



CARBON INTENSITY INDICATOR IMPLEMENTATION OPTIONS FOR OUT OF PORTFOLIO ENGINES

Wärtsilä 46-classic engines

Lappeenranta–Lahti University of Technology LUT

Master's programme in Energy technology

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ABSTRACT

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Carbon intensity indicator implementation options for out of portfolio engines

W46-classic engines

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This Master's thesis focuses on the implementation and options of maritime regulations for vessels equipped with conventional Wärtsilä W46 engines. The study specifically addresses the challenges faced by these vessels in meeting the latest emission guidelines set by the International Maritime Organization (IMO), with a particular emphasis on carbon dioxide reduction options.

The study was commissioned by a ship engine manufacturer and primarily examines out-of-portfolio engines. Its objective is to provide a comprehensive simplified analysis of the various measures and strategies that can be employed to ensure compliance with the IMO's emission guidelines. By exploring these options, this study aims to contribute to the development of effective solutions for reducing carbon dioxide emissions and improving the carbon intensity index (CII) in the maritime industry and installations with Wärtsilä W46 engines.

The research methods for the study were chosen to be the collection and utilization of real-time data and experiences from the vessels which was found challenging in the end. Received data stayed very narrow due to the poor participation of query and other reasons beyond the control. However, the study achieved the state where technical improvements are raised and offers valuable and useful information to engine manufacturer.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT

LUTin energiajärjestelmien tiedekunta

Energiatekniikka

Mike Wink

Hiilipäästöluvun sisäistämisen vaihtoehdot tuotannosta poistettuihin moottoreihin

- W46-moottorimalli

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Tämä diplomityö keskittyy merenkulun säännösten toteuttamiseen ja vaihtoehtoihin perinteisillä Wärtsilä W46 -moottoreilla varustetuille aluksille. Tutkimus käsittelee erityisesti näiden alusten kohtaamia haasteita, kun ne pyrkivät täyttämään kansainvälisen merenkulkujärjestön (IMO) asettamat uusimmat päästöohjeet, erityisesti hiilidioksidipäästöjen vähentämiseen liittyvät vaihtoehdot.

Tutkimus tehtiin laivanmoottorivalmistajan toimeksiannosta ja keskittyy pääasiassa tuotannon ulkopuolisiin moottoreihin. Tavoitteena oli tarjota kattava analyysi erilaisista toimenpiteistä ja strategioista, joita voidaan käyttää varmistaakseen IMO:n päästöohjeiden noudattaminen. Näiden vaihtoehtojen tutkiminen edistää tehokkaiden ratkaisujen kehittämistä hiilidioksidipäästöjen vähentämiseksi ja hiilidioksidin intensiteetti-indeksin (CII) parantamiseksi merenkulun alalla ja Wärtsilä-moottoreilla varustetuissa laivoissa.

Tutkimuksen tutkimusmenetelmiksi valittiin reaaliaikaisen tiedon sekä kokemusten kerääminen aluksilta, joita voitaisiin hyödyntää tutkimuksessa. Tämä osoittautui kuitenkin haastavaksi lopulta. Saadut tiedot olivat hyvin rajallista johtuen heikosta osallistumisesta ja muista ulkopuolisista syistä. Kuitenkin tutkimus saavutti tilan, jossa teknisiä parannuksia pystyttiin todentamaan ja tuomaan arvokasta sekä hyödynnettävää tietoa moottorivalmistajalle.

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SYMBOLS AND ABBREVIATIONS

Roman characters

C	ship's capacity	[DWT & GT (t)]
C_f	Carbon factor	
C_{FAE}	Conversion factor for fuel on Auxiliary engine	
C_{FME}	Conversion factor for fuel on Main engine	
D_t	Length	[m]
E_{CO_2}	Carbon dioxide emissions	[g]
f_c	Cubic capacity correction factor	
$f_{eff(i)}$	Efficiency factor of innovative energy efficiency technology on each engine i	
f_t	Technical/regulatory limitation on capacity	
f_j	Power correction factor for ship specific design elements. Depending on the vessel type and ice class j .	
f_l	General cargo factor	
f_m	Ice-class factor for ships having IA super classification.	
f_w	Speed reduction factor at sea	
i	Summation of each main and auxiliary engines	
n	Upper limit of summation	
M_{CO_2}	Total mass of CO ₂	[t]
O_f	Operating factor	
P	power	[kW]
$P_{AE(i)}$	Power of each auxiliary engine	[kW]
P_{AEeff}	The auxiliary power reduction due to innovative electrical energy efficient technology measured at P_{ME} .	[kW]

P_{eff}	The output of the innovative mechanical energy efficient technology for propulsion at 75% main engine power.	[kW]
$P_{ME(i)}$	Power of each main engine	[kW]
P_{PTI}	Shaft motor power	[kW]
$SFOC_{AE}$	Specific fuel oil consumption Auxiliary engine	[g/kWh]
$SFOC_{ME}$	Specific fuel oil consumption Main engine	[g/kWh]
$SFOC$	Specific fuel oil consumption	[g/kWh]
V_{ref}	Speed in knots	[kn (Nautical miles/h)]
W	Transport work	[DWT-NM]
W_s	Supply-based transport work	[DWT-NM]

Abbreviations

CII	Carbon intensity indicator
CNSL	Cashew nutshell liquid
CRI	Common-rail generation 1
CRII	Common-rail generation 2
DWT	Dead weight tonnage
GT	Gross tonnage
EEDI	Energy Efficiency Design Index
EEXI	Energy efficiency existing ship index
EIAPP	Engine International Air Pollution Prevention
GHG	Greenhouse gas
IMO	International Maritime Organization
MARPOL	The international convention for the prevention of pollution from ships
MEPC	The Marine Environment Protection Committee
PTI	Power-take-in
PTO	Power-take-out
SEEMP	Ship energy efficiency management plan

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1 Introduction

The shipping industry plays a major role in global transportation and covers 90 per cent of global transport needs. In the year 2022, global shipping was responsible of 3 per cent of global greenhouse gas emissions (GHG) according to a European Commission article In Horizon magazine (King, 2022). The topic of reduction GHG has been under study by different parties and the main target is to find sustainable solutions and to contribute to ambition targets agreed in the Paris agreement signed in 2015.

The marine industry has been found one of the largest polluting industries and the main source of ship GHG emissions is the exhaust gases from the engines installed to ship (Lindstad et al., 2021). In year 2018 International Maritime Organization (IMO) announced demanding regulations for GHG emissions reductions. This generates actions for ship owners to follow and optimize the existing emissions to correspond latest requirements (Chen et al., 2019). IMO works for the United Nations and is responsible of safe international shipping and pollution prevention actions. The agency keeps the shipping industry fair for all when rules and standards are followed and aims for better solutions in the marine industry (IMO, 2019a).

The International Convention for the Prevention of Pollution from Ships (MARPOL) is a general convention adopted by IMO in the year 1973. The convention covers the whole shipping industry and contains topics related vessels clean operation and ensuring environment-friendly sailing. The Convention includes six technical Annexes and Annex number six focuses on the pollution prevention of the ships. In year 2019, new amendments were added to Annex six relating to the existing vessel carbon emissions (IMO, 2019b).

The latest regulations for ships regarding to carbon dioxide emissions and the current carbon intensity indicator have not studied widely since the carbon intensity indicator (CII) follow-up became mandatory for ships in 2023. Studies are focusing mostly on the operational aspect and leaving opportunities on the machinery side out of the study. The potential to improve the vessel operation more sustainable way by improving existing machinery will be expected to have a reducing effect on carbon emissions. Challenges are the limitations of ship design and economic impact.

1.1 Background and objectives

This master's thesis was done to find options and solutions for existing vessels to implement the latest regulations relating to carbon dioxide emissions. International Maritime Organization (IMO) has set a new way to rank the vessels with carbon intensity indicator as a part of the carbon reduction plan. The Carbon intensity indicator (CII) became mandatory to calculate for vessels over 5.000 gross tons transporting cargo or passengers from the 1st of January 2023 forward (DNV, 2023a). This thesis focuses only on the power production of the vessels with traditional diesel engines and is more detailed with specific Wärtsilä W46-classic model engines. There is still a large amount of aged W46-classic model engines in operation which has the potential to continue operation, so solutions and guidelines are required.

Since the CII was introduced lately for the maritime industry, it is challenging to find united information or simplified instructions to follow. There have always been regulations and rules related to marine operation, but it is not so clear which party will follow up and guide vessel owners with possible options and improvements. The target of this study is to collect information for vessels equipped with Wärtsilä W46-classic engines and provide clear options to improve the CII of the vessel from an engine point of view. The study focuses on the engine properties for optimized fuel efficiency and opportunities to utilize different fuels with realistic convention work.





The study does not focus on operational arrangements or vessel design related to the reduction of carbon dioxide emissions precisely. The study considers only vessels with pre-defined specific engine model that uses liquid fuel as a main fuel. The study consists also of the fuel specifications and its relation to carbon emissions. Emissions studied in this thesis are mainly focusing on carbon dioxides and do not focus on Nitrous oxide NO_x emissions with high interest. NO_x emission regulations are studied only partially, and relevant points are collected in the thesis.

2 Carbon intensity indicator

Carbon intensity indicator (CII) is a measurable value for vessel carbon dioxide emissions which are transporting cargo or passengers above 5,000 GT. CII was created to support global target to reduce greenhouse gas emissions of maritime traffic. CII reports are mandatory after 1st of January 2023 and the first report should be delivered to controlling division no later than 31st of March 2024 (DNV, 2021a).

The IMO strategy for reduction of GHG emission from ship was adopted in 2008 and it is divided to short- mid- and long-term measures. CII falls under strategy's short-term measures and the main target is to reduce carbon intensity 40 % compared to year 2008 (ClassNK, 2021). Short-term measures are taken place in industry including newbuilds and existing ships as presented in the Table 1.

Table 1. Short term measures for GHG reduction (DNV 2021a).

	 Technical & Design	 Operational
 Newbuilds	EEDI	
 Existing ships	EEXI	CII rating SEEMP

To calculate the CII, existing vessels must calculate Efficiency Existing Ship Index (EEXI) and newbuilds must determine the Energy Efficiency Design Index (EEDI). EEXI calculations came mandatory for existing vessels to proof the energy efficiency and for collecting fuel consumption data. Classification societies will act on behalf of flag state and approves the possible improvements regarding to energy efficiency devices and components. This regulation was stated to start 1st of January 2023 (DNV, 2023a).

2.1 Calculation instructions for carbon intensity

The vessels will receive CII rating according to result of attained CII calculations. Ratings are divided to five different letters and will tell the current situation of the vessel regarding to the carbon dioxide intensity. The current ratings are shown in Table 2 with explanations.

Table 2. CII ratings

Rating	Explanation	Order	Action
A	Major Superior	Best	No action needed
B	Minor Superior		No action needed
C	Moderate		No action needed
D	Minor inferior		Actions needed after 3 years
E	Inferior performance level	Lowest	Plan for corrective actions needed after 1 year

The CII measures the total carbon dioxide emissions divided the annual base cargo transported and travelled distance. Vessels will receive a grade which determinates the vessels current situation and possible corrective actions in the future. Vessels which receive grade D for three years in a row or E for one year should implement some corrective actions to receive grade C or better (Gianni et al., 2022).

