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CONSIDERATION OF HOW TO PROGRESS THE MATTER OF REDUCTION OF GHG EMISSIONS FROM SHIPS

Calculated EEOI improvements using ship energy efficiency methods

Submitted by IMarEST and RINA

SUMMARY

Executive summary: This information document focuses on the potential of technical and operational methods for reducing CO_2 emissions. This is useful for future CO_2 emission targets. The document contains calculated EEOI values for three cargo ship types using different technical and operational methods at various operating speeds. This is an updated work of a study carried out for the Danish Shipowners Association. The main conclusions of the information document are set out in paragraphs 7 to 10.

Strategic direction: 7.3

High-level action: 7.3.2

Output: 7.3.2.1

Action to be taken: Paragraph 11

Related documents: MEPC 70/18/Add.1; MEPC 69/INF.11, MEPC 69/INF.18, MEPC 69/INF.8; MEPC 68/INF.24; MEPC 67/INF.3; MEPC 63/INF.2, MEPC 63/INF.7, MEPC 62/INF.7 and MEPC/Circ.684

Introduction

1 The aim of this document is to provide state-of-the-art understanding of the opportunities for reducing the CO_2 emissions of international shipping – directly pertaining to the Roadmap item "Emission reduction opportunities (near-, mid- and long-term actions), including alternative fuels" as per document MEPC 70/18/Add.1, annex 11.

2 Much information has been previously provided on the performance of technologies and on the efficiency of operational methods. IMO has recently commissioned two studies, one that includes the development of a computer tool submitted under reference MEPC 69/INF.18

and another with experience from case studies on board ships under reference MEPC 69/INF.11. Before this there have also been documents on technical and operational efficiency methods submitted by OCIMF under reference MEPC 63/INF.7, by IMarEST under reference MEPC 62/INF.7 and by Lloyd's Register and DNV under reference MEPC 63/INF.2, as well as the Second IMO GHG Study. All the studies to date consider speed as a method for reduction of CO_2 emissions by itself. The Danish Shipowners Association recent study uses a more comprehensive and accurate calculation process; the emission reduction due to different technical and operational methods is calculated as a percentage change in EEOI, which is calculated based over a range of operating speeds for three cargo ship types.

3 CO_2 emissions from international shipping can be calculated as:

$$CO_2\ (gCO_2) = EEOI\ (gCO_2/t{\cdot}nm) \times \text{Transport Demand}\ (t{\cdot}nm)$$

Therefore, for a given transport demand, the CO_2 emission reduction is described by the EEOI reduction. The EEOI incorporates the consideration of changes to the amount of cargo supplied in a given time consequent from an increase/decrease in ship speed. The EEOI is therefore the parameter used consistently throughout the document and in the presentation of the results.

Calculation process

4 To estimate the emission reduction potential three ships have been examined with a design/operating specification and a baseline EEOI that is representative of a 2010 ship. The specification is defined by the Third IMO GHG Study under reference MEPC 67/INF.3, with additional information given under reference MEPC 68/INF.24, and refers to ships with a high design speed (relative to some of the current new builds) which uses a reduced "slow steaming" operating profile. For this reason, an additional ship (to the three ships) was added with a lower design speed that is closer to the reduced "slow steaming" operating profile. The results of a survey on energy efficiency methods, which shipowners and ship operators participated, submitted in document MEPC 69/INF.8, were used to identify the baseline "take-up" of energy efficiency technologies and operational methods. From the survey, in document MEPC 69/INF.8, it was not clear which technology methods different ships are using or which technology methods are being used in combinations with other technology methods on the same ship. For this reason, an optimistic assumption was made to combine all the technical methods that we know are currently being used by the shipping industry into a single combination of technical methods that were applied to each of the cargo ship types in this study. Technical methods that were used by more than 10% of ships in the survey, in document MEPC 69/INF.8, were included in this single combination of technical methods.

5 The previous studies on this subject have looked into individual technologies and operational conditions in isolation. This document progresses beyond these studies by looking at combinations of technologies and their impact at the level of a "whole ship" (integrated auxiliary and main machinery/propulsion/hull form/operating conditions). This progression is important, because when analysed at the level of combination, reduction potential can be lower than when considered as the summation of individual technology’s potential.

6 Annex 1 to this document provides the results of calculations on the performance of technologies to reduce CO_2 emissions of bulk carriers, tankers and container ships and their variation with the operational speed of the ship. The energy efficiency of combinations of methods is also included. Annex 3 provides explanation to the calculations that have been carried out. There are also references to this document that provide further information, which are listed in both annexes.

Conclusions

7 This study shows the maximum CO_2 emission reduction opportunity from combinations of energy efficiency methods for specific cargo ships compared to 2010 baseline ships. This was calculated in terms of EEOI. The use of technical methods in 2015 was compared to what reductions in CO_2 emissions might be possible if additional technologies and operational methods not currently being used were used by the shipping industry. It was found that:

.1 This document's conclusions are consistent with findings in the Second and Third IMO GHG Studies. The Second IMO GHG Study identified reduction potentials of 25-75% on 2007 ship parameters, through a combination of technical and operational methods. Much of this potential was attributable to speed reductions, which were further observed in the Third IMO GHG Study, becoming evident during 2010 to 2012.

.2 Further operating speed reductions, beyond those already seen in 2010, do not necessarily result in EEOI reductions and can result in diminishing returns on emissions reduction as the ship's equipment is operated increasingly far away from its design point (particularly the original design/reference speed and power output for which propellers and machinery may have been optimized).

.3 By combining technical methods available in 2015, according to document MEPC 69/INF.8, it was found that a reduction of 3.4% to 10.2% is possible on the 2010 baseline ships from technologies that were in use in 2015, assuming that the same operational speed is maintained. The EEOI over a range of speeds is included in the annexes.

.4 By adopting and combining additional technical methods not used in 2015, but available on the market (including air lubrication, contra-rotating propellers, higher cost hull coatings and recovering additional waste heat), it was found that a 7.5% to 19.4% reduction in EEOI was possible whilst maintaining the same operational ship speed. This does not include wind energy.

.5 A further possible EEOI reduction of 3.1% to 6.1%, was identified by the combination of operational methods.

.6 To go beyond a 7.5% to 19.4% EEOI reduction for technical methods requires a combination of a significant reduction in design speed (or speed associated with a ship's design optimization), the use of wind energy and/or fuels with a lower carbon factor (electrification, bioenergy or synthetic fuels). Evidence of significant reduction in design/optimal speed has already been observed in some fleets (e.g. container ships) and experience in the use of renewables and non-fossil fuels is increasing. The United States Navy has extensively tested bio-fuels on board ships and there are also companies on the market providing renewable energy and sustainable fuels.

.7 When combining multiple technical methods with high use of wind energy (Flettner rotors) and a reduced fuel carbon factor by using bio-fuels, the EEOI reduction opportunity becomes between 53.8% and 80.9% (50% reduction in carbon factor) and between 76.9% and 90.5% (75% reduction in carbon factor). This is whilst maintaining the same operational speed.

8 This is an important reframing of the challenge ahead for shipping – incremental energy efficiency (technical and operational) appears necessary but not sufficient, decarbonization of the energy supply for ships (e.g. renewable energy and non-fossil fuels) are likely to be key to achieve decarbonization.

9 The study focuses on the further emission reduction potential due to technology and operational methods applied to 2010 baseline ships. There are therefore several important limitations that should be taken into consideration when using the document's findings:

.1 Whilst the analysis carried out here is intended to be representative of typical cargo ships, there are ships with specific designs and operating profiles that may not be represented by the findings in this study. For these ships their specific reduction potential could be greater or lesser.

.2 Relative to the 2010 baseline ships, there is a significant number of older ships.

.3 This study concentrates on EEOI reduction potential of an individual ship. Fleet composition changes (e.g. greater proportion of larger ships) is a way to further reduce fleet average EEOI, but is not considered in this document.

.4 A driver of the variability in EEOI that has not been considered in this document is utilization (the transport work actually performed relative to the potential transport work (t·nm)). In document MEPC 68/INF.24, evidence is presented that utilization is not constant with time and this may drive variations to EEOI that counteract those considered when limiting the drivers of change in EEOI to technical and operational methods. By association, methods (e.g. logistics optimization) that increase utilization represent an important opportunity for emission reduction that have not been considered here.

.5 A number of new technologies are currently entering into ships driven by wider MARPOL developments (e.g. ballast water treatment systems, scrubbers). The cumulative impact of compliance with these and other environmental regulations on the emission reductions presented here is the subject of ongoing work.

10 This work has considered the CO_2 emissions reduction opportunity for various ship types and operational speeds. Future work can expand this work to consider the uncertainty in the performance of technical and operational methods.

