impacts of further regulation

Shipping as a sector has a number of externalities (impacts on the wider environment) which are increasingly being controlled and internalised. Most current are issues around air pollution, which produces negative air quality and health consequences, but non-indigenous invasive species risks (for example associated with ballast water discharge and hull fouling), are also significant. Listed below are some of the areas that will or might face regulation in the future

- Ballast Water Treatment, now ratified at IMO, will involve the fitment of treatment equipment which will increase auxiliary energy consumption
- Methane and VOC emissions (from both combustion slip, bunkering and venting), will impact the exhaust treatment and on board equipment (e.g. they can be controlled by catalysis if they can be captured)
- SOx, PM and NOx emissions, whilst no plans exist to further increase stringency, areas where Tier III machinery will be required are likely to increase (e.g. Baltic NECA), and further reduction may also be applied in port and coastal regions where health impacts are greatest. This could include increasing regulation to incentivise or dictate the use of shore power when at berth
- HFO bans, it is possible that because of oil pollution risks in combination with control of PM/BC impacts, may lead HFO (even with emissions control technology) to be banned from certain high sensitivity sea areas such as the Arctic (it is already banned in the Antarctic)
- Black Carbon is emitted when incomplete combustion occurs and is an important climate forcer. Its definition and measurement is challenging and has taken some time to discuss at IMO, but it may become increasingly important and have implications for any machinery combusting hydrocarbon fuels

Many of the above ($SO_x$, $NO_x$, BC, Methane) emissions will impinge on the profitability of different machinery configurations – by increasing the capital expenditure required to fit compliant machinery for certain fuels. This could lead to different outcomes to the estimated optima. In general, the profitability is likely to reduce for conventional fossil hydrocarbon fuels which variously have challenges associated with sulphur or methane slip, as well as $NO_x$ and BC.

In addition to increased cost, there may be parasitic impacts (e.g. increased auxiliary energy demand, or reduced SFC due to back pressure from exhaust treatment devices). These are unlikely to be significant relative to the scale of the decarbonisation challenge (parasitic carbon intensity impacts might be of the order of 1-2% so significantly lower than the large scale decarbonisation). However, in combination they suggest:

- An era of increasing equipment capital cost, complexity and operator skill/training
- A need for careful, holistic analysis of a wide landscape of uncertain regulations that could change the optimal selection of fuel and machinery

## 5.2 What do these findings imply regarding international shipping's 'fair share'?

The concept of shipping's 'fair share' was first introduced at MEPC 69 in MEPC 69/7/2. It refers to the concept that in the global efforts to decarbonise, shipping as a fossil fuel and $CO_2$ emitting sector will need to contribute its 'fair share' of decarbonisation. The debate arose because international shipping is not easily disaggregated into national responsibilities (unlike other sectors), and because international shipping and aviation were explicitly omitted from the Paris Agreement text, implicitly placing the obligation for their GHG emissions' control on IMO and ICAO respectively.

The debate at MEPC 69/7/2 was inconclusive and the GHG topic will be debated again at MEPC 70. There is no agreed method or value for shipping's fair share, and this section of the report is not intended to presume an outcome from the forthcoming MEPC debates, only extract indications of potential ways in which those debates could evolve for the purposes of this study.

By exploring how constraints placed on the overall $CO_2$ emissions of the sector can be accommodated by changes in the shipping system, this study has focused on evidence for the global fleet (proxied by the container, dry, wet bulk and gas carrier fleets) around:

- What level of 'fair share' is possible
- How might international shipping respond to different levels of 'fair share'

The results from the different scenarios suggest that there are foreseeable technological changes and mechanisms (e.g. offsetting), which in various combination could enable any of the proposed $CO_2$ trajectories so all are 'possible'. The specifics of how the sector might change vary, depending on the assumptions made. For the scenarios where there is a moderate to high rate of decarbonisation (Scenarios 4-8), then broadly the results can be summarised as either:

- Low in-sector change
    - Biofuel availability is consistent with the higher levels modelled and the sector mainly
    - The sector mainly offsets its emissions
- High in-sector change and wider infrastructure changes
    - The adoption of a synthetic fuel for example hydrogen

Correspondingly, the change in carbon intensity (mostly represented as EEOI in this study) that is required depends on the specifics of the scenario, but is broadly consistent with changes estimated in previous studies[16], and shows levels of change that even by 2050 (80-90% lower relative to 2010), are achievable from a number of different permutations shown in the technical and operational ship specifications in Section 4.1.