In year 2020 IMO introduced four potential scenarios for CII calculations which were divided by the different factors related to ships operation. Since there are multiple different purpose ships operating with different ways, the common formula for CII value calculation may not be the optimal. Introduced four different CII equations are presented as supply-based, demand-based, sailing time-based and distance-based limits which may cause negative impact for total emissions. The CII calculation and CO₂ reduction actions may increase the overall emissions in theoretical level (Wang, 2021). According to latest IMO instructions referring to 78th session of Marine Environment Protection Committee (MEPC) in 2022, only two equation is currently in use, and it is supply-based method and demand-based method (MEPC, 2022a).

In action of receiving poor grade, the vessel should implement the corrective actions to Ships Energy Efficiency Management Plan (SEEMP). SEEMP is the tool for shipowners to plan and point out the actions required to maintain the index and is mandatory part to determinate

the CII as presented in Figure 1. As studied in this thesis the possible upgrades in main engine will be implemented to SEEMP part 3 which represents ship operational carbon intensity plan (DNV,2023a).

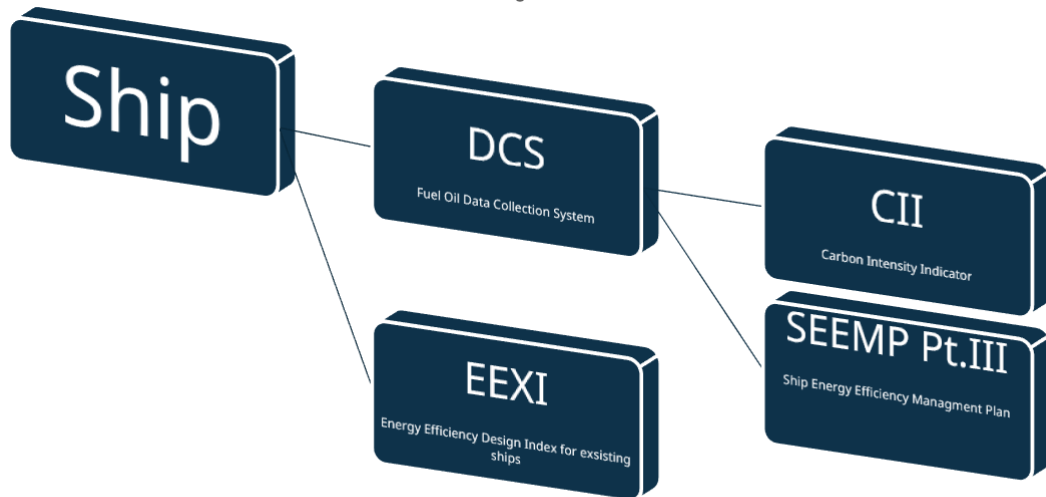


Figure 1 Illustration of corrective action plan (DNV, 2023a)

2.1.1 Ship Energy efficiency management plan part III

Ship energy efficiency management planning became mandatory for all ships 1st of January 2013, along with the Energy Efficiency Design Index (EEDI). The changes were adopted by the Marine Environment Protection Committee during the 62nd session in July 2011 (Nautilus 2023). The SEEMP consists of three parts which all are related to efficiency improvements of the ship. Technically vessels must focus on all the parts of the SEEMP since all are related to the vessel efficiency. The plan should include measures to improve energy efficiency, such as optimizing voyage planning, reducing fuel consumption, and adopting energy-saving technologies. Part III is highly related to the CII calculation which includes the collected data from part II where fuel oil consumption is followed. By following all SEEMP regulations, shipowners can contribute to reducing carbon dioxide emissions and improving the overall energy efficiency of their vessels.

Part I in its simplest form is generally the mechanism for ship or ship owning company to follow and compare the ships current state to existing company energy management policy

and upcoming improvements to fulfil regulations. This part includes the topics from the planning to monitoring of the necessary efficiency improvements.

Part II focuses on the fuel oil consumption data collection on the ships of 5.000 gross tonnage and above. The vessel should provide and describe mechanism of fuel oil consumption which will be reported to the administrative party. This part of SEEMP includes the reporting of used fuel oil in any consumable machinery. The travelled distance and hours underway are the also required data to be recorded according to regulation 27 of MARPOL Annex IV.

Part III is only focusing on the vessels operational carbon intensity. According to 78th MEPC session in 2022 the ships on 5.000 gross tonnage or above should provide used method to calculate attained annual CII and the method to report it to following administration. Vessel must provide the next three-year estimated index and planning how it could be achieved. The document is updating all the time when new actions and self-evaluating is done. The document will be necessary to update when improvements for the main engine are done in a way to improve CII (MEPC, 2022b).

2.2 Global situation with existing ships

As the global target is to find out ways to decarbonize the marine industry, new tools and indexes are stated by IMO and followed up by registration sociates. Existing vessels will need to act to fulfil regulations and could be challenging for installation with more aged machinery.

The CII calculation is consisting of every vessel under IMO which are transporting goods or passengers over 5.000 gross tonnage or above. There are numerous of aged vessels operating still all over the globe where the emission regulations are affecting, and actions needed to be done. To calculate CII the vessels must know their current situation of the vessel efficiency. New amendment to International Convention for the Prevention of Pollution from Ships Annex VI was implemented to use in 2018 (IMO, 2023a).

The index CII was introduced to vessels with the calculation of energy efficiency existing ship index (EEXI). This index indicates vessels energy efficiency compared to a baseline. The calculation of EEXI is mandatory for existing ships 400 gross tons and above and came into force by the amendments in MARPOL Annex IV 1st of November 2022.

2.3 Energy efficiency of the vessels

EEXI describes CO₂ emissions created per capacity of gross tonnage or death weight tonnage per mile sailed. It will determine the standardized CO₂ emissions related to installed engine power, speed, and transport capacity. EEXI is only a design index and not related to operational actions (DNV, 2023c). This means that the vessel main engine efficiency plays a huge role in calculation since the specific fuel oil consumption is needed. Fuel oil consumption data collection came mandatory for all ships over 5.000 gross tonnage by the Marine environment protection committee in 2019 (MEPC, 2016).

EEXI is closely related to the Energy Efficiency Design Index (EEDI), which applies to new ships. The EEXI formula calculates the energy efficiency of an existing ship by comparing its actual energy efficiency to a reference line based on the EEDI. EEXI is a regulatory tool to assess and improve the energy efficiency of existing ships, similar to how the EEDI applies to new ships. Simplified equation for EEDI is presented in equation 1.

The EEXI concept formula for main engine is presented in equation 2. Equation was modified from the original source because of incorrect unit describing the main engine power. In the article A scenario-based assessment of the EEXI and carbon intensity indicator (CII) regulations written by Murat Bayraktar the concept equation is using unit's grams per kilowatt hour (Bayraktar et al., 2023). The correction describes the concept more understandable way but does not fulfil the technical writing rules. Mathematically correct way to calculate EEXI is to use original equation presented in equation 3.

$$EEDI = \frac{E}{W} \quad (1)$$

Where:

<i>EEDI</i>	Energy efficiency design index	
<i>E_{CO2}</i>	Carbon dioxide emissions	[g]
<i>W</i>	Transport work	[DWT-NM]

$$EEXI = \frac{C_F * SFOC * P_{ME}}{GT * V_{ref}} \text{ or } EEXI = \frac{C_F * SFOC * P_{ME}}{DWT * V_{ref}} \quad (2)$$

Where:

<i>EEXI</i>	Energy Efficiency of Existing ship index	[g/t.mile]
<i>C_f</i>	Carbon factor depending on fuel <i>f</i>	[t-CO ₂ /t-Fuel]
<i>SFOC</i>	Specific fuel oil consumption	[g/kWh]
<i>P_{ME}</i>	Main engine power	[kW]
<i>GT</i>	Capacity gross tonnage of the vessel	[t]
<i>DWT</i>	Capacity dead weight tonnage	[t]
<i>V_{ref}</i>	Reference vessel speed at rated engine power	[knots]

In the calculation of EEXI, the engine power is usually assumed to be 75% which is related to operation profile of the engine. If vessel has implemented power limitation process the assumed power should be 83 % of maximum power. Specific fuel consumption is available for some engines in NO_x technical file. Installations which don't have the measures recorded to technical file or factory test run reports are not available, estimated default values could be used. Estimated default values are stated in Annex 7 MEPC.333(76) to be 190 g/kWh for main engines. This thesis focuses only on the main engine perspective. Auxiliary engines are also affecting factor for the evaluation but not taken for closer study in this thesis. Vessel capacity is presented as 70% of total dead weight or gross tonnage of the vessel. Vessel

reference speed represents the vessel speed is presented in nautical miles per hour. in summer load line at rated engine power. Installations with delivered speed-power curve could use the info from there to calculations. If the sea trial documents are not available, the estimated ship speed need to be determined by using guideline calculation formulas presented by MEPC (Bayraktar et al. 2023, MEPC, 2021a).

$$EEXI= \quad (3)$$

$$\begin{aligned} & [(\prod_{j=1}^n f_j) \cdot (\sum_{i=1}^{n_{ME}} P_{ME(i)} C_{FME(i)} SFOC_{ME(i)}) + (\sum_{i=1}^{n_{AE}} P_{AE(i)} C_{FAE(i)} SFOC_{AE(i)}) \textcircled{1}] \\ & + ((\prod_{j=1}^n f_j \sum_{i=1}^{n_{PTI}} P_{PTI(i)} - \sum_{i=1}^{n_{eff}} f_{eff(i)} P_{AE_{eff}(i)}) C_{FAE} SFOC_{AE}) \\ & - (\sum_{i=1}^{n_{eff}} f_{eff(i)} P_{eff} C_{FME} SFOC_{ME} \textcircled{2}) \\ & \div (f_t f_c f_l C f_w V_{ref} f_m) \end{aligned}$$

Where:

$EEXI$	Energy Efficiency of Existing ship index [g-CO ₂ /DWT-Nautical mile]
f_j	Power correction factor for ship specific design elements. Depending on the vessel type and ice class j .
$P_{ME(i)}$	Power of each main engine [kW]
i	index of summation
n	upper limit of summation
C_{FME}	Conversion factor for fuel on Main engine
$SFOC_{ME}$	Specific fuel oil consumption Main engine [g/kWh]
$SFOC_{AE}$	Specific fuel oil consumption Auxiliary engine [g/kWh]
$P_{AE(i)}$	Power of each auxiliary engine [kW]

C_{FAE}	Conversion factor for fuel on Auxiliary engine
P_{PTI}	Shaft motor power [kW]
$f_{eff(i)}$	Efficiency factor of innovative energy efficiency technology on each engine i
P_{AEff}	The auxiliary power reduction due to innovative electrical energy efficient technology measured at P_{ME} . [kW]
P_{eff}	The output of the innovative mechanical energy efficient technology for propulsion at 75% main engine power. [kW]
f_t	Technical/regulatory limitation on capacity
f_c	Correction factor depending on cubic capacity.
f_l	General cargo factor
C	Capacity DWT or GT [t]
f_w	Speed reduction factor at sea
V_{ref}	Ship speed [knot]
f_m	Ice-class factor for ships having IA super classification.
①	If the part of the Normal Maximum Sea Load is provided by shaft generators, SFC_{ME} and CF_{ME} may- for that part of the power-be used instead of SFC_{AE} and CF_{AE}
②	In case of $P_{PTI(i)} > 0$, the average weighted value of $(SFOC_{ME} * C_{FME})$ and $(SFOC_{AE} * C_{FAE})$ to be used for calculation of P_{eff} .