Action requested of the Working Group

11 The Working Group is invited to note the information provided in this document and to take action as appropriate.

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ANNEX 1

CALCULATED EEOI IMPROVEMENTS USING SHIP ENERGY EFFICIENCY TECHNOLOGY

1 Introduction

1.1 Shipping in Changing Climates

The Shipping in Changing Climates (SCC) project connects the latest climate change science with knowledge, understanding and models of the shipping sector in a whole systems approach. It seeks to explore the potential to cut CO_2 through the use of technical and operational changes in shipping and to understand how the sector might transition to a more resilient and low-carbon future; it also seeks to explore different climate change scenarios and related food and fuel security issues to gain an understanding of the direct and indirect impacts of climate change on the shipping sector. These scenarios can be used to build evidence and understanding around the range of potential future directions that the shipping industry may take.

The RCUK Energy funded project brings together researchers from UCL (Energy Institute, Mechanical Engineering and Laws), Manchester, Southampton, Newcastle and Strathclyde, in close collaboration with a core industry stakeholder group of Shell, Lloyd's Register, Rolls Royce, BMT and Maritime Strategies International, but drawing on the expertise and connections of over 35 companies and organizations worldwide. This document represents the collective opinions of the authors and should not be assumed to represent the views of all the researchers across the project or the project's industry partners and their organizations.

1.2 Introduction and scope of document

This document focuses on the emissions reductions that might be possible for new build and existing ships by using technical and operational methods. This document goes beyond existing work by giving a range of efficiency gains, represented as changes in EEOI, for different ships and different ship operating speeds. The work is relevant to the tasks defined in the future roadmap for reducing CO_2 emissions.

The results presented in this document were generated by using the Whole Ship Model (WSM), developed in the Shipping in the Changing Climates (SCC) project, which can calculate the performance of thousands of different ship variants in order to see how efficiency gains can vary with different ship types, sizes and speeds.

2 Calculation process

The engineering calculations used in the Whole Ship Model (WSM) is a bottom-up approach, piecing together the individual components of each ship in order to accurately model the changes to a baseline (2010) ship due to technical efficiency.

The most relevant aspects of the WSM are explained in annex 2 to this document, a more detailed recent description from October 2016, can be found in Calleya et al. (2016), in the High-Performance Marine Vehicles (HIPER) conference proceedings at: http://data.hiper-conf.info/Hiper2016_Cortona.pdf.

The WSM contains an iterative ship design process that incorporates the demands of technical and operational efficiency methods and energy demands, fixing the main characteristics of the ship according to the methods that are used and the required specification of the ship, including cargo and design speed. The performance of the designed ship is then calculated by simulating the operation of the ship over a range of operating speeds. This is carried out for each ship and technical and operational efficiency method combination that is to be examined and includes all the key components of the ship's systems, including the propeller, resistance and engine.

Annex 2 gives a short summary of the technologies and operational efficiency methods that are included in this study. The work in the document is updated from the work carried out for the Danish Shipowners Association with Lloyd's Register (Smith et al. [2016], available from https://www.shipowners.dk/en/focus-areas/miljoe-og-klima/klimapolitik/).

3 EEOI Improvements from different energy efficiency methods

The interaction between technologies in combination with different ship designs is included in the calculation process in the WSM, this allows the impact of the propeller, engine and hull performance to be included. The WSM has also been setup to represent the performance of 2010 baseline ships. For example, the block coefficient and auxiliary engine power requirements have been selected based on 2010 data.

3.1 Calculation of 2010 baseline EEOI

The EEOI, as defined in IMO MEPC Circ.684 [2009], is a measure of the cargo carrying efficiency of a ship, in terms of CO_2 emissions (fuel consumption (*FC*) X carbon factor (*CF*)) per cargo (m_{cargo}) distance (*D*) travelled for each fuel (*j*) over a number of voyages (*i*):

$$Average\ EEOI = \frac{\sum_i \sum_j \left(FC_{ij} \times CF_j\right)}{\sum_i \left(m_{cargo,i} \times D_i\right)}$$

The EEOI resulting from the introduction of different technical and operational methods has been compared to the EEOI of the same baseline ships in 2010, with no technical and operational methods. The 2010 reference EEOIs used in this study are given in document MEPC 68/INF.24 using data from the Third IMO GHG Study [Smith et al., 2014]. The carbon factor of Heavy Fuel Oil (HFO) is taken from MEPC/Circ.684.

3.2 Ships specifications

The outputs from the WSM for a number of technical energy efficiency methods focus on three specific ships:

.1 A 14.8 knot design speed MR Tanker.

.2 A 25.1 knot design speed 5000 TEU Container ship.

.3 A 15.3 knot design speed Panamax Bulk carrier.

The three ships used in this study have a baseline EEOI and design speed that is consistent with a 2010 baseline using documents MEPC 67/INF.3 and MEPC 68/INF.24.

The three ships were chosen to represent the shipping industry and because they have very different cargo and speed requirements, which can result in different technical and operational methods being more effective on some ships compared to others.

An additional 19.2 knot design speed container ship is included in annex 2. This was used to examine the impact of having a ship with a design speed close to its operational speed.

3.3 Definition of current combinations of technology methods

A combination of technology methods representing the current trends in the shipping industry has been chosen based on a survey that took place in 2015 (MEPC 69/INF.8); these are:

.1 rudder bulb (this is combined with end-plated propeller);

.2 end-plated propeller (this is combined with rudder bulb);

.3 engine derating;

.4 speed control of pumps and fans;

.5 energy saving lighting; and

.6 waste heat recovery (conventional steam).

The performance of the end-plated propeller and rudder bulb were calculated independently and combined in the WSM. The reference by Nielsen et al. [2012] gives the compatibility between different efficiency technologies including end-plated propellers and rudder bulbs.

From the survey, in document MEPC 69/INF.8, it was not clear which technology methods different ships are using or which technology methods are being used in combinations with other technology methods on the same ship. For this reason, an optimistic assumption was made to combine all the technical methods that we know are currently being used by the shipping industry into a single combination of technical methods that were applied to each of the cargo ship types in this study. Technical methods that were used by more than 10% of ships in the survey, in document MEPC 69/INF.8, were included in this single combination of technical methods.

Note that superstructure aerodynamics and weight reduction were also investigated in this study, but were found to have a negligible reduction in EEOI for the ships that were examined.

3.4 Definition of future combinations of technology methods

Future combinations of technologies include technologies that were being used by the shipping industry in 2015 (described in section 3.3) as well as technologies that are not being used at the moment but could be used by the shipping industry in the future. Note that most of the future technologies are currently available on the market, this is described in annex 3.

An additional 2% change in the frictional resistance of each ship was included from the application of high cost hull coatings.

The future combinations of technologies differ depending on the ship and whether they include wind technologies or not; these are:

.1 contra rotating propeller;

.2 stern flap or block coefficient reduction (depending on the ship, this is explained below tables 3, 6 and 9);

.3 air lubrication;

.4 all types of waste heat recovery (including conventional steam, organic Rankine cycle and turbo compounding);

.5 engine derating;

.6 speed control of pumps and fans;

.7 energy saving lighting;

.8 high cost hull coating; and

.9 maximum Flettner rotors (where wind technologies are considered, not used on container ships).

3.5 Variability in wind energy

Favourable, but realistic, weather conditions were used for the calculation of the performance of Flettner rotors. This was decided in order to get the maximum range of the possible change in EEOI, depending on the ship and the route. It was found that on some routes the reduction in EEOI is smaller.

Unlike other technical methods, wind energy can also be scaled to meet different cost requirements. For this reason, two different ship designs with Flettner rotors were considered in the Whole Ship Model (WSM). A "wind minimum" design has three Flettner rotors and should be compatible with most bulk carriers and oil tankers on most routes. The "wind maximum" design has a Flettner rotor on each bulkhead and, being more costly, this is likely to be only adopted on favourable routes. Flettner rotors were also considered to be more practical for ships with a smaller impact on deck operations compared to sails or kites.

The "wind maximum" design has been used in the combination of future technologies so it represents the maximum possible performance from wind energy. The different variants are labelled as Min. Flettner rotor and Max. Flettner rotor in tables 1 and 7.

3.6 Technical EEOI improvements for a 14.8 knot design speed MR Tanker

Three tables show the EEOI of the MR Tanker fitted with different technical energy efficiency methods.

The average annual EEOI for a MR Tanker in 2010 was based on the ship being 81% loaded with an average (median) annual speed of 11.7 knots. In the following tables the EEOI of energy efficiency methods operated at the 2010 EEOI speed is in bold and reductions of EEOI of more than 30% are highlighted.

