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Ilja Rautiainen

Impact of Propulsion Solution on Energy Efficiency Index and Carbon Intensity Indicator in existing Ropax Ships

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Tässä insinöörityössä tutkittaan Azimuth-propulsiojärjestelmän vaikutusta IMO:n EEDI, EEXI ja CII energiatehokkuusindekseihin. Työn tavoitteena oli arvioida akselilinjan ja Azimuth-propulsiojärjestelmän eroa energiatehokkuudessa ja selvittää, millaisia eroja järjestelmien välillä on CII ja EEDI lukemiin. Työn toinen tavoite oli selvittää ja arvioida taloudellisia vaikutuksia, jos dieselsähköinen Azimuth-propulsiojärjestelmä asennettaisiin laivaan akselilinjan sijaan.

Propulsioratkaisun vaikutusta CII ja EEDI arvoihin tutkittiin vertailemalla kahta samanlaista laivaa ja niiden propulsion käyttämää energiaa yhden kalenterivuoden aikana. Työssä vertailtiin Viking Grace ja Viking Glory aluksia, koska ne ovat samassa kokoluokassa ja kulkevat samaa reittiä. Viking XPRS aluksen osalta selvitettiin ja arvioitiin taloudelliset vaikutukset, jos akselilinja korvattaisiin dieselsähköisellä propulsiolla. Laskelmat perustuivat alustaviin suunnitelmiin, jotka tehtiin laivalle. Suunnitelmat lähetettiin arvioitaviksi Helsingin telakalle ja OSK suunnittelutoimistolle, jotka arvioivat hinnan projektin työlle ja suunnittelulle. ABB:n myynti toimitti kustannusarvion propulsiojärjestelmän ja voimalaitoksen komponenttien osalta.

Tässä opinnäytetyössä esitettyjen tietojen perusteella todettiin, että Azimuth-propulsiojärjestelmää käyttämällä voidaan saada noin yhdeksän prosentin hyöty propulsiotehossa. Energiatehokkuusvertailun perusteella todettiin, että ero CII-arvossa akselilinjan ja Azimuth-propulsion välillä oli 13 %. Takaisinmaksuaika propulsiojärjestelmän muutostyölle oli 9–11 vuotta.

Asiasanat:

Carbon Intensity Indicator, Energy Efficiency Design Index, International Maritime Organization

Master’s Thesis | Abstract

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Impact of Propulsion Solution on Energy Efficiency Index and Carbon Intensity Indicator in existing Ropax Ships

This master’s thesis research focuses on studying the impact of Azimuth propulsion solutions on energy efficiency index EEDI/EEXI and carbon intensity indicator CII. The goal was to evaluate the difference between shaft line and Azimuth propulsion solutions on energy efficiency and how this would impact the attained CII and EEDI values. Second goal of this thesis was to evaluate the economic effect of retrofitting diesel-electric Azimuth propulsion system to a ship with conventional mechanical shaft line propulsion solution.

The method used to study the impact of propulsion solution on CII and EEDI was to compare actual data of propulsion motors energy consumption from the selected ships Grace and Glory. The ship selected to study the cost for propulsion and power plant retrofit solution was Viking XPRS. The cost calculations were based on the preliminary plans that were made and presented to Helsinki Shipyard and OSK design office for cost estimation. ABB sales provided price for Azipod® thruster equipment. ROI for this solution was calculated based on the data provided by Viking line for fuel savings.

In this thesis it was found based on the provided data that Azimuth propulsion solution can provide approximately 9% improvement in required propulsion power. After the comparison it was concluded that CII value could drop approximately 13% between shaft line and Azimuth propulsion. Payback time in ROI calculations was between 9-11 years and the cost effectiveness in this type of investment is depending on how expensive CO_2 emissions will be in the future.

Keywords:

Carbon Intensity Indicator, Energy Efficiency Design Index, International Maritime Organization

Content

Abbreviations

AIS	Automatic identification system
B	Breadth
C	Capacity
CF	Conversion factor between fuel consumption and CO_2 emission
CII	Carbon Intensity Indicator
CII_R	Reference value for carbon intensity performance
d	Draught
D_t	Total Distance Travelled
DWT	Deadweight
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ETS	Emission Trading System
F_{nL}	Froude Number
FC	Total mass of fuel oil used in calendar year
F_m	Correction Factor for ice-classed ships IA Super and IA
F_{jRoRo}	Correction Factor for ro-ro passenger ship
F_{cRoPax}	Cubic capacity correction factor
GA	General Arrangement

GHG	Green House Gasses
GT	Gross Tonnage
IMO	International Maritime Organization
L_{PP}/Bp	Length between perpendiculars
M	Total mass of CO2 emissions in grams
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
PAE	Power of Auxiliary Engines
PME	Power of Main Engines
P	Shaft power
RORO	Roll-on/Roll-off
ROPAX	Roll-on/Roll-off passenger
SFC	Specific Fuel Consumption
V_{ref}	Reference speed
W	Transport work
Z	Annual reduction factor for CII
∇/D	Displacement

1 Introduction

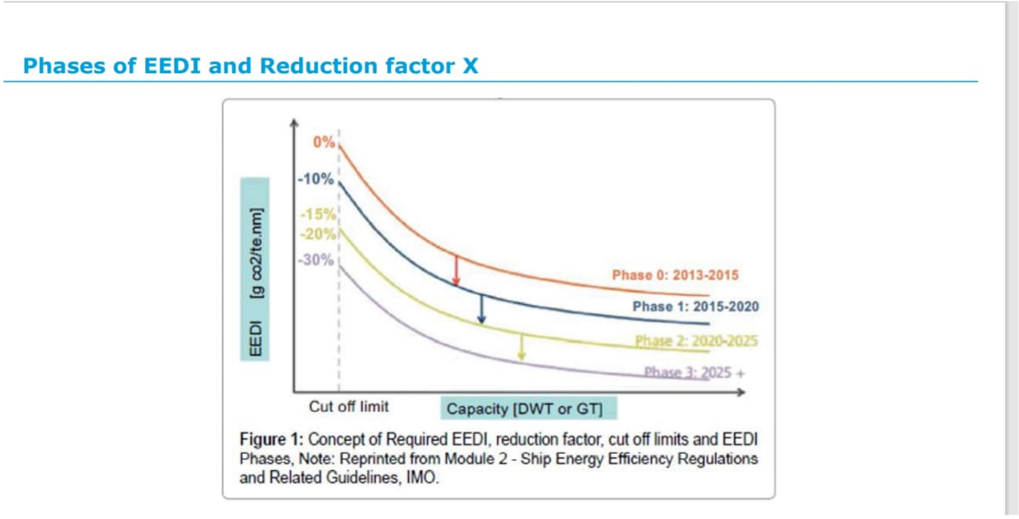
1.1 Topic and background

According to IMO GHG Study 2014 the estimated CO_2 Emissions form global shipping was approximately 2.2% from all emissions in 2012. And according to the study these emissions could grow between 50% and 250% by 2050. The goal of International Maritime Organization is to reduce greenhouse gasses emissions by 50% by 2050 compared to 2008 level. Thus, IMO has introduced mandatory measures for ships to measure their CO_2 emissions and to improve energy efficiency. These instruments' goal is to reduce environmental impact of global shipping and encourage shipping companies to take action to improve their ships energy efficiency. (1,4)

The motivation for this thesis comes from International Maritime Organization Strategy on Reduction of Greenhouse Emissions from Ships. This strategy includes new rules also for existing ships, that they must comply. The rules include Energy Efficiency Existing Ship Index (EEXI), for vessels of 400 GT and above and Carbon Intensity Indicator, for vessels of 5000 GT and above (CII). These measures will be mandatory for all ships from 1 January 2023. (1)

EEXI is an IMO instrument that measures and rates the designed energy efficiency of the ship. The calculated EEXI will be specific to each ship, and this indicates the performance of the ship's energy efficiency compared to a baseline indicated by IMO for different ship types. (1)

As seen in figure 1 EEXI and EEDI are compared to pre-defined baseline that will be lowered in each phase. The attained EEXI/EEDI value must be below this required baseline. (1)



Phases of EEDI and Reduction factor X

Figure 1: Concept of Required EEDI, reduction factor, cut off limits and EEDI Phases, Note: Reprinted from Module 2 - Ship Energy Efficiency Regulations and Related Guidelines, IMO.

Figure 1 EEDI baselines for ships (47 DNV)

CII is an instrument that will be mandatory for ships over 5000 gross tonnage and unlike EEXI, this will measure how efficiently the vessel will transport goods or passengers. This will be measured by the ratio between CO_2 mass and total transport work in a calendar year (IMO). The CII measures the operational efficiency of the ship. (1)

This Carbon Intensity Indicator value will become stricter over time. In this method the ships are given letter A, B, C, D or E according to the value that CII calculation gives. The value is then reduced each year according to agreed reduction factor as seen in figure 2. Thus, shipping companies will have to adapt and take action to make their fleet more efficient to comply with these new regulations. (1)

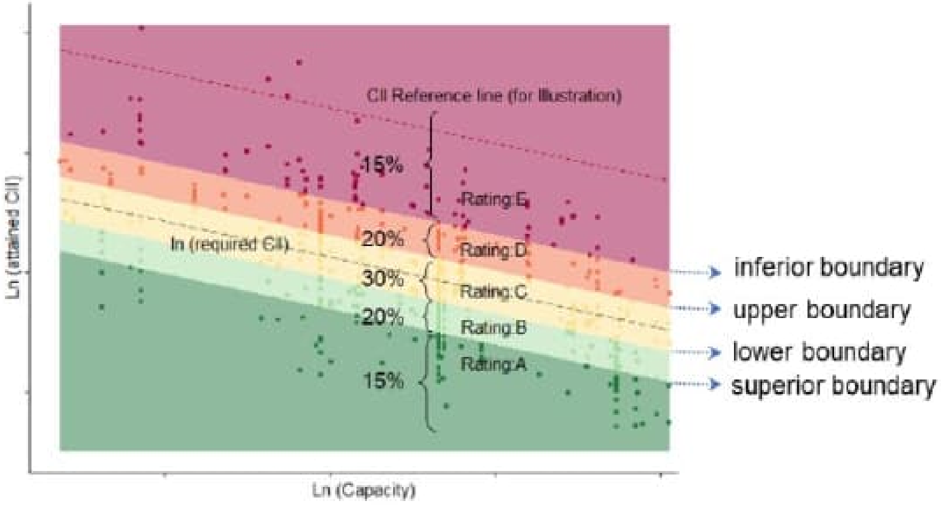


Figure 2 CII performance rating scale (48 IMO)

The topic for this master's thesis is to study the impact of Azimuth propulsion system on Energy Efficiency Index (EEDI, EEXI) and in Carbon Intensity Indicator (CII). Azimuth propulsion is a system where the thrusters are installed inside pod units that can be rotated horizontally in any direction. With this type of system, the vessel does not need rudders nor traditional shaft lines. Also, the number of traverse thrusters can be reduced or totally removed in some cases.

1.2 Thesis targets

The aim for this work is to solve, how Azimuth propulsion system will impact on energy efficiency and could it have positive results on reduction of greenhouse gasses of the vessel.

The second goal is also to solve what kind of actions existing ships should take to achieve these IMO set requirements for CII and EEXI/EEDI values, and what kind of effects the new propulsion solution could have in the long term. Would this investment be cost-effective? If existing ships do not act and does not comply with these rules, will these vessels be unable to operate internationally?

Because of this IMO strategy to reduce GHG emissions from existing ships, shipping companies will have to make some investments and improvements to their fleet in order comply with these new rules. This thesis will focus on what kind of impact propulsion retrofit solution will have on CII and EEXI/EEDI values. Additionally, this work will research the economic effect on these actions. What kind of payback time would this kind of investment have? What would be the cost and consequences of doing nothing?

1.3 Limitations

Selected vessel type for this study was approximately ten- to twenty-year-old roro passenger ships. Also, the power limitation was selected to be focused on ships with more than 7 MW of total propulsion power. Roro passenger ship is a type of vessel that can transport vehicles and passengers.

All other ship types were left out from this thesis because of time limitation and by adding more ship types to this study, would be too wide scope. The impact of CII and EEXI regulations will be different for all ship types and required actions to comply with these rules will vary. The propulsion power limitation was selected to be 7MW or above because these rules effect only ships above 400 GT for EEXI/EEDI and ships over 5000 GT for CII. For this thesis the research was selected on potential ship category that would be affected by both requirements, CII and EEXI/EEDI.

2 IMO Regulation on Energy Efficiency for Ships

2.1 International Maritime Organization IMO

IMO is a specialized agency under united nations and its role is to oversee and create regulatory framework for global shipping. The agency is responsible to set standards on maritime safety, security and set measures for the prevention of marine and atmospheric pollution by ships. IMO was formally founded in 1948. (6)

As shipping is international industry and it transport more than 80 per cent of global trade, it is important to agree and adopt regulations and standards on an international basis. IMO was founded as a forum for this purpose. These measures cover all aspects of global shipping from ship design, construction, manning, operation, and disposal. (6)

The two most important agreed conventions that IMO created for international shipping was International Convention for the Safety of Life at Sea (SOLAS) and convention for pollution, International Convention for the Prevention of Pollution from Ships (MARPOL). And as stated in the IMO Article 1(a) of the convention, the purposes of the organization are "to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships". The agency also has power and responsibility to deal with legal and administrative matters related to maritime industry. (7)

2.2 Energy Efficiency Design Index EEDI

EEDI regulations are part of MARPOL annex VI, Regulations for the Prevention of Air Pollution from Ships. These regulations are focusing on the energy efficiency of ships and according to IMO regulation 20 of chapter 4, “The goal of this chapter is to reduce the carbon intensity of international shipping, working towards the levels of ambition set out in the *Initial IMO Strategy on reduction of GHG emissions from ships.”*. (8)

EEDI is an instrument that measures the designed energy efficiency of the ship and is applicable to all ships over 400 gross tonnage. This attained EEDI will have to be calculated for each new ship once and existing ship that has undergone a major conversion. This value must be lower than the reference value that is set by IMO from 2013 to 2025, from phase 0 to phase 3. In each phase the reference value will be lowered from 2008 baseline and from, 2025 onwards this will be 30% less for all ship types. The verification process is done according to IMO verification guidelines in two stages. First is preliminary verification of the calculation in design stage and second is final verification at sea trial. (9)

The attained EEDI is a value of ship’s designed energy efficiency determined in formula 1.

$$\text{EEDI} = \frac{CO_2\ emission}{Transport\ work} \qquad (1)$$

The CO2 emission is calculated considering the designed power used for propulsion and for auxiliaries such as hotel load. The carbon content of used fuel is also included in the calculation. (10)

The transport work is estimated by multiplying the ship capacity with the reference speed at design draught according to the IMO regulations. For passenger ferry, the capacity used is deadweight. (10)

The complete EEDI formula is provided in formula 2 as stated in IMO Resolution MEPC.308(73).

$$\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}*\right) + \left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}**\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \cdot f_m} \quad (2)$$

“*If part of the Normal Maximum Sea Load is provided by shaft generators, *SFCME* and *CFME* may – for that part of the power – be used instead of *SFCAE* and *CFAE”(11)*

“** In case of *PPTI(i)* > 0, the average weighted value of (*SFCME* **.** *CFME*) and (*SFCAE* **.** *CFAE*) to be used for calculation of *Peff ”(11)*