2.4 Calculation of carbon intensity

Calculation guidelines are given by IMO and presented in the document MEPC.336(76). This document includes guidelines and calculating methods to figure out the attained CII value. To reach accurate and specific CII value vessel operating data should be collected according to vessel SEEMP.

2.4.1 Calculation guidelines

The calculation of the vessel attained CII is presented in equation 4 in the most simple form:

$$\textit{Attained CII}_{ship} = M_{CO_2} / W \quad (4)$$

Where:

<i>Attained CII_{ship}</i>	Grams of CO ₂ per tonne-mile [gCO ₂ /DWT-Nautical mile]
<i>M_{CO₂}</i>	Total mass of CO ₂ [g]
<i>W</i>	Total transport work in given calendar year [DWT*nautical miles]

The total mass of CO₂ emissions expresses the annual CO₂ emissions in grams from all the consumed fuel. The equation for *M* is presented in equation 5:

$$M_{CO_2} = FC_j \times C_{fj} \quad (5)$$

Where:

<i>j</i>	Fuel oil type [HFO,MGO...]
<i>FC_j</i>	Total mass of fuel type <i>j</i> consumed [g]
<i>C_{fj}</i>	CO ₂ mass conversion factor of fuel

The estimated supply-based transport work W_s could be solved with equation 6. The estimation is used in the absence of actual collected work data. The capacity unit will deviate depending on the vessel type (MEPC, 2021b).

$$W_s = C \times D_t \quad (6)$$

Where:

W_s	Supply-based transport work	[DWT-Nautical mile]
C	Ship's capacity	[DWT or GT (t)]
D_t	Total distance travelled	[NM]

2.4.2 Reference lines for calculation

Calculating of ship attained CII will need to compare to reference lines which need to be created according to available data. According to the latest requirements from IMO reference values are available from the year 2019 for different types of ship capacities. The reference line will show the so-called starting point of CII index depending on the ship capacity based on pre-collected data (MEPC, 2022c).

The reference CII is calculated with the equation presented as equation 7:

$$CII_{ref} = aC^{-c} \quad (7)$$

Where:

CII_{ref}	Reference value of year 2019
a	Estimated parameter of collected data through IMO data collection system 2019
C	Capacity [t]
c	Estimated parameter of collected data through IMO data collection system 2019

The estimated parameters are shown for different ship type in Table 3.

Table 3. Parameters for determining the 2019 ship type specific reference lines (MEPC, 2022c).

Ship type		Capacity	<i>a</i>	<i>c</i>
Bulk carrier	279 000 <	279 000	4 745	0.622
	<279 000	DWT	4 745	0.622
Gas carrier	65 000 <	DWT	14 405 ⁷	2,071
	< 65 000	DWT	8 104	0,639
Tanker		DWT	5 247	0,610
Container ship		DWT	1 984	0,489
General cargo ship	20 000 <	DWT	31 948	0,792
	<20 000	DWT	588	0,3885
Refrigerated cargo carrier		DWT	4 600	0,557
Combination carrier		DWT	5 119	0,622
LNG carrier	100 000 <	DWT	9 827	0,000
	65 000 < <100 000	DWT	14 479 ¹⁰	2,673
	< 65 000	65 000	14 779 ¹⁰	2,673
Ro-ro cargo ship (vehicle carrier)	57 700 GT<	57 700	3 627	0,590
	30 000 GT< < 57 700 GT	GT	3 627	0,590
	< 30 000 GT	GT	330	0,329
Ro-ro cargo ship		GT	1 967	0,485
Ro-ro passenger ship	Ro-ro passenger ship GT 2023	GT	2 023	0,460
	0.460 High-speed craft designed to SOLAS chapter X	GT	4 196	0,460
Cruise passenger ship		GT	930	0,383

Example CII reference calculation could be determined for general cargo ship under 20.000 DWT as follows in Figure 2:

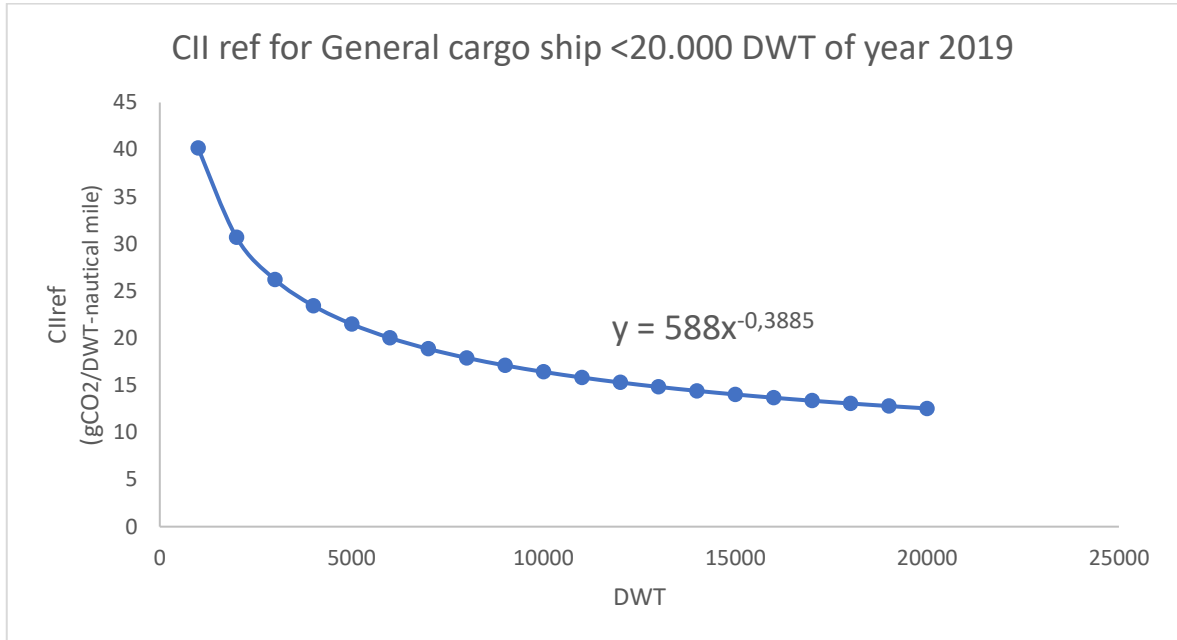


Figure 2. CII ref for general cargo vessel 2019.

The 2019 CII reference value will be as a guideline for upcoming reductions implemented in the 76th Marine Environmental Protection Committee. The annual operational CII for a specific year will need to be calculated by using pre-stated reduction factors provided by IMO. The reduction factor is approved until the year 2026 (MEPC, 2021c).

Whit the reduction factors it is possible to calculate required operational CII when using equation 8.

$$\text{Required annual operational CII} = (1 - Z/100) \times \text{CII}_{\text{ref}} \quad (8)$$

Where:

Z general reference

CII_{ref} Reference CII [$\text{gCO}_2/\text{DWT-nautical mile}$]

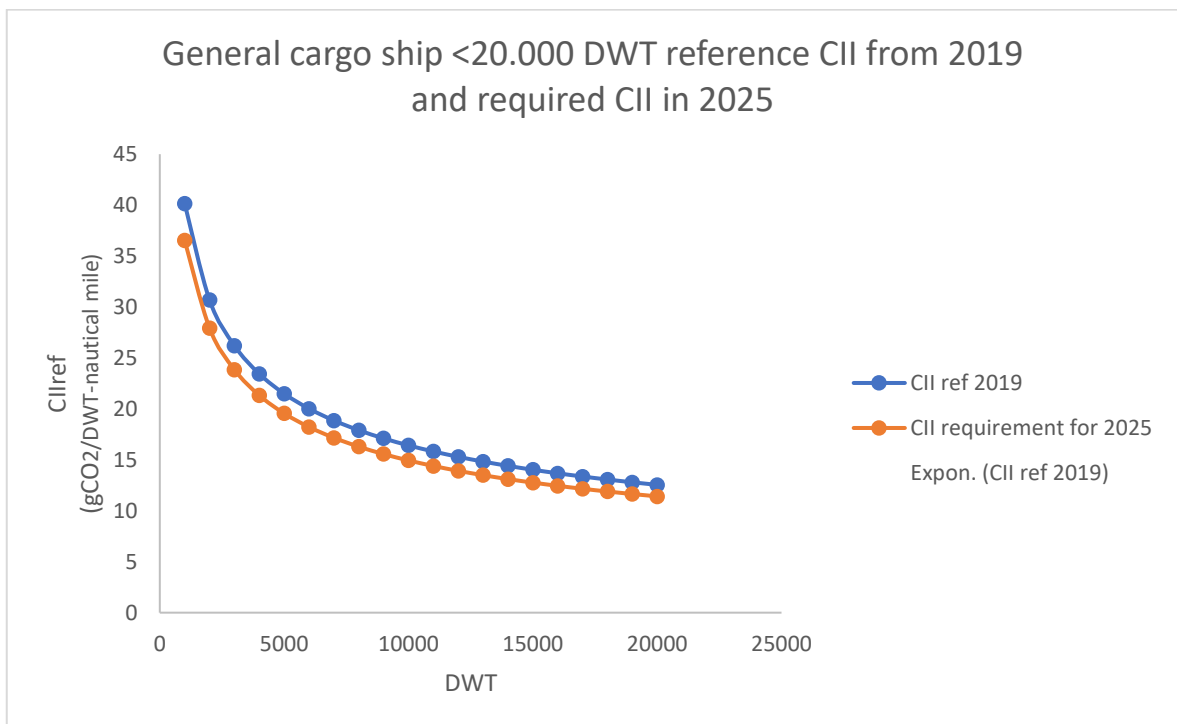


Figure 3. Required CII value in 2025 for general cargo vessel compared to 2019 CII reference value.

Reduction factor (Z) for specific year is presented in the Table 4.

Table 4. Reduction factors (Z) for the CII calculation compared to 2019.

Year	Reduction factor relative to 2019
2020	1%
2021	2%
2022	3%
2023	5%
2024	7%
2025	9%
2026	11%
2027	To be decided
2028	To be decided
2029	To be decided

2.4.3 Operational energy efficiency performance rating and boundaries

To compartmentalize each vessel for the correct rating, some guideline work should be done to create a boundary for the scale. Collected data from the year 2019 shows that individual ships are divided for different rating scales and only 30 percent of vessels are close to required CII and giving the rating C (MEPC, 2022d). The requested CII rating decreases linearly during the years as shown in the example graph below in Figure 4. Rating guidelines can be determined with rating vectors given for each ship type. Rating vector implementation is explained in Figure 5.