	Operating Speed (knots)	**Baseline**	**Rudder bulb**	**Vane wheel**	**Contra rotating propeller (CRP)**	**End plated propeller**	**Air lubrication (AL)**	**Min. Flettner rotor**	**Max. Flettner rotor (FR)**
MR Tanker – hydrodynamic and renewable	4.4	80.2%	80.0%	79.9%	80.9%	80.0%	86.2%	71.3%	73.0%
	5.9	72.0%	71.7%	71.4%	72.8%	71.7%	75.9%	55.5%	57.0%
	8.8	77.6%	77.1%	76.6%	77.6%	77.1%	78.6%	56.5%	49.1%
	9.6	82.6%	82.0%	81.4%	81.9%	82.0%	83.0%	60.5%	52.6%
	10.4	88.0%	87.3%	86.6%	86.5%	87.3%	87.8%	65.0%	56.7%
	11.1	94.2%	93.4%	92.6%	91.7%	93.4%	93.6%	70.4%	61.8%
	11.5	98.1%	97.2%	96.4%	95.0%	97.2%	97.3%	73.8%	65.1%
	11.7	**100.0%**	**99.1%**	**98.2%**	**96.6%**	**99.1%**	**99.1%**	**75.5%**	**66.7%**
	11.8	101.5%	100.6%	99.7%	97.9%	100.6%	100.5%	76.8%	68.0%
	12.6	110.2%	109.2%	108.2%	105.4%	109.2%	108.8%	84.4%	75.3%
	14.1	135.7%	134.3%	133.0%	129.0%	134.3%	133.5%	104.7%	94.7%
	14.8	157.0%	155.4%	153.8%	152.0%	155.4%	154.5%	119.0%	108.0%

Table 1: EEOI of hydrodynamic and renewable methods for a MR Tanker (compared to 2010)

	Operating Speed (knots)	**Baseline**	**WHR steam (conventional)**	**WHR organic Rankine cycle (ORC)**	**WHR series turbocompounding**	**WHR parallel turbocompounding**	**Engine tuning**	**Engine derating**	**Speed controlled pumps and fans**
MR Tanker – Waste heat recovery (WHR) and machinery modification methods	4.4	80.2%	80.4%	80.2%	76.9%	80.2%	79.6%	79.9%	79.6%
	5.9	72.0%	72.2%	72.0%	69.5%	72.0%	71.4%	71.5%	71.5%
	8.8	77.6%	78.1%	77.6%	76.0%	77.6%	77.0%	76.8%	77.3%
	9.6	82.6%	83.2%	82.6%	81.1%	82.6%	82.0%	81.6%	82.3%
	10.4	88.0%	88.6%	88.0%	86.6%	88.0%	87.3%	86.8%	87.7%
	11.1	94.2%	94.9%	94.2%	92.9%	94.2%	93.4%	92.8%	94.0%
	11.5	98.1%	98.9%	96.6%	96.8%	98.1%	97.3%	96.6%	97.8%
	11.7	**100.0%**	**100.8%**	**98.4%**	**98.7%**	**100.0%**	**99.2%**	**98.5%**	**99.8%**
	11.8	101.5%	102.3%	99.8%	100.2%	101.5%	100.7%	99.9%	101.2%
	12.6	110.2%	107.6%	108.0%	109.0%	107.8%	109.3%	108.5%	110.0%
	14.1	135.7%	132.3%	132.1%	134.6%	132.6%	134.6%	133.4%	135.5%
	14.8	157.0%	153.0%	152.3%	156.0%	153.8%	155.7%	154.3%	156.8%

Table 2: EEOI of Waste Heat Recovery (WHR) and machinery modification methods for a MR Tanker (compared to 2010)

	Operating Speed (knots)	**Baseline**	**Block coefficient reduction (BR)**	**Current combination (used in 2015)**	**Future combination (with CRP, AL, ORC, BR)**	**Future combination with wind (with CRP, AL, ORC, BC and FR)**	**Future combination with FR and 25% carbon factor**	**Future combination with FR and 50% carbon factor**	**Future combination with FR and 75% carbon factor**
MR Tanker – block coefficient reduction and combinations	4.4	80.2%	79.7%	79.3%	85.7%	70.8%	53.1%	35.4%	17.7%
	5.9	72.0%	71.3%	71.0%	74.8%	53.8%	40.4%	26.9%	13.5%
	8.8	77.6%	76.1%	76.3%	74.8%	42.7%	32.0%	21.4%	10.7%
	9.6	82.6%	80.8%	81.1%	77.7%	45.1%	33.8%	22.6%	11.3%
	10.4	88.0%	85.8%	86.3%	81.1%	48.0%	36.0%	24.0%	12.0%
	11.1	94.2%	91.5%	92.4%	83.5%	50.1%	37.6%	25.0%	12.5%
	11.5	98.1%	95.1%	96.1%	83.7%	50.1%	37.6%	25.1%	12.5%
	11.7	**100.0%**	**96.9%**	**97.8%**	**84.7%**	**51.0%**	**38.3%**	**25.5%**	**12.8%**
	11.8	101.5%	98.2%	99.2%	85.5%	51.8%	38.8%	25.9%	12.9%
	12.6	110.2%	106.2%	103.7%	90.3%	55.9%	42.0%	28.0%	14.0%
	14.1	135.7%	129.3%	126.5%	109.3%	68.7%	51.5%	34.3%	17.2%
	14.8	157.0%	148.3%	146.1%	131.4%	79.5%	59.7%	39.8%	19.9%

Table 3: EEOI of block coefficient reduction and combinations of methods for a MR Tanker (compared to 2010). Note that the future combinations also include some technologies being used in 2015 and stern flaps or block coefficient reduction, depending on the ship type (this is explained in section 3.4)

The ship specific measure shown in table 3 is a block coefficient reduction, which is applicable to both tankers and bulk carriers. This is the benefit of improving the shape of the ship for better through-water performance. Container ships already have a lower block coefficient so this design option has not been applied to the 5000 TEU container ship. The right columns show the impact of changing fuels to bio-fuels blends with a lower carbon factors to that of HFO.

3.7 Technical EEOI improvements for a 25.1 knot design speed 5000 TEU container ship

Three tables show the EEOI of the 5000 TEU container ship fitted with different technical energy efficiency methods.

The average annual EEOI for a 5000 TEU container ship in 2010 was based on the ship being 68% loaded with an average (median) annual speed of 16.3 knots. In the following tables the EEOI of energy efficiency methods operated at the 2010 EEOI speed is in bold and reductions of EEOI of more than 30% are highlighted.

	Operating Speed (knots)	**Baseline**	**Rudder bulb**	**Vane wheel**	**Contra rotating propeller (CRP)**	**End plated propeller**	**Air lubrication (AL)**
5000 TEU container ship – hydrodynamic and renewable	7.5	77.1%	76.6%	76.2%	78.5%	76.6%	80.0%
	10.0	75.9%	75.3%	74.8%	77.1%	75.3%	76.8%
	14.9	92.0%	91.1%	90.2%	91.4%	91.1%	90.7%
	16.3	**100.0%**	**98.9%**	**98.0%**	**98.3%**	**98.9%**	**98.2%**
	17.6	108.4%	107.2%	106.2%	105.4%	107.2%	106.1%
	18.8	119.0%	117.7%	116.4%	114.2%	117.7%	116.2%
	19.5	125.4%	124.0%	122.7%	119.5%	124.0%	122.4%
	19.8	128.5%	127.0%	125.7%	122.0%	127.0%	125.4%
	20.1	130.9%	129.4%	128.0%	124.0%	129.4%	127.7%
	21.3	146.5%	144.7%	143.2%	137.0%	144.7%	142.8%
	23.8	193.8%	191.5%	189.3%	179.5%	191.5%	189.0%
	25.1	231.9%	229.1%	226.5%	220.8%	229.1%	226.3%

Table 4: EEOI of hydrodynamic and renewable methods for a 5000 TEU container ship (compared to 2010)