Whilst the calculated carbon prices are not considered to be accurate in absolute terms, they are indicative of the relative differences between scenarios in terms of cost, and they imply that all else being equal, higher rates of decarbonisation will incur higher costs sooner.

Combining this evidence suggests that the question of 'fair share' is not constrained by 'what is feasible', but is more clearly determined by the trade-off between costs and any associated negative consequences (e.g. impacts on trade) relative to steps being undertaken by other sectors and economies. Because this study has not had a scope to evaluate in detail the negative consequences (e.g. impacts on trade), this restricts the consideration to one where parallels are drawn through the egalitarian principles discussed in the external factors assumptions report for the derivation of the family of potential fair share quantities.

The analysis produced two egalitarian derived estimates

- 23Gt budget (20102100), estimated from developed countries' NDCs
- 79Gt budget (2010-2100), estimated from developing countries' NDCs

Defining shipping as most like either a developed or a developing country is not obvious. International shipping is a service for both types of country and frequently enables connections between the two types of country. Any egalitarian amount should therefore be a hybrid between the two. Furthermore, the best available science indicates that in combination the NDCs still exceed the Paris Agreement temperature targets (well below 2 degrees, aiming for 1.5), and so through the ratchet mechanism both types of country will need to increase their ambition and level of commitment.

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[16] Smith, T.W.P, Traut, M., Bows-Larkin, A., Anderson, K., McGlade, C., and Wrobel, P. (2015) CO2 Targets, Trajectories and Trends for International Shipping. Shipping in Changing Climates project, www.lowcarbonshipping.co.uk

In the definition of its fair share, shipping through the IMO could choose either a leader or follower role. Taking a follower role, it could identify a fair share derived from these existing commitments and wait for the ratchet mechanism to increase stringency. Alternatively shipping could anticipate the inevitable ratcheting up of ambition and identify its fair share relative to the expected longer term stringency.

An obvious advantage of anticipating now a longer term more stringent ambition is that for a signal such as shipping that will require time to mature and adopt technology, the sooner a reliable signal is provided for that change, the better.

Solely for the purpose of providing guidance at this stage of the debate, recognising the fact that shipping is neither representative of a developed or developing country, and that stringency of NDCs will need to be increased through the ratchet mechanism, international shipping's 'fair share' is best approximated for now by this study's 33Gt budget proposal.

## 5.3 What do these findings imply about further developments of IMO end EU policy to control GHG emissions

The purpose of this study is to focus on the scenarios corresponding to different targets for the shipping sector's CO2 emissions. A hypothetical MBM in the form of a carbon price is used to simulate how a price mechanism might incentivise the sector's take up of energy efficiency interventions and low carbon fuels. However this MBM was used for the purposes of simulation only – not because a carbon price is presumed to be the most cost-effective policy mechanism to enable a low carbon transition.

There is not space to do justice to the complicated discussion of the relative merits of different instruments in this report. However, some initial comments relevant to the general policy debate around GHG have been extracted here.

### 5.3.1 Carbon prices (ETS or levy), vs. command and control regulation

A lot of the debate on measures has centred on the merits of Emission Trading Schemes vs. Bunker levies (ETS vs. Levy). For the scenarios explored using GloTraM, the two are comparable – the difference is only on whether the levy/price signal is set automatically by the market or manually by a policy maker e.g.:

- Levy – the results of simulations (such as those used in this study), can estimate and forecast the levy price needed to enable a certain trajectory for the sector's $CO_2$ emissions. That price level can then be continuously reviewed and adapted depending on the measured trajectory of the sector (e.g. if undershooting, the levy price trajectory can be increased, if overshooting, reduced)
- ETS – the market determines the price point because a mechanism of allocation of allowances under a reducing cap creates a market price through a trading mechanism. E.g. the cap defines the $CO_2$ trajectory of the sector.