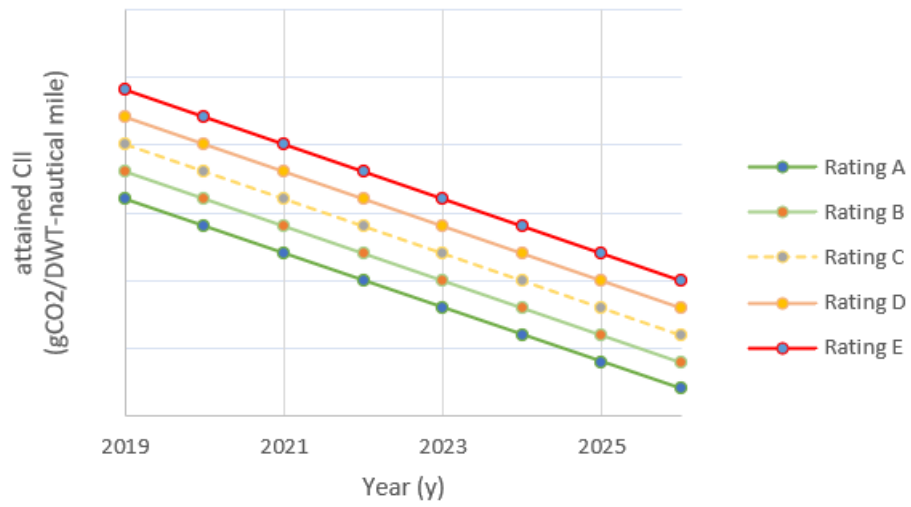


Figure 4. Example CII rating decrease during the years. Modified from DNV.

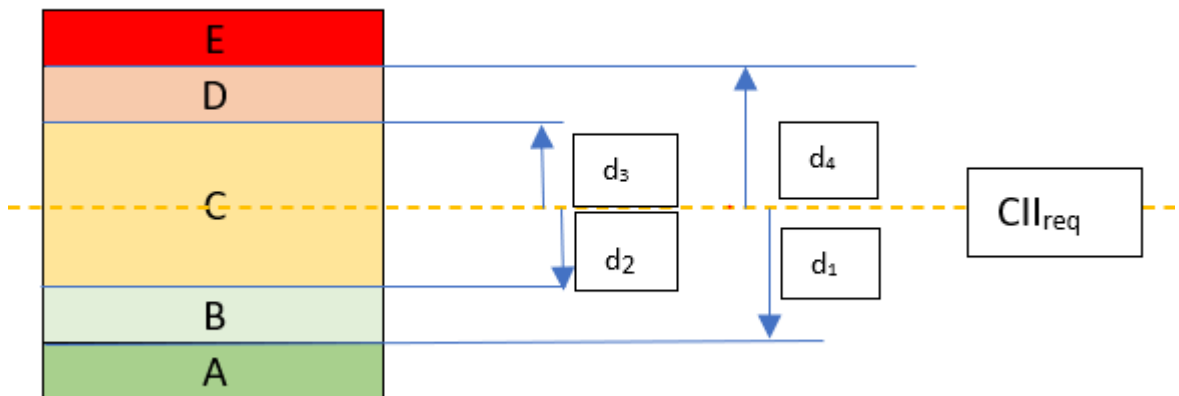


Figure 5. Rating vectors for rating boundary calculation.

Estimated rating vectors are collected from the statistics of the 2019 attained CII of the concerned ship type. The boundary calculation follows the required CII rating and depending on the vector it gives the correct boundary value. Ship type-specific rating vector values are presented in Table 5 and the boundary calculation equation model in equation 8.

Table 5. Rating vector determination for boundary calculation of different ship type (IMO MEPC 2022d.)

<i>Ship type</i>	<i>Capacity in CII calculation</i>	<i>dd vectors (After exponential transformation)</i>			
		<i>Exp(d1)</i>	<i>Exp(d2)</i>	<i>Exp(d3)</i>	<i>Exp(d4)</i>
<i>Bulk carrier</i>	DWT	0,86	0,94	1,06	1,18
<i>Gas carrier</i>	DWT	0,81	0,91	1,12	1,44
	DWT	0,85	0,95	1,06	1,25
<i>Tanker</i>	DWT	0,82	0,93	1,08	1,28
<i>Container ship</i>	DWT	0,83	0,94	1,07	1,19
<i>General cargo ship</i>	DWT	0,83	0,94	1,06	1,19
<i>Refrigerated cargo carrier</i>	DWT	0,78	0,91	1,07	1,20
<i>Combination carrier</i>	DWT	0,87	0,96	1,06	1,14
<i>LNG carrier</i>	DWT	0,89	0,98	1,06	1,13
		0,78	0,92	1,10	1,16
<i>Ro-ro cargo ship (vehicle carrier)</i>	GT	0,86	0,94	1,06	1,16
<i>Ro-ro cargo ship</i>	GT	0,76	0,89	1,08	1,27
<i>Ro-ro passenger ship</i>	GT	0,76	0,92	1,14	1,30
<i>Cruise passenger ship</i>	GT	0,87	0,95	1,06	1,16

$$\begin{aligned}
\text{Superior boundary A} &= \exp(d_1) \times CII_{req} & (8) \\
\text{Lower boundary B} &= \exp(d_2) \times CII_{req} \\
\text{Upper boundary D} &= \exp(d_3) \times CII_{req} \\
\text{Inferior boundary E} &= \exp(d_4) \times CII_{req}
\end{aligned}$$

Where:

CII_{req}	Required CII value in year [gCO ₂ / (DWT or GT-nautical mile)]
$Exp(d_x)$	Rating vectors from table 5.

The rating vectors will help to estimate upcoming changes for ship CII. As presented in Figure 6 the ship attained a CII value will change during the years if no actions are taken. In point A the vessel attained CII value falling to a B rating in the year 2022. If no actions are taken to improve vessel's carbon intensity the vessel will fall to an E rating in the year 2025 presented in the Figure 6 as point B. When a ship falls to an E rating it has one year to improve the vessel's carbon intensity to a rating C or better which allows the ship to operate for three years. This is presented in the Figure 6 as point C.

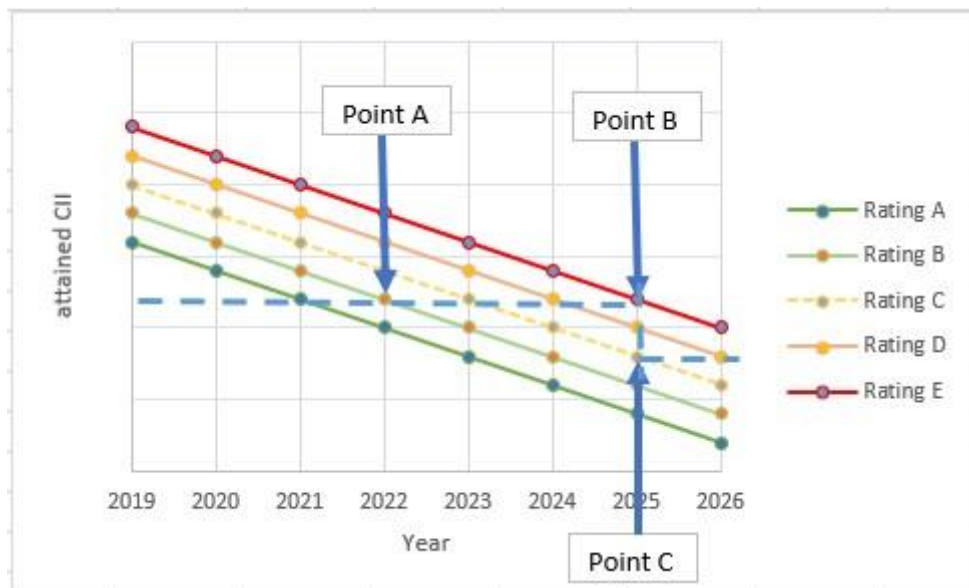


Figure 6. Example of CII rating changes.

2.4.4 CO₂ conversion factors and correction factors

As studied the ship attained a CII rating depending on the operational characteristics and collected fuel consumption data. Fuel is one major factor in the basic equation and different fuels have different effects to ship CII rating along with the operational correction factors. In 2018 during the 76th MEPC session, the correction factors for different fuels were introduced and could be applied to the simplified CII calculation introduced in Figure 7. Correction factors for voyage adjustments and other related factors are taken into consideration in the 78th MEPC session and presented as a guideline for further use. In this study, the more detailed focus is on the fuel consumption side and the effects of the main engine.

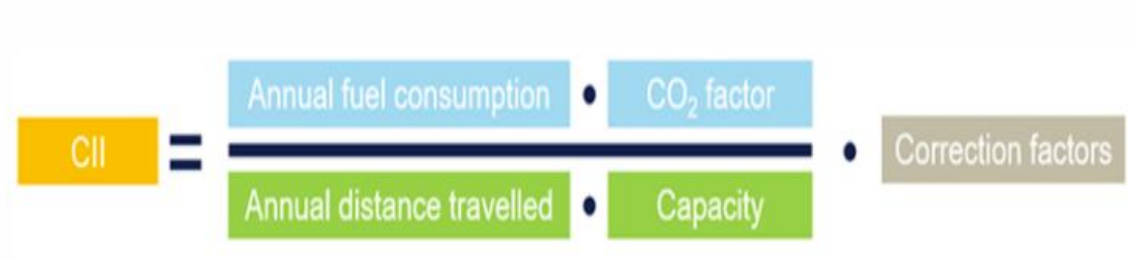


Figure 7. Simplified CII calculation with correction factors (DNV, 2021).

The collected formula from classification society Det Norske Veritas (DNV) introduced in Figure 7 is presented in equation 9.

(9)

$$CII = \frac{FOC_{annual} C_f}{D_t C} O_f$$

Where:

FOC_{annual}	Annual fuel oil consumption of the ship [t/year]
C_f	Carbon factor of the fuel [t-CO ₂ /t-fuel]
D_t	Distance travelled [NM]
C	Ship capacity [DWT or GT (t)]
O_f	Affecting operational factors

CO₂ conversion factor C_F is based on the carbon content of used fuel. CO₂ emissions are measured in grams based on the consumed fuel in grams and on a larger scale could be presented as tons. The CO₂ factor corresponds to the fuel recorded in the ship's fuel consumption report included in the ship's technical file. Fuel types, references, energy content, carbon content and CO₂ factors are presented as follows:

Table 6. Carbon factor for common marine fuels (MEPC, 2018).

Fuel type	Reference	Lower caloric value (kJ/kg)	Carbon content	C_F (t-CO₂/t-fuel)
Diesel/Gas oil	ISO 8217 Grades DMX through DMB	42 700	0,8744	3,206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	41 200	0,8594	3,151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	40 200	0,8493	3,114
Liquefied Petroleum Gas (LPG)	Propane	46 300	0,8182	3,000
	Butane	45 700	0,8264	3,030
Liquefied Natural Gas (LNG)	NO reference	48 000	0.7500	2,750
Methanol	NO reference	19 900	0,3750	1,375
Ethanol	NO reference	26 800	0,5217	1,913

Main engine perspective the current situation shows that traditional Wärtsilä 46 engine utilizes the fuels which are having highest carbon content of the table. The currently used fuels in Wärtsilä 46 engines are highlighted in green. Improvements for the different fuel utilization will be one of the topics handled during this study.