“Note: This formula may not be applicable to a ship having diesel-electric propulsion, turbine propulsion or hybrid propulsion system, except for cruise passenger ships and LNG carriers.” (11)

Power of main engines as stated in IMO guidelines on the method of calculation of the attained EEDI and in International Association of Classification Societies (IACS) procedure for calculation of EEDI, the PME(i) in non-conventional propulsion system can be used as PTI. This value will be 75% of the installed propulsion power including chain efficiency of the transformers, frequency converter and electric motor. (11, 10)

$$\text{PME(i)} = \frac{\sum(0.75 \times MPP(i))}{\eta_{PTI} \times \eta_{Gen}} \quad (3)$$

Power of auxiliaries (PAE) can be determined either from the electrical power table or calculated as an estimate according to IMO guidelines. PAE value for passenger and ro-ro passenger ships should be estimated from the consumed electric power without propulsion when the ship is operating at reference speed. Since this information is not available, the calculation will be done according to the IMO guidelines MEPC.308(73) chapter 2.2.5.6. (11, 10)

For ships with propulsion power 10 000 kW or above:

$$\text{PAE} = \left\{0.25 \times (MCR_{ME(i)} + \frac{PTI_{(i)}}{0.75})\right\} + 250 \quad (4)$$

The CF value in EEDI calculation is conversion factor between fuel consumption and CO_2 emission. This factor can be found in MEPC.308(73) chapter 2.2.1 as shown in table 1. (11)

Table 1 Conversion factor between fuel consumption and CO_2 emission

Type of fuel	**Reference**	**Lower calorific value (kJ/kg)**	**Carbon content**	***CF*** **(t-CO2/t-Fuel)**
1 Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	42,700	0.8744	3.206
2 Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	41,200	0.8594	3.151
3 Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	40,200	0.8493	3.114
4 Liquefied Petroleum Gas (LPG)	Propane	46,300	0.8182	3.000
5 Liquefied Natural Gas (LNG)		48,000	0.7500	2.750

SFC is the certified fuel consumption that is measured in g/kWh. This value can be found in NO_x technical file or manufacturer product guide. If the main engine is using LNG as primary fuel and SCF is measured in kJ/kWh, this must be corrected to the SFC value of g/kWh. For this, the calorific value of the LNG shall be 48,000 kJ/kg as required by IMO guidelines. (15)

Correction factor for ro-ro passenger ship (f_{jRoRo}) is computed from formula 4 and 5. Parameters are determined by IMO guidelines. (11)

$$f_{jRoRo} \frac{1}{F_{n_L}^{\alpha} \times \left(\frac{L_{PP}}{B_S}\right)^{\beta} \times \left(\frac{B_S}{d_S}\right)^{\gamma} \times \left(\frac{L_{PP}}{\nabla^{1/3}}\right)^{\delta}} \qquad (5)$$

Froude number:

$$F_{nL} = \frac{0.5144 \times V_{ref}}{\sqrt{L_{pp}} \times g} \qquad (6)$$

Parameters used for Froude number calculation (f_{jRoRo}) as presented in IMO guidelines are α= 2.5, β= 0.75, γ= 0.75, δ= 1.00.

Cubic capacity correction factor for Ro-ro passenger ships (f_{cRoPax}) having DWT/GT ratio below 0.25, then according to IMO guidelines, the following factor should apply. (11)

$$fcRoPax = \left(\frac{(DWT/GT)}{0.25}\right)^{-0.8} \tag{7}$$

According to IMO Resolution MEPC.308(73) the value for correction factor for ice-classed ships IA Super and IA (F_m) shall be 1.05. (11)

The required EEDI is a value that is calculated to compare it to the attained EEDI. This value is different for each phase from 0-3, for ro-ro passenger ship phase 3, with reduction factor of 30% from 2008 baseline, will come into force 1 January 2025. The attained EEDI value must be lower than the reference line value calculated from IMO regulation 24. The purpose of EEDI is to provide basis for comparison for the design of new ships and to establish minimum efficiency level depending on vessels type and size. (16)(17)

Since required EEDI reference line values are based on collected data from different ship types, the reference line for ro-ro passenger ships with non-conventional propulsion has not been established by IMO. (17)

As mentioned in IMO regulation 24 the attained EEDI shall be as follows: “Attained EEDI ≤ Required EEDI = $(1-\frac{X}{100})\cdot$ Reference line value”. X for the equation is selected from the table in appendix 1 for ro-ro passenger ship. (16)

Reference line value is calculated using parameters found in table 2. (16)

Formula 7 for reference value calculation as described in IMO rules.

$$a \times b^{-c} \tag{8}$$

Table 2 – *“Parameters for the determination of reference values for the different ship types”*(16)

Ship type		**Capacity**	*a*	*c*
Ro-ro cargo ship (vehicle carrier)	57,700 GT and above	57,700	3672	0.590
	30,000 GT and above, but less than 57,700 GT	GT	3672	0.590
	Less than 30,000 GT	GT	330	0.329
Ro-ro cargo ship		GT	1967	0.485
Ro-ro passenger ship	Ro-ro passenger ship	GT	2023	0.460
	High-speed craft designed to SOLAS chapter X	GT	4196	0.460
Cruise passenger ship		GT	930	0.383

As seen from the equation and parameters, EEDI reference line is different for all ship types and is related to the capacity of the ship.

2.3 Energy Efficiency Existing Index EEXI

The EEXI regulation will be mandatory for all ships over 400 GT from 1st of January 2023 and first annual reporting will be completed in 2023. This measure is part of IMO short term strategy to reduce GHG from shipping, same as EEDI and is intended for existing ships that do not have EEDI certification. (29)

A ship’s calculated EEXI is done with same parameters as EEDI, with some changes related to ships designed reference speed, speed-power curve if this information is not available for older ships. (30)

Ship’s that have attained EEXI will then be compared to the required EEXI reference line, with reduction factor compared to the EEDI reference line. (31)

“Attained EEXI ≤ Required EEXI = $(1-\frac{y}{100})\cdot$ EEDI Reference line value” (31)

According to IMO MARPOL regulation 25 value y for ro-ro passenger ship is 5 and EEDI reference line value is to be used from phase 2. This means that the required energy efficiency design index for existing ships in this segment is 95% from phase 2 EEDI reference line. The attained EEXI must be below this required EEXI for individual ship. However, this requirement does not apply to ro-ro passenger ships with non-conventional propulsion. (31)

2.4 Ship Energy Efficiency Management Plan SEEMP

The Ship Energy Efficiency Management Plan serves as an operational tool aimed at improving a ship’s energy efficiency in a cost-effective manner. There are three parts to a SEEMP and in these stages it encourages ship owners and operators to consider new technologies and practices, when trying to improve and optimize the operational performance of a ship of fleet. (32)

SEEMP part I is mandatory for all ships over 400 GT and the purpose of this part is to create a system to reduce carbon intensity and improve energy efficiency of a ship’s operation. The ship specific plan can be linked to broader company energy management plan for operating and controlling its fleet. (33)

The ship specific SEEMP includes planning and ship specific measures to improve the operational carbon intensity and efficiency. These measures can include speed optimization, weather routing, hull maintenance, retrofitting energy efficient devices, and the use of alternative fuels. (33)

Part II of SEEMP is mandatory for ships over 5000 GT and it is called the ship fuel oil consumption data collection plan. The goal for this is to develop vessel specific system to collect information required by regulation 27. This includes distance travelled, annual fuel oil consumption and type of fuels, and hours spent at sea. (33)

Part III of the management plan is for the ship's operational carbon intensity and is also mandatory for ships over 5000 GT. In this document is presented the method for calculating the attained CII value, required annual operational CII and implementation plan showing how to achieve the required CIIs. Additionally, SEEMP must include the plan for corrective actions if the ship's operational CII is rated as D for three consecutive years or as E for one year. (33)

2.5 Carbon Intensity Indicator CII

The Carbon Intensity Indicator (CII) is an important initiative that IMO has introduced for regulating GHG emissions in international shipping. The IMO goal is to reduce carbon intensity of all ships by 40% by 2030 compared to 2008 baseline and CII is one of the key components of IMO's effort to cut down emissions produced by global shipping and lower the overall carbon footprint. (20)

The CII is a measurement tool that assesses the energy efficiency of a vessel and is measured in grams of CO_2 emitted per capacity and distance travelled. The CII must be calculated for all ships over 5000 gross tonnage and above and based on the carbon intensity, the ships will be rated A, B, C, D and E. These ratings indicate the performance level of specific vessel and will be recorded in the ship's Energy Efficiency Management Plan (SEEMP). Ships that are rated E for one year or D for three consecutive years will have to make plan for corrective action on how to achieve required C rating. (20)

In order to continuously improve the energy efficiency of operating ships, IMO has determined annual reduction factors for the CII ratings. This means that the required rating C that all ships with 5000 GT and above must comply, will be harder to achieve in the future. As this will be mandatory for all ships starting from 1 January 2023 the IMO's Marine Environment Protection Committee

(MEPC) will review the effectiveness of these actions by 1 of January 2026. Even though corrective action plan is documented in SEEMP, it is unknown what the sanctions will be for ships, that will not fulfil the set performance level of C in the future. (20)

As stated by the IMO regulations on energy efficiency of ships, regulation 28 the required annual operational CII is calculated as shown in formula 8.

CII:

$$(1 - \frac{z}{100}) \times CII_R \qquad (9)$$

CII_R is the reference value for carbon intensity performance of different ship types in 2019. (23)

Z means the annual reduction factor to 2019 reference line from 2023 to 2030. However, the reduction factor has been decided from 2023 to 2026 and years 2027 to 2030 will be decided at later stage. (21)(22)

The parameters for determining the annual reduction factor and ship specific CII reference value are defined in IMO guidelines G2 and G4.

The formula for determining 2019 reference value for different ship types.

$$aCapacity^{-c}. \qquad (10)$$

Parameters for the formula are given in table 3 for reference line calculations. (23)

Table 3 ”Parameters for determining the 2019 ship type specific reference lines” (23)

Ship type		**Capacity**	*a*	*c*
Tanker		DWT	5247	0.610
Container ship		DWT	1984	0.489
General cargo ship	20,000 DWT and above	DWT	31948	0.792
	less than 20,000 DWT	DWT	588	0.3885
Refrigerated cargo carrier		DWT	4600	0.557
Combination carrier		DWT	5119	0.622
LNG carrier	100,000 DWT and above	DWT	9.827	0.000
	65,000 DWT and above, but less than 100,000 DWT	DWT	144779E10	2.673
	less than 65,000 DWT	65,000	14479E10	2.673
Ro-ro cargo ship (vehicle carrier)	57,700 GT and above	57,700	3672	0.590
	30,000 GT and above, but less than 57,700 GT	GT	3672	0.590
	Less than 30,000 GT	GT	330	0.329
Ro-ro cargo ship		GT	1967	0.485
Ro-ro passenger ship	Ro-ro passenger ship	GT	2023	0.460
	High-speed craft designed to SOLAS chapter X	GT	4196	0.460
Cruise passenger ship		GT	930	0.383

As the reference line is relative to ship capacity, this value will be different for each individual ship. After determining the reference value, the reduction factors will be deducted from this. Table 4 is shown the annual reduction factor for years 2023-2026, years 2027-2030 (- **) have not yet been determined by IMO and these values will be presented at later stage.

Table 4 “Reduction factor (Z%) for the CII relative to the 2019 reference line” (22)

Year	Reduction factor relative to 2019
2023	5%*
2024	7%
2025	9%
2026	11%
2027	- **
2028	- **
2029	- **
2030	- **

After the required reference line for each year have been calculated, an annual operational energy efficiency rating will be assigned to each individual ship. These five ratings are A, B, C and D namely, superior boundary, lower boundary, upper boundary, and inferior boundary as shown in figure 4. For these five rating levels, four boundaries are defined with denoted vectors given by IMO guidelines. (24)

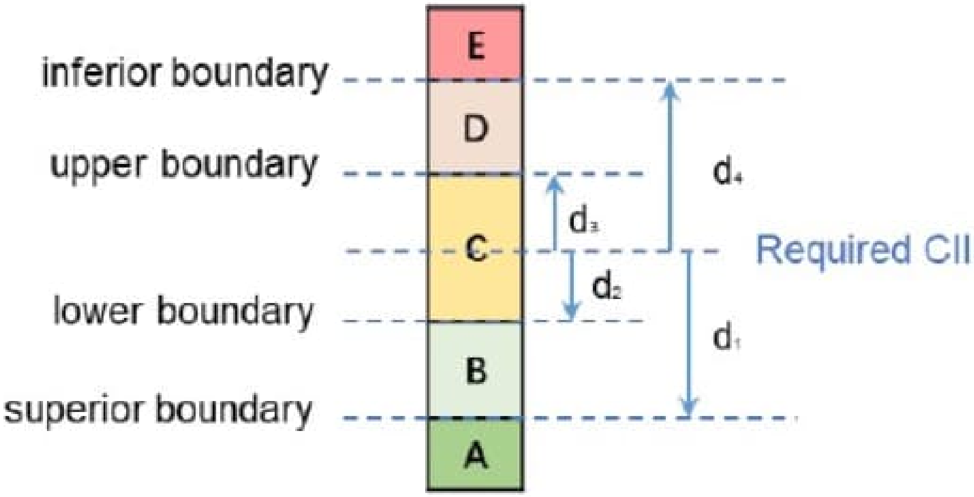


Figure 3 dd vectors presented for the five rating boundaries A, B, C, D and E. (24)

The parameters for each vector can be selected from table 5 provided by IMO to be used for calculating rating boundaries for specific ship.

Table 5 “dd vectors for determining the rating boundaries of ship types” (24)

Ship type		Capacity in CII calculation	*dd* vectors (after exponential transformation)			
			exp(d1)	exp(d2)	exp(d3)	exp(d4)
Bulk carrier		DWT	0.86	0.94	1.06	1.18
Gas carrier	65,000 DWT and above	DWT	0.81	0.91	1.12	1.44
	less than 65,000 DWT	DWT	0.85	0.95	1.06	1.25
Tanker		DWT	0.82	0.93	1.08	1.28
Container ship		DWT	0.83	0.94	1.07	1.19
General cargo ship		DWT	0.83	0.94	1.06	1.19
Refrigerated cargo carrier		DWT	0.78	0.91	1.07	1.20
Combination carrier		DWT	0.87	0.96	1.06	1.14
LNG carrier	100,000 DWT and above	DWT	0.89	0.98	1.06	1.13
	less than 100,000 DWT		0.78	0.92	1.10	1.37
Ro-ro cargo ship (vehicle carrier)		GT	0.86	0.94	1.06	1.16
Ro-ro cargo ship		GT	0.76	0.89	1.08	1.27
Ro-ro passenger ship		GT	0.76	0.92	1.14	1.30
Cruise passenger ship		GT	0.87	0.95	1.06	1.16

After comparing the required CII value to the four boundaries, a rating can be determined for specific ship. For example, the required CII for Glory and Grace in year 2023 is, 11.72 $\frac{g\ CO_2}{GT\ t{-}nm}$ and 12.42 $\frac{g\ CO_2}{GT\ t{-}nm}$, then values for boundaries are selected from the table for ro-ro passenger ship and calculated. Vectors d1, d2, d3 and d4, for the selected ship type are 8.91, 10.79, 13.36 and 15.24 $\frac{g\ CO_2}{GT\ t{-}nm}$. (24)

The CII according to IMO guidelines is the ratio between total mass of emissions and transport work. This is presented in its simplest form in formula 11. (25)

$$\text{Attained CII} = M / W \tag{11}$$

Where M, is the total mass of CO2 emissions in grams and W is the transport work in a calendar year. (25)

The total mass M of CO_2 emissions in CII calculations means all consumed fuel oil types on board multiplied with the mass conversion factor of the specific fuel type. The formula for the mass of CO_2 emissions calculations according to IMO guidelines is written in formula 12. (24)

$$M = FC_j \times C_{F_j} \tag{12}$$

j is the fuel oil type, FC is the total mass of fuel oil used in calendar year and C_F is the conversion factor for the specific fuel oil type. The fuel oil conversion factor is defined in EEDI guidelines. (24)

Transport work W is determined by multiplying a ship's cargo capacity by the distance it travels within calendar year, as shown in formula 13. (24)

$$W = C \times D_t \tag{13}$$

C means capacity of the specific ship, for ro-ro passenger ships capacity used is gross tonnage and D_t is the total distance travelled. (24)

The basic idea for operational carbon intensity formula is to evaluate the ships operational energy efficiency. However, as the simple form for the equation is M / W, the guidelines also provide means to use correction factors and voyage adjustments for CII calculations.