	Operating Speed (knots)	**Baseline**	**WHR steam (conventional)**	**WHR organic Rankine cycle (ORC)**	**WHR series turbocompounding**	**WHR parallel turbocompounding**	**Engine tuning**	**Engine derating**	**Speed controlled pumps and fans**
5000 TEU container ship – Waste heat recovery (WHR) and machinery modification methods	7.5	77.1%	77.5%	77.1%	75.0%	77.1%	76.5%	76.3%	76.7%
	10.0	75.9%	76.3%	75.9%	74.3%	75.9%	75.3%	75.0%	75.6%
	14.9	92.0%	92.7%	92.0%	90.9%	92.0%	91.3%	90.6%	91.8%
	16.3	**100.0%**	**100.8%**	**100.0%**	**99.0%**	**100.0%**	**99.2%**	**98.4%**	**99.8%**
	17.6	108.4%	109.4%	108.4%	107.5%	108.4%	107.6%	106.6%	108.3%
	18.8	119.0%	120.1%	119.0%	118.1%	119.0%	118.0%	116.9%	118.8%
	19.5	125.4%	126.6%	125.4%	124.6%	125.4%	124.4%	123.2%	125.3%
	19.8	128.5%	129.7%	128.5%	127.7%	128.5%	127.5%	126.2%	128.4%
	20.1	130.9%	132.1%	130.9%	130.1%	130.9%	129.8%	128.6%	130.7%
	21.3	146.5%	147.9%	143.2%	145.7%	146.5%	145.3%	143.8%	146.3%
	23.8	193.8%	189.1%	187.8%	193.1%	189.1%	192.3%	190.2%	193.7%
	25.1	231.9%	226.1%	224.0%	231.3%	227.1%	230.1%	227.5%	231.8%

Table 5: EEOI of Waste Heat Recovery (WHR) and machinery modification methods for a 5000 TEU container ship (compared to 2010)

	Operating Speed (knots)	**Baseline**	**Stern flap (SF)**	**Current combination (used in 2015)**	**Future combination (with CRP, AL, ORC, SF)**	**Future combination and 25% carbon factor**	**Future combination and 50% carbon factor**	**Future combination and 75% carbon factor**
5000 TEU container ship – stern flap and combinations	7.5	77.1%	77.8%	75.2%	77.1%	57.9%	38.6%	19.3%
	10.0	75.9%	76.5%	73.8%	73.9%	55.4%	37.0%	18.5%
	14.9	92.0%	92.8%	88.9%	86.2%	64.7%	43.1%	21.6%
	16.3	**100.0%**	**100.9%**	**96.6%**	**92.5%**	**69.4%**	**46.2%**	**23.1%**
	17.6	108.4%	109.4%	104.6%	98.9%	74.2%	49.5%	24.7%
	18.8	119.0%	120.0%	114.7%	107.2%	80.4%	53.6%	26.8%
	19.5	125.4%	126.4%	120.9%	109.7%	82.3%	54.8%	27.4%
	19.8	128.5%	129.5%	123.8%	111.8%	83.8%	55.9%	27.9%
	20.1	130.9%	131.9%	126.0%	113.4%	85.0%	56.7%	28.3%
	21.3	146.5%	147.5%	135.3%	120.6%	90.4%	60.3%	30.1%
	23.8	193.8%	194.6%	177.2%	155.8%	116.8%	77.9%	38.9%
	25.1	231.9%	231.8%	211.5%	194.1%	145.6%	97.0%	48.5%

Table 6: EEOI of stern flap and combinations of methods for a 5000 TEU container ship (compared to 2010). Note that the future combinations also include some technologies being used in 2015 and stern flaps or block coefficient reduction, depending on the ship type (this is explained in section 3.4)

The ship specific method shown in table 6 is a stern flap, which is applicable to container ships that operate at higher speeds, but not to both tankers and bulkers. This is the benefit of improving the wake of the ship for better through-water performance. The right columns show the impact of changing fuels to bio-fuels blends with a lower carbon factors to that of HFO.

3.8 Technical EEOI improvements for a 15.3 knot design speed Panamax bulk carrier

Three tables show the EEOI of a MR Tanker fitted with different technical energy efficiency methods.

The average annual EEOI for a Panamax bulk carrier in 2010 was based on the ship being 90% loaded with an average (median) annual speed of 11.9 knots. In the following tables the EEOI of energy efficiency methods operated at the 2010 EEOI speed is in bold and reductions of EEOI of more than 30% are highlighted.

	Operating Speed (knots)	**Baseline**	**Rudder bulb**	**Vane wheel**	**Contra rotating propeller (CRP)**	**End plated propeller**	**Air lubrication (AL)**	**Min. Flettner rotor**	**Max. Flettner rotor (FR)**
Panamax bulk carrier – hydrodynamic and renewable	4.6	43.2%	42.7%	42.5%	43.6%	42.7%	49.3%	31.9%	34.1%
	6.1	46.8%	46.1%	45.8%	47.1%	46.1%	50.3%	28.8%	28.3%
	9.1	67.2%	65.9%	65.3%	65.8%	65.9%	66.7%	45.3%	29.1%
	9.9	75.9%	74.4%	73.7%	73.5%	74.4%	74.6%	53.0%	35.8%
	10.7	84.6%	82.8%	82.0%	80.8%	82.8%	82.4%	60.5%	42.6%
	11.5	94.1%	92.2%	91.2%	88.9%	92.2%	91.2%	69.2%	50.6%
	11.9	**100.0%**	**97.9%**	**96.8%**	**93.8%**	**97.9%**	**96.6%**	**74.6%**	**55.7%**
	12.1	102.9%	100.7%	99.6%	96.2%	100.7%	99.3%	77.2%	58.1%
	12.2	105.1%	102.8%	101.7%	98.1%	102.8%	101.3%	79.2%	60.0%
	13.0	117.9%	115.3%	114.1%	108.9%	115.3%	113.4%	90.8%	71.2%
	14.5	154.4%	151.0%	149.3%	141.5%	151.0%	148.1%	121.8%	100.5%
	15.3	184.7%	180.5%	178.5%	172.5%	180.5%	177.2%	144.1%	120.4%

Table 7: EEOI of hydrodynamic and renewable methods for a Panamax bulk carrier (compared to 2010)

	Operating Speed (knots)	**Baseline**	**WHR steam (conventional)**	**WHR organic Rankine cycle (ORC)**	**WHR series turbocompounding**	**WHR parallel turbocompounding**	**Engine tuning**	**Engine derating**	**Speed controlled pumps and fans**
Panamax bulk carrier – WHR and machinery modifications	4.6	43.2%	43.3%	43.2%	41.7%	43.2%	42.8%	42.8%	42.9%
	6.1	46.8%	47.0%	46.8%	45.7%	46.8%	46.4%	46.2%	46.6%
	9.1	67.2%	67.7%	67.2%	66.5%	67.2%	66.7%	66.1%	67.1%
	9.9	75.9%	76.6%	75.9%	75.3%	75.9%	75.3%	74.6%	75.8%
	10.7	84.6%	85.3%	84.6%	83.9%	84.6%	83.9%	83.1%	84.4%
	11.5	94.1%	95.0%	94.1%	93.6%	94.1%	93.4%	92.5%	94.0%
	11.9	**100.0%**	**101.0%**	**100.0%**	**99.4%**	**100.0%**	**99.2%**	**98.2%**	**99.9%**
	12.1	102.9%	103.9%	100.9%	102.3%	102.9%	102.0%	101.0%	102.8%
	12.2	105.1%	106.1%	103.0%	104.5%	105.1%	104.2%	103.1%	105.0%
	13.0	117.9%	114.7%	115.2%	117.4%	114.8%	116.9%	115.7%	117.8%
	14.5	154.4%	150.3%	150.1%	154.0%	150.5%	153.2%	151.5%	154.4%
	15.3	184.7%	179.3%	178.8%	184.2%	180.6%	183.2%	181.1%	184.6%

Table 8: EEOI of Waste Heat Recovery (WHR) and machinery modification methods for a Panamax bulk carrier (compared to 2010)

	Operating Speed (knots)	**Baseline**	**Block coefficient reduction (BR)**	**Current combination (used in 2015)**	**Future combination (with CRP, AL, ORC, BR)**	**Future combination with wind (with CRP, AL, ORC, BR and FR)**	**Future combination with FR and 25% carbon factor**	**Future combination with FR and 50% carbon factor**	**Future combination with FR and 75% carbon factor**
Panamax bulk carrier – block reduction, method combinations	4.6	43.2%	43.4%	42.0%	49.3%	34.6%	26.0%	17.3%	8.7%
	6.1	46.8%	46.5%	45.2%	49.6%	26.9%	20.2%	13.4%	6.7%
	9.1	67.2%	65.4%	64.4%	62.6%	22.9%	17.2%	11.5%	5.7%
	9.9	75.9%	73.4%	72.7%	68.7%	28.0%	20.9%	13.9%	7.0%
	10.7	84.6%	81.3%	80.8%	74.5%	33.0%	24.8%	16.5%	8.3%
	11.5	94.1%	89.9%	89.8%	79.3%	37.1%	27.8%	18.6%	9.3%
	11.9	**100.0%**	**95.2%**	**95.3%**	**80.6%**	**38.1%**	**28.6%**	**19.1%**	**9.5%**
	12.1	102.9%	97.7%	97.9%	82.2%	39.6%	29.7%	19.8%	9.9%
	12.2	105.1%	99.7%	100.0%	83.4%	40.7%	30.5%	20.4%	10.2%
	13.0	117.9%	111.0%	107.3%	90.7%	47.2%	35.4%	23.6%	11.8%
	14.5	154.4%	142.9%	139.1%	116.2%	65.7%	49.3%	32.9%	16.4%
	15.3	184.7%	168.9%	167.4%	145.7%	81.1%	60.8%	40.5%	20.3%

Table 9: EEOI of block coefficient reduction and combinations of methods for a Panamax bulk carrier (compared to 2010). Note that the future combinations also include some technologies being used in 2015 and stern flaps or block coefficient reduction, depending on the ship type (this is explained in section 3.4)

As with the MR Tanker, the ship specific method shown in table 9 is a block coefficient reduction, which is applicable to both tankers and bulkers. This is the benefit of improving the shape of the ship for better through-water performance. Container ships already have a lower block coefficient so this design option has not been applied to the 5000 TEU container ship. The right columns show the impact of changing fuels to bio-fuels blends with a lower carbon factors to that of HFO.