2.5 Vessel affected by the new regulations.

Since the regulations of CII consider all vessels over 5.000 gross tonnages that are transporting goods or passengers the thesis must be limited to consider only existing vessels installed with conventional Wärtsilä 46 engines as main engines. Limiting the study of vessel CII rating to only vessels with W46 engines can be reasonable for several technical reasons:

- **Standardization:** Focusing on vessels with a specific engine type, such as W46 engines, allows for better standardization and comparability of data. It ensures that the study is based on a consistent set of technical specifications, making it easier to analyze and compare the carbon intensity of different vessels.
- **Engine Efficiency:** By focusing on vessels with W46 engines, the study can specifically evaluate the performance and impact of these engines on carbon intensity.
- **Data Availability:** Limiting the study to vessels with W46 engines can be driven by the availability of data. It could be easier to collect accurate and reliable data on vessels with a specific engine type, making the study more feasible and accurate.
- **Research Scope:** The study may have a specific research scope or objective that requires a focused analysis on vessels with W46 engines. For example, if the aim is to assess the effectiveness of a particular emission reduction technology or measure implemented on vessels with W46 engines, it would be logical to limit the study to those vessels.

It's important to note that the decision to limit the study to vessels with W46 engines should be based on the specific goals and requirements of the study.

Engine model was chosen to be conventional W46 with any configuration of cylinder amount if those are working as main engines. The population of operating engines was verified to be 823 on the field according to data collected 23.10.2023 from Wärtsilä. Engine amount is normally higher than number of vessels as most of the vessels have more than one main engine installed.

In the realm of maritime transportation, the vessels equipped with W46 engines are considered relatively old installations, prompting a crucial question regarding their current status. Shipowners are faced with the imperative task of assessing the potential costs associated with upgrading these ships, while simultaneously evaluating the benefits that such an endeavour would yield. It is worth noting that the estimated lifespan of a ship typically ranges between 25 to 30 years (Safety4Sea, 2020).

The latest vessels that were fitted with conventional W46 main engines were constructed prior to 2019, and there is a possibility that they can still operate in compliance with the implemented CII regulations. However, it is important to acknowledge that the sale of the W46 engine model, including power plant engines, was officially discontinued in 2019 (Wärtsilä, 2023).

It is imperative for shipowners and industry experts to carefully consider the implications of these circumstances and make informed decisions regarding the future of their vessels. By conducting a comprehensive analysis of the potential costs and benefits associated with upgrading these ships, stakeholders can ensure compliance with regulations and optimize the performance and longevity of their maritime assets.

Lifetime of the ship is related to many different things. Operating vessels are constantly suffering hard conditions depending on where the vessel is operating and what is the main purpose of the vessel. This leads to need of maintenance and repair works at some point of vessels lifetime. Ship management will provide maintenance plan for the vessels depending on the age of the vessel.

As per SOLAS regulation 1/7 ships are required to drydock at least once in five years to perform maintenance actions for ship hull and manoeuvring equipment's. Drydocking is often very expensive and the ship management will have plan to maximize the benefit of minimum time. Regular drydocking is extending the lifetime of the vessel when larger scale of works is done in smaller steps or before larger scale of damage. Shipowners which have multiple vessels for example passenger vessels will often upgrade the fleet with new vessels. This will cause cost and shipowners will evaluate the situation with older vessels. This often leads to situation where older ships are sold to other party or scrapped because of too high repair cost compared to possible benefit to continue operation.

2.6 Consequences of new regulations

Since the new regulations are set by IMO, the classification societies are following the existing vessel's state. New regulations should be followed, and necessary actions are obliged to be performed.

Consequences of not informing the vessel CII, EEXI and SEEMP part 3 could lead to legal actions. Classification societies and flag states are committed to following rules and regulations. This means if the vessel is not following mandatory regulations, it is an illegal action and classification society could claim the vessel operation. Since the regulations are new the possible claims or regulation neglection is not recorded.

3 Wärtsilä 46-classic engine

Wärtsilä 46-classic is a 4-stroke, turbocharged medium-speed engine with intercooled charge air and direct fuel injection. Wärtsilä W46 engine model was produced from 1988 to 2019. Marine engines were stopped for sale in year 2013. The engine was sold for marine installations with high success, and it is still famous of its simple design and reliable operation due to conventional diesel technology. The engine model was designed for both marine installation and power production installations on land and was fulfilling necessary Tier 1 requirements for NO_x emission levels.

The conventional engine design with jerk pump solution allows the operation with different types of liquid fuels with relatively small costs and most of the installed engines operated with heavy fuel oil before the regulations of SO_x emissions reduction came. In the jerk pump system, a separate fuel injection pump is installed in each cylinder. The pump takes movement from the camshaft drive and the plunger creates the pressure during movement. The start of the injection is constant, and amount of the fuel is adjusted by the position of the plunger (Taylor, 1996).

Common rail technology for W46 engines was introduced to get compliance to fulfil IMO Tier 2 regulations. This thesis does not focus on NO_x emission reduction but utilizes the studies done for NO_x reduction in marine engines. The benefit of the common rail fuel injection is the adjustment options for fuel injection timing. The timing of the injection has a huge effect on emissions especially for NO_x emissions. Another benefit is the better overall efficiency.

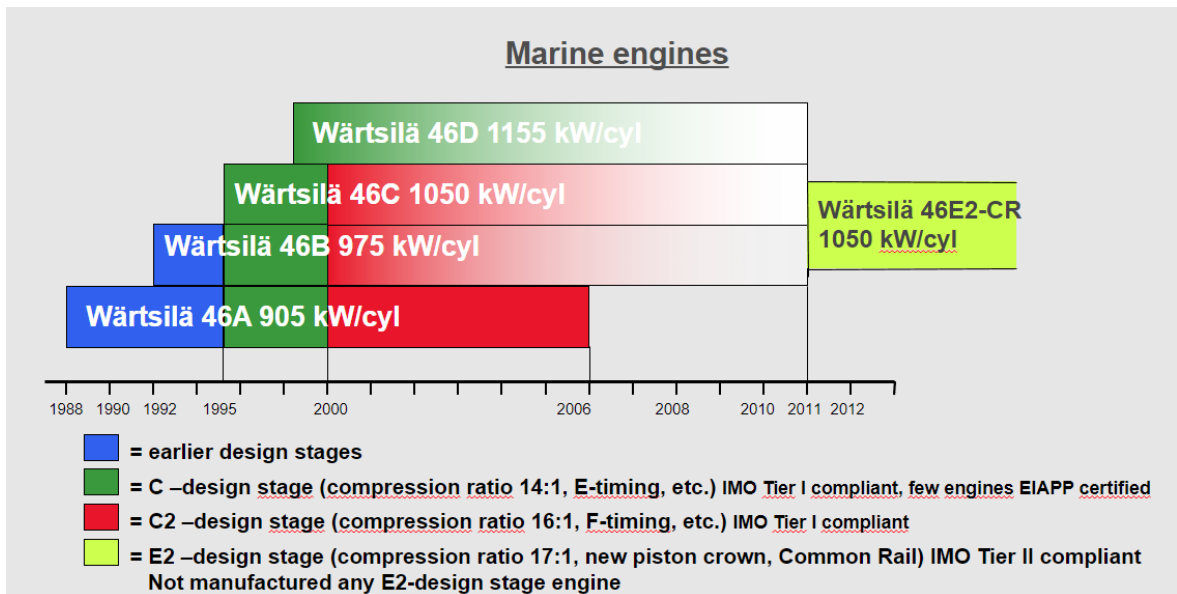


Figure 8. Design stages of Wärtsilä 46-classic engines (Wärtsilä, 2022)

Product development is inevitable for engines because of constantly changing regulations and demand for more environment-friendly operations. New products were introduced after Wärtsilä 46-classic engines but improvements for this specific engine model operation too. Different design stages presented in Figure 8 are developed to optimize the engine to work more efficiently way with some mechanical component-related changes and adjusting the timings of the valves and fuel injection. The driving factor for design stages and development were the IMO Tier compliance and Nitrous oxide reduction.

3.1 Engine main data and fuel consumption

Depending on the installation the main engine will provide power for the propulsion system of the ship. Traditional diesel-mechanic propulsion is arranged with a gearbox and propeller shaft. Another option is to have a diesel-electric arrangement where the engine is connected to an alternator which provides electricity for propulsion. Installed W46-classic engines in the field will present both arrangements which will affect the operation profile of the engines. Diesel-electric engines could run at constant speed when the engine operation profile is designed for a certain load and speed where engine efficiency is optimum. In diesel-mechanical propulsion, the engine runs with variable speed and follows the propulsion curve shown in Figure 9. Installations with diesel-mechanic propulsion and controllable pitch propellers are more challenging to adjust for optimum performance with high efficiency.

Wärtsilä 46

Operating field for CP-propeller

Rated speed 500 rpm, MCR 1050 kW/cyl

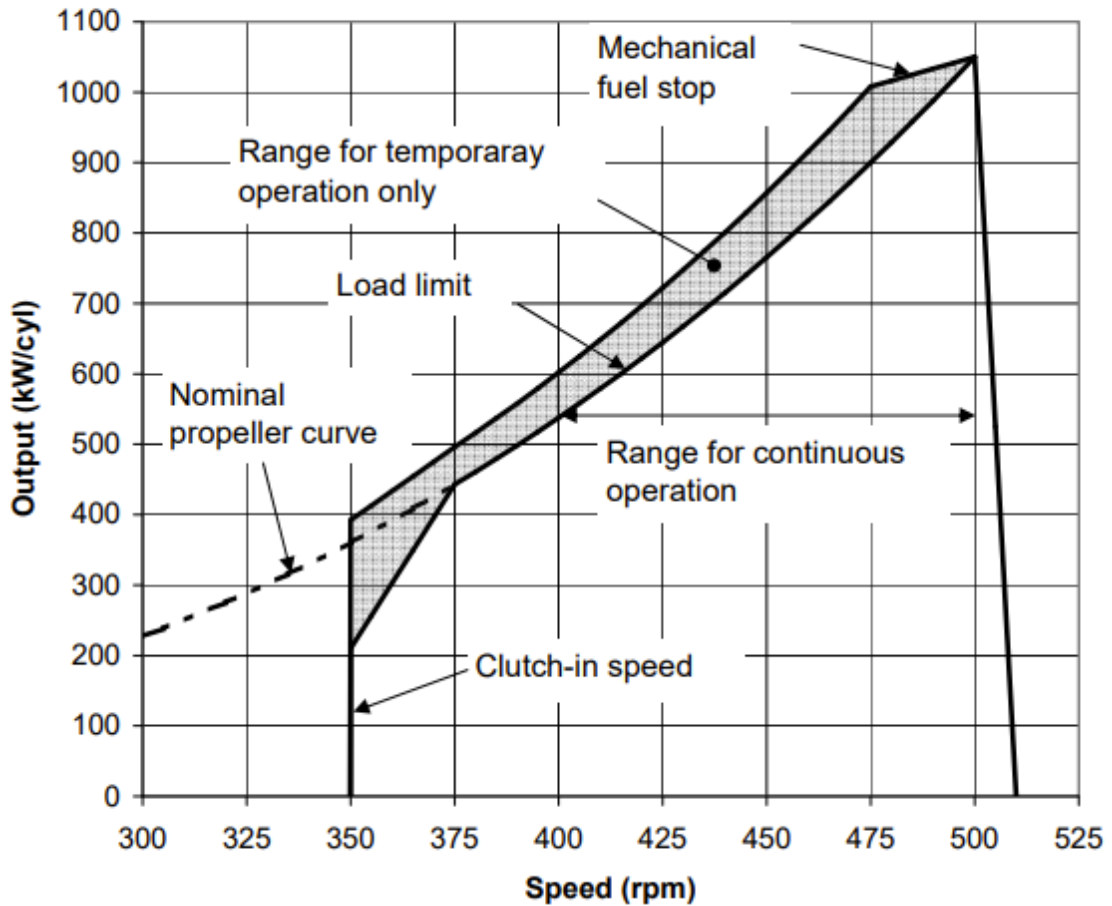


Figure 9. Example operating field for W46 engine with CP-propeller (Wärtsilä 46, 2007).