Formula 14 is used for attained CII with correction factors and voyage adjustments as determined in IMO regulations. (25)

$$\frac{\sum_j C_{F_j} \times \{FC_j - (FC_{voyage j} + TF_j + (0.75 - 0.03 y_i) \times (FC_{electrical\ j} + FC_{boiler j} + FC_{others j}))\}}{F_i \times F_m \times F_c \times F_{i,VSE} \times Capacity \times (D_t - D_x)} \tag{14}$$

2.6 EU Emissions Trading System

The EU Emissions Trading System (ETS) is developed by European Union to accelerate the reduce of emissions from global shipping. Maritime transport inside European Union represents approximately 3-4 percent of all CO2 emissions emitted and ETS is a system that encourages shipping companies to improve their overall energy efficiency financially. (43)

The EU ETS is a system that defines the maximum amounts of greenhouse gasses that can be emitted from all sectors, and shipping will be part of this starting from January 2024. All ships over 5000 GT entering EU ports will be required be part of ETS and reports CO2 emissions regardless of what flag state they sail. This covers 50% of emissions from voyages that start or end outside of EU and 100% of emissions from voyages that are done inside EU ports, also he overall cap of allowed emissions will decrease over time. (43)

This means that all shipping companies must buy and use ETS emission allowances for each metric tonne of reported CO2 emissions. The companies must use their first allowances by end of September 2025 for the emissions reported in 2024 through THETIS-MRV, a platform operated by European Maritime Safety Agency (EMSA). (43, 44)

In the first phase of implementation, shipping companies do not have to include all emitted CO2 emissions this new emission trading system. This is done in stages from 2025 to 2027 as follows: (43)

- 2025: 40% of emissions that were reported in 2024
- 2026: 70% of emissions that were reported in 2025
- 2027 forward: 100% of emissions (43)

3 Analysis of the current market situation

3.1 Market size and ship type

The current legislation that is being implemented by International Maritime Organization, is aiming to reduce greenhouse gas emissions from all ships by 40% by 2030 compared to the 2008 level. EEXI, EEDI and CII are instruments that are considered as short-term measures aimed at achieving this goal, in IMO GHG strategy. These measures push ship owners to act to improve their vessels energy efficiency.

Most of the vessels in this ship type have been made with conventional propulsion with shaft line and there are very few diesel-electric ro-ro passenger ships in service according to Clarkson data. Since this ship type operates in many different speed profiles during voyage and depending on the route, the conventional shaft line propulsion makes it less efficient than diesel-electric propulsion for this type of use.

Currently, according to Clarkson data, there are 970 over 5000 GT ro-ro passenger ships in service in the world that have conventional mechanical propulsion system installed. Because IMO is requiring more energy efficient operation for existing ships as well with CII ratings, this could make Azimuth retrofit solution viable for some of the vessels in this category.

In figure 5 the CII reference lines are presented in terms of capacity for ro-ro passenger ships in years 2019-2026. As seen from the graph the evaluated 13% improvement in operational energy efficiency could be most beneficial in the range of 10 000-35 000 GT capacity ships, because in this range the CII reference line declines rapidly, and propulsion solution would have greater impact on ship CII rating.

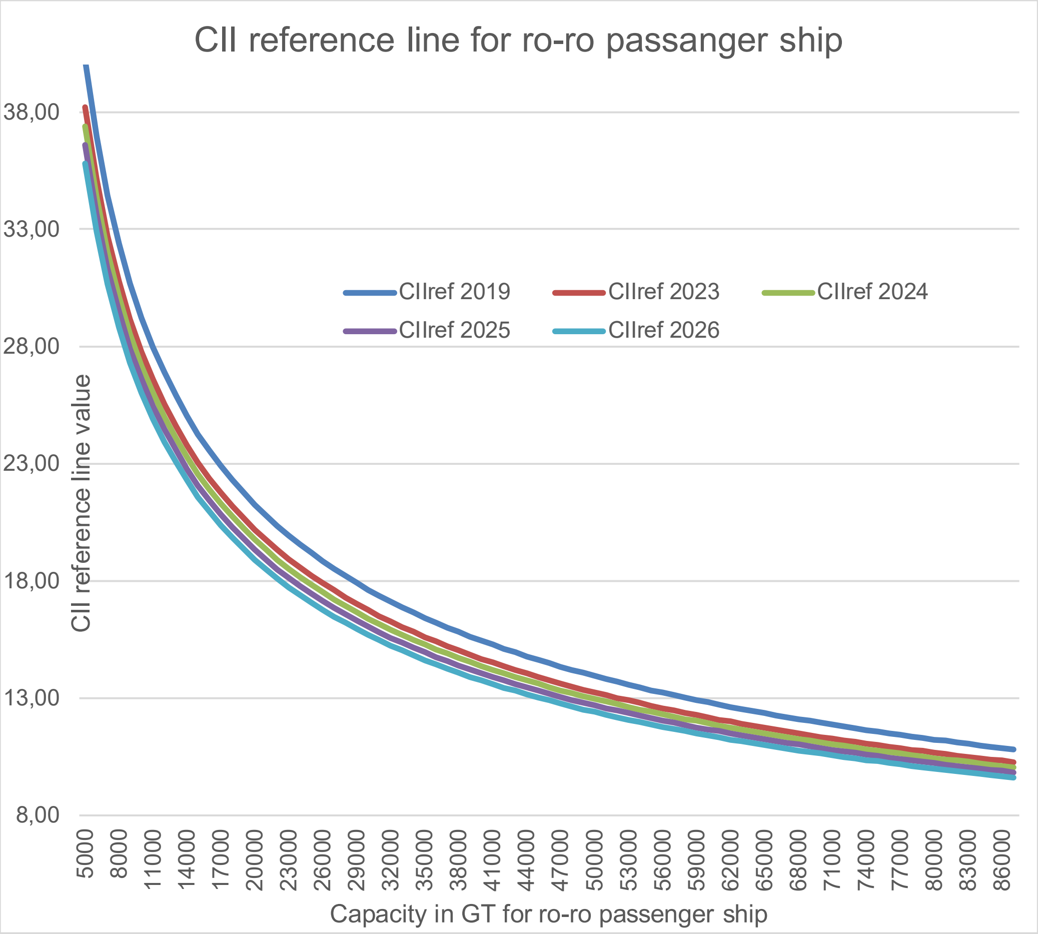


Figure 4 CII reference line for ro-ro passenger ship

According to the Clarkson data the average fleet age is 23,2 years and average scrapping age 34,5 years as shown in table 6.

Table 6 Average age of fleet and average scrapping age

Vessel Scrapping Age Baseline Assumptions*

Vessel Type		Avg. Age of Fleet	Avg. Scrapping Age 96-22		Baseline Scrapping Age*		
			Years	No.	Low*	Base	High*
Passenger Ferries	>30,000 GT	19,2	28,7	6	- 1-2yrs	28	+ 1-2yrs
Passenger Ferries	10-30,000 GT	23,2	34,5	194	- 1-2yrs	31	+ 1-2yrs
Passenger Ferries	2-9,999 GT	23,6	37,0	321	- 1-2yrs	34	+ 1-2yrs
Passenger Ferries	**2,000+ GT**	**23,0**		**521**			

Source: Clarkson

Based on this assumption the potential ship that could benefit from propulsion retrofit would be approximately 15- to 5-year-old vessel. This means that the owner would have more than 15 years of operation before the average scrapping age, after completing this type of project.

After applying these parameters to Clarkson data, the potential number of vessels that could benefit from Azipod® propulsion retrofit installation is 193 vessels.

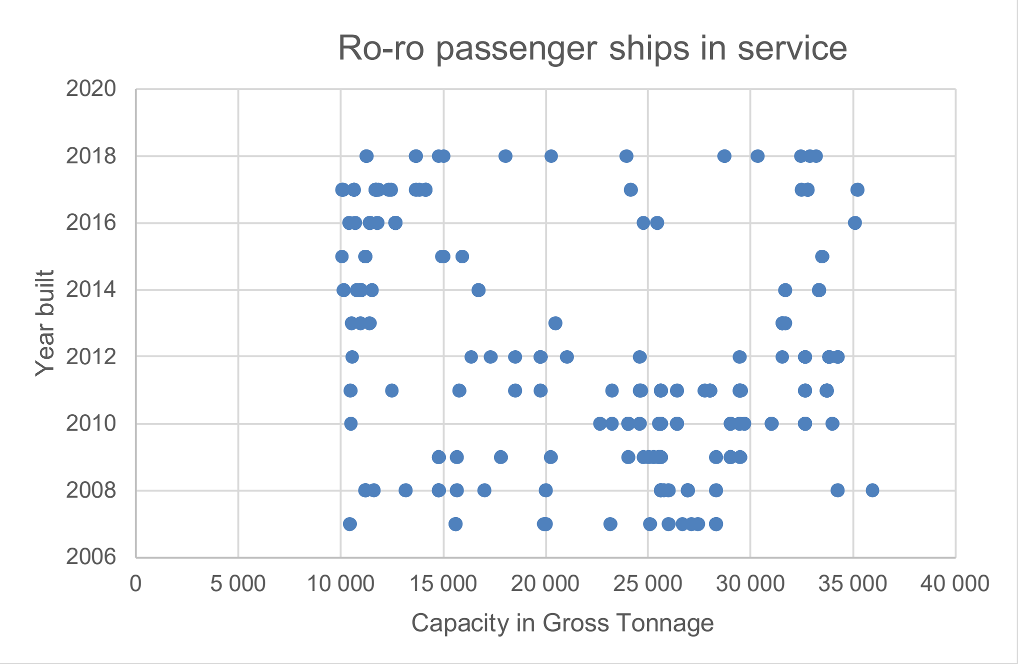


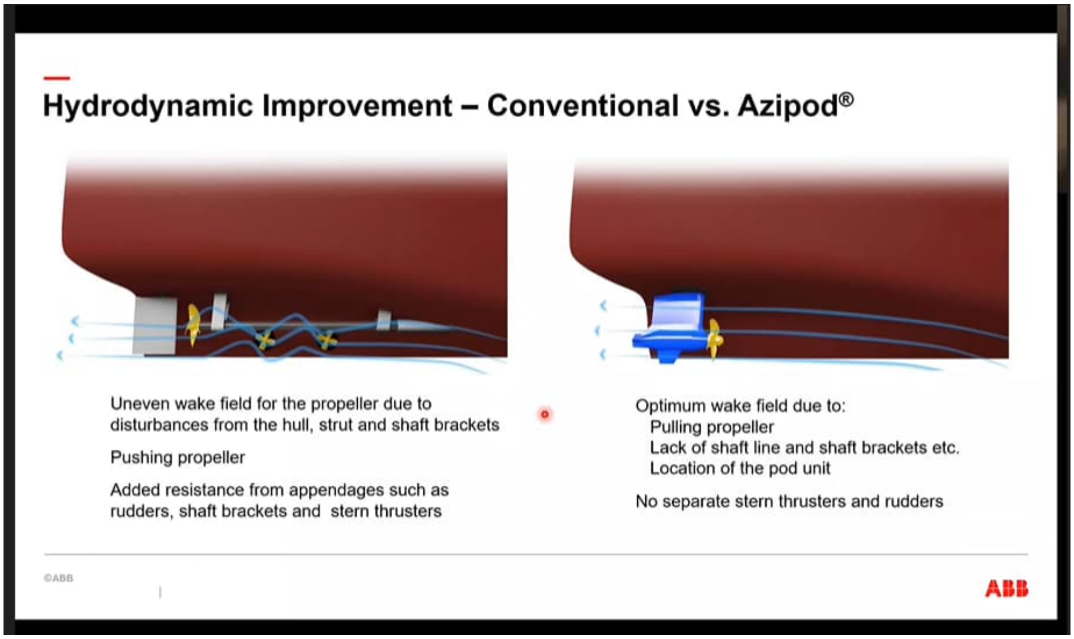
Figure 5 Ro-ro passenger ships in service

Propulsion power demand for this size of vessels is approximately in the range of 4-7MW for 10 000 to 15 000 GT and 7,5-14,5MW for 15 000 – 35 000 GT. Suitable products from ABB Azipod® units are DO for the smaller ones and MO for the larger vessels and as presented in figure 6 there are 59 vessels for DO power range and 134 vessels for MO power range. These products are also designed to for low deck height and that allows them to be placed under car deck for roro passenger vessels. (45)

3.2 Electric Azimuth Propulsion solution for improving energy efficiency

Based on the data, it is evident that the ship equipped with pods, consumes less energy for propulsion motors. ABB's propulsion solution improves a ship's energy efficiency by optimizing hydrodynamic design and having more efficient propeller. Also, electrical steering gear results to smaller losses in steering. These benefits have direct impact in the vessel's greenhouse gas (GHG) emissions. (28)

The typical improvement in propulsion demand is 7-15% when comparing vessel with twin screw to twin azimuth solution. This is because, in pulling propeller solution, no shaft line, rudder, and shaft bracket is needed. Because of this feature, this propulsion solution also gives the propeller better cavitation characteristics. Also, with diesel-electric propulsion it is possible to run main engines at constant speed and use optimum number of generators at different speed profiles. (28)



Hydrodynamic Improvement – Conventional vs. Azipod®

Uneven wake field for the propeller due to disturbances from the hull, strut and shaft brackets

Pushing propeller

Added resistance from appendages such as rudders, shaft brackets and stern thrusters

Optimum wake field due to:
- Pulling propeller
- Lack of shaft line and shaft brackets etc.
- Location of the pod unit

No separate stern thrusters and rudders

©ABB

Figure 6 hydrodynamic improvements (28)

3.3 Alternative methods

There are many different alternative methods for improving energy efficiency and lower greenhouse gas emissions for ships. These include wind assisted propulsion, waste heat recovery, air lubrication and alternative fuels. These systems are gaining more attention from shipowners as IMO is tightening the energy efficiency rules and is targeting to lower shipping environmental footprint.