3.9 Operational methods to reduce EEOI

A combination of methods to reduce EEOI amounted to a 3.1% to 6.1% reduction in EEOI for the same operating speed depending on the ship type.

Similar to the technical efficiency methods, operating methods were calculated at a range of operational speeds. Any changes to the operational methods have to be considered in combination with the condition of the hull and the on-board equipment. For this work, a constant 9% increase in resistance was assumed because of degradation and hull fouling. This is important because it affects how hull cleaning operational methods are calculated in the WSM. Note that hull coatings should also be considered carefully with hull cleaning and hull fouling.

Three operating methods to reduce EEOI were investigated:

.1 trim optimization;

.2 propeller polishing; and

.3 hull cleaning.

The performance of these methods were examined in combination but it was assumed that hull cleaning and propeller polishing could not be used together in combination, so only hull cleaning and trim optimization were used in combination.

	Operating Speed (knots)	**Baseline**	**Trim optimization (TO)**	**Propeller polishing (PP)**	**Hull cleaning (HC)**	**Operational combination (TO and HC)**
MR Tanker – operational methods	4.4	80.2%	80.1%	79.8%	79.9%	79.6%
	5.9	72.0%	71.8%	71.3%	71.5%	71.0%
	8.8	77.6%	77.3%	76.3%	76.7%	75.8%
	9.6	82.6%	82.2%	81.1%	81.5%	80.5%
	10.4	88.0%	87.5%	86.2%	86.7%	85.5%
	11.1	94.2%	93.6%	92.2%	92.8%	91.4%
	11.5	98.1%	97.5%	95.9%	96.6%	95.1%
	11.7	**100.0%**	**99.3%**	**97.8%**	**98.4%**	**96.9%**
	11.8	101.5%	100.8%	99.2%	99.9%	98.3%
	12.6	110.2%	109.5%	107.6%	108.4%	106.7%
	14.1	135.7%	134.7%	132.3%	133.7%	131.4%
	14.8	157.0%	156.0%	153.0%	155.0%	152.3%

Table 10: EEOI of operational methods and a combination of operational methods for a MR Tanker (compared to 2010)

	Operating Speed (knots)	Baseline	Trim optimization (TO)	Propeller polishing (PP)	Hull cleaning (HC)	Operational combination (TO and HC)
5000 TEU container ship – operational methods	7.5	77.1%	77.1%	75.9%	76.3%	75.8%
	10.0	75.9%	75.4%	74.5%	74.1%	73.1%
	14.9	92.0%	91.3%	89.8%	89.5%	88.1%
	16.3	**100.0%**	**99.3%**	**97.5%**	**97.3%**	**95.7%**
	17.6	108.4%	107.6%	105.6%	105.4%	103.6%
	18.8	119.0%	118.1%	115.8%	115.8%	113.7%
	19.5	125.4%	124.4%	122.0%	122.0%	119.9%
	19.8	128.5%	127.5%	125.0%	125.1%	122.9%
	20.1	130.9%	129.9%	127.3%	127.4%	125.2%
	21.3	146.5%	145.3%	142.4%	142.7%	140.1%
	23.8	193.8%	192.2%	188.3%	189.3%	185.8%
	25.1	231.9%	230.0%	225.2%	227.0%	222.8%

Table 11: EEOI of operational methods and a combination of operational methods for a 5000 TEU container ship (compared to 2010)

	Operating Speed (knots)	Baseline	Trim optimization (TO)	Propeller polishing (PP)	Hull cleaning (HC)	Operational combination (TO and HC)
Panamax bulk carrier – operational methods	4.6	43.2%	42.8%	42.4%	42.3%	41.9%
	6.1	46.8%	46.2%	45.6%	45.4%	44.9%
	9.1	67.2%	66.1%	65.0%	64.6%	63.5%
	9.9	75.9%	74.7%	73.4%	72.9%	71.7%
	10.7	84.6%	83.1%	81.5%	81.0%	79.6%
	11.5	94.1%	92.4%	90.7%	90.1%	88.5%
	11.9	**100.0%**	**98.2%**	**96.3%**	**95.7%**	**93.9%**
	12.1	102.9%	101.0%	99.0%	98.4%	96.6%
	12.2	105.1%	103.1%	101.1%	100.5%	98.6%
	13.0	117.9%	115.6%	113.4%	112.8%	110.6%
	14.5	154.4%	151.5%	148.5%	148.1%	145.2%
	15.3	184.7%	181.2%	177.4%	177.5%	174.1%

Table 12: EEOI of operational methods and a combination of operational methods for a Panamax bulk carrier (compared to 2010)

The hull coating that was examined was based on document MEPC 62/INF.7 (specifically hull coating 2).

The limitation to this study is that the operational methods were examined on a steady state basis. In order to account for this, an average deterioration in the ship's hull and engine performance, from the designed condition of 9% was assumed.

The data for some of the operational methods (but not their combinations) are presented in the tables in sections 3.6, 3.7 and 3.8 and annex 2.

3.10 Comparison with existing studies on efficiency methods submitted to the IMO

A study carried out for the IMO by SSPA, in document MEPC 69/INF.11, uses questionnaires and case studies that explain the SSPA's experience in efficiency methods that are currently being adopted. The SSPA case studies discuss the practicalities of utilizing technical and operational efficiency methods. The demographic of the case studies in document MEPC 69/INF.11 and its application to international shipping is unclear, however some of the technical efficiency methods that are being described as being adopted; including engine derating, do correspond with document MEPC 69/INF.8, which has been used as a reference for this study to understand what methods are being used by the shipping industry at the moment.

Document MEPC 69/INF.18 explains the assumptions used in the energy efficiency appraisal tool commissioned by the IMO. The spreadsheet tool includes an investment calculation and gives some degree of uncertainty for each efficiency method. Although some care is taken to ensure that technical methods are properly combined, these are not combined as part of the ship design process, but are considered individually. This reduces the accuracy of the model. The biggest inaccuracy is that changing the ship speed is considered as an operational method instead of being an input to the calculation process. In reality the operating speed of the ship impacts on the effectiveness of methods and their profitability.

Further comparisons can be made with earlier studies. The Second IMO GHG Study identified reduction potentials of 25-75% on 2007 ship parameters, through a combination of technologies and operational methods (Buhaug et al. [2009]).

Similar reductions in emissions to this study and Buhaug et al. [2009] were found in a study by OCIMF in document MEPC 63/INF.7. The literature review by OCIMF found:

.1 a 6.5% CO_2 emissions reduction from propulsion methods;

.2 a 7.0% CO_2 emissions reduction from machinery methods (this includes recovering waste heat from exhaust emissions and using sails); and

.3 a 30.0% CO_2 emissions reduction from reducing resistance (this includes a reduction in design speed, which accounts for 24% of this value).

The OCIMF study also mentioned that propulsion options are not cumulative. It should also be noted that the OCIMF study does contain information on the negative impact on CO_2 emissions because of compliance with regulations and the application of ballast water treatment systems, scrubbers, etc.

A study submitted by IMarEST with document MEPC 62/INF.7 contains costs and performance gains for different energy efficiency methods and ship types, which also includes a high and low performance gain for each method. Both IMarEST and another study submitted by Lloyd's Register and DNV in document MEPC 63/INF.2 considered speed reduction as a method with a high reduction in CO_2 emissions.
To summarize, the CO_2 emission reduction potential of the methods in this study are similar to those given in past IMO submissions. Studies so far have considered operational speed as a method. This study considers speed as an additional parameter that has an impact on the EEOI of a ship together with the other different methods

3.11 Overall findings on the gains from energy efficiency methods

If the technical methods that were being widely implemented in 2015 were used in combination and at the same operating speed as in 2010, which is unlikely, then a decrease in EEOI of 4.7% for a 5000 TEU container ship and 3.3% for a MR Tanker may be achievable due to technology that is currently being used by the shipping industry. Hull coatings and operational methods accounted for 3.2% reduction in EEOI at 11.7 knots and a 4.3% reduction in EEOI at 16.3 knots for the container ship.

