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Nelly Forsman

ICEEDI Power requirements according to FSIC rules and EEDI compliance

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FOREWORD

In this report no 104, the Winter Navigation Research Board presents the results of the study which evaluates whether the ice correction factors need to be improved in the future in order to allow high ice class notation and compliance with EEDI. The study also evaluates how energy efficiency improvements can be applied to ice-classed vehicles.

The study did analysis on both old and new vessels with high ice class, 1A or 1A Super. According to calculations, it is possible to achieve a high ice class and still comply with EEDI regulation even for future requirements. During the study it was found that there is no need for modification of the ice correction factors.

The Winter Navigation Research Board warmly thanks Mrs. Nelly Forsman for this report.

Helsinki and Norrköping

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Lauri Kuuliala	Anders Dahl
Finnish Transport and Communications Agency	Swedish Maritime Administration
Markus Karjalainen	Stefan Eriksson
Finnish Transport Infrastructure Agency	Swedish Transport Agency

REPORT

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Project Manager:
Nelly Forsman

Author:
Nelly Forsman
nelly.forsman@sspa.se
+46 730 72 9160

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ICEEDI

Power requirements according to FSIC rules and EEDI compliance

The project is funded by the Finnish-Swedish Winter Navigation Research Board and investigates the power requirements according to Finnish Swedish Ice Class Rules (FSICR) and Energy Efficiency Design Index (EEDI) compliance for ice classed vessels.

SSPA Sweden AB

Christian Finnsgård
Vice President
Head of SSPA Research

SSPA Sweden AB

Nelly Forsman
Project manager
Maritime Operations

Summary

Regulations for energy efficiency of ships were adopted by IMO in 2011. The Energy Efficiency Design Index (EEDI) regulations require a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different ship type and size segments. The required EEDI level is gradually tightened in phase 1, 2 and 3. In order to allow a higher propulsive power to ensure ice going capability, the regulation includes correction factor for ice classed vessels. The study intend to evaluate the need for improved ice correction factor for compliance of EEDI in the future.

The Finnish-Swedish Ice Class Rules (FSICR) were developed to ensure smooth progress for ships sailing in ice conditions. The rules apply to vessels operating in first year ice during winter time. The ice class regulations define the minimum engine output, hull strength, machinery and rudder strength of ships navigating in ice (Trafi, 2017). For the current study, the requirements of propulsion power, i.e. minimum engine output, are central.

The study evaluates whether the ice correction factors need to be improved in order to allow high ice class notation and compliance with EEDI in the future. The study also identifies and evaluates measures for improved energy efficiency, and how these can be applied to ice-classed vessels to comply EEDI.

A number of existing vessels with high ice class, 1A or 1A Super, were selected for analysis. For comparison reasons, the analysis includes both new vessels, from 2015, 2016 and 2017, which are covered by EEDI phase 1, as well as some older vessels, which need not be compliant with EEDI regulation. Calculations of attained EEDI for the analysed vessels show that it is possible to achieve a high ice class and still comply with EEDI regulation even for future requirements in phase 2 and 3. There are vessels today fulfilling both EEDI and high ice class notations. The results are to some extent unexpected since some previous studies have indicated that it might be difficult to comply with EEDI for vessels with high ice class notation. The overall ice going capability of the fleet operating in the Bothnia Sea may though be weaker in the future since many of existing vessels have higher installed power than required by the FSICR. With regard to the new EEDI requirements, this will not be possible in the future.

Many measures and devices have been developed and several of these can be applied to improve the energy efficiency also on ice-classed vessels. Further improvements of the technology are likely in the future. A low EEDI, complying with requirements in phase 2 and 3, can be obtained by a through selection of engine system in order to reduce the fuel consumption of the vessel. In order to reduce the CO_2 emissions further, usage of LNG as fuel can be considered.

Based on the result of current study, no need for modification of the ice correction factors is identified. The ice correction factors seem to reflect the required additional power needed for ice-classed vessels.

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1 Introduction

The project is funded by the Finnish-Swedish Winter Navigation Research Board and investigates the power requirements according to Finnish Swedish Ice Class Rules (FSICR) and Energy Efficiency Design Index (EEDI) compliance for ice classed vessels.

1.1 Background

Regulations for energy efficiency of ships were adopted by IMO in 2011. The EEDI was made mandatory for new ships with the adoption of amendments to MARPOL Annex VI (resolutions MEPC.203(62)), by Parties to MARPOL Annex VI, which was later amended by resolution MEPC.245(66). The EEDI regulations require a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different ship type and size segments. The regulation includes a correction factor for ice classed vessels in order to allow a higher propulsive power to ensure ice going capability. It is considered doubtful whether proposed EEDI correction factors for ice classed ships may ensure installation of enough propulsive power when the EEDI requirements are tightened in 2020 and 2025.

The Finnish-Swedish Winter Navigation Research Board’s call for projects in 2016 therefore invited research organizations to apply for financing of projects, which would focus to find out if the current correction factors for power are still sufficient.

1.1.1 Finnish Swedish Ice Class Rules

The Finnish-Swedish Ice Class Rules (FSICR) were developed to ensure smooth progress for ships sailing in ice conditions. The rules apply to vessels operating in first year ice during winter time. The ice class rules use design points to ensure that the ship is properly reinforced to handle the increased loads due to ice encounters. The ice class regulations define the minimum engine output, hull strength, machinery and rudder strength of ships navigating in ice (Trafi, 2017).

For the current study, the requirements of propulsion power, i.e. minimum engine output, are central. The requirements are based on an extensive theoretical R&D work and full scale measurements (Juva, 2002). The requirements are introduced based on calculation of hull resistance in a brash ice channel for the specified vessels size and hull form and ice channel thickness depending on ice class notation. The propulsion power should not be less than given by calculations using the formulas, and for ice class IA, IB or IC not less than 1 000 kW and for IA Super not less than 2 800 kW (Trafi, 2017).

The required minimum installed power for the desired ice class for a certain vessel can also be retrieved from model tests in ice tanks. Model tests generally implies that the minimum power requirements are reduced, compared to the calculated requirement. For the current study, the power requirements according to calculations are considered.

1.2 Objectives

The study intend to evaluate the need for improved correction factor for compliance of EEDI. If it is found required, a proposal for improved correction factors will be provided by the study. Potential improvements of the correction factors will ensure that an efficient and safe winter navigation in the Northern Baltic Sea can be maintained when the EEDI requirements are tightened in 2020 and 2025.

The study will analyse and systematically compare existing technical and possible innovative measures to bridge diverging minimum power requirements imposed by the FSIC regulations and tightened EEDI requirements.

1.3 Methodology

The EEDI regulation is reviewed in order to analyse the significance of each parameter included.

A literature study is conducted to identify innovative measures for improved onboard energy efficiency.

The EEDI of a number of existing vessels which are ice classed will be investigated in order to analyse whether these would be able to comply also with the EEDI in phase 2 and phase 3. The identified innovative measures for improved energy efficiency will be evaluated based on their potential for imposed EEDI for ice classed vessels. If the measures are found insufficient to bridge the gap, the need for adjustment of correction factor will investigated.

2 EEDI regulation

Marine Environmental Protection Committee (MEPC) first adopted chapter 4 of MARPOL Annex VI; *Regulations on energy efficiency for ships* in July 2011 at its 62nd session. Since then, a number of resolutions on amendments have been adopted. In addition to regulation 19, 20 and 21 in Chapter 4, EEDI is regulated by four resolutions:

MEPC.254(67) and its amendments (MEPC.261(68))
2014 Guidelines on survey and certification of the Energy Efficiency Design Index (EEDI)

MEPC.245(66) and its amendments (MEPC.263(68), MEPC.281(70)) and its corrigendum
2014 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships

MEPC.231(65)
2013 Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI)

MEPC.233(65)
2013 Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI) for cruise passenger ships having non-conventional propulsion

The EEDI regulation applies to new ships of 400 gross tonnage and above and to ships which has undergone a major conversion. The regulation states that the attained EEDI for new ships shall be less than or equal to the required EEDI (Eq. 1).

$$attained\ EEDI \leq required\ EEDI \qquad (1)$$

The required EEDI for a certain ship is calculated based on the reference line defined in MEPC.231(65) and MEPC.233(65) and with regard to the reduction factor stated in regulation 21 in Chapter 4 of MARPOL Annex VI (Eq.2).

$$required\ EEDI = \left(1 - \frac{x}{100}\right) \times reference\ line\ value \qquad (2)$$

Where x is the reduction factor (in percamtage), which is used to tighten the EEDI regulation in phases over time by increasing its value.

The regulations aims at reducing the CO_2 emissions from shipping by improving the energy efficiency. The regulation encourage implementation of innovative measures for improved energy efficiency related to the propulsion of new built ships.

2.1 Attained EEDI

The attained EEDI for a new ship aims to be measure of the ship's energy efficiency and is measured in g CO_2/ton-mile, as simplified in Eq. 3 and 4.

$$EEDI = \frac{CO_2\ emissions}{transport\ work} \qquad (3)$$

$$EEDI = \frac{Engine\ power \times SFC \times C_F}{DWT \times speed} \qquad (4)$$

Where SFC is the specific fuel consumption of the engines, measured in g/kWh. C_F is a non-dimensional conversion factor between fuel consumption measured in g and the CO_2 emissions based on carbon content of the fuel. The different values of C_F to be applied for various fuels are presented in Table 2.1.

Table 2.1 Lower calorific values, carbon content and emission factors for different fuels.