Wind assisted propulsion system (WASP) uses the power of the wind to assist propulsion and to improve the ships efficiency. There are several different technologies and concepts that have been developed, these include rigid or soft wing sails, Flettner rotors and ventilated foils as shown in figure 23. Wind assisted propulsion systems have great potential to improve shipping efficiency and to help the decarbonization targets set by IMO. (40)

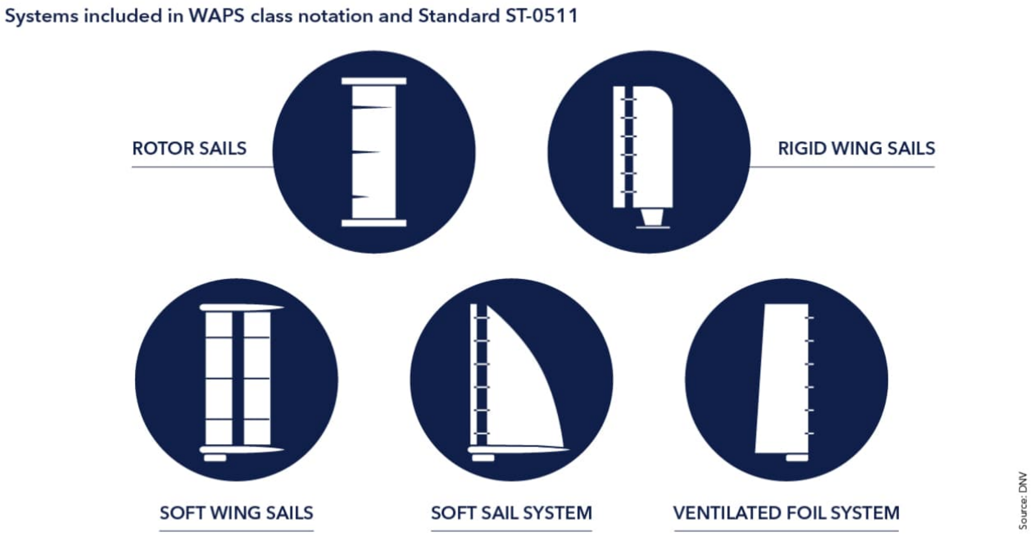


Figure 7 WAPS systems included in class notation by DNV (39)

Waste heat recovery system (WHRS) is a system with various equipment that is installed on board to support and assist the ships main machinery. This system is designed to recover a portion of energy contained in the fuel, that would otherwise be inefficiently used by the main engines. This energy would be lost as heat into the atmosphere or sea water. (35)

The mechanical efficiency of the main engines is close to 50% and the rest of the potential energy in the fuel itself is not converted to into shaft power and is lost to heat and friction. The WHRS focuses on recovering energy from these losses as much as possible and what is economically reasonable. The main components for this type of system are: (35)

- Dual pressure exhaust boiler
- Steam turbine generator
- Exhaust gas power turbine
- propeller shaft generator
- Boiler feed water heaters
- An electric system and power management system

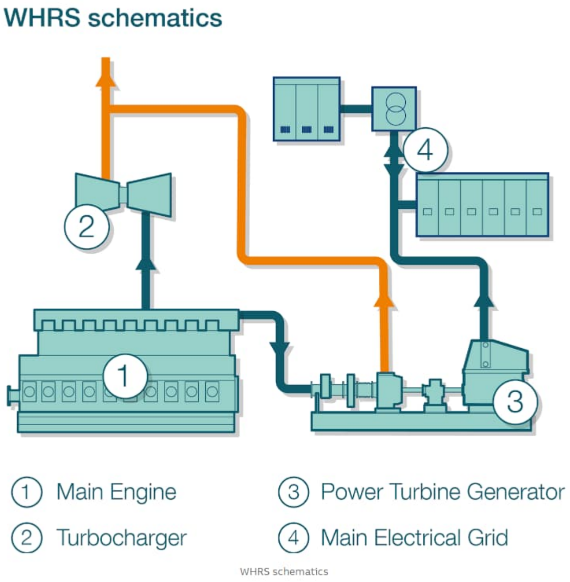


Figure 8 WHRS schematics ABB (36)

Air lubrication system provides constant flow of air bubbles to lubricate the flat bottom area of a ship’s hull. A vessel’s hull resistance in water consists of various elements, with frictional resistance being one of the most dominant. The Air lubrication system puts air into the boundary layer between stationary and moving water to lower the hull’s frictional resistance. (37)

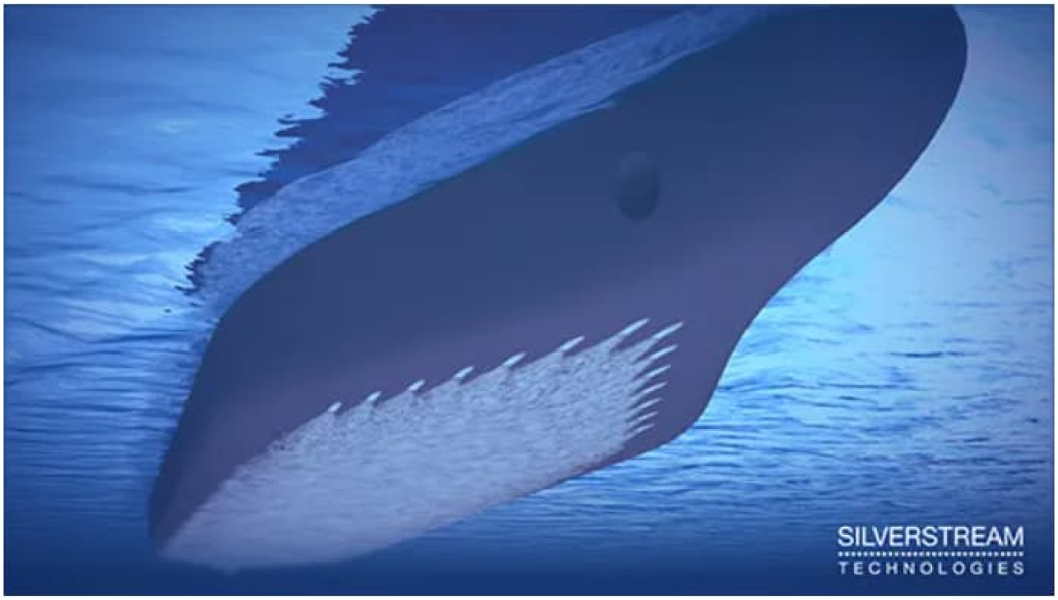


Figure 9 Air lubrication Wärtsilä (38)

Alternative fuels such as liquefied natural gas (LNG), liquefied petroleum Gas (LPG), methanol, ethanol, hydrogen, ammonia, and biofuel have been promising solutions in finding ways to decarbonize global shipping. IMO has made decision in 2020 to limit sulphur content in fuels to 0,5% and this has accelerated the development and use of alternative fuels in shipping industry. (41)

Because carbon content is defined by IMO for some of these alternative fuels, this can have major impact in ships, CII, EEDI and EEXI values. For example, LNG retrofit can lower CII value for a ship by up to 35% if this would only be used instead of MDO. Other fuels with low carbon content are methanol and ethanol compared to light fuel oil and heavy fuel oil.

Other way to improve ships fuel efficiency and to lower EEDI, CII and EEXI values is to redesign the propeller. This method uses computational fluid design (CFD) to evaluate the performance of the existing propeller and its interaction with the ship's hull. New design of the propeller with reduction in engine power and speed can lead to better fuel efficiency. Best results are often achieved with

CFD already in building phase, but this can provide solution in improving existing vessels energy efficiency. (42)

4 EEDI and CII calculations for Viking Glory and Viking Grace

For this thesis the calculation for the EEDI and CII value will be done for ro-ro passenger ships Viking Glory and Viking Grace, to compare the effect of propulsion solution on their energy efficiency values.

Both ships have diesel-electric propulsion system installed and are classified with Finnish-Swedish ice class 1A super, with the difference being shaft line propulsion and ABB Azipod® propulsion system. Viking Grace is fitted with shaft line and Viking Glory with Azipod® propulsion and both vessels use LNG for primary fuel. Other difference with the selected vessels is that they use different main engines and do not have same machinery arrangement, this will also have effect in the calculated EEDI values.

Ro-ro passenger ships with diesel-electric propulsion system are considered by IMO as non-conventional propulsion and according to Regulation 19, these types of ships do not have to comply with EEDI and EEXI regulations. For this thesis EEDI calculations for the vessels are made for probable future references. Some ship particulars are estimated to be able to evaluate the impact of Azimuth propulsion and diesel-electric shaft line propulsion systems for energy efficiency design index.

4.1 EEDI calculation for Viking Grace and Viking Glory

Information of the ships main dimensions are selected from Net Norske Veritas and Loyd’s Register data and are shown in table 7. Reference speed in EEDI calculations means the speed that the vessel is sailing with 75% main engine power. Information for vessel speed is only available from public sources and may not be accurate, this reference speed can be lower with 75% engine power.

Table 7 Main particulars

Principal dimensions	VIKING GLORY	VIKING GRACE
Length overall (m)	222.59	218.21
Length bp (m)	203.15	200.02
Breadth moulded (m)	34.94	31.8
Draught (m)	7.15	7.015
Gross tonnage (t)	65 211	57 565
Deadweight (t)	8087	6107
Reference speed (knots)	22.1	22
Installed propulsion power (kW)	2 X 11 200	2 x 10 500

(12, 13, 18, 19)

Parameters used for EEDI reference line calculation are explained in chapter 2.2. The reference line, with reduction factors for Viking Grace and Viking Glory in phases 0 to 3 are as shown in figure 4. The capacity used for EEDI calculations for ro-ro passenger ships will be DWT as explained in chapter 2.2, DWT for Grace is 6107 and 8087 for Glory.

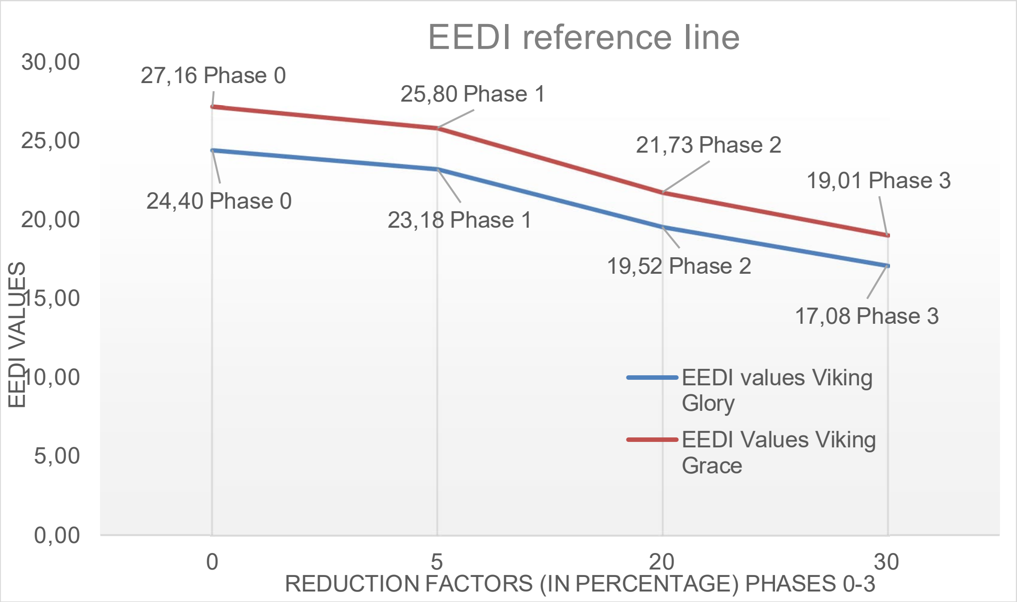


Figure 10 EEDI reference value

In this thesis the reference line is calculated for the selected ship type using information that is available, which for ro-ro passenger ships is for conventional propulsion. The reference line for non-conventional propulsion is not available at the time of writing for this ship type.

Main engines SFC for the selected ships can be found in Wärtsilä product guides.

Viking Glory:

- Wärtsilä 10V31DF, pilot fuel SFC at 75% load, 5,9 g/kWh (LFO)
- Heat rate (total) for LNG, 7440 kJ/kWh, 155 g/kWh (LNG)
- Wärtsilä 10V31DF, SFC at 75% load, 182,3 g/kWh (LFO)

Viking Grace:

- Wärtsilä 8L50DF, pilot fuel SFC at 75% load, 1,5 g/kWh (LFO)
- Heat rate (total) for LNG, 7720 kJ/kWh, 160,8 g/kWh (LNG)
- Wärtsilä 8L50DF, SFC at 75% load, 188,2 g/kWh (LFO)

The volumetric displacement used for the calculations for these ships is not available from public sources and is unknown. This value can be estimated using the ship's main dimensions and block coefficient. The value for block coefficient for Grace and Glory is selected using data from existing ships of same type and is presented in formula 15. (14)

$$\nabla(m^3) = L_{bp} \times B \times D \tag{15}$$

L_{bp} = Length between perpendiculars

B = Breadth in meters

D = Draught in meters

Displacement for Glory:

$$(203.15\text{m} \times\ 34.94\text{m} \times 7.15\text{m} \times\ 0.65) =\ 32\,900\, m^3$$

Displacement for Grace:

$$(200.02\text{m} \times\ 31.8\text{m} \times 7.015\text{m} \times\ 0.65)\ =\ 29\,000 m^3$$

As presented in chapter 2.2, main engine power PME(i) is calculated based on equation 3 and the power of auxiliaries equation 4. Froude number, correction factors *fjRoRo* and *fcRoPax* are calculated using formulas 6,5 and 7. After applying the below values to the formulas the attained EEDI can be calculated for Grace and Glory.

Glory:

$$\text{PME(i): } \frac{(0.75 \times 2 \times 11200 kW)}{0.945 \times 0.974} = 18\,300 \text{ kW}$$

$$\text{PAE: } \left\{0.025 \times (33000 + \frac{22400}{0.75}\right\} + 250 = 1\,820 \text{ kW}$$

$$F_{nL} = \frac{0.5144 \times 22.1}{\sqrt{203.15 \times 9.81}} = 0.255$$

$$fj_{RoRo} \frac{1}{0.2546^{2.50} \times \left(\frac{203.15}{34.94}\right)^{0.75} \times \left(\frac{34.94}{7.15}\right)^{0.75} \times \left(\frac{203.15}{32900^{\ 1/3}}\right)^{1}} = 0.392$$

fcRoPax : $\left(\frac{(8087/65211)}{0.25}\right)^{-0.8}$ = *1.75*

CF (LFO) = 3.151

SFC (LFO)= 5.9 g/kWh

CF (LNG) = 2.75

SFC (LNG) =155 g/kWh

$F_{m=}$ 1.05

EEDI: $\frac{(0.3918\times(18252+1821.6))\times((3.151x5,9)+(155x2.75))}{1.7521\times8087\times22.1\times1.05}$ = **10.6** $\frac{\boldsymbol{g\ CO_2}}{\boldsymbol{t-nm}}$

Grace:

PME(i) : $\frac{(0.75\times2\times10500kW)}{0.945\times0.974}$ = 17 100 kW

PAE: $\left\{0.025\times(30400+\frac{21000}{0.75}\right\}+250$ = 1 710 kW

F_{nL} = $\frac{0.5144\times22}{\sqrt{200.02\times9.81}}$ = 0.2554

fjRoRo $\frac{1}{0.2554^{2.50}\times\left(\frac{200.02}{31.8}\right)^{0.75}\times\left(\frac{31.8}{7.015}\right)^{0.75}\times\left(\frac{200.02}{29000\ ^{1/3}}\right)^{1}}$ = *0.378*

fcRoPax : $\left(\frac{(6107/57565)}{0.25}\right)^{-0.8}$ = *1.99*

CF (LFO) = 3.151

SFC (LFO) = 1,5 g/kWh

CF (LNG) = 2.75

SFC (LNG) = 161 g/kWh

$F_{m=}$ 1.05

EEDI: $\frac{(0.3776\times(17111.5+1710))\times((3.151\times1,5)\ +(2.75\times160,8)}{1.985\times6107\times22\times1.05}$ = **11.3** $\frac{\boldsymbol{g}}{\boldsymbol{t-nm}}$

The power requirement for Grace with Glory’s capacity is 9% greater when utilizing Admiralty coefficient for propulsion power as explained in chapter 4.2. When applying this to the calculations, Viking Grace PME(i) is 18660kW.