The maximum possible EEOI reduction by reducing speed is high compared to combined technical and operational methods. Combinations of methods with a small speed reduction can easily result in and EEOI decrease of over 10%, this is similar to previous studies.

Using a future combination of technologies, without reducing speed, results in a reduction in EEOI of 10.4% for the 5000 TEU container ship and 32.4% for the MR Tanker. This is mainly due to the MR Tanker benefiting from both block coefficient reduction and wind technologies, which are more effective for slower ships and have more deck space that could be used. While tankers and bulk carriers can benefit from technologies, as other studies have shown there is much potential to reduce EEOI from reducing speed.

According to this work and the survey in document MEPC 69/INF.8, there are technical and operational methods on the market that have not been used by the shipping industry, even though they have shown a reduction in fuel consumption, represented as a reduction in EEOI. This could be happening because of the existence of market barriers or because the economic incentive is not sufficient.

As more methods are used in combination, the potential reduction in EEOI decreases. While there are some ways to reduce waste heat from places where heat is not normally recovered, the potential gains appear to be much less than air lubrication and wind technologies.

3.12 Designing ships to particular speeds and conditions

As ships often operate away from their design point the efficiency of some components decreases. For example, it can be seen in table 5 that a conventional waste heat recovery plant is not efficient until the 5000 TEU container ship gets close to its 25.1 knots design speed. The 25.1 knots design speed ship had a 16.3 knots median speed in 2010 and in this case all the theoretical reductions in EEOI due to WHR would have been lost.

In order to fully demonstrate the gains from designing ships to match their operating speed the same 5000 TEU container ship was designed with a design speed of 19.2 knots, instead of 25.1 knots. So the 16.3 knots median EEOI speed now occurs at 85% of the maximum speed of the ship. Table 13 shows all the waste heat recovery methods for a 19.2 knots design speed ship. Annex 2 gives the calculated results for the lower design speed container ship with a range of technical and operational methods. It can be seen that these devices are more effective at the median ship speed in 2010 and speeds just below the median ship speed compared to the 25.1 knots ship in table 5.

	Speed (knots)	**Baseline**	**WHR steam (conventional)**	**WHR organic Rankine cycle (ORC)**	**WHR series turbocompounding**	**WHR parallel turbocompounding**
19.2 knot 5000 TEU Container Ship – Waste heat recovery (WHR)	5.8	79%	78.8%	78.6%	75.3%	78.6%
	7.7	70%	70.3%	70.0%	67.6%	70.0%
	11.4	74%	74.5%	74.1%	72.4%	74.1%
	12.5	78%	78.3%	77.8%	76.3%	77.8%
	13.4	82%	82.7%	82.2%	80.7%	82.2%
	14.4	87%	87.8%	87.1%	85.8%	87.1%
	14.9	90%	90.9%	88.7%	88.9%	90.1%
	15.2	92%	92.4%	90.2%	90.5%	91.7%
	15.3	93%	93.7%	91.3%	91.7%	92.9%
	16.3	**100%**	**97.8%**	**97.9%**	**98.8%**	**97.9%**
	18.2	120%	117.5%	116.9%	119.3%	117.6%
	19.2	137%	133.5%	132.4%	135.8%	134.1%

Table 13: EEOI of Waste Heat Recovery (WHR) methods for a 19.2 knots design speed 5000 TEU Container Ship

In the WSM the block coefficient of the hull has to also increase. The block coefficient is recalculated for the lower design speed. Generally, faster ships have a more slender hull form to reduce resistance. This can achieve large changes in EEOI without considering technical or operational methods.

Some technologies, such as air lubrication, have an auxiliary power demand in use, which is impacted by how the ratio between the propulsion and auxiliary power vary with ship speed. Most technologies, particularly hydrodynamic technologies, have more potential of reducing EEOI at higher speed, however wind technologies work in the opposite direction, producing higher EEOI reductions at lower speeds.

4 Conclusions

The findings from this study are consistent with findings in the Second and Third IMO GHG Studies. The Second IMO GHG Study identified reduction potentials of 25% to 75% on 2007 ship parameters, through a combination of technologies and operational methods with much potential attributable to speed reductions, which were then observed in the Third IMO GHG Study, becoming apparent during 2010 to 2012.

This study shows that whilst maintaining the same operating speeds the maximum CO_2 emission reduction opportunity from combinations of incremental energy efficiency technologies is a reduction in EEOI of 7.5% to 19.4% depending on the ship type. This does not include wind energy.

Operational methods account for a potential additional reduction of 3.1% to 6.1% due to operational methods to the baseline 2010 ships used in this study (this does not include speed reductions, which are also given in the study).

This study has also shown that, when using waste heat recovery and the operational speed is changed so that the ship is operating far away from its design point, the original design/reference speed and power output for which propellers and machinery may have been optimized, there are diminishing returns on emissions reduction that could in certain cases increase emissions.

The 2010 baseline ships fitted with a combination of technologies, found to be used from those shipping companies that were surveyed in 2015, have a maximum EEOI reduction of 3.4% to 10.2%, whilst maintaining the same operational speed. The survey, as indicated in document MEPC 69/INF.8, showed that the uptake of energy efficiency technologies is low, the wide scale implementation of which may be impeded due to the existence of market barriers and failures.

There are several reasons for the lack of uptake of the energy efficiency methods that show significant improvement in energy efficiency and high reduction potentials in emissions (see for example in the case of wind technologies [Rehmatulla, Parker, Smith, & Stulgis, 2017]. The lack of implementation can be due to market barriers (e.g. access and cost of capital, risks) and market failures (e.g. split incentives and imperfect and asymmetric information) [Rehmatulla & Smith, 2015b]. There is increasing evidence for the existence of market failures in shipping, especially related to split incentives [Rehmatulla & Smith, 2015a] and imperfect and asymmetric information [Prakash, Smith, Rehmatulla, Mitchell, & Adland, 2016] and this is an important finding as policy intervention is one way to rectify these market failures.

To go beyond a 7.5% to 19.4% EEOI reduction for technical methods requires some combination of a significant reduction in design speed (or speed associated with a ship's design optimization), the use of wind energy and/or fuels with a lower carbon factor (electrification, bioenergy or synthetic fuels). When combining multiple technical methods with an additional reduced fuel carbon factor by using bio-fuels and high use of wind energy (Flettner rotors), the EEOI reduction opportunity becomes between 53.8% and 80.9% (50% reduction in carbon factor) and between 76.9% and 90.5% (75% reduction in carbon factor). This is whilst maintaining the same operational speed.

This is an important reframing of the challenge ahead for shipping – incremental energy efficiency (technical and operational) appears necessary but not sufficient, decarbonization of the energy supply for ships (e.g. renewable energy and non-fossil fuels) are likely to be key to achieve deep decarbonization.

A number of new technologies are currently entering into ships driven by wider MARPOL developments (e.g. ballast water treatment systems, scrubbers). The cumulative impact of compliance with these and other environmental regulations on the emission reductions presented here is the subject of ongoing work.

This work has considered the variability in CO_2 emissions reduction from different ship types and operational speeds. Future work will expand this work to consider the uncertainty in the performance of technical and operational methods. The analysis and calculation of technical and operational methods has used stringent data, and assumptions.

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ANNEX 2

ADDITIONAL CALCULATED EEOI IMPROVEMENTS

1 Technical EEOI improvements for a 19.2 knot design speed 5000 TEU container ship

Three tables show the EEOI of a 5000 TEU container ship fitted with different technical energy efficiency methods.

The average annual EEOI for a 5000 TEU container ship in 2010 was based on the ship being 68% loaded with an average (median) annual speed of 16.3 knots. In the following tables the EEOI of energy efficiency methods operated at the 2010 EEOI speed is in bold and reductions of EEOI of more than 30% are highlighted.