Type of fuel		Lower calorific value (MJ/kg)	Carbon content	C_F (g_{CO2}/g_{fuel})
Diesel/Gas oil		42.7	0.8744	3.206
Light Fuel Oil (LFO)		41.2	0.8594	3.151
Heavy Fuel Oil (HFO)		40.2	0.8493	3.114
Liquefied Petroleum Gas (LPG)	Propane	46.3	0.8182	3.000
	Butane	45.7	0.8264	3.030
Liquefied Natural Gas (LNG)		48.0	0.7500	2.750
Methanol		19.9	0.3750	1.375
Ethanol		26.8	0.5217	1.913

Attained EEDI is calculated by the formula in Eq. (5).

$$\frac{\overbrace{\left(\prod_{j=1}^{n} f\right)_j \left(\sum_{i=1}^{nME} P_{ME}\cdot C_{FME_{(i)}}\cdot SFC_{ME_{(i)}}\right)}^{\text{Main engine}} + \overbrace{\left(P_{AE}\cdot C_{FAE}\cdot SFC_{AE}\right)}^{\text{Auxiliary engine}} + \overbrace{\left(\left(\prod_{j=1}^{n} f_j\cdot\sum_{i=1}^{nPTI} P_{PTI_{(i)}} - \sum_{i=1}^{neff} f_{eff_{(i)}}\cdot P_{AEeff_{(i)}}\right) C_{FAE}\cdot SFC_{AE}\right)}^{\text{Shaft generators/motors}} - \overbrace{\left(\sum_{i=1}^{neff} f_{eff_{(i)}}\cdot P_{eff_{(i)}}\cdot C_{FME}\cdot SFC_{ME}\right)}^{\text{Innovative energy efficiency power generation}}}{\underbrace{f_i\cdot f_e\cdot f_l\cdot f_w}_{\text{Correction factors}}\cdot Capacity\cdot V_{ref}}$$

Equation (5)

Term	Unit	Description
Capacity	tonne	Ship capacity in deadweight or gross tonnage at summer load line draught (for container ships, 70% of deadweight applies)
C_{FAE}	g_{CO2}/g_{fuel}	Carbon factor for fuel for auxiliary engines
C_{FME}	g_{CO2}/g_{fuel}	Carbon factor for fuel for main engines
f_c	-	Correction factor for capacity of ships with alternative cargo types that impact the deadweight-capacity relationship (e.g. LNG ships in gas carrier segment)
f_{eff}	-	Correction factor for availability of each innovative energy efficiency technologies
f_i	-	Correction factor for capacity of ships with technical/regulatory elements that influence ship capacity
f_j	-	Correction factor for ship specific design features (e.g. ice-class ships)
f_w	-	Correction factor for speed reduction due to representative sea conditions
n_{eff}	-	Number of innovative technologies
n_{ME}	-	Number of main engines
n_{PTI}	-	Number of power take-in system (e.g. shaft motors)
P_{AE}	kW	Power of auxiliary engines, required auxiliary engine power to supply normal maximum sea load including necessary power for propulsion machinery/systems and accommodation.
P_{ME}	kW	Power of main engine, 75% of the rated installed power (MCR) for each main engine (i)
P_{TI}	kW	Power of shaft motor
SFC_{AE}	g/kWh	Specific fuel consumption for auxiliary engines as per NOx certification
SFC_{ME}	g/kWh	Specific fuel consumption for main engines as per NOx certification
V_{ref}	knots	Reference ship speed attained at propulsion power equal to P_{ME} and under calm sea and deep water operation at summer load line draught

Total propulsion power is defined as:

$$\sum MCR_{ME(i)} + \frac{\sum P_{PTI(i)}}{0.75}$$

For ships with a total propulsion power of 10 000 kW or above, power of auxiliary engines P_{AE} is defined as:

$$P_{AE} = \left(0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right)\right) + 250$$

For ships with a total propulsion power below 10 000 kW, power of auxiliary engines P_{AE} is defined as:

$$P_{AE} = \left(0.05 \times \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right)\right)$$

2.1.1 Ice correction factors

The power correction factor,f_j, is a correction factor to account for ship specific design elements, such as ice classification. For ice-classed ships the factor is calculated based on L_{PP} and dependent on ice class.Table 2.2 shows the formulas for calculation of f_{j0} and f_{jmin} , where f_j should be taken as the greater value of f_{j0} and f_{jmin}, but not greater than $f_{j,max} = 1$.

Table 2.2 Power correction factor f_j for ice classed ships.

Ship type	f_{j0}	f_j,min depending on the ice class			
		IA Super	IA	IB	IC
Tanker	$\frac{0.308\ L_{PP}^{1.92}}{P_{ME}}$	$0.15\ L_{PP}^{0.3}$	$0.27\ L_{PP}^{0.21}$	$0.45\ L_{PP}^{0.13}$	$0.7\ L_{pp}^{0.06}$
Bulk carrier	$\frac{0.639\ L_{PP}^{1.754}}{P_{ME}}$	$0.47\ L_{PP}^{0.09}$	$0.58\ L_{PP}^{0.07}$	$0.73\ L_{PP}^{0.04}$	$0.87\ L_{PP}^{0.02}$
General cargo ship	$\frac{0.0227\ L_{PP}^{2.483}}{P_{ME}}$	$0.31\ L_{PP}^{0.16}$	$0.43\ L_{PP}^{0.12}$	$0.56\ L_{PP}^{0.09}$	$0.67\ L_{PP}^{0.07}$
Refrigerated cargo ships	$\frac{0.639\ L_{PP}^{1.754}}{P_{ME}}$	$0.47\ L_{PP}^{0.09}$	$0.58\ L_{PP}^{0.07}$	$0.73\ L_{PP}^{0.04}$	$0.87\ L_{PP}^{0.02}$

When calculating the attained EEDI, the power correction factor applies to: $\sum_{i=1}^{nME} P_{ME} \cdot C_{FME_{(i)}} \cdot SFC_{ME\,(i)}$, which describes the CO_2 emissions from the main engine. With a correction factor below 1, the attained EEDI is reduced.

A power correction factor f_j can also be calculated and applied to shuttle tankers with propulsion redundancy, ro-ro cargo, ro-ro passenger and general cargo ship. For other ship types, f_j should be taken as 1.0.

The capacity correction factor f_i, for any technical/regulatory limitation on capacity applies to ice-classed vessels when calculating the attained EEDI. f_{i0} and f_{imax} are tabulated in Table 2.3. f_i should be taken as the lesser value of f_{i0} and f_{imax}, but not less than $f_{imin} = 1$. A greater f_i will reduced the attained EEDI as it is in the dominator of the equation (5).

Table 2.3 Capacity correction factor f_i for ice classed ships.

Ship type	f_{i0}	f_i,max depending on the ice class			
		IA Super	IA	IB	IC
Tanker	$\frac{0.00138\ L_{pp}^{3.331}}{Capacity}$	$2.1\ L_{PP}^{-0.11}$	$1.71\ L_{PP}^{-0.08}$	$1.47\ L_{PP}^{-0.06}$	$1.27\ L_{PP}^{-0.04}$
Bulk carrier	$\frac{0.00403\ L_{PP}^{3.123}}{Capacity}$	$2.1\ L_{PP}^{-0.11}$	$1.8\ L_{PP}^{-0.09}$	$1.54\ L_{PP}^{-0.07}$	$1.31\ L_{PP}^{-0.05}$
General cargo ship	$\frac{0.0377\ L_{PP}^{2.625}}{Capacity}$	$2.18\ L_{PP}^{-0.11}$	$1.77\ L_{PP}^{-0.08}$	$1.51\ L_{PP}^{-0.06}$	$1.28\ L_{PP}^{-0.04}$
Containership	$\frac{0.1033 * L_{PP}^{2.329}}{Capacity}$	$2.1\ L_{PP}^{-0.11}$	$1.71\ L_{PP}^{-0.08}$	$1.47\ L_{PP}^{-0.06}$	$1.27\ L_{PP}^{-0.04}$
Gas carrier	$\frac{0.0474\ L_{PP}^{2.59}}{Capacity}$	1.25	$2.1\ L_{PP}^{-0.12}$	$1.6\ L_{PP}^{-0.08}$	$1.25\ L_{PP}^{-0.04}$

2.2 Reference line

MEPC.231(65) and MEPC.233(65) determines reference lines for EEDI for different types of ship dependent on size of ship. The guidelines in MEPC.231(65) applies to bulk carrier, gas carrier, tanker, container ship, general cargo ship, refrigerated cargo carrier, combination carrier, ro-ro cargo ship, ro-ro cargo ship (vehicle), ro-ro passenger ship and LNG carrier. The guidelines in MEPC.233(65) applies only to *cruise passenger ships having non-conventional propulsion.* It shall be noted that a method for calculating reference lines has not been established for passenger ships other than cruise ships having non-conventional propulsion.

The reference line is a curve representing an average index value, as a function of size, fitted on a set of individual estimated EEDI values for a defined group of ships delivered between 1 January 1999 and 1 January 2009 (For ro-ro and ro-pax, data from the period 1 January 1998 to 1 January 2010 is used).

The estimated EEDI values, $Estimated\ Index\ value$, for the defined group of ships is calculated by Eq (7) (excluding containerships and ro-ro cargo ships).

$$Estimated\ Index\ value = 3.1144 \times \frac{190 \times \sum_{i=1}^{n_{ME}} P_{MEi} + 215 \times P_{AE}}{Capacity \times V_{ref}} \qquad (7)$$

For container ships, $Capacity$ is replaced by $70\%\ DWT$. For ro-ro cargo ships Eq. (7) is multiplied with the additional factor, f_{jRoRo} or f_{RoRov} for ro-ro vehicle carrier. For ro-ro passenger ships Eq. (7) is multiplied with f_{jRoRo} and divided by f_{cRoPax}. For LNG carriers the calculation of estimated index value is dependent on whether if it is direct drive diesel, dual fuel diesel – electronic or steam turbine. The different equations are outlined in appendix 2 to MEPC.231(65).

The data of the ships used to calculate the reference line is retrieved from the IHS Fairplay database. Through a regression analysis of the data, the reference line and its set of parameters for each ship category are retrieved.

The $Reference\ line\ value$ for a vessel covered by MEPC.231(65) is then calculated by the formula in Eq. (6):

$$Reference\ line\ value = a \times (100\%\ DWT)^{-c} \qquad (6)$$

Where a and c are parameters determined from the regression curve fit. Table 2.4 shows parameter values for different ship categories.

Table 2.4 Parameter a and c used to calculate reference line value of a selected number of ship categories.

Ship type defined in regulation	a	c
Bulk carrier	961.79	0.477
Gas carrier	1120.00	0.456
Tanker	1218.80	0.488
Container ship	174.22	0.201
General cargo ship	107.48	0.216
Refrigerated cargo	227.01	0.244
Combination carrier	1219.00	0.488
Ro-ro cargo	1405.15	0.498
Ro-ro passenger	752.16	0.381
LNG carrier	2253.7	0.474
Ro-ro cargo (vechicle) (where DWT/GT<0.3)	$DWT/GT^{-0.7} \times 780.36$	0.471
Ro-ro cargo (vechicle) (DWT/GT>=0,3)	1812.63	0.471

Figure 2.1 shows the reference lines based on the parameters in Table 2.4, i.e. EEDI as a function of dwt.