Calculated EEDI:

$$\text{EEDI: } \frac{(0.3918\times(18660+1821.6))\times((3.151x5{,}9)+(155x2.75))}{1.7521\times8087\times22\times1.05} = \mathbf{10.9}\ \frac{\boldsymbol{g\ CO_2}}{\boldsymbol{t-nm}}$$

$$\frac{10{,}9\ (Grace\ after\ conversion)}{10{,}75\ (Glory)} = 1{,}015$$

The difference in EEDI for the two ships with Azimuth propulsion and Shaft line is 1,5% with these assumptions. As the reference line for diesel-electric propulsion is not defined by IMO, and the EEDI values are calculated for non-conventional propulsion system, these values are not comparable. The reference line values are shown for information and could be different if more ships in ferry segment will shift from mechanical propulsion to diesel-electric in the future.

4.2 CII calculations for Grace and Glory

The reference values for ships in this thesis are calculated as described in chapter 2.5 as follows:

Viking Glory: $2023 \times 65\ 211^{-0.460}$ = 12,3$\frac{\boldsymbol{g\ CO_2}}{\boldsymbol{GT\ t-nm}}$

Viking Grace: $2023 \times 57\ 565^{-0.460}$ = 13,1 $\frac{\boldsymbol{g\ CO_2}}{\boldsymbol{GT\ t-nm}}$

CII reference line is presented in figure 6 with annual reduction factors as explained in chapter 2.5 for years 2019-2026.

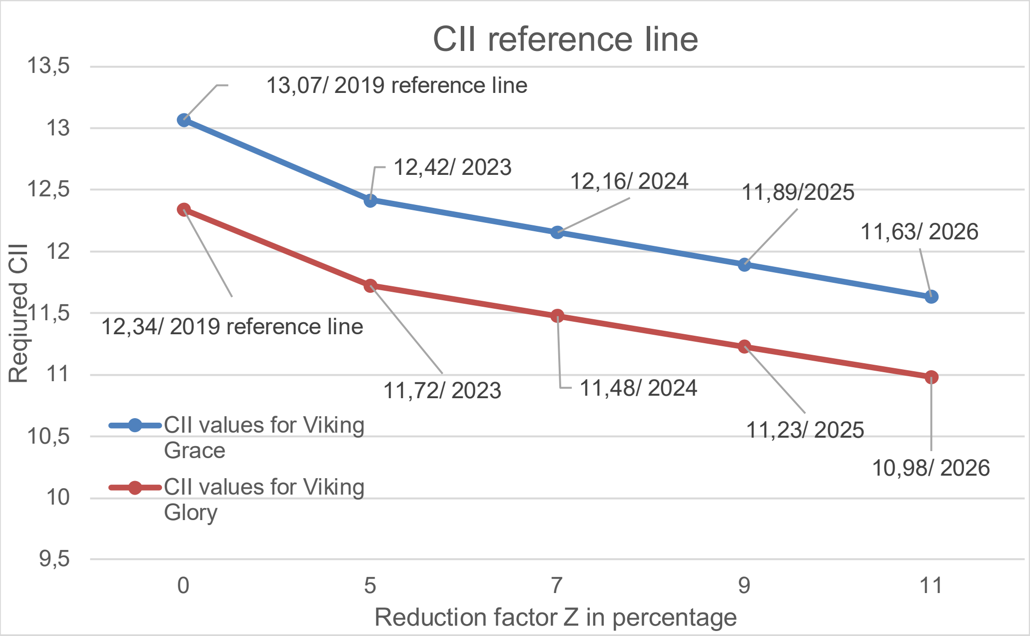


Figure 11 CII reference line for Grace and Glory with reduction factors

Boundaries for Viking Glory and Viking Grace are calculated in figure 7 and 8, for years 2023-2026 as described in chapter 2.5.

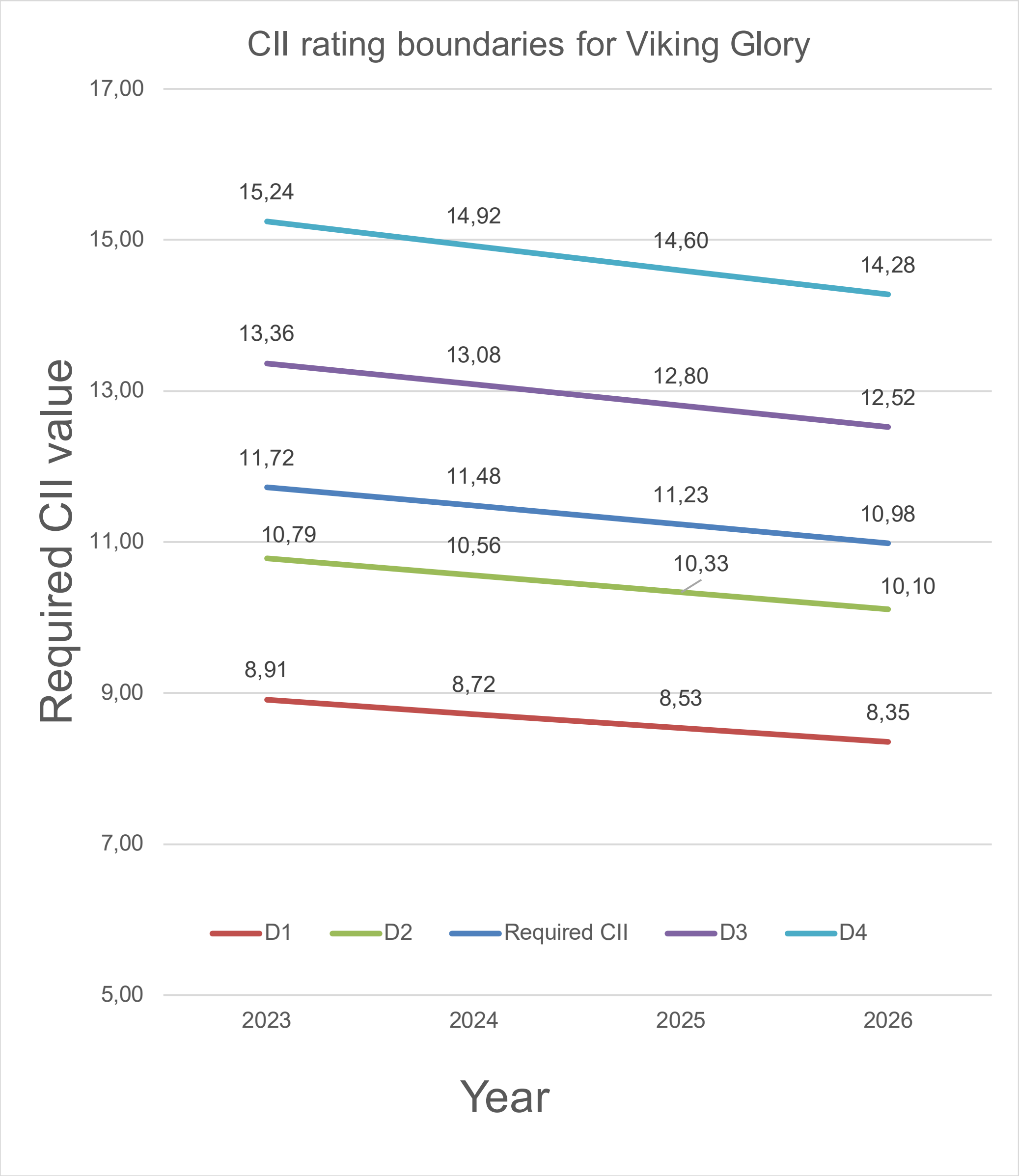


Figure 12 Rating boundaries for Viking Glory

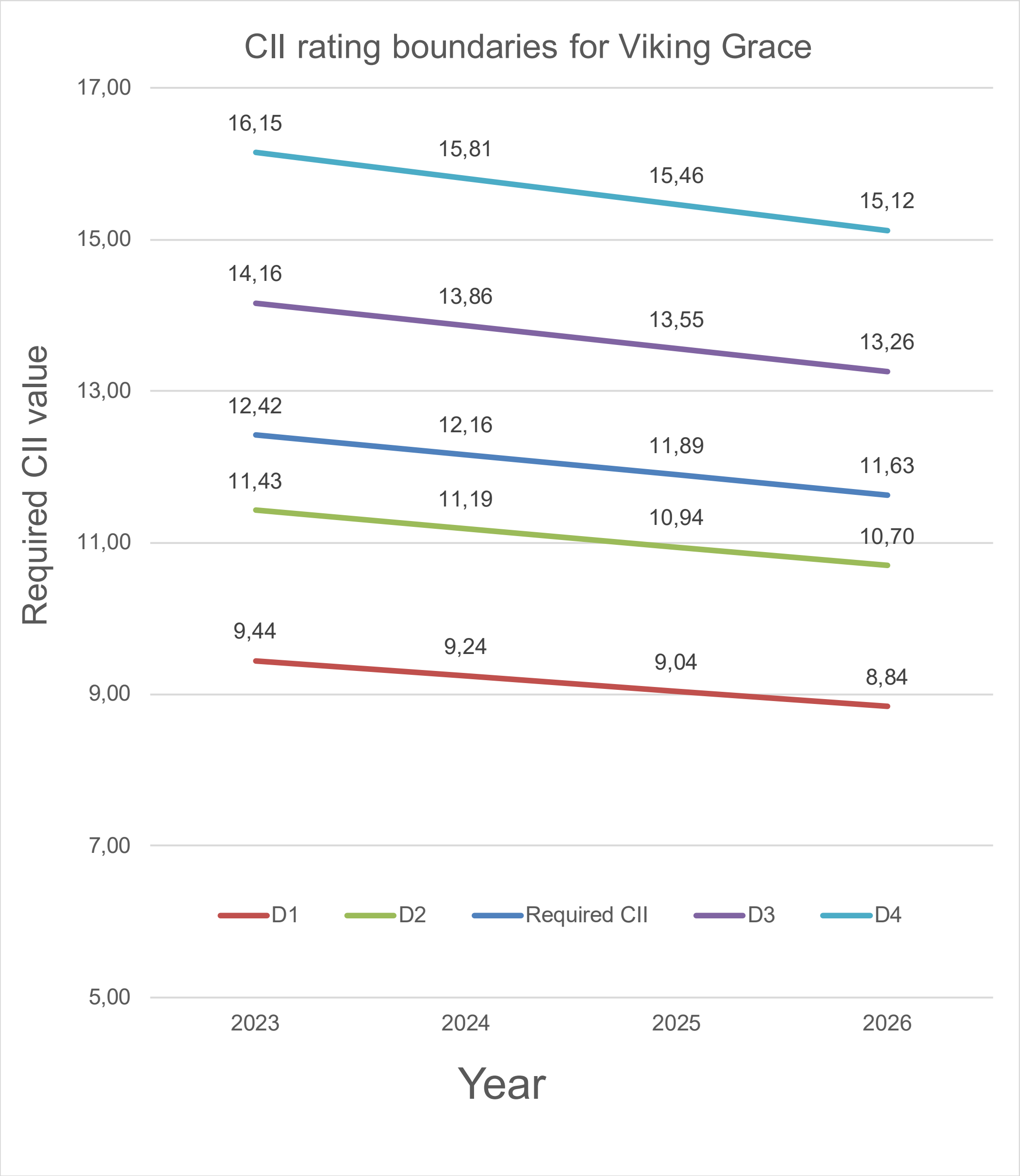


Figure 13 Rating boundaries for Viking Grace

As seen from the graphs, different color lines represent the required boundary value for each year from 2023 to 2026. The rating is defined based on these boundaries. For exampe, if specific ship has CII value higher than the D4 vector, then the rating for that ship would be E and if the ship would get lower CII value than D1 vector, then the rating would be A for that ship.

The required CII value is proportional to ship capacity and as seen from the calulations, the more capacity the ship has it also means that the vessel has to be more energy efficient.

The attained CII calculations for the selected ships in this thesis are used to demonstrate the difference that propulsion solution will have on their operational energy efficiency rating.

Majority of the correction factors and voyage adjustments as shown in formula 14 does not apply for ro-ro passenger ships, thus in this thesis, only parameters that are applicable are explained and used for the calculations.

Fuel consumption conversion factor for fuel type j CF_j is selected from EEDI guidelines MEPC.308(73) chapter 2.2.1 in table 8. (11)

Table 8 Fuel conversion factor for different fuel types

Type of fuel	**Reference**	**Lower calorific value (kJ/kg)**	**Carbon content**	***CF* (t-CO2/t-Fuel)**
1 Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	42,700	0.8744	3.206
2 Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	41,200	0.8594	3.151
3 Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	40,200	0.8493	3.114
4 Liquefied Petroleum Gas (LPG)	Propane	46,300	0.8182	3.000
5 Liquefied Natural Gas (LNG)		48,000	0.7500	2.750

The total mass of used fuel FC_j for the example calculations are taken from data provided by Viking line for one calendar year, from October 2022-2023. From this data Viking Line has removed January and February since Grace was in dry docking. Also, Hotel load and fuel type is removed from the equation to make the results comparable. Only power used for propulsion is included in the calculation.

Energy used by propulsion motors:

Viking Glory: 57354,99 MWh

Viking Grace: 60921,49 MWh

LNG used in grams:

Glory: $57354{,}99\mathrm{MWh} \times 1000 \times \frac{155\mathrm{g}}{\mathrm{kWh}} = 8\,890\ \mathrm{ton}$

Grace: $60921{,}49\mathrm{MWh} \times 1000 \times \frac{155\mathrm{g}}{\mathrm{kWh}} = 9\,440\ \mathrm{ton}$

LFO used in grams:

Glory: $57354{,}99\mathrm{MWh} \times 1000 \times 182{,}3\frac{\mathrm{g}}{\mathrm{kWh}} = 10\,460\ \mathrm{ton}$

Grace: $60921{,}49\mathrm{MWh} \times 1000 \times 182{,}3\frac{\mathrm{g}}{\mathrm{kWh}} = 11\,100\ \mathrm{ton}$

Viking Grace and Glory have different main engines and these engines have different certified fuel consumption for pilot fuel and LNG as explained in chapter 4.1, this variation is removed from the calculations by using only Viking Glory engine values. Because energy used by propulsion motors is known, the main engine SCF values from Glory can be used with assumption that these ships would have same machinery arrangement.

According to IMO Resolution MEPC.308(73) the value for correction factor for ice-classed ships IA Super and IA (F_m) shall be 1.05.(11)

For CII calculations the capacity used will be gross tonnage as stated in IMO rules.