	Operating Speed (knots)	**Baseline**	**Rudder bulb**	**Vane wheel**	**Contra rotating propeller (CRP)**	**End plated propeller**	**Air lubrication (AL)**
5000 TEU container ship – hydrodynamic and renewable	5.8	78.6%	78.2%	78.0%	79.5%	78.2%	85.0%
	7.7	70.0%	69.5%	69.2%	70.9%	69.5%	73.9%
	11.4	74.1%	73.0%	72.5%	73.9%	73.0%	75.3%
	12.5	77.8%	76.6%	76.1%	77.0%	76.6%	78.5%
	13.4	82.2%	80.8%	80.2%	80.5%	80.8%	82.4%
	14.4	87.1%	85.6%	84.9%	84.5%	85.6%	86.9%
	14.9	90.1%	88.6%	87.8%	87.0%	88.6%	89.7%
	15.2	91.7%	90.1%	89.3%	88.3%	90.1%	91.2%
	15.3	92.9%	91.3%	90.5%	89.3%	91.3%	92.3%
	16.3	**100.0%**	**98.2%**	**97.3%**	**95.2%**	**98.2%**	**99.0%**
	18.2	120.3%	117.9%	116.8%	113.7%	117.9%	118.4%
	19.2	136.8%	134.0%	132.6%	131.3%	134.0%	134.4%

Table 14: EEOI of hydrodynamic and renewable methods for a 5000 TEU container ship (compared to 2010)

	Operating Speed (knots)	Baseline	WHR steam (conventional)	WHR organic Rankine cycle (ORC)	WHR series turbocompounding	WHR parallel turbocompounding	Engine tuning	Engine derating	Speed controlled pumps and fans
5000 TEU container ship – Waste heat recovery (WHR) and machinery modification methods	5.8	78.6%	78.8%	78.6%	75.3%	78.6%	78.0%	78.2%	78.0%
	7.7	70.0%	70.3%	70.0%	67.6%	70.0%	69.5%	69.5%	69.6%
	11.4	74.1%	74.5%	74.1%	72.4%	74.1%	73.5%	73.2%	73.8%
	12.5	77.8%	78.3%	77.8%	76.3%	77.8%	77.2%	76.8%	77.5%
	13.4	82.2%	82.7%	82.2%	80.7%	82.2%	81.5%	81.0%	81.9%
	14.4	87.1%	87.8%	87.1%	85.8%	87.1%	86.4%	85.9%	86.9%
	14.9	90.1%	90.9%	88.7%	88.9%	90.1%	89.4%	88.8%	89.9%
	15.2	91.7%	92.4%	90.2%	90.5%	91.7%	91.0%	90.3%	91.5%
	15.3	92.9%	93.7%	91.3%	91.7%	92.9%	92.2%	91.5%	92.7%
	16.3	**100.0%**	**97.8%**	**97.9%**	**98.8%**	**97.9%**	**99.2%**	**98.4%**	**99.8%**
	18.2	120.3%	117.5%	116.9%	119.3%	117.6%	119.3%	118.3%	120.1%
	19.2	136.8%	133.5%	132.4%	135.8%	134.1%	135.7%	134.4%	136.6%

Table 15: EEOI of Waste Heat Recovery (WHR) and machinery modification methods for a 5000 TEU container ship (compared to 2010)

	Operating Speed (knots)	Baseline	Stern flap (SF)	Current combination (used in 2015)	Future combination (with CRP, AL, ORC)	Future combination and 25% carbon factor	Future combination and 50% carbon factor	Future combination and 75% carbon factor
5000 TEU container ship – stern flap and combinations of methods	5.8	78.6%	78.7%	77.1%	80.0%	60.0%	40.0%	20.0%
	7.7	70.0%	70.2%	68.4%	69.8%	52.3%	34.9%	17.4%
	11.4	74.1%	74.3%	71.6%	70.2%	52.7%	35.1%	17.6%
	12.5	77.8%	78.1%	75.0%	72.6%	54.5%	36.3%	18.2%
	13.4	82.2%	82.4%	79.1%	75.6%	56.7%	37.8%	18.9%
	14.4	87.1%	87.4%	83.7%	77.5%	58.1%	38.8%	19.4%
	14.9	90.1%	90.4%	86.5%	79.3%	59.5%	39.6%	19.8%
	15.2	91.7%	92.0%	87.9%	78.4%	58.8%	39.2%	19.6%
	15.3	92.9%	93.2%	89.0%	79.1%	59.3%	39.5%	19.8%
	16.3	**100.0%**	**100.3%**	**92.3%**	**83.3%**	**62.4%**	**41.6%**	**20.8%**
	18.2	120.3%	120.6%	109.7%	98.3%	73.7%	49.1%	24.6%
	19.2	136.8%	137.1%	124.3%	114.7%	86.0%	57.4%	28.7%

Table 16: EEOI of stern flap and combinations of methods for a 5000 TEU container ship (compared to 2010). Note that the future combinations also include some technologies being used in 2015 and stern flaps or block coefficient reduction, depending on the ship type (this is explained in section 3.4)

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ANNEX 3

SHIP PERFORMANCE CALCULATION USING WHOLE SHIP MODEL

1 Introduction

The engineering calculations used in the Whole Ship Model (WSM) is a bottom-up approach, piecing together the individual components of each ship in order to accurately model the changes to ships due to technical and operational efficiency methods.

The most relevant aspects of the WSM are explained in this annex, a more detailed recent description from October 2016, in the High-Performance Marine Vehicles (HIPER) conference proceedings at http://data.hiper-conf.info/Hiper2016_Cortona.pdf.

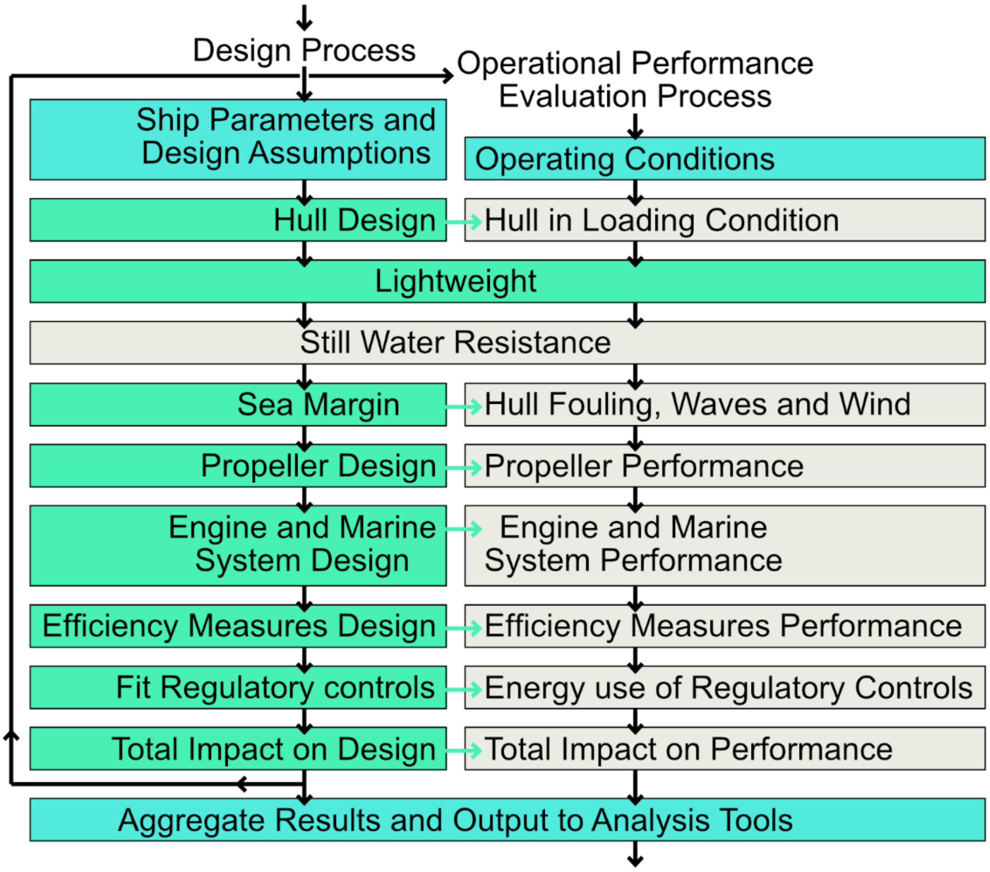

Figure 1: Whole Ship Model Overview

The Whole Ship Model contains an iterative ship design process that incorporates the demands of efficiency methods, fixing the main characteristics of the ship. The performance of the designed ship is then calculated by running the ship at a range of speeds. This is carried out for each ship and technical efficiency method combination that is to be examined, as shown in figure 1.

2 Resistance, propeller and engine performance calculations

The resistance and propeller performance are calculated using a regression method based on ship model tests at MARIN by Holtrop and Mennen [1982] updated by Holtrop [1984] and the Wageningen B-series propellers by Oosterveld & Oossnan [1975], respectively. The engine model selects the main and auxiliary machinery required by the ship specification; using engine data provided by MAN Diesel & Turbo project guides [Man Diesel & Turbo, 2013].