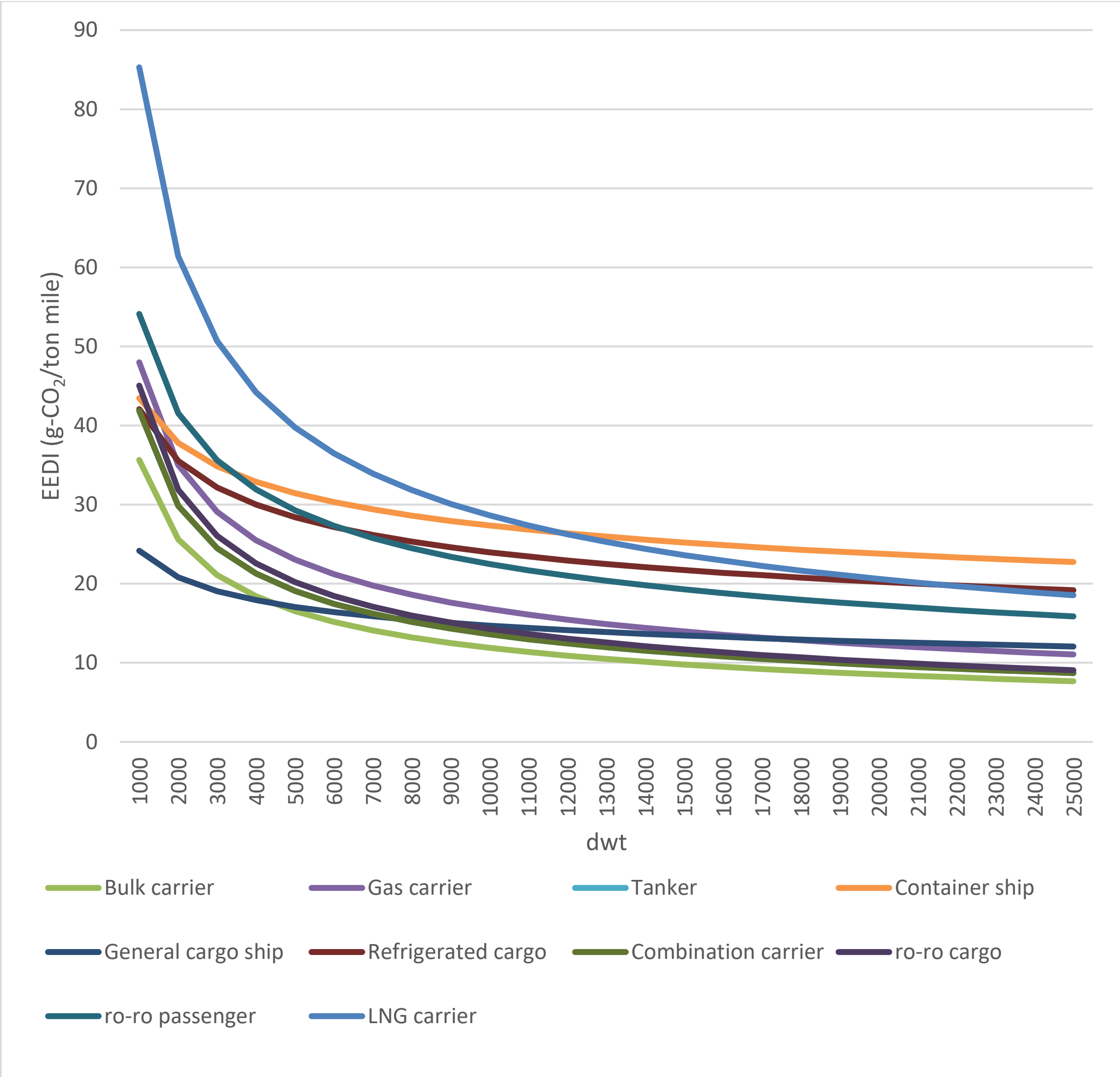

Figure 2.1 Reference lines for different ship categories based on parameters in Table 2.4.

For cruise ships having non-conventional propulsion, the $reference\ line\ value$ is calculated according to Eq. (8).

$$Reference\ line\ value = 170.84 \times b^{-0.214} \quad (8)$$

Where b is the gross tonnage of the ship.

2.3 Required EEDI

The required EEDI is based on the reference line of each ship type. The required EEDI is then reduced with reduction factor x in equation (2). The reduction factor for the three phases for the different ship are presented in Table 2.5.

Table 2.5 Reduction factor x in phase 1, 2 and 3 for different ship types.

Ship Type	Size	Phase 0 1 Jan 2013 – 31 Dec 2014	Phase 1 1 Jan 2015 – 31 Dec 2019	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Jan 2025 and onwards
Bulk carrier	20,000 DWT and above	0	10	20	30
	10,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Gas carrier	10,000 DWT and above	0	10	20	30
	2,000 – 10,000 DWT	n/a	0-10*	0-20*	0-30*
Tanker	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Container ship	15,000 DWT and above	0	10	20	30
	10,000 – 15,000 DWT	n/a	0-10*	0-20*	0-30*
General Cargo ships	15,000 DWT and above	0	10	15	30
	3,000 – 15,000 DWT	n/a	0-10*	0-15*	0-30*
Refrigerated cargo carrier	5,000 DWT and above	0	10	15	30
	3,000 – 5,000 DWT	n/a	0-10*	0-15*	0-30*
Combination carrier	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
LNG carrier***	10,000 DWT and above	n/a	10**	20	30
Ro-ro cargo ship (vehicle carrier)***	10,000 DWT and above	n/a	5**	15	30
Ro-ro cargo ship***	2,000 DWT and above	n/a	5**	20	30
	1,000 – 2,000 DWT	n/a	0-5* **	0-20*	0-30*
Ro-ro passenger ship***	1000 DWT and above	n/a	5**	20	30

	250 – 1,000 DWT	n/a	0-5* **	0-20*	0-30*
Cruise passenger ship*** having non-conventional propulsion	85,000 GT and above	n/a	5**	20	30
	25,000 – 85,000 GT	n/a	0-5* **	0-20*	0-30*

** Reduction factor to be linearly interpolated between the two values dependent upon ship size. The lower value of the reduction factor is to be applied to the smaller ship size.*

*** Phase 1 commences for those ships on 1 September 2015.*

**** Reduction factor applies to those ships delivered on or after 1 September 2019, as defined in paragraph 43 of regulation 2.*

3 Analysis of attained EEDI

3.1 Selection of vessels for evaluation

In the study *EEDI and Finnish-Swedish ice class rules – Impact study and operational aspects* (Westerberg, 2014), a large number of vessels trafficking Bay of Bothnia and Bothnia Sea were analysed. In the analysis it was found that several of vessels in the current fleet, which do not have to comply with the EEDI regulation have a installed power higher than required for its ice class notation. Several vessels having a high ice class notation and which would comply with future EEDI requirements were also found.

In the current study, a smaller amount of vessels was selected for analysis of their EEDI as well as their achievement of FSICR.

The selected vessels all traffic the Bay of Bothnia and Bothnia Sea and have ice class 1A or 1A Super. Vessels with high ice class were selected since the previous study indicated that those in particular might have difficulties to comply with future EEDI regulation. For comparison reasons, the analysis includes both new vessels, from 2015, 2016 and 2017 which are covered by EEDI phase 1, as well as some older vessels which need not be compliant with EEDI regulation.

3.2 Case study

Eleven vessels are analysed based on data from sea-web database. The sea-web data does not include the speed at 75% of MCR which is the definition of V_{ref} in the EEDI formula. Only service speed, which is assumed to be the speed at 85% of MCR, is found in sea-web. The power output is generally a square function of the speed, based on this assumption V_{ref} have been approximated as:

$$V_{ref} = service\ speed\ \times \sqrt{\frac{75}{85}}$$

Type of fuel to determine carbon factor, C_F, have been assumed based on fuel tank capacity in sea-web and the engine type; low speed and medium speed diesel engines are assumed to run mainly on HFO if the HFO fuel tanks are the largest. High speed diesel engines are assumed to run on distillate fuel (MGO), as well as ships with the largest fuel tanks being MGO tanks. The Specific Fuel Consumption, SFC, is according to engine designers specification if available.

Based on the vessels' retrieved ice class, the corresponding minimum power output according to the FSICR (Trafi, 2010) was calculated for each vessel and compared to actual power of main engine. The equations includes several hull parameters of which not all could be retrieved, in those cases the coefficients and parameters have been estimated.

Table 3.1 lists the analysed vessels and the calculated EEDI. The table also includes which phase the calculated EEDI complies with as well as the calculated power requirements according to FSICR (P_{FSICR}).

Table 3.1 Calculated EEDI and its corresponding phase compilmance for selected vessels.

Ship name	Ship type	Year build	DWT	P_{ME} (kW)	Ice Class	EEDI	Phase	P_{FSICR} (kW)
Suula	Tanker	2005	14 665	8450	1A Super	10.31	1	7281
Philipp Essberger	Tanker	2003	5 738	3839	1A	13.99	3	2829
Arklow Cadet	General Cargo	2016	5 085	1740	1A	11.24	3	1738
Symphony Sea	General Cargo	2016	10 600	3000	1A	9.80	3	2625
Nordic Odin	Bulk Carrier	2015	76 180	12000	1A	3.80	1	7155
Vistula Maersk	Container	2017	42 000	16080	1A	10.84	3	7378
Norse Spirit	Tanker	2017	148 167	14600	1A	2.89	2	20992
Delphis Bothnia	Container	2016	24 700	11655	1A	16.94	2	6434
Waikiki	Tanker	2017	112 829	14280	1A	3.01	2	14005
Louis	General Cargo	2008	8 250	3000	1A	11.75	3	2323
Stena Arctica	Tanker	2005	117 099	15860	1A Super	3.28	2	19765

The calculated minimum engine power, P_{FSICR}, is larger than the specified main engine power for all vessels, with exception for Stena Arctica which is therefore assumed to have retrieved its ice class through ice model test. For the container vessels, the exceedance of P_{FSICR}, is significant.