Specific fuel oil consumption is the fuel consumption of the engine at specific load and speed. On marine side it is often introduced as grams per kilowatt hour. By defining the specific fuel oil consumption, it is possible to find the most efficient range for engine operation. Figures 10 and 11 represents the typical specific fuel oil consumption curves for variable-speed and constant-speed engines. In the figures the estimation of consumption increase is presented depending on the engine load or speed. Engines are often optimized to operate approximately 80 percent load where the specific fuel oil consumption is lowest.

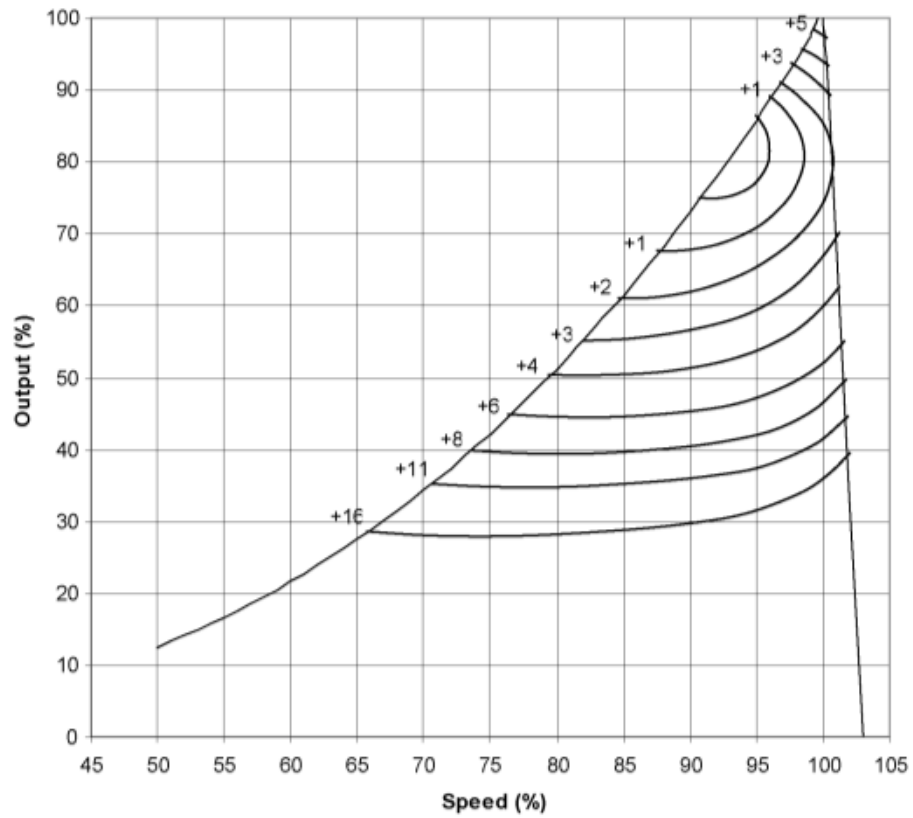


Figure 10 Typical specific fuel oil consumption variable speed [g/kWh]

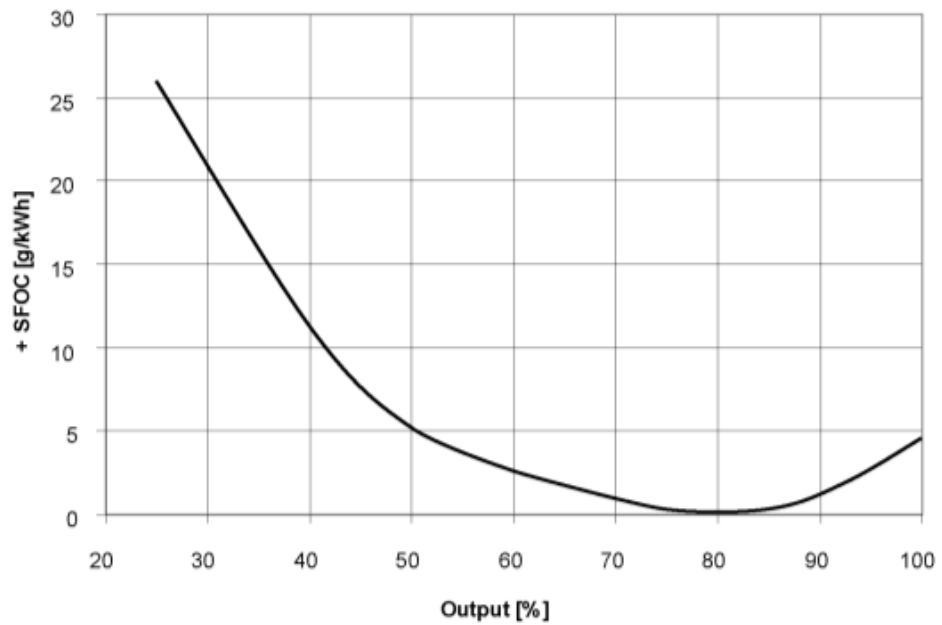


Figure 11. Typical specific fuel oil consumption constant speed engines [g/kWh]

4 Improvement options for current situation

While the CII is primarily influenced by the operating actions it is important to study all options in equipment level and possible improvement potentials. As presented in previous sections the vessel efficiency was studied with EEXI calculations including engine power and speed. Referring to those aspects it was noted that engine efficiency and vessel speed represents major role in the calculations.

Vessel speed and power reduction options are introduced for vessels with different propulsion systems to comply with required EEXI index. The reduction of sailing speed and power is based on the fuel consumption where the total amount of fuel used is reduced during the voyage. The example of vessel total fuel oil consumption in different engine load is presented in Figure 12. In the example the total fuel oil consumptions are collected from W46-classic engine test run tables and represents only an estimation. The graph gives better understanding of the relation with load and consumption. Options are available and provides easy and efficient solution for ships (Wärtsilä, 2021).

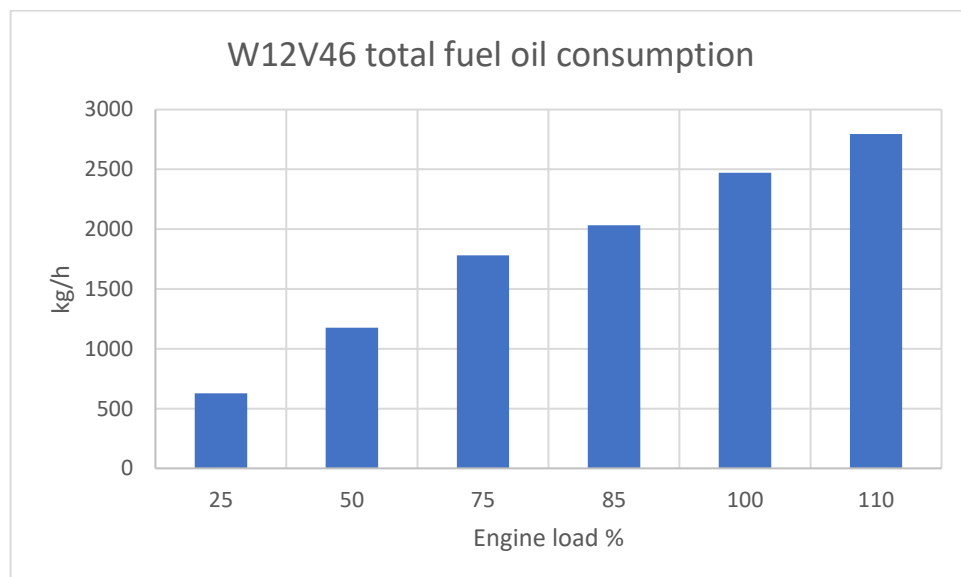


Figure 12. Example of total fuel oil consumption related to engine load.

Reduction of sailing speed could affect heavily to vessel operation and business negatively is the profitability of the business is related to achieved benefit of faster sailing and short cargo transport. In the context of ro-ro vessels, which often make multiple runs per day, reducing operational speed can result in a reduction of achieved visits to certain ports. In such cases, finding alternative optimization solutions becomes crucial to improve carbon intensity and vessel efficiency.

The reduction of speed offers numerous benefits, particularly when the schedule allows for flexibility. Traditionally, ships operate by reaching their destination quickly and then waiting near the port or on the pier for cargo unloading. However, this approach leads to increased idle time and continuous operation of auxiliary engines, resulting in higher fuel consumption and emissions. While arriving just on time for unloading can reduce consumption and emissions, it is primarily an operational function rather than a long-term improvement strategy (Tekniikka ja Talous, 2024).

When observing the engine in functional and technical perspective, the load reduction has other impacts to the engine which can not be seen immediately. Long time operation with low load affects the engine inner components by the reduced air flow and flushing properties. Low load operation affects the turbocharger speed and efficiency due the reduced charge air pressure which causes soot and carbon deposit built-up to engine components such as turbocharger nozzle rings and combustion chamber. As presented in figures 10 & 11 the engines are working more efficiently on 80-95% load where combustion of fuel is more complete and gas flows through the engine is efficient.

4.1 Optimization options

When ship operational aspect including load reduction is left out from the evaluation of engine optimization the focus turns towards the fuel and consumption related improvements. Optimization options could include mechanical improvements in component level or parametrical improvements in engine operation. The consumption reduction of fuel which has high carbon factor or change of fuel are the key elements for improvement.

4.1.1 Mechanical improvements in engine level

To optimize engine efficiency and fuel oil consumption normally requires mechanical changes in existing engines. The mechanical changes should be available for shipowner without major modifications in ship design. Many of existing W46-classic engines have traditional jerk pump arrangements in the engine fuel system which was common in the time when first W46-classic engines were manufactured. In earlier design each cylinder in the engines have individual fuel injection pump which feed fuel to mechanically functioned fuel injection valves. Fuel injection timing depends on the fixed adjustment and when camshaft starts the compression in the fuel injection pump. In this design the starting of the injection is constant which does not allow timing adjustment during the operation.

The studies done for manipulating the injection timing are showing that fuel injection timing will have an effect to NO_x emissions and fuel oil consumption in internal combustion engines (Öztürk et al., 2020). Advanced fuel injection timing increases the combustion temperature and increases NO_x emission levels when the fuel consumption has been seen reduced. Retarded fuel injection timing has shown reduction of NO_x emission levels with cost of fuel efficiency. Retarded injection timing utilized in part load operation allows less fuel to enter the cylinder and, in that way, decreases the total fuel oil consumption in larger scale.

This could be executed by replacing original fuel injection plunger to variable injection timing model presented in Figure 13, which is available for W46-classic engines in specific design stage. This could be considered as the first option to reduce the specific fuel oil consumption which will affect the total fuel consumption in annual scale. Estimated reduction of specific fuel oil consumption with the variable timing plunger in heavy fuel oil (HFO) operation is 2,5-3 g/kWh. The achieved benefit with new type of plunger is related to fuel viscosity.