3 Added resistance and degradation calculations

Added resistance is the increase in ship resistance due to the direction of the wind and waves, which may also include air resistance. Degradation is the deterioration of the ship's hull, engine and propeller over time. At any point in the lifetime of the ship both added resistance and degradation, which include hull fouling, can vary significantly depending on the operating conditions of the ship. Added resistance and degradation are represented as a 9% increase in the required power for all ships, representing an average value over the lifetime of the ship. Keeping this calculation constant also allows for comparisons to be made between ships.

In the design process, a sea margin of 15% is used (which is 10% for smaller ships), this is to calculate the performance of current ships.

4 Calculating the impact of energy efficiency methods

Efficiency methods are a group of technologies – hydrodynamic, mechanical or electrical – and operational choices – maintenance, routing and voyage optimisation – which, either individually or as a group, have an impact on the energy demand on board. Energy efficiency methods are defined in a Python file separate from the WSM, allowing different models to be used. The performance and cost of each energy efficiency measure are calculated based on their impacts on the ship. Ship impacts due to energy efficiency methods can be described as impacts on the calculated parameters that describe the ship for the engine and on-board machinery, the resistance (of the ship's hull) or other parameters. The way efficiency methods are combined is described in more detail in Calleya et al. [2016]. By describing the energy efficiency methods at the level of their physical interaction with the ship the performance of different energy efficiency methods can be calculated for different combinations of ships and energy efficiency methods.

5 Energy efficiency methods used in this study

This table is a brief summary of the technologies that were considered for work carried out for the Danish Shipowners Association by Smith et al. [2016] that have been used in this study. For ship operators and investors in energy efficiency methods, it is more important to see what is being used on ships at the moment, so a column has been added to the table to show what is being used at the moment. This is based upon a survey conducted in 2015 that is explained in document MEPC 69/INF.8.

For the calculations in this document a bulbous bow was assumed to be part of the baseline ship specification. Although we know that a bulbous bow is not always appropriate, as explained in Grech La Rosa et al. [2015], they are often used.

Table 17, below, gives a brief explanation of the assumptions and data sources used; each technical efficiency method is based on a mathematical model, where indicated sea trials, model test data or research, have been used to back up the physics/engineering models in the WSM. Where mathematical models are based entirely on research they still do contain complex engineering/physics models. Some models are very complex and some are simpler, that is only scaling on one parameter.

Energy efficiency measure	**Currently available**	**Description**	**Scaling assumptions**	**Data Sources**
Rudder bulb	Yes	Rudder bulbs are fitted behind the propeller and improve propulsion efficiency	Calculated as a constant change in propulsion efficiency.	Sea trials.
Preswirl stator duct	Yes	A propeller duct with static blades that improves propulsion efficiency.	Calculated as a function of the propeller diameter and ship speed.	Sea trials.
Trim optimization	Yes	Changing the operating trim of the ship to reduce resistance.	Based on recorded in-service efficiency gains.	Sea trials.
Vane wheel	Yes	A freely rotating wheel behind the propeller that reduces propeller efficiency.	Calculated as a constant change in propulsion efficiency - very few trials exist.	Sea trials.
Contra rotating propeller	No	Two propellers on the same shaft rotating in opposite directions to improve propulsion efficiency	First principles model. Potential efficiency increase is high but very few trials exist.	Research.
End-plated propeller	Yes	Propeller that has shaped tips to reduce tip vortices improving propeller efficiency.	In particular the performance of a Contracted Loaded Tip (CLT) propeller has been calculated. The percentage saving varied with ship operational speed and propeller loading.	Sea trials and model tests.
Stern flap	Yes	Propeller that has shaped tips to reduce tip vortices improving propeller efficiency.	Calculated as a function of the parameter of the ships hull and speed. Based on US Navy trials.	Sea trials and model tests.
Low cost hull coating	Yes	Hull coating with a lower reduction in resistance and a lower cost	Constant reduction to the viscous resistance.	Based on MEPC 62/INF.7.
High cost hull coating	Yes	Hull coating with a bigger reduction in resistance and a higher cost	Constant reduction to the viscous resistance.	Based on MEPC 62/INF.7.
Air lubrication	Yes	A layer of air is injected on the flat bottom of the hull that reduces frictional resistance.	Reduction in the viscous resistance, values used come from running this model at different sea states. The benefit of this technology increases with operational speed. Checked against sea trial data.	Sea trials and Research.
Block coefficient reduction	Yes	Some bulk and oil tankers have large block coefficients to reduce build cost by making the	A number of ship studies were carried out to find the impact of reducing block coefficient. Constant	Research.

Energy efficiency measure	Currently available	Description	Scaling assumptions	Data Sources
		hull form more slender there is potential for large reductions in fuel consumption.	reduction in the overall and viscous resistance. Beam and length are kept the same.	
Flettner rotors	Yes	Rotating cylinders on the deck of the ship produce lift using the Magnus effect that can be used to provide thrust to the ship.	A first principles model is used that takes into account the required motor power. Thrust depends on the ship's operational speed. Constant values for drag, lift and momentum coefficients as well as wind speed and direction. Benefit of this device is highly dependent on route and weather conditions.	Research.
Superstructure mass reduction	No	Using alternative materials to reduce the weight of the superstructure.	Uses composite material and includes adhesives, bonds and fire retardant materials. The thickness of the composite material is such that it replicates the strength and stiffness of the marine steel.	Research.
Aerodynamic superstructure	No	Changing the shape of the superstructure to reduce wind resistance.	Constant reduction in the overall and viscous resistance. Dependent on the ship type.	Research.
Solar power	Yes	panels on deck that capture energy from sunlight and convert to electricity.	A constant insolation incident on a horizontal plane is used based on the global annual averaged values. A pessimistic efficiency is assumed for the solar panel so it can represent better the conditions in multiple routes. Panels are installed on top of the superstructure or when available deck space is available (up to 50%).	Research.
Energy saving lighting	Yes	Power savings due to a change from incandescent to LED.	Illuminated volumes inside the ship between 20% to 30%. Rooms illuminance requirements given by the American Bureau of Shipping [2012].	Research.
WHRS steam	Yes	Works with the exhaust gas system waste heat after it has gone through the waste heat boiler.	Based on the Rankine cycle. Depends on the engine loading and heat demand on board, considers ancillaries but assumes that there are no leakages from the system.	Research.

Energy efficiency measure	**Currently available**	**Description**	**Scaling assumptions**	**Data Sources**
			Increase in the exhaust gas backpressure is considered by a constant increase in the specific fuel oil consumption.	
WHRS ORC	No	Based on the Rankine cycle but uses organic fluids (i.e. that contains carbon atoms in its structure).	Assumes nonflammable refrigerant. Uses the waste heat available after the incoming air compression in the turbocharger. Depends on the engine loading and heat demand on board, considers ancillaries but assumes that there are no leakages from the system.	Research.
Turbocompounding series	No	Produces electrical work from the exhaust gas system after it has passed the turbine from the turbocharger.	It is applicable for auxiliary engines. Increase in the exhaust gas backpressure is considered by a constant increase in the specific fuel oil consumption.	Research.
Turbocompounding parallel	No	Uses a portion of the exhaust gas via a bypass system in the exhaust manifold to produce electrical power via a generator.	Used for the main engine. Power turbine efficiency changes with the engine loading.	Research.
Hybrid turbocharging	No	It generates electricity only when the engine load is higher than 60% MCR. Electricity generated will reduce the auxiliary engine loading but at the same time the generator can act as a motor to boost pressure rapidly and improve the transient response.	Convertors and harmonic filters are considered. A constant auxiliary load reduction is considered.	Research.
Engine tuning	Yes	Optimize the engine for the most commonly requested loadings.	Constant reduction for the main engine's specific fuel consumption.	Research.
Engine derating	Yes	Only case considered is when the main operates at a lower Brake Mean Effective Pressure (BMEP) while keeping maximum constant power.	Constant reduction for the main engine's specific fuel consumption.	Research.
Short term battery power	Yes	Lithium-ion batteries coupled with a shaft generator. Discharge and charge times and efficiency are kept	The benefit will be a reduction in the auxiliary engines fuel consumption while maneuvering at port.	Research.

Energy efficiency measure	**Currently available**	**Description**	**Scaling assumptions**	**Data Sources**
		constant as well as for the convertor, main switchboard and transformer efficiencies.		
Speed controlled pumps and fans	Yes	Control the usage of pumps and fans at variable speed according to the actual need.	Constant reduction in main engine and auxiliary power equipment.	Research.
Propeller polishing	Yes	Regular propeller polishing.	Constant change in propeller efficiency.	
Hull cleaning	Yes	Regular hull cleaning.	Constant change in the overall resistance.	Research.

Table 17: Summary of modelling assumptions for each energy efficiency method

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