According to the calculations, many of the vessels comply with phase 3 and 2, which is surprising since those levels of EEDI are not yet required.

The ice corrections factors have a major impact for the EEDI of the vessels, reducing the attained EEDI of on average 22%, thus also enable compliance with EEDI regulation.

3.2.1 Sensitivity analysis

Of the analysed vessels, only two vessels, Norse Spirit and Louis, are assumed to be running on MGO, all the others are specified with bunker tanks for HFO. To investigate the sensitivity of fuel type and carbon factor, calculations of EEDI based on the carbon factor for MGO have been carried out, see Table 3.2.

Table 3.2 Comparison of EEDI and corresponding phase based on usage of MGO for main engine instead of HFO.

Ship name	Ship type	Year build	DWT	Ice Class	EEDI	Phase	EEDI - MGO.	Phase - MGO.
Suula	Tanker	2005	14665	1A Super	10.31	1	10.61	0
Philipp Essberger	Tanker	2003	5738	1A	13.99	3	14.37	3
Arklow Cadet	General Cargo	2016	5085	1A	11.24	3	12.60	3
Symphony Sea	General Cargo	2016	10600	1A	9.80	3	10.78	3
Nordic Odin	Bulk Carrier	2015	76180	1A	3.80	1	3.90	1
Vistula Maersk	Container	2017	42000	1A	10.84	3	11.15	3
Norse Spirit	Tanker	2017	148167	1A	2.89	2	2.89	2
Delphis Bothnia	Container	2016	24700	1A	16.94	2	17.42	2
Waikiki	Tanker	2017	112829	1A	3.01	2	3.11	2
Louis	General Cargo	2008	8250	1A	11.75	3	12.43	3
Stena Arctica	Tanker	2005	117099	1A Super	3.28	2	3.37	1

In the previous study *EEDI and Finnish-Swedish ice class rules – Impact study and operational aspects* (Westerberg, 2014), the specific fuel consumption was assumed to be 190 g/kWh for main engine and 215 g/kWh for auxiliary engine for all the investigated vessels. Those values are also the ones used to calculate the estimated index value for each ship contained in the set of ships used to determine the reference line (MEPC.231(65)).

Table 3.3 shows a comparison of EEDI based on values used in 2014 and the engine specific values used in the current analysis.

Table 3.3 Comparison of EEDI with different specific fuel consumption.

Ship name	Ship type	Year build	DWT	Ice Class	EEDI Engine spec.	EEDI SFC_{ME}=190 SFC_{AE}=215	Phase Engine spec	Phase SFC_{ME}=190 SFC_{AE}=215
Suula	Tanker	2005	14665	1A Super	10.31	11.46	1	0
Philipp Essberger	Tanker	2003	5738	1A	13.99	16.02	3	3
Arklow Cadet	General Cargo	2016	5085	1A	11.24	12.69	3	3
Symphony Sea	General Cargo	2016	10600	1A	9.80	11.31	3	3
Nordic Odin	Bulk Carrier	2015	76180	1A	3.80	4.25	1	0
Vistula Maersk	Container	2017	42000	1A	10.84	12.37	3	3
Norse Spirit	Tanker	2017	148167	1A	2.89	4.33	2	1
Delphis Bothnia	Container	2016	24700	1A	16.94	18.29	2	1
Waikiki	Tanker	2017	112829	1A	3.01	3.47	2	1
Louis	General Cargo	2008	8250	1A	11.75	12.43	3	3
Stena Arctica	Tanker	2005	117099	1A Super	3.28	3.77	2	0

The specific fuel consumption used in previous study yields significant higher EEDI compared to when EEDI is calculated with fuel consumption specified by the engine manufacturer.

The calculations of minimum engine power for FSICR involves several assumptions and estimations of hull dimeters and propeller dimensions. The values presented have been calculated according to the formulas for new ships (section 3.2.2 of the regulations). For comparison, minimum engine power have been calculated according to formulas valid for existing ships of ice class 1A Super or 1A (section 3.2.4 of the regulations), which can be used *when, for an existing ship, values for some of the hull form parameters required for the calculation method in section 3.2.2 are difficult to obtain.*

The power calculated with this formula, P_{FSICR2} generate higher values and thus higher requirements of engine power, see Table 3.4.

Table 3.4 Comparison of minimum engine power requirements according to FSICR calculated using two different methods.

Ship name	Ship type	P_{ME} (kW)	Ice Class	EEDI	Phase	P_{FSICR} (kW)	P_{FSICR2} (kW)
Suula	Tanker	8 450	1A Super	10.31	1	7 281	8 495
Philipp Essberger	Tanker	3 839	1A	13.99	3	2 829	3 754
Arklow Cadet	General Cargo	1 740	1A	11.24	3	1 738	2 412
Symphony Sea	General Cargo	3 000	1A	9.80	3	2 625	4 467
Nordic Odin	Bulk Carrier	12 000	1A	3.80	1	7 155	8 644
Vistula Maersk	Container	16 080	1A	10.84	3	7 378	8 311
Norse Spirit	Tanker	14 600	1A	2.89	2	20 992	18 403
Delphis Bothnia	Container	11 655	1A	16.94	2	6 434	7 184
Waikiki	Tanker	14 280	1A	3.01	2	14 005	15 260
Louis	General Cargo	3 000	1A	11.75	3	2 323	3 647
Stena Arctica	Tanker	15 860	1A Super	3.28	2	19 765	23 227

3.3 Power- and capacity correction

As an example of the value of power correction factor, Table 3.5 shows the calculated f_{j0} and f_{jmin}, for $L_{pp} = 130\ m$ and $P_{ME} = 4\ 500\ kW$. The value of f_j should be taken greater of f_{j0} and f_{jmin}, but not greater than $f_{j,max} = 1$.

Table 3.5 Calculated f_{j0} and f_{jmin} for L_{PP} = 130 m, Capacity=14 000 and P_{ME} = 4 500, i.e. an installed power of 6 000 kW.

Ship type	f_{j0}	f_j,min depending on the ice class			
		IA Super	IA	IB	IC
Tanker	0.784	0.646	0.750	0.847	0.937
Bulk carrier	0.725	0.728	0.815	0.887	0.959
General cargo ship	0.895	0.675	0.77	0.868	0.942
Refrigerated cargo ships	0.725	0.728	0.815	0.887	0.959

f_{j0} is a function of P_{ME} and L_{PP}, while f_{jmin} is only a function of L_{PP}. Figure 3.1 shows f_{jmin} dependent on L_{PP} for ice class 1A Super and 1A.

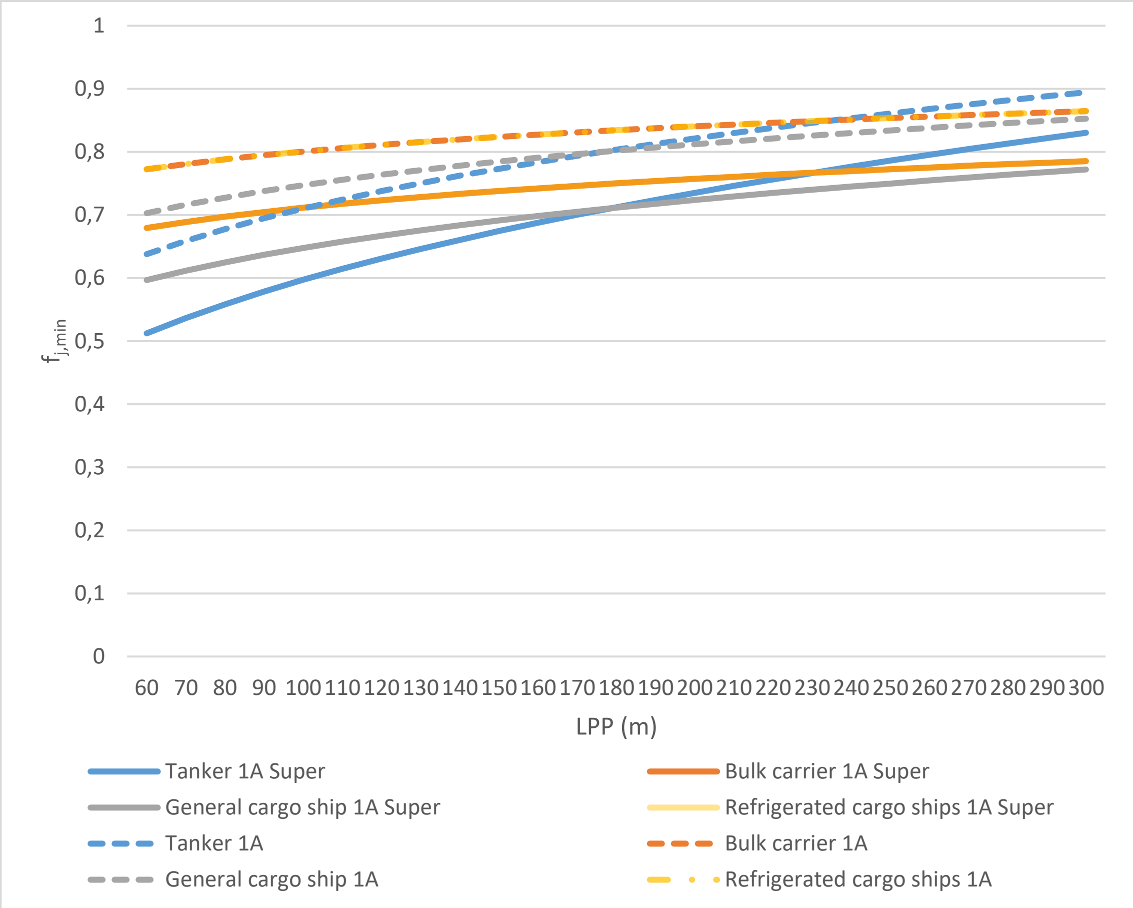

Figure 3.1 Power correction factor $f_{j,min}$ for ice class 1A Super and 1A.

Table 3.6 shows the calculated values of the capacity correction factors f_{i0} and f_{imax} for $Capacity = 14\ 000$ and $L_{pp} = 130\ m$.

Table 3.6 Calculated f_{i0} and f_{imax} for LPP = 130 m and PME = 4 500, i.e. an installed power of 6 000 kW.