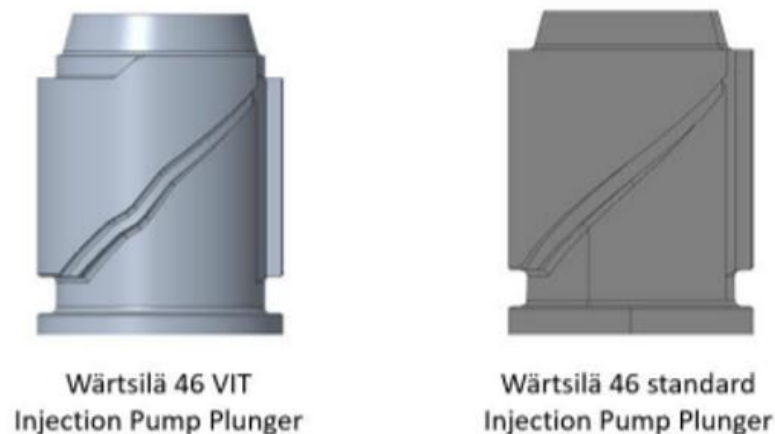


Figure 13. Variable injection timing plunger for W46-classic engines (Wärtsilä, 2021b).

Second mechanical upgrade option for the existing engines is to replace traditional jerk pump arrangement in the engines with common-rail system. In common-rail system the fuel is delivered to cylinder via common-rail line where the fuel is pressurised to specified pressure. The benefit with this arrangement is that each cylinder have constantly same status to start the injection. Injection timing is then controlled more specifically and individually for each cylinder. The control for injection could be done mechanically, hydraulically, or electrically. In theory, engine automation system could adjust the fuel injection timing, but it will require automation system upgrade for existing W46-classic engines.

Wärtsilä has common-rail generation two (CRII) available for W46-classic engines and it is currently in use on some installations. This upgrade includes fully electrically controlled injectors which improves the controllability. CRII is developed from common-rail generation one (CRI) arrangement where injection components were improved by implementing accumulation properties for injector. Improvements achieved with latest developments are shown in specific fuel oil consumption. According to recorded data from available installations the estimated and achieved reduction in SFOC is 2-3 g/kWh. This was achieved in installation optimized to 75%-85% engine load range with LFO fuel (Wärtsilä, 2022).

4.1.2 Performance upgrade packages

Mechanical improvements will in some cases require some other actions with the engine. Turbocharger and sufficient charge air is important for efficient operation of the internal combustion engines. To achieve the most optimal situation the engine might need some performance upgrades depending on the age and design stages. Performance upgrade packages includes changes in turbocharger design which have the positive impact for combustion properties. When engine is supplied with sufficient air it allows fuel to burn more efficiently which allows more options in scavenging and valve timing. Higher boost pressure will allow to utilize lower overlapping of the inlet and exhaust valves (Wärtsilä, 2021b).

4.2 Fuel conversion

The other efficient way to reduce carbon dioxide emissions is to converse engine to operate with low carbon fuels. As Table 6 was presenting, the use of natural gas (NG) or liquified natural gas (LNG) have smaller carbon content compared to fossil fuels and gives better carbon factor for CII calculation. This type of fuel conversions has been done for W46-classic engines but only for power plant installations. Changing engine main fuel in ship will require major conversion works to ship design including tank arrangements. Even the engine related conversion actions are well known and possible for W46-classic engines the cost of whole conversion will increase probably too high for ship owner.

Biofuels are rising trend in shipping industry and seen very promising in the path of decarbonized shipping. Ship owners has shown interest to liquid biofuels (LGB) due the ability to use those without major conversions (Ovrum et al., 2023). Biofuel term consist of fuels which are originated from sustainable sources or fuel blends where some amount of fossil fuels is replaced with different type of biofuels. Wärtsilä has provided official external bulletin for customers to operate specified biofuels if certain requirements are fulfilled (Wärtsilä, 2022c). The bulletin document WS02N203 (Appendix 2) is enclosed to this study.

The challenge with biofuels is to comply the IMO NO_x limits when fuels are derived by other methods than petroleum referring. Engines are certified with Engine International Air Pollution Prevention (EIAPP) certification where components affecting to engine NO_x

emissions are listed and changes to those NO_x critical components will require updated certification. In IMO MEPC 78th meeting in June 2022 unified interpretation regarding the biofuel operation was approved. With this interpretation the use of biofuel does not require additional NO_x emission measurements if NO_x critical components and settings are not deviating from original approved technical file. When focusing on the CII and carbon dioxide emission reduction it is mandatory to observe also the other regulations affecting to vessel operation (Wärtsilä, 2022c).

The real benefit with biobased fuels is the carbon factor in CII calculations. Different biobased fuels can reduce the carbon factor easily which makes the use of biobased fuels attractive. Marine industry is constantly trying to find options to increase the use of liquid biofuels and latest innovation is to utilize blended cashew nutshell liquid (CNSL) in fuels. Wärtsilä was involved for test where 30% of cashew nut shell liquid was mixed with low sulphur RMA10 grade fuel in co-operation with legislation society. The benefit with this fuel is to reduce the well-to-wake value and utilize the waste product from other industry. The behaviour of the CNSL on marine use is not clear and the test is currently ongoing (Shippax, 2024).

4.2.1 Tank-to-wake evaluation

The expression tank-to-wake consists of the emissions created from the fuel only during the combustion process in ship. The evaluation of vessels emission when biofuel is burnt during the sailing is not notably varying from the emissions produced with fossil fuels. The biofuels consist also carbons which are released to atmosphere by the combustion process. The reduction of carbon dioxide emissions is not achieved with biofuels when focus is only on the combustion process. In some cases when lower heating value (LHV) of the fuel is lower compared to fossil fuel, the CO₂ emissions may be even higher. If the tank-to-wake CO₂ emissions are examined the only option to reduce the emissions is to produce less emission which could be considered as lower fuel consumption or utilize fuels which are not creating any CO₂ emissions like Hydrogen. This is still under investigation and development and that is one reason why the biofuels and emissions are evaluated from the origin of the fuel and not by the short time emissions.

4.2.2 Well-to-wake evaluation

In MEPC 88th session in 2023 the guidance was given to use biofuels and evaluate the well-to-wake emissions. Well-to-wake evaluation consists of the fuels total CO₂ emissions from the origin to the combustion. When biofuels are produced more sustainable way it affects the total emissions positively and by that reduces the carbon factor in the CII calculations. Biofuels which are certified, meeting sustainability criteria and reducing at least 65 per cent of greenhouse gas (GHG) including CO₂ emissions are allowed to utilize carbon factor specified for the certified fuel (MEPC, 2023).

When calculating the ship CII, the carbon factor is one option which could be affected by the engine manufacturer. When engine is capable to burn efficiently fuels which are having lower carbon factor it allows to utilize minor benefit of available biofuels.

4.3 Energy storing and hybrid solutions.

The storing of produced energy in certain installations could be one of the efficient ways to reduce fuel oil consumption of the engines. The hybrid solutions could be one of the options to reduce vessel CII rating where produced energy is stored to batteries. Batteries will be utilized for example during manoeuvring. This solution would be possible to implement in engines with shaft generators. Utilizing stored energy will reduce the use of primal mover which will reduce the consumption and emissions. Example arrangement of battery systems is presented at Figure 14.

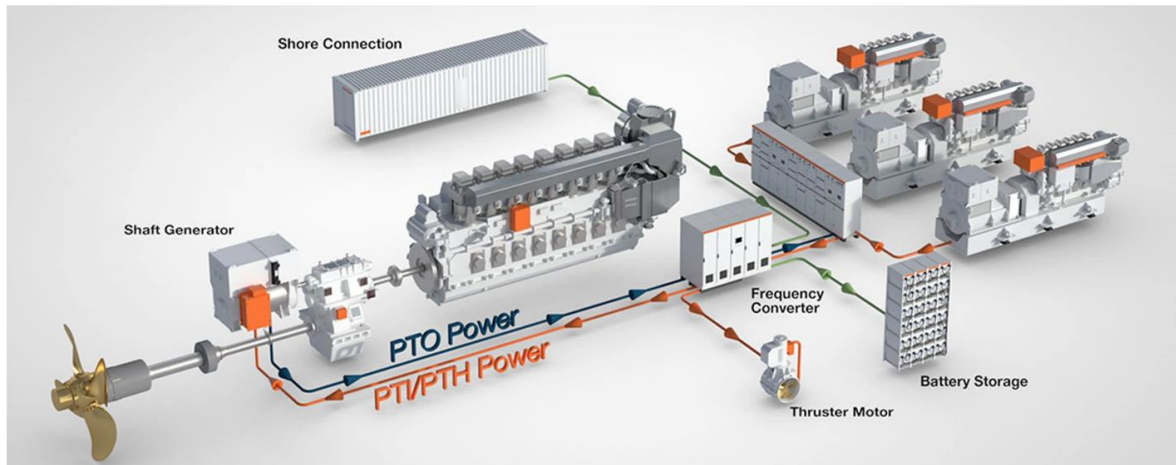


Figure 14. Example of available hybrid solutions (Wärtsilä, 2023c).

PTI (Power Take-In) and PTO (Power Take-Off) hybrid solutions can help reduce the CII rating in vessels by optimizing the power generation and consumption onboard.

PTI allows a vessel to connect to an external power source, such as a shore power supply or a renewable energy source, while at berth or during low-power demand periods. This reduces the need for the vessel's engines to run, resulting in lower fuel consumption and emissions. By using cleaner and more efficient power sources, the CII rating can be significantly reduced.

PTO, on the other hand, enables the vessel to harness excess power from the main engines or other onboard power sources and convert it into usable energy. This energy can be used to power auxiliary systems or stored for later use. By utilizing this excess power, the overall fuel consumption and emissions can be reduced.

By combining PTI and PTO hybrid solutions, vessels can optimize their power generation and consumption, resulting in reduced fuel consumption and emissions. This, in turn, leads to a lower CII rating, indicating a more environmentally friendly and sustainable operation.

Even the main benefit is mostly to drop off auxiliary engines during the manoeuvring the vessel annual total fuel consumption is reduced by the utilization of electrical power which in optimum situation is generated during the normal operation.

Retrofitting of this type of solution will require mostly upgrades for other machinery in the vessel than the main engine. Upgrading gearbox with shaft generator and implementing

hybrid solutions does not affect the daily main engine operation. In case the propulsion could be operated without running the main engine for limited time, the reduction in annual main engine fuel oil consumption could be observed.

4.4 Carbon capture solutions for main engine emissions

Utilization of existing technology in exhaust gas after treatment is one of the popular ways to reduce CO₂ emissions. As learnt from the past, the exhaust gases could be treated before releasing it to the atmosphere. Different types of exhaust gas washers are utilized in marine industry for a long time to tackle with the SO_x emissions and most of the vessels are already equipped with scrubber solutions. Example system arrangement is presented in Figure 15.

Studies have shown that using amine rich solvent mixture for washing the exhaust gases, it is possible to capture approximately 90 % of CO₂ from the exhaust gases. In the closed loop system, where solvent is circulated in closed system and not led to sea like in an open loop system, the solvent is guided to separate stripper where utilizing heat the CO₂ is taken off from the solvent and stored (Force technology, 2024).