Glory: 65 200 GT

Grace: 57 600 GT

The total distance travelled D_t for the ships are taken from data provided by Viking line from October 2022-2023.

Glory: 100 900 nm

Grace: 100 600 nm

CII calculation for Viking Glory with parameters used for ro-ro passenger ships as presented in formula 14.

CF_j (LNG) = 2.75

CF_j (LFO) = 3.151

F_m = 1.05

D_t = 100 900 n-mile

$F_{C_j}(LNG)$ = 8 890 ton

$F_{C_j}(LFO)$ = 10 460 ton

Capacity: 65 200 GT

Attained CII LNG: $\frac{2.75\times 8890023450}{1.05\times 100975{,}90\ \times 65\ 211}$ = $\mathbf{3{,}5}\ \frac{\boldsymbol{g\ CO_2}}{\boldsymbol{GT\ t{-}nm}}$

Attained CII LFO: $\frac{3.151\times 10455814677}{1.05\times 100975{,}90\ \times 65\ 211}$ = $\mathbf{4{,}8}\ \frac{\boldsymbol{g\ CO_2}}{\boldsymbol{GT\ t{-}nm}}$

CII calculation for Viking Grace with same parameters as Glory.

CF_j (LNG) = 2.75

CF_j (LFO) = 3.151

F_m = 1.05

D_t = 100 600 n-mile

$F_{C_j}(LNG)$ = 9 440 ton

$F_{C_j}(LFO)$ = 11 110 ton

Capacity: 57 600 GT

Attained CII LNG: $\frac{2.75\times 9442830950}{1.05\times 100586{,}83\ \times 57\ 565}$ = $\mathbf{4{,}3}\ \frac{\boldsymbol{g\ CO_2}}{\boldsymbol{GT\ t{-}nm}}$

Attained CII LFO: $\frac{3.151\times 11105987627}{1.05\times 100586{,}83\ \times 57\ 565}$ = $\mathbf{5{,}8}\ \frac{\boldsymbol{g\ CO_2}}{\boldsymbol{GT\ t{-}nm}}$

As seen from the calculation Grace is approximately 13% smaller ship than Glory when comparing capacity (GT), thus in this thesis Admiralty coefficient will be used to evaluate the increased power demand for Grace, if the ships were the same size.

The admiralty coefficient is a tool that allows the comparison of two different ships. This can also be used to give first estimates on vessel speed and power requirements. This coefficient is based on data from existing ships and is used for rough first stage estimates on potential power requirements of a ship. (27)

$$C = \frac{D^{2/3}V^3}{P} \qquad (15)$$

P= Shaft power in kW

D= Displacement in t

V =Speed in knots

Viking Grace Admiralty coefficient:

$$\frac{29727.9^{2/3}22^3}{21000} = 487$$

After determining admiralty coefficient for Grace, this number is used again to estimate the new power requirement for the same ship, but with Glory displacement, so we have an estimate on how much more Grace would need power, if it was the same size as Glory.

$$P = \frac{33812.9^{2/3}22^3}{486.58} = 22\ 900\ \mathrm{kW}$$

$$\frac{22882{,}4kW}{21000kW} = 1{,}09$$

The power demand for Grace with same displacement as Glory is 9% greater.

After conversion by using admiralty coefficient, in these calculations is used same capacity for Grace as Glory and all parameters related to power consumption is increased by 9%.

Energy used by propulsion motors:

Viking Grace: $60921{,}49\text{MWh} \times 1{,}09 = 66\,400\text{ MWh}$

LNG used in grams:

Grace: $66404{,}42\text{MWh} \times 1000 \times 155\text{g/kWh} = 10\,290\text{ ton}$

CF_j (LNG) = 2.75

F_m = 1.05

D_t = 100 900 n-mile

$F_{C_j}(LNG)$ = 10 290 ton

Capacity: 65 200 GT

Attained CII LNG: $\frac{2.75 \times 10292685100}{1.05 \times 100975{,}90 \times 65\,211} = \mathbf{4{,}1}\ \frac{\boldsymbol{g\,CO_2}}{\boldsymbol{GT\ t{-}nm}}$

In the CII calculations the goal is to evaluate the effect of propulsion solution in ropax-ships on their Carbon intensity Index values. The selected ships in the comparison are Viking Glory and Grace because the ships have similar hull size and they operate the same route, only difference being the used propulsion solution. The effect of ship size, fuel used, and distance travelled in the equation, has been removed, to be able to evaluate and compare the impact of different propulsion solutions in CII value. For this purpose, only energy that was used for propulsion is used in these calculations.

As seen from the CII calculations the change in fuel type from LNG to LFO gives the ships approximately 35% higher CII value.

Grace:

$$\frac{5{,}76\ (\mathbf{LFO})}{4{,}27\ (LNG)} = 1{,}35$$

Glory:

$$\frac{4{,}77\ (LFO)}{3{,}54\ (LNG)} = 1{,}35$$

Comparison between different propulsion systems is made between Glory and Grace after conversion.

$$\frac{4{,}09\ (Grace\ after\ conversion)}{3{,}54\ (Glory)} = 1{,}16$$

As seen from the comparison, propulsion solution can give approximately 16% improvement in carbon intensity index. However, since admiralty coefficient was used for the power estimation and this coefficient is only used for early-stage estimates, it is not enough to account all the variables that effect on energy efficiency. The resistance of the hull is affected by hydrodynamics and hull lines for Glory is designed with Azipod® propulsion and could have more efficient design, than Grace. The 16% efficiency improvement comes from removed components such as rudder, shaft brackets and stern thrusters that create drag. Because of this we can assume, that these variables will affect the results around 13%, and approximately 3% efficiency originates from generally improved hull design. Thus, if Azimuth propulsion system would be installed in Grace hull form, approximately 13% improvement could be expected to CII values.

5 Case study for propulsion retrofit

5.1 Viking XPRS propulsion retrofit

Ferry that fits the parameters as described in chapter 3.1 and could benefit from propulsion retrofit project is selected for this case study to be Viking XPRS. This vessel was delivered 2008 from Aker Yards shipyard in Helsinki, Finland and has mechanical shaft line installed. The ship operates Helsinki-Tallinn route with different speed profiles, and this can have major impact on the ships power consumption. Diesel-electric propulsion solution could improve the ships overall efficiency and lower its carbon footprint.

Table 9 Main particulars

Principal dimensions	VIKING XPRS
Length overall (m)	185
Length bp (m)	170
Breadth moulded (m)	27.7
Draught (m)	6.75
Gross tonnage (t)	35918
Deadweight (t)	5184
Reference speed (knots)	25
Installed propulsion power (kW)	40 000

(13, 34)

Viking XPRS has mechanical shaft line installed and the GA from Shippax database (55) is highlighted in figures 15, 16 and 17 with components that should be removed to make space for the new diesel-electric propulsion system. These components include Stern thruster, rudders, shafts, propeller shafts, steering gears, stern tubes, propellers, generators (PTO) and reduction gears.

Current GA

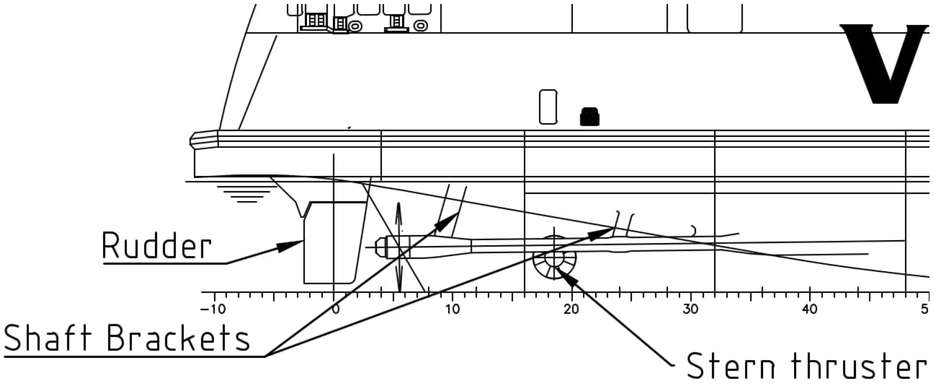


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Figure 14 Side profile aft (55)

Deck 2 aft with steering gear

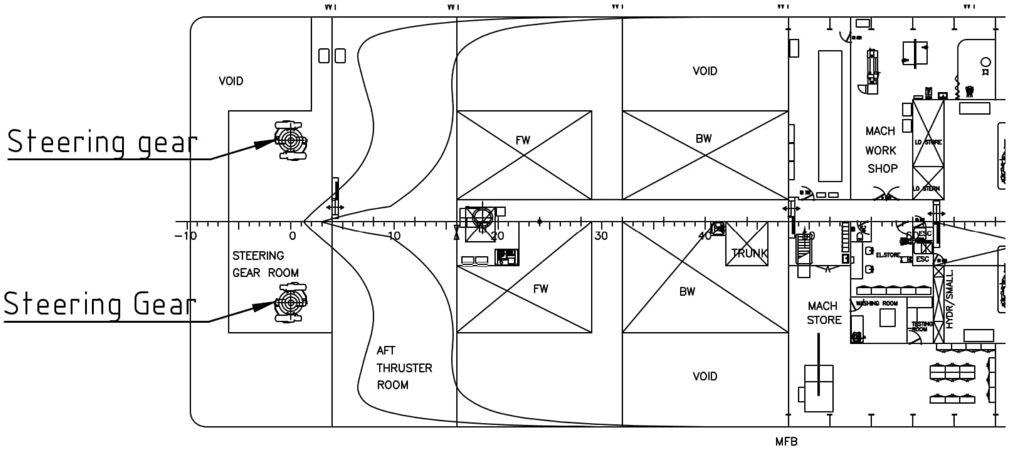


Figure 15 Deck 2 aft with steering gear (55)

Deck 1 Machinery room

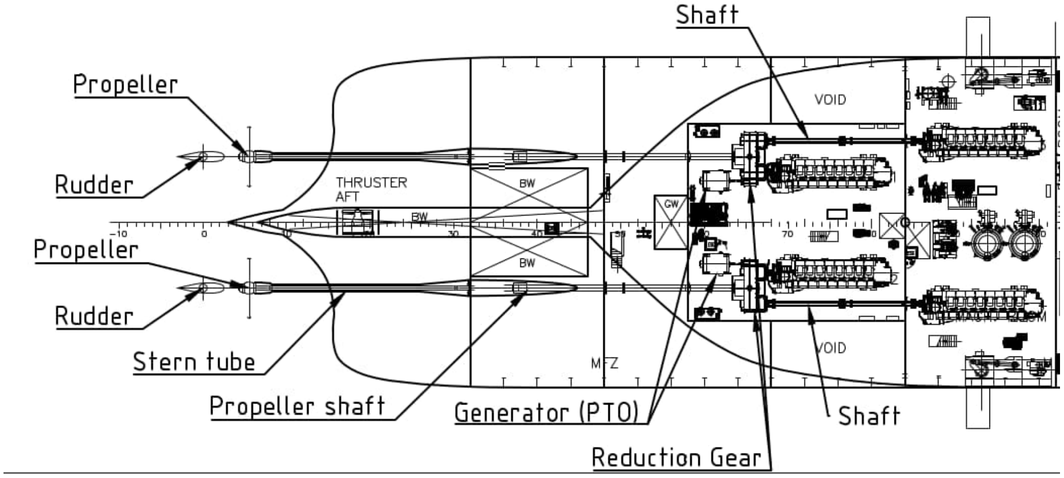


Figure 16 Deck 1 Machinery room (55)

After removing components related to old propulsion solution, room for new equipment is made to aft steering room as shown in figure 16. Also, main engine room (figure 17) and aft thruster room (figure 18) will have to modified to create space for new equipment. This requires modifications to be made in hull structures. The aft side profile is presented in figure 15 with Azipod® propulsors installed to XPRS hull.

New GA

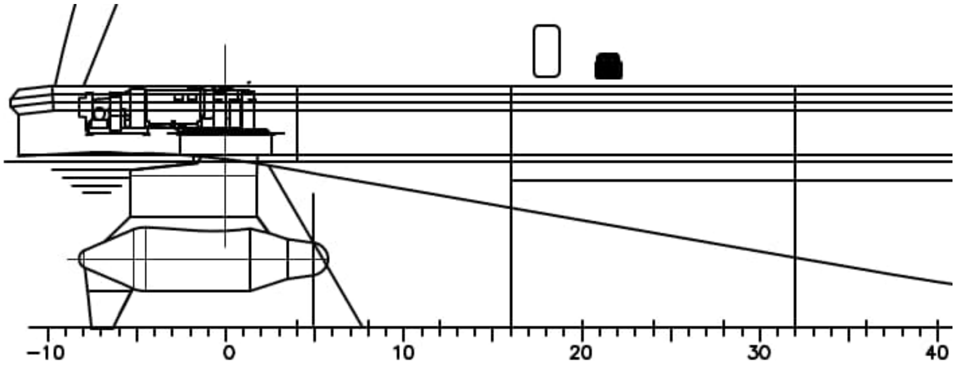


Figure 17 Side profile aft with Azipod® thrusters (55)

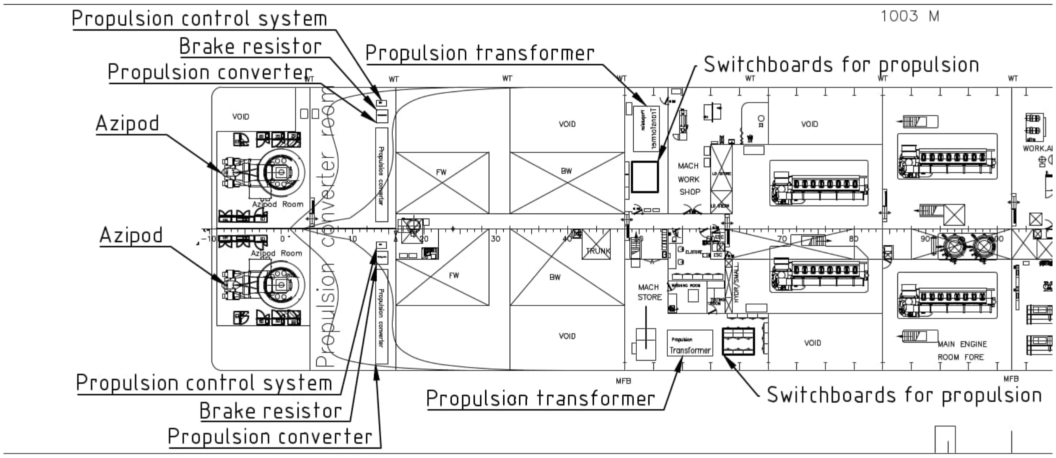


Figure 18 Deck 2 with Azipod® room, converter room and main switchboard rooms (55)

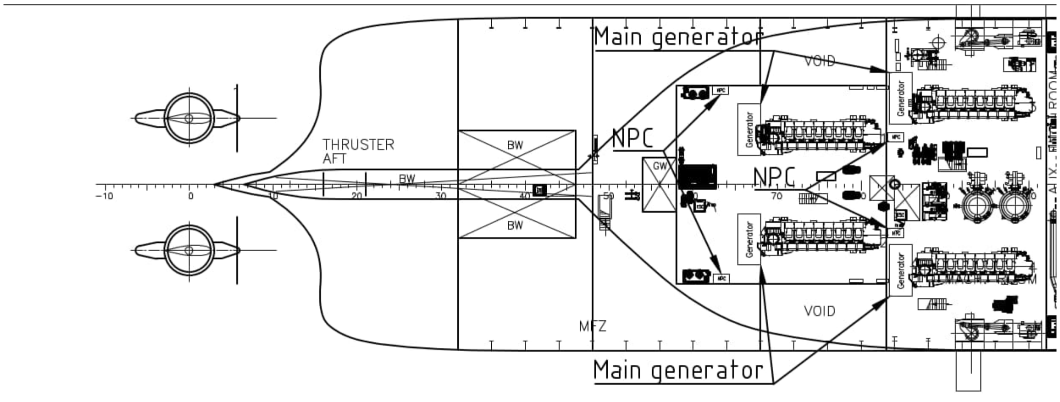


Figure 19 Deck 1 with new Main engine room layout (55)

The plan for this retrofit solution included moving bulkhead separating the main engines in deck 1 (figure 20) to create space for main generators. The other area where modifications in the hull would be required is the old steering gear room (figure 19). In this drawing the bulkheads are moved further aft and to the sides, to create more space for the equipment.