Ship type	f_{i0}	$f_{i,max}$ depending on the ice class			
		IA Super	IA	IB	IC
Tanker	1.229	1.152	1.098	1.045	1.229
Bulk carrier	1.229	1.161	1.095	1.027	1.229
General cargo ship	1.276	1.199	1.128	1.054	1.276
Container ship	1.229	1.158	1.098	1.045	1.229
Gas carrier	1.250	1.171	1.084	1.029	1.250

Figure 3.2 shows f_{imax} as a function of L_{pp} for the higher ice class notations.

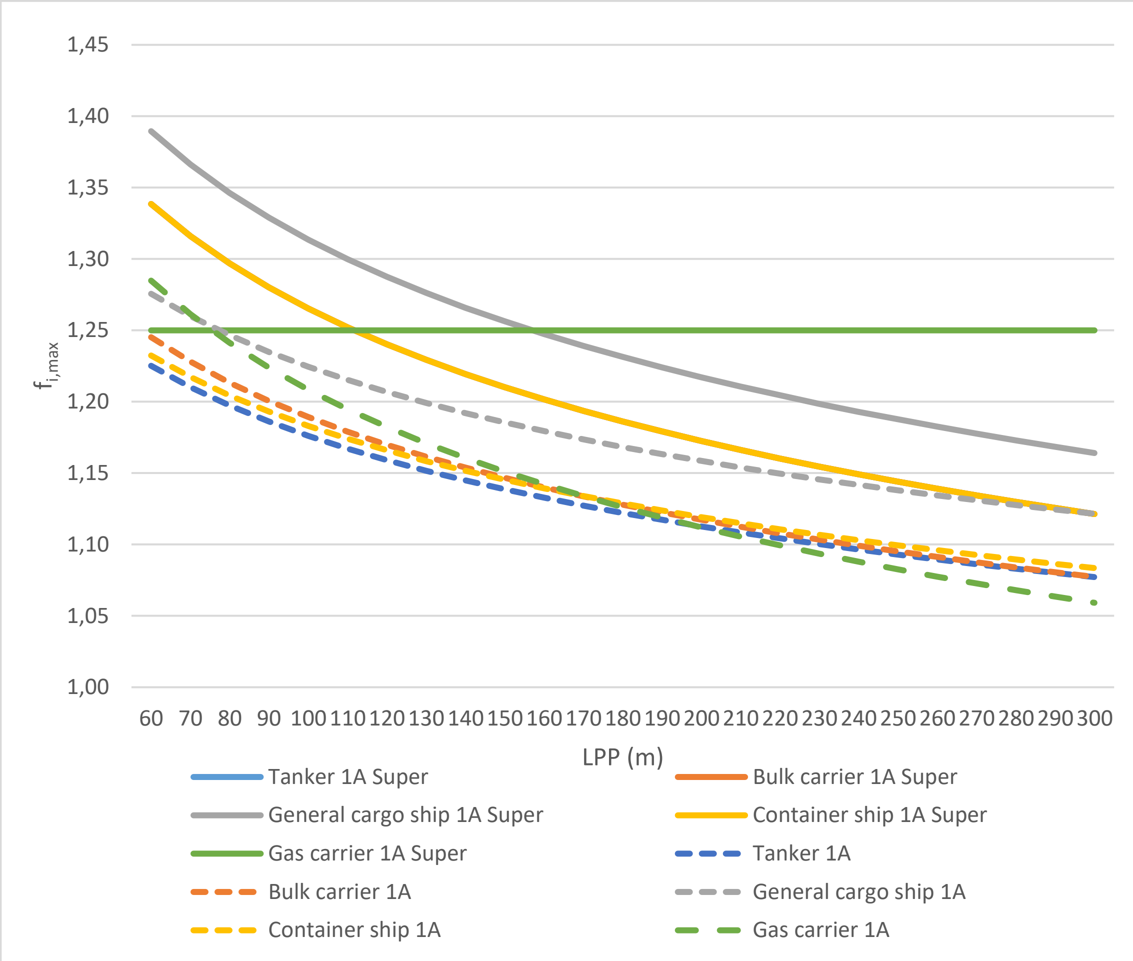

Figure 3.2 Capacity correction factor $f_{i,max}$ for ice class 1A Super and 1A.

For ice classed tankers, bulk carriers and general cargo ships both the power correction and the capacity correction factor applies. When those are combined the reduction of attained EEDI is significant, especially for smaller vessels.

Table 3.7 shows the percentage reduction of attained EEDI for ice correction dependent on ice class and type based on the values of f_i and f_j calculated in Table 3.5 and Table 3.6, i.e. for a vessel with $L_{pp} = 130\ m, P_{ME} = 4\ 500\ kW$ and $Capacity = 14\ 000$.

Table 3.7 Calculated percentage reduction with ice class notation dependent on ice class and ship type for L_{PP} = 130 m, Capacity=14 000 and P_{ME}= 4 500, i.e. an installed power of 6 000 kW.

Ship type	**Percentage reduction with ice class notation**			
	IA Super	IA	IB	IC
Tanker	28%	28%	22%	10%
Bulk carrier	37%	29%	19%	7%
General cargo ship	11%	11%	11%	6%
Refrigerated cargo ships	27%	18%	11%	4%
Containership	0%	0%	0%	0%
Gas carrier	1%	1%	1%	1%

In case of a containership with the above specified dimensions, no ice reduction is obtained. For a 130 m containership the capacity would need to be below 8 500 TEU in order to yield a reduction with f_i.

The influence of ice correction factors for the eleven vessels covered by the case study have been analysed. Table 3.8 shows the calculated EEDI, with and without ice class correction, i.e. when $f_i = 1$ and $f_j = 1$. The table also includes the percentage reduction of attained EEDI with regard to the ice correction factor and which phase the calculated EEDI complies with.

Table 3.8Attained EEDI for analysed vessels, both with ice correction factors are accounted for and when those are disregarded, i.e. f_i=1 and f_j=1.

Ship name	**Ship type**	**Ice Class**	**EEDI**	**EEDI with f_i=f_j=1**	**Percentage reduction with ice correction**	**Phase**	**Phase with f_i=f_j=1**
Suula	Tanker	1A Super	10.31	17.38	69%	1	0
Philipp Essberger	Tanker	1A	13.99	19.92	42%	3	0
Arklow Cadet	General Cargo	1A	11.24	13.95	24%	3	3
Symphony Sea	General Cargo	1A	9.80	9.80	0%	3	3
Nordic Odin	Bulk Carrier	1A	3.80	4.91	29%	1	0
Vistula Maersk	Container	1A	10.84	10.84	0%	3	3
Norse Spirit	Tanker	1A	2.89	3.35	16%	2	0

Delphis Bothnia	Container	1A	16.94	16.94	0%	2	0
Waikiki	Tanker	1A	3.01	3.81	26%	2	0
Louis	General Cargo	1A	11.75	12.67	8%	3	3
Stena Arctica	Tanker	1A Super	3.28	4.23	29%	2	0

The results are differentiated, where Symphony Sea and the two container vessels do not obtain any reduction, whereas the large tanker with ice class 1A Super obtains a reduction of 69%. For containerships, only capacity correction applies and for the current vessels $fi = 1$. Common for the three vessels without ice correction is a low EEDI which applies to phase 3 without ice correction. On average, the reduction of EEDI for the eleven vessel is 22% with regard to the ice correction factors

4 Identification of measures and technologies to comply with EEDI

With the levels being tightened over time, the EEDI aims to stimulate continued technical development of all the components influencing the energy efficiency of a ship. The study included in *MEPC 63/INF.2 Assessment of IMO mandated energy efficiency measures for international shipping* (Lloyd´s Register and DNV GL, 2011) lists technologies that is expected to be used for reducing future ship's EEDI, see Table 4.1.

Table 4.1 Technologies for EEDI reduction (Lloyd´s Register and DNV GL, 2011).

No	Reduction measure
1	Optimised hull dimensions and form
2	Lightweight construction
3	Hull coating
4	Hull air lubrication system
5	Optimisation of propeller-hull interface and flow devices
6	Contra-rotating propeller
7	Engine efficiency improvement
8	Waste heat recovery
9	Gas fuelled (LNG)
10	Hybrid electric power and propulsion concepts
11	Reducing on-board power demand (auxiliary system and hotel loads).
12	Variable speed drive for pumps, fans, etc.
13	Wind power (sail, wind engine, etc.)
14	Solar power
15	Design speed reduction (new builds)

The technologies for improved energy efficiency listed can have both direct effect on the EEDI as it implies deduction in the formula, or more indirect effects such as design aspects aiming to decrease the resistance. A review of different measures have been conducted. Identified measures are classified into groups and described below.

In addition to technologies listed, the energy efficiency is also be improved by operational measures, such as slow steaming etc. Such measures will not affect EEDI as the regulation is limited to take into account design measures.

4.1 Hull optimization

By usage of new powerful analytical tools optimization of ship particulars have been improved. These tools enable multi-objective optimizations of e.g. hydrodynamics, ship structures and stability.

Further hull optimization in the design process probably have the potential to improve the energy efficiency for most vessels. Hull optimization includes several possibilities and aspects.

Ship particulars

Capacity is determined as deadweight (dwt), and by increasing the dwt, the energy efficiency may improve in terms of g CO_2/tonne-nm as the fuel consumption will not increase proportionally and larger vessels are generally more energy efficient. The largest savings occur for high speed ships and is most significant for smaller vessels (ABS, 2013). However, since the required EEDI is a function of dwt, increased dwt will reduce the level of required EEDI. The possibilities to comply with both FSICR for higher ice classes and the required EEDI may though be enhanced for larger vessels (Westerberg, 2014), which is an incentive to increase the capacity.

The usage of dwt as measure of capacity for EEDI implies that there no distinguish between tonne of cargo and a tonne of ballast. For e.g. container ships “usable” TEU capacity might had been more accurate measure of cargo carried. This also implies that ships with large ballast, limiting the carrying capacity can retrieve the same EEDI as a vessel with higher cargo capacity.

Changing the capacity also involves adjustments of principal dimensions. A higher length/beam ratio generally reduces wavemaking resistance. Adjustments of block coefficient reducing C_b, may also improve the hull efficiency leading to reduction of required power.

Also the reference speed, V_{ref}, which is determined through sea trial analysis have a direct impact of the attained EEDI and is of outermost importance. A reduction of service will reduce the fuel consumption significantly and hence improving the energy efficiency, e.g. for an oil tanker, a reduction of 1 knot reduces the fuel consumption by 17 to 22% (ABS, 2013).