The two are equivalent in GloTraM because there is no sophistication in the model about how future carbon prices are defined (which might be different in practice for an ETS and levy type scheme). Beyond this, there are relative pros and cons of both of these, many of which have been discussed previously, and need further review.

However, a third type of instrument would be to use further command and control regulation, similar to EEDI (e.g. mandatory standards on carbon intensity that also cover the entire fleet). In light of evidence about the persistence of split incentives that disrupt the ability for shipowners to obtain rewards for more efficient designs, unless these failures can be minimised they will artificially inflate the price signal needed to achieve a certain level of decarbonisation (as has been shown in all the scenarios which include a degree of persistence of market barriers limiting the return of cost-savings to the ship owner). This could place command and control regulation at an advantage with respect to the cost-effectiveness of achieving a given environmental objective, relative to price signal mechanisms. The risk associated with command and control regulation is in the design of any index used for its implementation. An index/indicator (such as EEDI / EEOI) sets an objective function for a sector and therefore provides parameters that can be 'gamed' in order to achieve compliance potentially without having the full desired effect on the ultimate metric (total $CO_2$ emissions). Given the complicated multi-stakeholder environment (owners, charterers, yards, managers, equipment manufacturers etc.), an index can also be problematic in that it is often applied as a target for one stakeholder group only, and therefore fails to create the right incentives in the wider stakeholder space.

Whichever instrument is ultimately chosen, as its detail is defined, the scenario results generated here may need reconsideration.

### 5.3.2 MRV and DCS

The first steps for further GHG regulation in both the EU and IMO debates have been the design of Monitoring Reporting and Verification (MRV) and Data Collection System (DCS) schemes. Both appear likely to be in use from the later part of this decade. Both will produce important data and information which can assist the sector's decarbonisation. Particularly in the context of this study's findings:

- Given the uncertainty in future transport demand scenarios, and the difficulty of accurately estimating present transport demand, it will be important for these schemes to measure cargo carried so that actual carbon intensities (e.g. emissions relative to cargo carried) can be calculated. Without such metrics, absolute increases or decreases in carbon emissions could be spuriously misinterpreted as positive or negative trends in the short-term, leaving signals for corrective action to be missed until the mid-term when gross changes were observable.
- Given the scale of the change required, this data will provide an important time-series which can be constantly revisited to review the consequences of any policy and check for unintended consequences (positive and negative). The more open this data is the more organisations can do their own estimates of the impacts on the sector during the transition and improve the likelihood of negative consequences being spotted sooner rather than later.
- Given the existence of market barriers and failures in the sector, the more these schemes can address this by providing more transparency on fuel consumption and efficiency that can be used to ensure these are reflected in the market, the lesser the carbon price signal to achieve a given amount of decarbonisation will need to be.

Whilst the administrative burden associated with any scheme should not be trivialised or ignored, the above implies the importance of these schemes for the wider GHG objective.

### 5.3.3 Compliance/enforcements

All the GloTraM scenarios generated in this report assume that there would be perfect global compliance with any regulation. In practice this may be less for example because

- In order to reach an agreement at IMO, it may be necessary to offer voluntary compliance to certain countries (e.g. as per the use of route exemptions in potential ICAO measures)
- Delays to implementation and shortcomings to enforcement in all regions can occur with any global regulation

It is premature to design how to anticipate these risks, but they should be kept in mind in the interpretation of any of the scenario results and the instruments that are ultimately used as policy levers to create the desired outcome. If considered to be significant, a stringency increase could be applied to ensure that a margin is available to allow for lower levels of stringency being achieved in practice.