Because there is not enough information available for the original design of the selected vessel, all GA modifications made are preliminary and are not complete plans for the ship. For full scale design of this type of retrofit, would require steel structure drawings and comprehensive concept, basic and detail design review.

5.2 CII calculation for Viking XPRS after conversion

Energy used in 2022 is calculated from information available in THETIS-MRV (europa.eu), since total fuel consumption and average fuel consumption per nautical mile is known. (54)

Average fuel consumption: 159,9 kg / n mile

Total fuel consumption: 12 110 m tonnes

$D_t = \frac{12106910}{159{,}93} = 75\ 700\ \mathrm{n} - \mathrm{mile}$

CII calculation for Viking XPRS:

CF_j (LFO) = 3.151

F_m = 1.05

D_t = 75 700 n-mile

$F_{C_j}(LFO)$ = 12 110 ton

Capacity: 35 918 GT

Attained CII LFO: $\frac{3.151 \times 12\ 106\ 910\ 000}{1.05 \times 75701{,}3\ \times 35\ 918}$ = **13,4** $\boldsymbol{\frac{g\ CO_2}{GT\ t-nm}}$

CII reference line and rating boundaries for Viking XPRS are shown in figures 15 and 16.

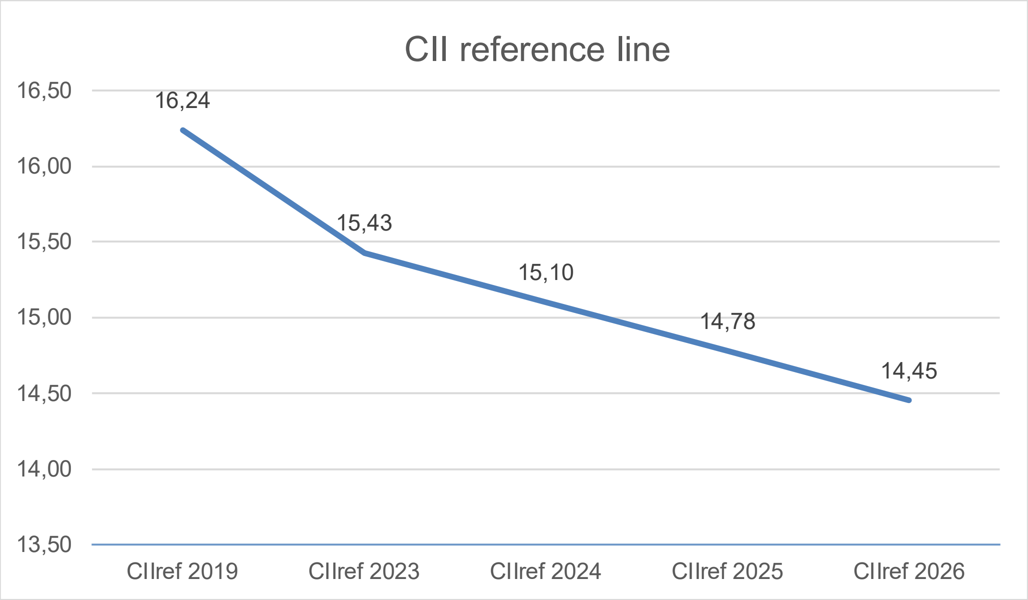


Figure 20 CII reference line for Viking XPRS

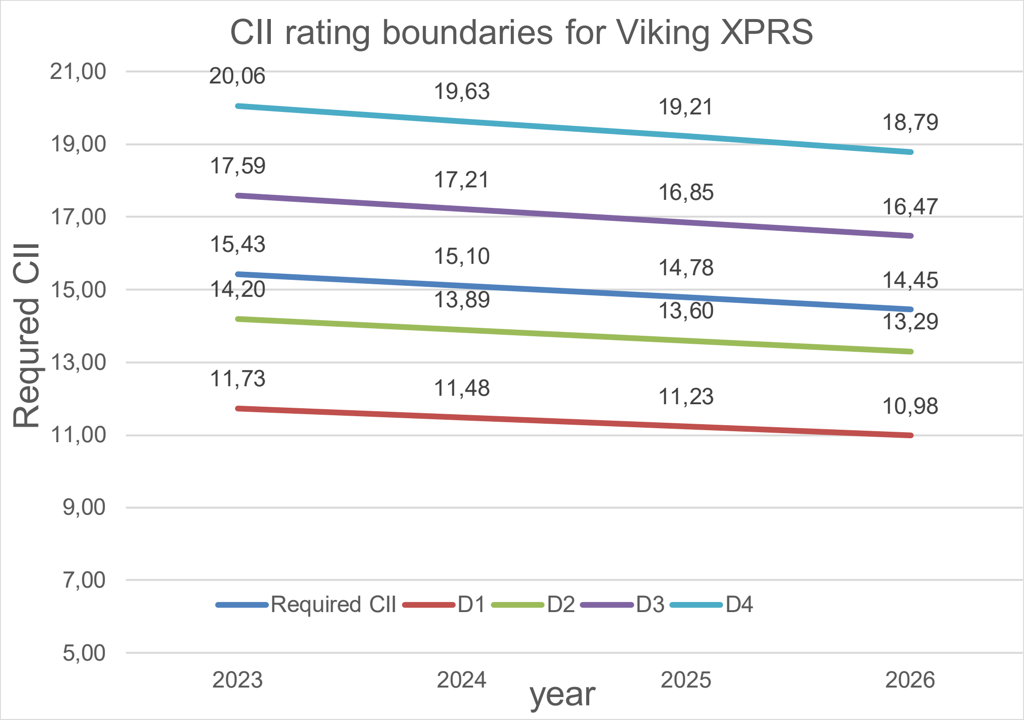


Figure 21 Rating boundaries for Viking XPRS

With fuel consumption information from year 2022 Viking XPRS would receive CII rating B for year 2023-2024 and rating C for year 2025-2026 as seen in figure 16.

The reduction factors for 2027-2030 have not been determined yet and this can lead to further decline in the ships CII value.

5.3 Costs and benefits

The cost and benefits for this retrofit solution are evaluated based on the information available. Helsinki shipyard provided rough price estimation on the shipyard cost for the installation of all ABB equipment, removal of old propulsion solution and hull steel modifications. This estimate is based on the preliminary design provided in chapter 5.1.

The design cost for the conversion is a rough estimate and is provided from OSK design office based on the drawings presented in chapter 4.1.

5.3.1 Cost

Estimated price of ABB equipment for new electrical grid, power plant and propulsion system provided by ABB sales for XPRS retrofit solution is presented in table 10.

Table 10 ABB equipment for power plant and Azipod® propulsion system

Item	Pcs	Name	Technical data
1	2	Azipod®	MO1800, with all relevant auxiliary equipment
2	4	Main Generator	Synchronous generator
3	4	NPC	Neutral Point Cubicle for earthing the main generator
4	4	AVR	Automatic Voltage Regulator
5	2	Propulsion Transformer	3-winding Propulsion Transformer
6	2	Propulsion Converter	Type: ACS6080
7	2	Breaking Resistor	natural air cooling, IP 23
8	1	RCS	Remote Control System for bridge and ECR.
9	2	PCS	Propulsion Control System including operator panels for ECR
10	2	MSWB	Main Switchboard
Total cost 19,350,000 EUR			

Estimate for shipyard cost for work and installation as provided by Helsinki Shipyard in table 11.

Table 11 Work and installation

Work	Description	Hours
Steel work	Including material and modification work.	
Electrical work	Including cable material and modification of the ship’s electrical grid.	
Removal of old equipment and miscellaneous work	Including steel work for covering holes from removed aft thrusters and shaft lines.	
Commissioning		
Main Engine Room conversion		
Total	Including all work, 52 EUR /Hour	100 000h
Total cost 5,200,000 EUR		

By estimating that producing production ready drawings for this kind of retrofit would take approximately 5% from the total production hours, this gives design hour estimation of 5000 hours. This would include basic design drawings, classification cost and detail design drawings. The hourly rate for design is estimated to be 150 EUR.

Cost for design: 5000 x 150 = 750 000 EUR

The total price estimation for this retrofit solution, with this information including shipyard work, design and ABB equipment is:

25 350 000 EUR

5.3.2 Benefits

The potential benefits for converting mechanical shaft line to diesel-electric with Azipod® propulsion comes from the fuel savings, because the required propulsion power is lower with this system. As shown in this thesis the difference between shaft line and Azipod® propulsion is 9%, thus the required propulsion power would be less than what it is now.

The reported total fuel consumption for Viking XPRS in 2018-2022 according to THETIS-MRV (europa.eu) is approximately 12 000 - 13 000 metric tonnes each year.(54) By utilizing admiralty coefficient, as explained in chapter 4.2 the estimation is, that after conversion, this value would be 9% lower and potential fuel savings can be calculated for each year.

Also, Azipod® propulsion provides better maneuverability capabilities, thus this makes maneuvering faster in port. This was tested in ABB digital simulator with two captains without any previous experience in operating vessel with Azipod® propulsion system. The test included captains performing maneuvering in the harbor with vessel equipped with Azipod® propulsion solution and conventional shaft line, and results showed that this operation was done 2 minutes faster with vessel equipped with Azipod® units. With this additional time, cruising speed can be lowered and this leads in more greater fuel savings. The estimated time saving in port maneuverability is estimated to be 2 min for each trip. (51)

The other important advantage for retrofit solution is environmental benefits as shipping CO_2 emissions will be regulated by IMO in the future. The CII value can be potentially lowered 13% from current level and EEXI and EEDI regulations will not be applicable, because IMO has not yet determined reference line for ro-ro passenger ships with non-conventional propulsion. The overall CO_2 emissions will decrease with diesel-electric power plant, as main generators can be run with optimal power range to minimize their specific fuel consumption.

5.4 Return on Investment

Viking XPRS is equipped with four Wärtsilä 8L46F engines with eight cylinders and total propulsion power of 40 000 kW. (49)

The estimate for fuel price is made comparing historical data of very low sulphur fuel oil price fluctuations. Since fuel oil price can have large variations over time the estimation for fuel price that is used in this thesis is as follows:

Very low sulphur fuel oil = 800 EUR / metric tonnes. (46)

However according to Wärtsilä product guide these main engines have total power of 38 400 kW and specific fuel consumption at 85% load 176,8 g/kWh. Also, according to THETIS-MRV (europa.eu) the reported annual time spent at sea for Viking XPRS is 4262 hours and estimate for days in operation for full calendar year is 350 days. With this information the calculation for total cost for annual fuel consumption is shown in table 12.

Table 12 Fuel cost calculation for Viking XPRS

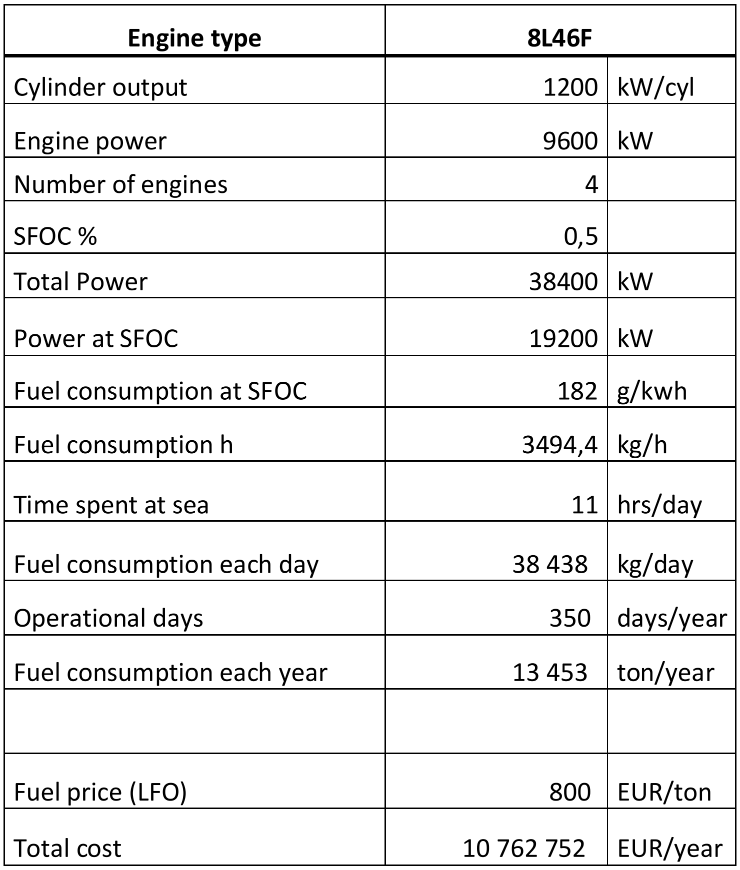
Engine type	**8L46F**	
Cylinder output	1200	kW/cyl
Engine power	9600	kW
Number of engines	4	
SFOC %	0,85	
Total Power	38400	kW
Power at SFOC	32640	kW
Fuel consumption at SFOC	176,8	g/kwh
Fuel consumption h	5770,752	kg/h
Time spent at sea	11,5	hrs/day
Fuel consumption each day	66 364	kg/day
Operational days	350	days/year
Fuel consumption each year	23 227	ton/year
Fuel price (LFO)	800	EUR/ton
Total cost	18 581 821	EUR/year

The reported fuel consumption for XPRS in years 2018-2022 is approximately 12 000-13 000 metric tonnes, as reported in THETIS-MRV (europa.eu).(54) This means that the calculations in table 12 are not correct and the main engines have clearly been operated with lower load than originally anticipated.

Data from automatic identification system (AIS) from marine traffic shows that the average vessel speed is approximately 20,4 kn. (50)

With the available information of the vessel's operational hours and fuel consumption the estimation for operation point for main engines is as shown in table 13. This value will be in line with the reported annual fuel consumption and can give more realistic evaluation for the total cost. However, these are only rough estimates and assumptions based on the information available and are not real figures for the engine power available for propulsion.