Lightweight construction of the hull also have potential to reduce the fuel consumption and improve the vessels energy efficiency.

Hull resistance

Generally, reduction of wetted surface area reduces frictional resistance for slow ship vessels. Forebody optimization includes bulb design, forward shoulder, and waterline entrance.

Use of bulbous bow as a design technology to improve energy efficiency is widespread (Rehmatulla, 2017). An optimized design of a bulbous bow may have great potential to increase the energy efficiency by decreasing the wave resistance, but the potential and the optimum design largely vary dependent on ship type and the its operational profile. A bulbous bow also influence the vessel’s ice going performance. A case study of a LNG carrier shows that a bow optimized for a high energy efficiency in open water would require significantly higher installed power compared to a traditional ice bow to achieve FSICR 1A

Super or 1A due to poor ice going performance. The study indicates that it might be difficult to achieve higher ice class (1A and 1ASuper) in phase 3 of EEDI (Winmos, 2016). Additional measures, in addition to forebody optimization, may be needed.

Hull resistance can also be reduced by aftbody optimization and thus through improvements of the floe around the stern, mitigation of stern waves, improve flow into the propeller etc. The total resistance may also be reduced by applications of appendages to the propulsion system at the stern of a vessel, e.g. kort nozzle, Mewis Duct, wake equalizing duct, pre-swirl stator, propeller boss cap fins (TrainMoS II, 2017).

4.2 Engine related measures

Both the main engine and auxiliary engine will have great impact of the attained EEDI. Measures for improved utilisation and higher efficiency of the engine systems exist and can be implemented on most vessels. Figure 4.1 shows a generic illustration of the marine power plant and indicates the systems covered by EEDI.

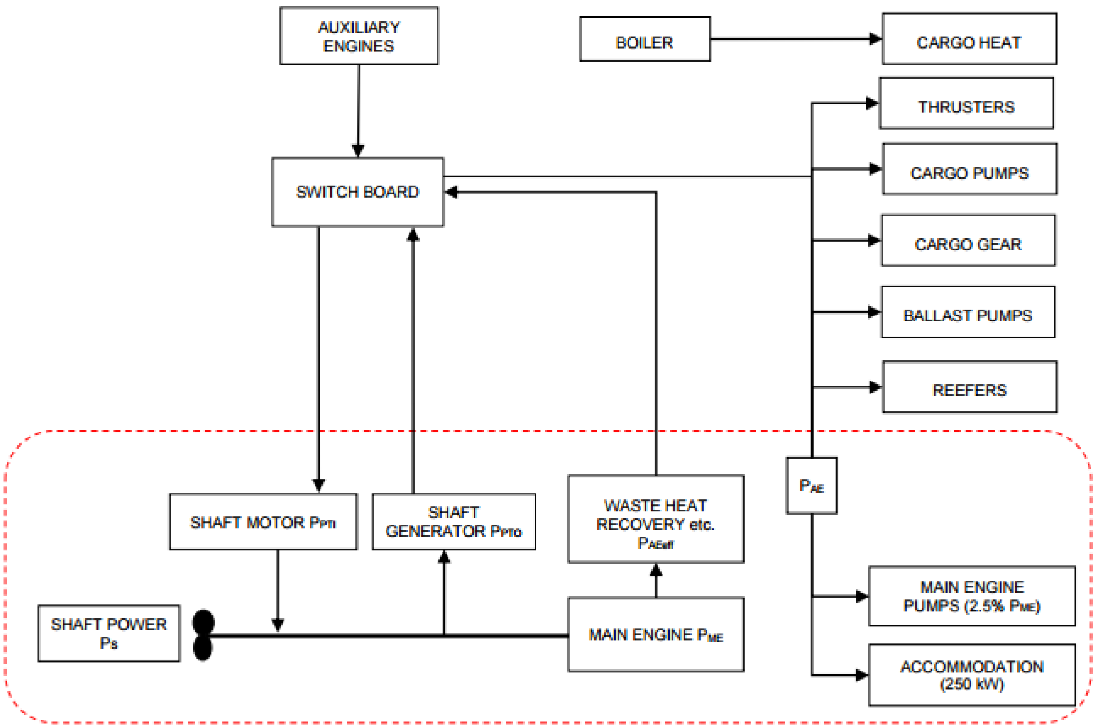

Figure 4.1 Simplified and generic marine power plant (MEPC.1/Circ.866). The red-drawn line indicates the systems covered by EEDI.

Main engine

One of the most effective ways of reducing the EEDI of a ship is to install a smaller main engine, thus reduce the ship's design speed. Extensive speed reductions could though lead to unsafe underpowered vessels that may lose manoeuvring capability in adverse weather conditions. In order to avoid such scenarios, interim guidelines for determining minimum propulsions power to maintain manoeuvrability has been adopted by IMO (Resolution MEPC.232(65), as amended by resolutions MEPC.255(67) and MEPC.262(68))

Less installed power of main engine will affect the ice going performance and thus result in difficulties of achieving ice class. In those cases, the fuel efficiency of the motor will be central. Of conventional diesel engines, low speed engines have the lowest specific fuel consumption (SFC), which have a direct impact to the attained EEDI. Medium speed diesel engines have slightly higher SFC, with an efficiency about 3-4% lower at similar power levels (ABS, 2013).

Also improvements on specific machinery parts and systems will reduce the specific fuel consumption and the energy demand from auxiliary systems and thus improve the efficiency for specific power. For a specific engine, improvements may include optimization of fuel injection timing and valves, lubrication system and cooling system. Electronic control system can also improve the total performance as it provides the capability for tuning and de-rating. A de-rated engine could be favourable in an EEDI perspective since it reduces the fuel consumption for the same power and speed for the vessel inputs into the EEDI equation.

Auxiliary engine

In the EEDI formula auxiliary power, P_{AE}, is taken into account as a fixed portion of the main engine power, and hence not as the actual power installed for auxiliary engines. However, efficient operation of auxiliary systems on board will improve the total power performance of ship, reducing the required energy production.

Electrical power for operation of auxiliary systems, crew accommodation, for any cargo purposes etc. can be produced from a shaft generator driven by the main engine. A shaft generator is considered to have better efficiency than a diesel-generator set (gen-set) and shaft generation operation therefore generates less emissions (IACS, 2015). Installations of shaft generators are accounted for in the EEDI formula and thus reduces the attained EEDI. For ships with installations of shaft generators, the main engine power, P_{ME}, is calculated as:

$$\sum P_{ME(i)} = 0.75 \times \sum (MCR_{ME(i)} - P_{PTO(i)}) \ with \ \times 0.75 \sum P_{PTO(i)} \leq P_{AE}$$

Where $P_{PTO(i)}$ is defined as 75% of the rated electrical output power MCR_{PTO}:

$$P_{PTO(i)} = 0.75 \times MCR_{PTO(i)}$$

For ships with very high power requirements, where electrical power output requirements exceeds P_{AE}, there is another option to account for shaft generators:

$$P_{ME(i)} = 0.75 \times P_{shaft,limit}$$

This means that P_{ME} in these cases is defined as 75% of the power to which the propulsion system is limited, $P_{shaft,limit}$. The additional power, higher than $P_{shaft,limit}$, of the main engine cannot be used for a higher ship speed. This can be safeguarded by the use of verified technical devices limiting the power to the propulsor (IACS, 2015).

For example, consider a ship having a 15 MW main engine with a 3 MW shaft generator. The shaft limit is verified to 12 MW. The EEDI is then calculated with only 75% of 12 MW as main engine power. The guidelines for calculating attained EEDI do not stipulate any limits as to the value of the shaft limit in relation to main engine power or shaft generator power.

The use of shaft generators is a well proven and often applied technology, particularly for high electrical power demands related to the payload e.g. reefer containers.

In the case where shaft motors are installed, the same guiding principles as for shaft generators, above, apply. But in contrast to shaft generators, motors do increase the total power to the propulsor and do increase ships' speed and therefore are therefore included in the total shaft power within the EEDI calculation. The total shaft power is thus main engine power plus the additional shaft motor power:

$$\sum P_{ME(i)} + \sum P_{PPT(i),shaft}$$

Where

$$\sum P_{PPT(i),shaft} = \sum 0.75 \times P_{SM,\max(i)} \times \eta_{PTI(i)}$$

The potential of shaft generator for reducing EEDI is assessed for the eleven vessels in the case study. The reduction of EEDI was found to correspond to approximately 1-3%.

4.3 Energy efficiency technologies

Guidance and methodology for calculation, survey and certification of innovative energy efficiency technologies is provided by MEPC.1/Circ.815 - *2013 Guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI.*

The guidance categorize different *Innovative Energy Efficiency Technologies* into four main categories depending on their characteristics and effects to the EEDI formula, see Table 4.2.

Table 4.2 Categorization of innovative energy efficiency technologies based on MEPC.1/Circ.815

Reduction of main engine power			Reduction of auxiliary power	
A	**B**		**C**	
Cannot be separated from overall performance of the vessel	Can be treated separately from the overall performance of the vessel		Effective all time	Depending on ambient environment
	B-1	B-2	C-1	C-2
	$f_{eff} = 1$	$f_{eff} < 1$	$f_{eff} = 1$	$f_{eff} < 1$
- Low friction coating - Bare optimization - Rudder resistance - Propeller design	- Hull air lubrication system	- Wind assistance (sails, Flettner rotors, kites)	- Waste heat recovery system (exhaust gas heat recovery and conversion to electric power)	- Photovoltic cells

The guidance includes detailed methodology for especially installations of hull air lubrication systems, wind propulsion systems and waste heat recovery system for generation of electricity.

Category A

Previous sections describes some of the listed technologies of category A, e.g. bare (hull) optimization and (to some extent) propeller design as these technologies do not imply any additional calculation procedures. Instead, those will shift the power curve, which results in the change of combination of propulsion power and reference speed, i.e. when V_{ref} is kept constant, P_{ME} will be reduced and when P_{ME} is kept constant, V_{ref} will be increased. Category A is considered to also include Propulsion Improving Devices (PIDs) as those cannot be separated from the overall performance of the vessel. Figure 4.2 lists examples of PIDs. The table also includes the potential of each, and how they can be combined.

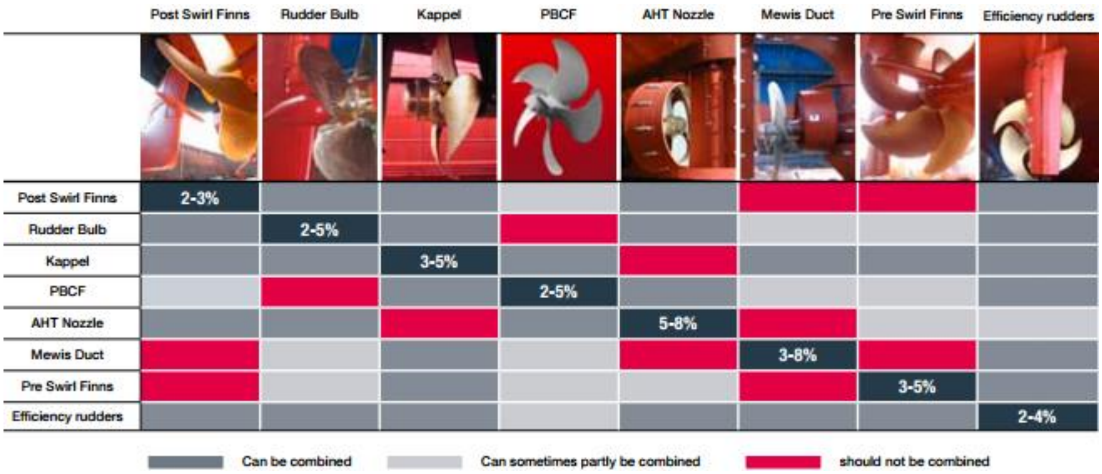

Figure 4.2 Propulsion Improving Devices (PIDs), their potential and how they can be combined (MAN Diesel & Turbo, 2017).

Hull coating is another innovative option that is still developing. Advanced texturing coating/paint is used to reduce skin friction. Several tests on commercial ships and laboratories have showed that high end products are able to reduce the overall ship's resistance by up to 8%. The reduction potential is dependent on vessel size, segment, operation profile and trading areas and is in the range of 1% to 4% on main engine fuel consumption (DNV GL, 2016).

Hull air lubrication systems

Air lubrication reduces the drag force on the wetted surfaces of the hull due to a lower viscosity of air compared to water. Powerboats and navy vessels have used this technique for decades to increase their cruising speed. The shipping industry now recognizes the potential of employing this concept for merchant vessels. Air lubrication expects to have a potential of 10% reduction in fuel consumption (ABS, 2013) even though the technology is still under development. There is two main methods; air cavity system and micro-bubbles.

With an air cavity system, a thin sheet of air is maintained over the flat portions of a ship's bottom with the aid of pumps and hull appendages. By maintaining a stable layer (typically for small Froude numbers) significant reductions in skin friction can be achieved.

With micro-bubble system, small size bubbles are injected through several nozzles into the water near the ship hull, which reduces the resistance. The bubbles need to be as close as possible to the solid surface of the hull. The attractiveness of micro-bubble systems is that stability in the flow of air over the hull does not have to be ensured as in the case of an air cavity (ABS, 2013). Also, the amount of power needed to create microbubbles would be lower than that needed for a cavity, and the amount of wetted surface treated larger, since micro-bubbles can be created anywhere over the hull instead of just over the flat of bottom.

The functionality of air lubrication may be limited when going in ice, but the systems shall still be applicable on ice-classed vessels to reduce the drag force when manoeuvring in open water.

Waste heat recovery

Waste heat recovery from the machinery reduces the need for power from auxiliary systems and therefore improves the total efficiency. This is accounted for in the formula for attained EEDI as an auxiliary power reduction P_{AEeff}. The availability factor $f_{eff(i)}$ for waste energy recovery system should be one (1) according to the guidelines for calculations of attained EEDI (MEPC.246(66)).

Wind assistance

There are several different technologies for utilization of wind power for propulsion of which soft sails, fixed sails, Flettner rotors, kite sails and wind turbines are the most discussed and tested ones. Table 4.3 summaries the applications along with an indications of their potential from an economic, environmental and social point of view.

Table 4.3 Summary of wind energy technology and their potential for shipping industry (IRENA, 2015).

	Retroft (RF)/ New Build (NB)	Vessel category, application and potential			
		< 400 tonnes	400 – <10 000 tonnes	10 000 – <50 000 tonnes	>50 000 tonnes
Soft sails	RF	●●●	●●●	●●●	●●
	NB	●●●	●●●	●●●	●●
Fixed wings	RF	●●	●●	●●	●
	NB	●●	●●●	●●●	●●
Rotors	RF	●●	●●	●●	●●
	NB	●●●	●●●	●●●	●●
Kites	RF/NB	●●	●●	●●	●
Turbines	RF/NB	●	●	●	●

	In commercial use	●●●	High potential (Scores well on all three metrics: economic, environmental and social)
	Proven		
	Proof-of-concept	●●	Medium potential (Scores on two of the three metrics)
	Design		
	Concept	●	Limited l (Scores on only one of the three metrics)
	Uncertain		
		N/A	Not available

Flettners rotors have been proven to work, e.g. E.ship has four large rotorsails that rise from its deck. Those are rotated via a mechanical linkage to the ship's propellers, see Figure 4.3.

Figure 4.3 E-ship 1 with four Flettner rotors.

Viking Line plans for an installation of rotors on their LNG fueled RoPax ferry. The Finnish company Norsepower Oy Rotors are contracted and analysis indicate that up to 20% fuel savings per year can be achieved on routes with favorable wind flows (World Maritime News, 2017).

The guidance of treatment of innovative efficiency technologies (MEPC.1/Circ815) applies to wind propulsion technologies that directly transfer mechanical propulsion forces to the ship's structure. Wind propulsion system will reduce the emissions from vessel but the contribution is dependent on wind conditions. The guidance therefore defines the available effective power as the product of the reference speed and the sum of the wind propulsion system force and the global wind probability distribution. The guidance MEPC.1/Circ.815 presents methodology for calculation of the available effective power $(f_{eff} \cdot P_{eff})$ for a wind propulsion system.

Solar photovoltaic

Solar photovoltaic (PV) power generation system installed on vessels can provide part of the electric power required, either for the propelling or for use onboard. The primary limitations for a full ship propulsion systems of solar power is the lack of sufficient deployment area onboard for PV panels and the energy storage required, full ship propulsion is likely to be confined to relatively small ships (IRENA, 2015).

The car carrier Auriga Leader was the first large ship to have auxiliary power partially supplied by photovoltaic panels. The 328 panels provide 40 kW, corresponding to about 10% of the ship's power while stationary in dock. Hybrid solutions with solar and wind systems have been developed and are installed on harbor ferries in Australia, Hong Kong and Shanghai. Similar technology for larger system to be used for tankers and bulk vessels is currently developed by e.g. Eco Marine Power.

MEPC.1/Circ provides methodology for calculation of auxiliary power reduction due to the PV power generation system. In this case, $(f_{eff} \cdot P_{eff})$ is the total net electric power (kW) generated by the PV power generation system.

4.4 Influence of different fuel types

The fuel used for both the main engines and auxiliary engines will influence the attained EEDI with regard to differential conversion factors, or emission factors, C_F, se Table 2.1. The emission factor C_F is based on the carbon content of the fuel and describes the amount of CO_2 emitted (kg) per kg fuel.

The EEDI regulation is based on the CO_2 emissions during combustion at the vessel. Thus, the emissions factors used in EEDI does not take into account any emissions derived from production and transportation of the fuel etc. The emission factors used corresponds to the so called tank-to-propeller emissions, in contrast to the so called well-to-propeller emissions which are usually used for environmental valuations and comparisons of fuels. For example, methanol is primarily produced from natural gas and energy is consumed in the production process, causing CO_2 emissions that are not covered in the tank to propeller perspective. Also the liquefaction of natural gas to LNG give rise to some additional emissions. Table 4.4 presents well-to-tank, tank-to-propeller and the total emissions for some different fuels. The table also includes emissions of methane (CH_4) and nitrogen dioxide (N_2O), which are both having a high greenhouse gas effect when emitted to the atmosphere. Their global warming potentials (GWP) are 28 and 265 respectively (Greenhouse Gas Protocol, 2017), which means that 1 kg of methane and 1 kg of N_2O corresponds to 28 kg CO_2 respectively 265 kg CO_2 in terms of climate effects. The fuels' greenhouse gas effect may thereby be compared in terms of CO_2-eqviavlents, which are also included in the table.

Table 4.4 Emissions from fuels, including both well to tank and tank to propeller. Data based on Life cycle assessment of present and future marine fuels (Brynolf, 2014)

	g/MJ	HFO	MGO	LNG	LBG	Methanol	Bio-methanol
CO_2	well-to-tank	6.7	7.1	8.3	25	20	17
	tank-to-prop.	77	73	54	0	69	0
	Total	83.7	80.1	62.3	25	89	17
CH_4	well-to-tank	0.072	0.078	0.033	0.17	0.011	0.042
	tank-to-prop.	4.5E-04	4.5E-04	0.63	0.79	0	0
	Total	0.07245	0.07845	0.663	0.96	0.011	0.042
N_20	well-to-tank	1.6E-04	1.7E-04	1.70E-04	2.8E-04	2.90E-04	2.2E-04
	tank-to-prop.	3.5E-03	3.5E-03	0	0	0	0
	Total	3.7E-03	3.7E-03	1.7E-04	2.8E-04	2.9E-04	2.2E-04
CO_2-ekv.		87	83	81	52	89	18

The EEDI regulation does not distinguish between fossil CO_2 and non-fossil/renewable which does not make any favour of bio fuel alternatives or similar. Renewable fuels are usually considered to have no CO_2 emissions in a tank to propeller perspective as they do not contribute to any net emissions to atmosphere during combustion. Although, the production of for instance Liquefied biogas (LBG) requires energy and hence causing some emissions which shall be accounted for. Both LNG and LBG cause emissions of methane during combustion, which are hard to avoid especially for combustion in otto process. To make EEDI to a measurement for greenhouse gases also methane should be included as well as accounting for fossil and non-fossil sources in order to encourage usage of biofuels.