Table 13 Fuel cost calculation for Viking XPRS with 50% load on ME



Engine type	**8L46F**	
Cylinder output	1200	kW/cyl
Engine power	9600	kW
Number of engines	4	
SFOC %	0,5	
Total Power	38400	kW
Power at SFOC	19200	kW
Fuel consumption at SFOC	182	g/kwh
Fuel consumption h	3494,4	kg/h
Time spent at sea	11	hrs/day
Fuel consumption each day	38 438	kg/day
Operational days	350	days/year
Fuel consumption each year	13 453	ton/year
Fuel price (LFO)	800	EUR/ton
Total cost	10 762 752	EUR/year

When calculating total fuel oil cost for diesel-electric propulsion system after conversion and utilizing admiralty coefficient as explained in chapter 4.2, it is estimated that 9% reduction can be made from total power at any given load point. Also, the improved maneuverability of Azimuth propulsion allows the ship to lower cruising speed because time in port can be reduced by 2 minutes as explained in chapter 5.3.2.

Since the schedule for Viking XPRS from Helsinki to Tallinn is 2,5 hours and average speed in this route is approximately 20,4kn the 2 min reduction can be made from cruising speed as shown in figure 23.

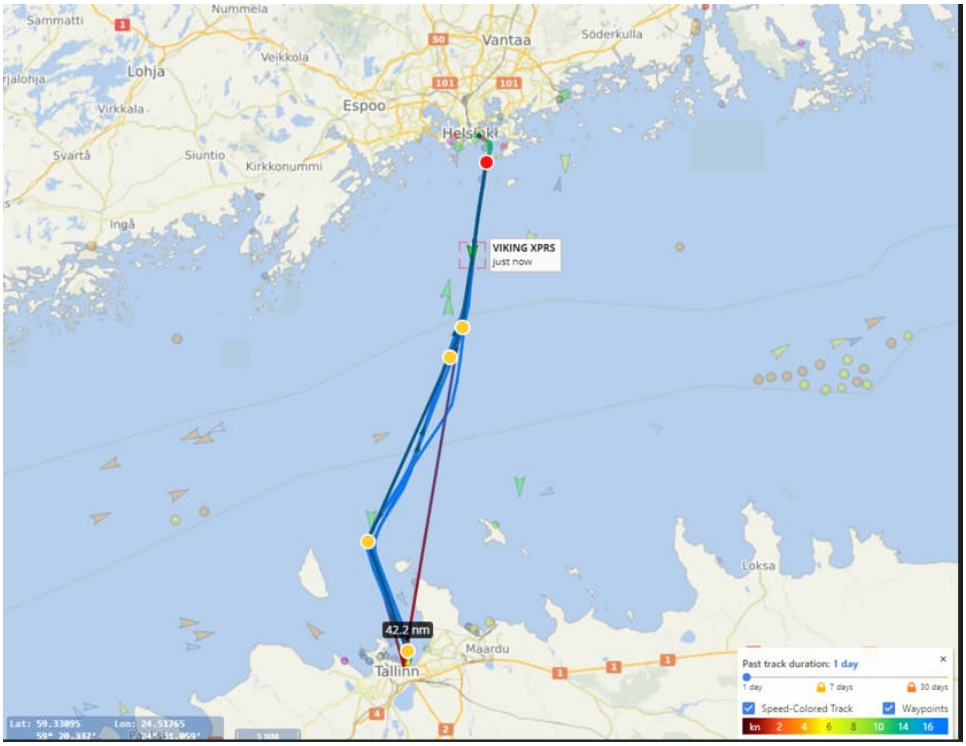


Figure 22 Speed-colored track for Viking XPRS (56)

Voyage near both ports have lower speed as shown in figure 24 and 25.

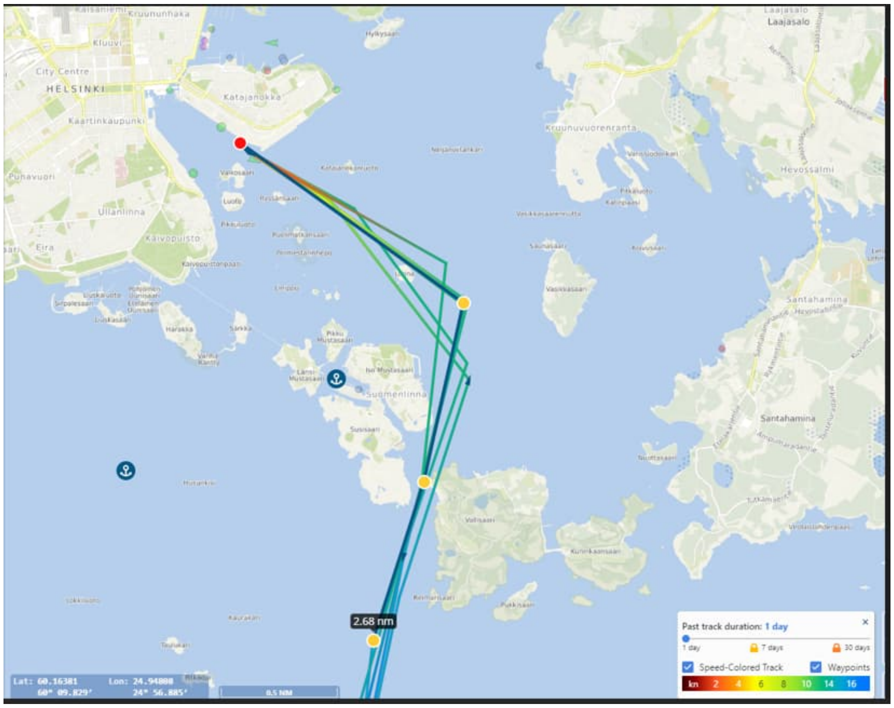


Figure 23 Speed-colored track for Viking XPRS (56)

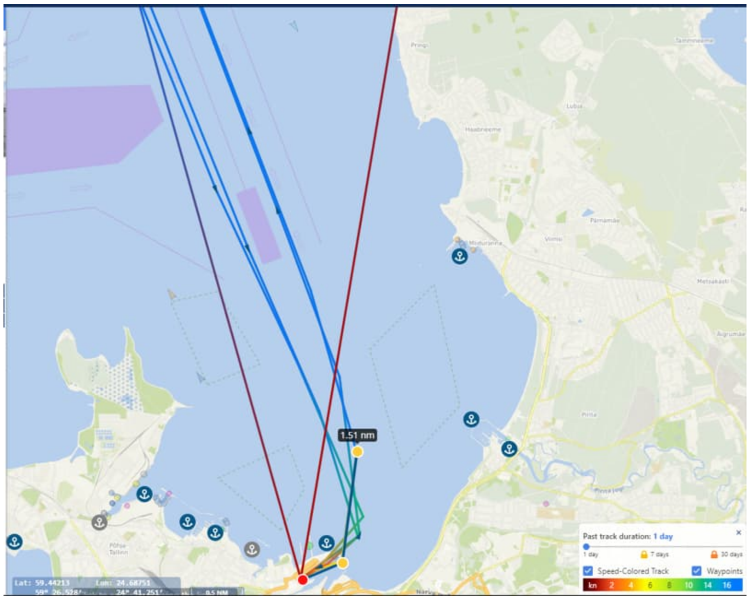


Figure 24 Speed-colored track for Viking XPRS (56)

The total distance for the estimated route is according to AIS data from vessel finder is 46,4 nautical miles. The increased time to cruising speed can be added to the part where the vessel sails with average speed as shown in figure 23. The time spent in cruising speed is calculated in formula 16 and new speed with additional time is calculated in formula 17.

$$\frac{42{,}2nm}{20{,}4kn} = 2{,}07h \tag{16}$$

$$\frac{42{,}2nm}{2{,}07h+0{,}033h} = 20{,}06\ kn \tag{17}$$

After determining the lowered speed, it is possible to evaluate the required engine power in relation to speed power curve. Typical assumption that is used in naval architecture that is called cube law, that states that relationship between ship's required power in relation to speed is cubic and estimate for this power can be calculated as shown in formula 18. (52)

$$P(v) = k \times V^3 \tag{18}$$

In this formula V is the speed in knots P(v) is the required power and k is constant. However, this speed is not cubic, but even greater figure as explained in Basic principles of ship propulsion by MAN energy solutions. Since the speed of the vessel is reported to be 25 knots as explained in chapter 5.1, this value used for cubic is 4,8 as presented in MAN paper. The estimation for required propulsion power with new cruising speed is presented in formula 19. (53)

$$P_2 = \frac{P_1}{\left(\frac{V_1}{V_2}\right)^{\beta}} \tag{19}$$

P1 / P2 = Engine power

V1 / V2 = Speed in knots

Beta = 4,8 for fast ships

The 9% reduction in is done from total power at SOFC as shown in table 13 and new required engine power is calculated in table 14 as presented in equation 19.

Table 14 Engine power P2

Engine power P2		
P1	17 472	KW
V1	20,4	knots
Beta*:	4,8	
V2	20,06	knots
P2	16 118	KW
Beta for "Fast" ships 4,8		

After new engine power is determined the total cost for fuel consumption for Viking XPRS can be done with diesel-electric propulsion system as shown in table 15. As seen from the table new required propulsion power for XPRS with this configuration is 16 118 kW. This means that two main engines with 85% load point will be enough to provide the ship’s required propulsion power.

Table 15 Fuel cost calculation for Viking XPRS with diesel-electric propulsion system.

Engine type diesel electric	**8L46F**	
Power at SFOC	16019	kW
Fuel consumption at SFOC	178,7	g/kwh
Fuel consumption h	2862,6	kg/h
Time spent at sea	11	hrs/day
Fuel consumption each day	31 489	kg/day
Operational days	350	days/year
Fuel consumption each year	11 021	ton/year
Fuel price (LFO)	800	EUR/ton
Total cost	8 871 283	EUR/year

Total annual savings from fuel consumption for the vessel with assumptions and information available in this thesis is:

$$13\,453\ \mathrm{ton} - 11\,089\ \mathrm{ton} = 2\,364\ \mathrm{ton/year}$$

$$2\,364\ \mathrm{ton} \times 800\ \mathrm{EUR} = 1\,891\,200\ \mathrm{EUR/year}$$

The total cost for retrofit 25 350 000 EUR is calculated in chapter 5.3.1. This includes estimate for ABB equipment for diesel-electric propulsion system, shipyard cost and design cost for this retrofit solution.

Return on investment calculation is done by adding the ETS CO_2 tax into the equations as shown in table 16. In this table there are four different price points for the EU ETS tax for each emitted CO_2 tonnes between EU ports as explained in chapter 2.6. Since this value is unknown in the future and will come into force in 2024, the estimation for the price points were made based on current price of the EU carbon permits.

The return on investment for the retrofit solution in years for Viking XPRS according to the calculations made in this thesis is 9-11 years. The CO_2 taxation level has big impact on ROI calculations and price for ETS emission permits are only estimates. Because the payback time is this long as seen in table 16, the investment would not probably be const effective especially considering that the attained CII is fulfilling the IMO requirements rating C up until 2026. However, this could change in the future since energy efficiency levels for ships will be reviewed by MEPC in 2026. It is still unknown what the sanctions will be if ships do not achieve rating C in future. Also, European Union ETS will come into force in 2024 and cost effectiveness for this kind of investment will be dependent on how expensive CO_2 emissions from ships will be made by EU and IMO in the future.

Table 16 Return on investment for propulsion retrofit

Fuel cost (estimate) 800 EUR/ton					
CO2 Tax level (EUR/ton)	60	80	100	120	140
Fuel saving per year (ton/year)	2 364	2 364	2 364	2 364	2 364
CO2 saving per year, with fuel conversion factor (t-CO2/t-Fuel) 3.151	7 449	7 449	7 449	7 449	7 449
Annual fuel savings (EUR)	1 891 200	1 891 200	1 891 200	1 891 200	1 891 200
Annual CO2 Tax between EU ports (EUR)	446 936	595 917	744 896	893 876	1 042 855
Annual saving (Fuel and CO2 Tax) EUR	2 338 138	2 487 117	2 636 096	2 785 076	2 934 055
Accumulated savings 15 years EUR	35 072 068	37 306 757	39 541 446	41 776 135	44 010 824
Accumulated savings 20 years EUR	46 762 757	49 742 342	52 721 928	55 701 514	58 681 099
Return on investment (years)	11	10	10	9	9
Total cost of retrofit project					25 350 000

6 . Conclusions

IMO and EU have set ambitious goals on reducing GHG emissions from global shipping and the introduced measures that are presented in this thesis forces shipping companies to act in improving energy efficiency of their fleet. As these regulations gets more tighter over time, the measures to achieve the energy efficiency goals will be harder to reach in the future and simply lowering vessel speed will not be enough to fulfil these new regulations. If existing ships does not comply with these new regulations, it is still unknown what the sanctions will be in the future. Worst case scenario would be that the vessel that is unable to comply would lose its certificate and would not be able to operate in countries under IMO jurisdiction.

The results of EEDI and CII calculations show that Azimuth propulsion can provide substantial improvement in energy efficiency of a ship compared to conventional shaft line propulsion. This improvement is most beneficial in operational efficiency CII because energy required for propulsion decreases potentially by 9%. This solution does not provide substantial improvement in Design index EEDI/EEXI, because it is not proportional to distance travelled, but capacity and reference speed of the ship.

When analyzing the total cost for this type of retrofit project it is noted that this requires comprehensive redesign of the ship and changes for steel structures and power plant. Converting mechanical shaft line to diesel-electric requires lot of work and modifications to make it feasible. This turned out to be very expensive and payback time for the vessel used in case study was calculated to be 9-11 years. The retrofit solution would not be cost effective for the vessel in this thesis, because the ship fulfils the new CII ratings that are set until 2026. However, this could change in the future depending on how expensive CO_2 emissions will be made in the future.

Other ship types were left out from this study and the potential benefits would need further research on what kind of impact diesel-electric azimuth propulsion would have on their EEDI/EEXI and CII values. As seen from the ROI calculations the cost for propulsion retrofit is very expensive and based on the findings in this thesis, the recommended age for this type of retrofit project would be roro vessels under 10 years old.

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Appendix 1

“*Reduction factors (in percentage) for the EEDI relative to the EEDI reference line”* (16)

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 Mar 2022	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Jan 2022 and onwards	Phase 3 1 Jan 2025 and onwards
Bulk carrier	20,000 DWT and above	0	10		20		30
	10,000 and above but less than 20,000 DWT	n/a	0–10*		0–20*		0–30*
Gas carrier	15,000 DWT and above	0	10	20		30	
	10,000 and above but less than 15,000 DWT	0	10		20		30
	2,000 and above but less than 10,000 DWT	n/a	0–10*		0–20*		0–30*
Tanker	20,000 DWT and above	0	10		20		30
	4,000 and above but less than 20,000 DWT	n/a	0–10*		0–20*		0–30*
Container ship	200,000 DWT and above	0	10	20		50	

	120,000 and above but less than 200,000 DWT	0	10	20		45	
	80,000 and above but less than 120,000 DWT	0	10	20		40	
	40,000 and above but less than 80,000 DWT	0	10	20		35	
	15,000 and above but less than 40,000 DWT	0	10	20		30	
	10,000 and above but less than 15,000 DWT	n/a	0–10*	0–20*		15–30*	
General Cargo ships	15,000 DWT and above	0	10	15		30	
	3,000 and above but less than 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 and above but less than 5,000 DWT	n/a	0-10*		0-15*		0-30*
Combination carrier	20,000 DWT and above	0	10		20		30
	4,000 and above but less than 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 and above but less than 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 and above but less than 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 and above but less than 85,000 GT	n/a	0-5*,**	0-20*		0-30*	