Since 2015, the Baltic Sea region is part of a SECA (Sulphur Emission Control Area) implying that the maximum allowed sulphur content in marine fuel is limited to 0,1%. Standard heavy fuel oil (HFO), and standard LFO, cannot be used without an installation of scrubber unit on the vessel. New low-sulphur and ultra-low-sulphur alternatives have been developed of bunker supplier to meet the new requirements. Also the conventional marine diesel/marine gas oil (MGO) fulfils the requirements for SECA, why many vessels in the Baltic Sea presently are operated with this fuel. The SECA has also encouraged the development of other alternative fuels. LNG is now available for vessels in several ports around the Baltic Sea as well as the Bothnia Bay and Bothnia Sea. Also methanol is sulphur free and is now considered as an alternative marine fuel.

4.4.1 Conventional fuels, LNG and methanol

Natural gas, and hence LNG, consists mainly of methane, about 90%. The methane molecule, CH_4, is the smallest hydrocarbon with only one carbon atom and four hydrogen. This results in a lower carbon content, on weight basis, than other fuels with longer carbon chains where the weight ratio between carbon and molecule weight becomes larger. Methane also has a high energy content, Lower Calorfic Value (kJ/kg), since this is dependent on the number of hydrogen bonds.

With regard to these two properties using LNG as fuel instead of other petroleum fuels, e.g. MGO and HFO, reduces the CO_2 emissions with approximately 20-25%.

Methanol has an even lower carbon content than LNG but a significant lower energy content. The amount of fuel needed is therefore increased, implying higher emissions on an energy basis compared to LNG, see Table 4.5.

Table 4.5 Lower calorific value (LCV), carbon content, emission factor C_F in kg CO_2/kg fuel and kg CO_2/MJ for fuels covered by the EEDI regulation.

Type of fuel	LCV (MJ/kg)	Carbon content	C_F (kg-CO_2/kg-fuel)	C_F (kg-CO_2/MJ-fuel)
Diesel/Gas oil (MGO)	42,7	0,8744	3,206	0,075
Light Fuel Oil (LFO)	41,2	0,8594	3,151	0,077
Heavy Fuel Oil (HFO)	40,2	0,8493	3,114	0,077
Liquified Petroleum Gas (LPG)	46,3 (Propane)	0,8182	3	0,065
	45,7(Butane)	0,8264	3,03	0,066
Liquified Natural Gas (LNG)	48,0	0,75	2,75	0,057
Methanol	19,9	0,375	1,375	0,069
Ethanol	26,8	0,5217	1,913	0,0713806

From Figure 4.4 it can be concluded that LNG generates least CO_2 emission per energy unit in fuel. This is reflected in the calculation of attained EEDI as CF is multiplied by the SFC.

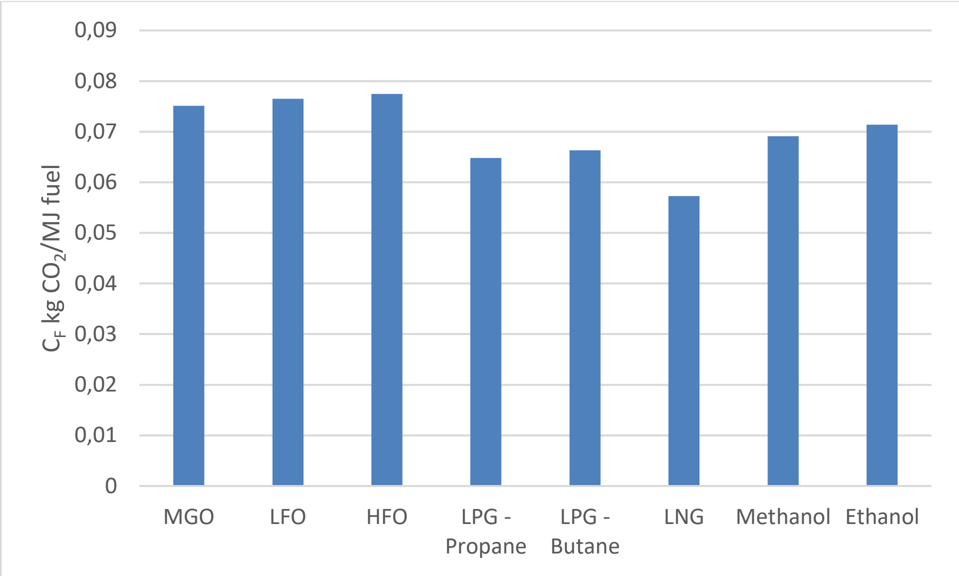

Figure 4.4 Comparison of CO_2 emissions from different fuel based on kg CO_2 emitted per MJ fuel.

The emission reduction with for example LNG compared to MGO, may though be slightly reduced due to the lower energy density and the required additional containment for LNG, which could impact the cargo capacity (Calleya, 2015)

4.4.2 Blend/Drop-in fuels

CO_2 emissions released to atmosphere can be reduced by use of renewable fuels/bio fuels. For most of the fossil fuels currently in use, there are bio alternatives, which have the same composition as the conventionally used, which enables blending or substitution. This is done for fuels for road traffic and shall be possible even for marine fuels. There are several types of bio diesel and the properties varies slightly among these. The properties of HVO (Hydrotreated Vegetable Oil) are similar to conventional diesel with just a minor difference of density, about 780 kg/m^3 for HVO compared to 860 kg/m^3 for conventional MGO. It can replace diesel, both as drop-in fuel and as a pure renewable alternative, which has been the case for road traffic where blends, and in some cases pure HVO, is available at many filling stations. Usage of HVO in marine engines shall not cause any implications, but verifications from the manufacturers will be required.

As the regulation for EEDI does not distinguish between fossil and non-fossil fuels, a blending and substitution cannot be accounted for in the EEDI formula. The potential to reduce CO_2 emissions by usage of biofuels it high though, as it is a direct option to decrease the net CO_2 emissions to atmosphere without compromising with the vessel's performance.

5 Results and discussion

Of the vessels covered by the case study, several are expected to comply future levels of EEDI, five vessels have an estimated EEDI that complies with phase 3. This indicates that is possible to comply with EEDI and achieve a high ice class. The analyzed vessels includes both new vessels, built 2016 and 2017, and some older vessels. The case study also cover different sizes of vessel, from 85 m up to 265 m in length between perpendiculars (L_{PP}).

The ice correction factors are found to have a significant importance for ice classed vessels. Based on the result in current study, the ice correction factors make it possible to obtain high ice class notation and still comply with EEDI, even in future phases.

5.1 Uncertainties

No actual EEDI verification for certain vessels have been available for analysis. The actual values used for calculating the attained EEDI is therefore unknown. The values used in the analysis are retrieved from sea-web and, where needed, adjusted and estimated. The specific fuel consumption (SFC) was found to be crucial for determining EEDI. Small differences of input values will affect the EEDI significantly.

Attempts for verification of the used data was made through recalculation of the fuel consumption figures given at sea-web for the analysed vessels. The figures given at sea-web, which are presented as a daily consumption at a certain speed, were considered to be unreliable as several of the calculated fuel consumption were unrealistic, whereas some were found to be similar to engine specification.

The actual reference speed, V_{ref}, used in the EEDI formula is determined through sea trials of the vessel. The results from sea trials have not been available and V_{ref} have therefore been estimated.

The case study was limited to eleven vessels. To be able to verify the ice correction factors for all types of vessels a more comprehensive analysis of different vessels is needed.

5.2 Potential of identified measures

Fuel with lower carbon content, e.g. LNG, will reduce the CO_2 emissions with approximately 20% compared to usage of MGO. It may thus be seen as the most straight forward why to improve EEDI. The ice class shall not affect the possibilities for adoption of alternative fuels and the measure is therefore considered to have a large potential to comply with EEDI and higher ice classes.

Several other technologies and measures for improvements of energy efficiency are available and can be applied. Optimization of propulsion and hull are the most implemented measures so far, and further optimization should still be possible, even for ice-classed vessels. The possibilities of hull optimization for reduced EEDI is though limited for ice-classed vessels as such optimization can result in poor ice going capabilities.

Engine related measures is found to have a relatively high potential to improve EEDI. Of outmost importance is a main engine with high efficiency and thus a low fuel consumption since the specific fuel consumption of the main engine (SFC_{ME}) will have a large impact on the attained EEDI.

Installation of shaft generator and shaft motor allows for higher main engine power but the potential is limited. The potential of other innovative measures, such as wind propulsion, is difficult to estimate. The potential probably varies dependent on vessel type and its operation. As the requirements on more energy efficient vessels are tightened, the innovative technologies may gain more interest. The technologies may then be further developed to become more efficient as measures to improve EEDI.

Analysis of the equations of FSICR for required power shows that the propeller diameter have a large impact for the required power. An increase of the propeller may offer possibilities to retrieve higher ice class notation. Large propeller generally improves the propulsion efficiency and shall not contradict possibilities to comply with EEDI. The possibilities for large propeller are thus limited by other design particulars of the ship.

6 Conclusions

The analysis of attained EEDI for vessels of the current fleet shows that it is possible to achieve a high ice class and still comply with EEDI regulation even for future requirements in phase 2 and 3. There are vessels today fulfilling both EEDI and high ice class notations. The results are to some extent unexpected since some previous studies have indicated that it might be difficult to comply with EEDI for vessels with high ice class notation.

The current study only considers the power requirements according to the rules. The actual ice going capability is therefore not evaluated. As has been concluded in previous investigations, the current fleet operating in the Bothnia Sea consists of many vessels with a higher installed power than required by the FSICR (Westerberg, 2014). With regard to the new EEDI requirements, this will not be possible in the future and the overall ice going capability of the fleet may therefore be weaker in the future.

The EEDI regulation aims to improve the energy efficiency of vessels and the tightened regulation will force the development towards reduced CO_2 emissions. Measures and improvements are need for both ice-classed vessels as well as for vessels without ice class notation.

Many measures and devices have been developed and several of these can be applied to improve the energy efficiency also on ice-classed vessels. Further improvements of the technology are likely. A low EEDI, complying with requirements in phase 2 and 3, can be obtained by a through selection of engine system in order to reduce the fuel consumption of the vessel. In order to reduce the CO_2 emissions further, usage of LNG as fuel can be considered.

Based on the result of current study, no need for modification of the ice correction factors is identified. The ice correction factors seem to reflect the required additional power needed for ice-classed vessels.

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