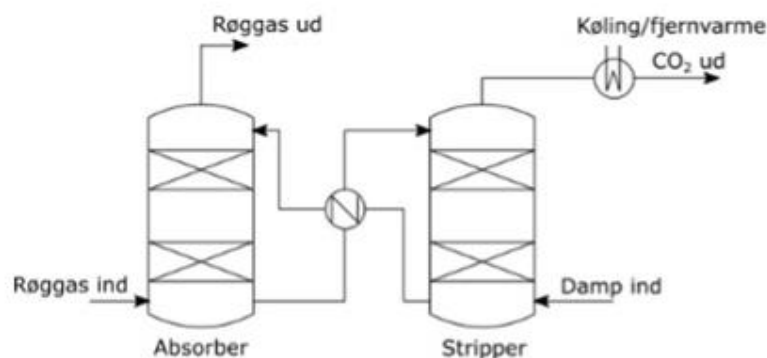


Figure 15. Basic idea of CO₂ capture and scrubber arrangement (Force technology, 2024).

5 Customer survey results and evaluation

As a part of study, shipowners were consulted with inquiry to receive up to date information from the field. Target was to collect reliable data of planned options from customer side with basic level questions and evaluate the results to find most popular method to improve the CII rating on ships. Installations for the survey were chosen by the accessibility and variations.

The survey was sent to nine installations and answers was received only from two installation in one owner. The result of survey was not successful and because the lack of received answers, the evaluation and ranking of best solution could not be verified accordingly. The inquiry (Appendix 1) is enclosed to the study.

6 Conclusions

The study was found very educational and to be wider topic than expected. The CII topic itself was relatively new in the time of the study so the sources for supporting materials was limited. The study was found useful to understand the general idea behind the CII evaluation and enabled to detect the improvement options from machinery side. As it was known from the beginning the study showed more clearly that the CII is more related to operational aspect and the mechanical machinery related ways are limited. However, when the principle behind the hole CII idea was divided in sections, it was interesting to see what the things are where it is possible to influence.

The idea of collecting up to date knowledge and experiences with customer survey was not successful which left the valuable information narrow. It can be admitted that the one of the important targets of the study was not achieved. This has no effect to the main objective of this study, which was to generate simplified instructions package for Wärtsilä customers and analyse the improvement options for W46 engines. That target was reached with available literature and practical field work.

According to findings of the study, there was not really one topic which could be considered the best solution from engine perspective to reduce vessel CII rating. The best results would be achieved with combination of different ways. The easiest solution is to utilize the available liquid biofuels and optimize the engine performance with available upgrade solutions. As explained in study the main option with older machinery is to reduce the consumption without affecting to normal operation of the vessel. This could be reached with reasonable mechanical changes and cost. Fuel conversions are having much larger affect, but the cost is normally too high for the vessels which are close to retirement. There is potential to develop battery systems which could be connected to biofuel powered engines which could improve the general view.

New fuels are constantly entering the markets such as methanol, ammonia and hydrogen which are studied to be promising solutions to reduce CO₂ emissions. The development work is mostly done for engines in production which limits the existing fleet options. When observing the conclusion of this thesis, it can be concluded that all options are possible to execute but the limiting factor for this is the costs and payback time. As mentioned, the

vessels which are installed with W46-classic engines are already aged installations which limits the profitability of major changes and actions. Since the feedback of the field did not achieve the wanted state and would need more wider study, this is only speculations.

Detailed emission data comparison between fossil fuel and biobased fuel was not received at the time of the study, which left the well-to-wake and tank-to-wake observation at a theoretical level. The real emission data collection was expected to show the difference between these two perspectives, but unfortunately, the data was not available since the ongoing field test was not finalized. The operation of the engine with new liquid biofuels such as CNSL remained unclear which has some potential to be one of the options to reduce carbon factor. This type of evaluation often requires endurance tests in a monitored environment to reach accurate feedback data.

The study highlights the growing attention and actions being taken in the marine industry regarding the relatively new topic of emissions reduction. This positive trend indicates that the industry is moving in the right direction to address the issue of increased emissions at all levels. There is a need for further studies and continuous development in this field even though the study achieved the technical target of analyzing the options for W46-classic engines. Even the study methods were not as successful as expected and real data was not received during the work, the study guides the path forward. Continuously changing regulations and rules are adding challenges but the thesis reached the target of collect the latest knowledge and offers easier guidelines to follow.

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CII & W46 customers inquiry

1. Vessel name, Type, Capacity & age

2. **Operation profile (distances & waiting times)** In which category your operation will fall.

- Long route & short waiting times
- Long route & long waiting times
- Short route & short waiting times
- Short route & long waiting times

3. **Engine use?**

Choose the closest option or explain your operation profile and the benefits.

- Low load operation with multiple engines
- High load operation with one or some engines
- Single main engine operation
- Something between

4. If you answered "something between" in previous section, please explain.

5. **Operation plans for the next years with the vessel?**

Focus on the regulation point of view.

- Normal Operation continues.
- Actions will be taken to continue operation.
- Planning for upgrades started.
- New vessel ordered.

6. **Current CII rate of the vessel?**

Received or calculated rating.

- A
- B
- C
- D
- E

7. What is the reason for the current rating?

8. **Actions to planned comply the upcoming CII rates?**

General thoughts and plans.

- Upgrades to machinery
 - Changes on the operational side
9. **Explain more detailed your choice in question 8?**

10. **Biggest challenges with latest regulations?**

Choose the closest option. Keep the business running

- High costs of improvements
- Unclear regulations
- Lack of improvement options
-

11. **Economical impact of new regulations?**

- Minor
- Medium
- High

12. **What will be the future fuel on your ship?**

- Low sulphur (HFO / DO / MGO / LFO)
- Bio based fuel (FAME / HVO)
- LNG

13. **Fuel consumption optimization?**

How you reduce fuel consumption in your daily operation.

14. **How beneficial you see vessel wise options/instructions to improve vessel CII?**

- Beneficial
- Not beneficial

15. Free comments

Appendix 2. External bulletin WS02N203

**Fuel oil specification for liquid
biofuel****Distribution to operators and owners of installations
concerned****For your information****Engines concerned**

The following WÄRTSILÄ® diesel and dual fuel engines:

- WÄRTSILÄ® 20
- WÄRTSILÄ® 25
- WÄRTSILÄ® 26
- WÄRTSILÄ® 31
- WÄRTSILÄ® Vasa 32
- WÄRTSILÄ® Vasa 32GD
- WÄRTSILÄ® Vasa 32LN
- WÄRTSILÄ® Vasa 32LNGD
- WÄRTSILÄ® 32
- WÄRTSILÄ® 32M
- WÄRTSILÄ® 38
- WÄRTSILÄ® 46
- WÄRTSILÄ® 46F
- WÄRTSILÄ® 50
- WÄRTSILÄ® 64

- WÄRTSILÄ® 20DF
- WÄRTSILÄ® 25DF
- WÄRTSILÄ® 31DF
- WÄRTSILÄ® 32DF
- WÄRTSILÄ® 34DF
- WÄRTSILÄ® 46DF
- WÄRTSILÄ® 46F-M
- WÄRTSILÄ® 46TS-DF
- WÄRTSILÄ® 50DF

Reference

Fuel, lubricating oil, cooling water

Introduction

Issue 1 of the bulletin was published in November 2012 to inform about the fuel characteristics for liquid biofuel.

This issue has been published to inform that WÄRTSILÄ® 25, 25DF, 32M 46F-M and 46TS-DF have been added to the bulletin.

Validity

Until further notice. Replacing issue 4, dated 29 December 2022.

Before taking any action, always check the available online systems for the latest revision of this document. Any locally stored or printed version is considered to be an uncontrolled document.

FUEL CHARACTERISTICS

1 Liquid biofuel characteristics and specifications

The Wärtsilä® diesel and Dual Fuel (DF) engine types specified in the table hereafter are capable for continuous operation on liquid biofuel (LBF) qualities with the properties included in the Tables 1.1, 1.2.1 – 1.2.4 and 1.3. For the Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO) operation included in Table 1.1 dedicated engine retrofit may be required.

For other engine types not listed in the table below, liquid biofuel with the characteristics specified can be considered case by case, please contact Wärtsilä for further information.

Liquid biofuel category – Main and back-up fuel

Engine type	Straight and pure vegetable oils, Table 1.1 ¹⁾	FAME / Biodiesel, Table 1.2.1 – 1.2.4 ¹⁾	Paraffinic diesel fuels, Table 1.3 ²⁾
Wärtsilä 20	Yes ³⁾	Yes	Yes
Wärtsilä 25	No	Yes ⁴⁾	Yes
Wärtsilä 26	Yes ³⁾	Yes	Yes
Wärtsilä 31	No	Yes ⁴⁾	Yes
Vasa 32	No	Yes	Yes
Vasa 32GD	No	Yes	Yes
Vasa 32LN	No	Yes	Yes
Vasa 32LNGD	No	Yes	Yes
Wärtsilä 32	Yes ³⁾	Yes	Yes
Wärtsilä 32M	No	Yes	Yes
Wärtsilä 38	No	Yes	Yes
Wärtsilä 46	Yes ³⁾	Yes	Yes
Wärtsilä 46F	No	Yes	Yes
Wärtsilä 50	Yes ³⁾	Yes	Yes
Wärtsilä 64	No	Yes	Yes
Wärtsilä 20DF	Yes ³⁾	Yes	Yes
Wärtsilä 25DF	No	Yes ⁴⁾	Yes
Wärtsilä 31DF	No	Yes ⁴⁾	Yes
Wärtsilä 34DF	Yes ³⁾	Yes	Yes
Wärtsilä 46DF	No	Yes	Yes
Wärtsilä 46F-M	No	Yes	Yes
Wärtsilä 46TS-DF	No	Yes ⁴⁾	Yes
Wärtsilä 50DF	Yes ³⁾	Yes	Yes

Liquid biofuel category – Pilot Fuel

Engine type	Straight and pure vegetable oils, Table 1.1	FAME / Biodiesel, Table 1.2.1 - Table 1.2.4 ¹⁾	Paraffinic diesel fuels, Table 1.3 ²⁾
Wärtsilä 20DF	No	Yes	Yes
Wärtsilä 25DF	No	Yes ⁴⁾	Yes
Wärtsilä 31DF	No	Yes ⁴⁾	Yes
Wärtsilä 32DF	No	Yes	Yes
Wärtsilä 32M	No	Yes	Yes

Engine type	Straight and pure vegetable oils, Table 1.1	FAME / Biodiesel, Table 1.2.1 – Table 1.2.4 ¹⁾	Paraffinic diesel fuels, Table 1.3 ²⁾
Wärtsilä 34DF	No	Yes	Yes
Wärtsilä 46DF	No	Yes	Yes
Wärtsilä 46F-M	No	Yes	Yes
Wärtsilä 46TS-DF	No	Yes ⁴⁾	Yes
Wärtsilä 50DF	No	Yes	Yes

Note 1: Liquid biofuels included in the Table 1.1 and 1.2.1 have typically lower “lower heating value” (LHV) than fossil fuels, while the capacity of fuel injection system influencing on guaranteed engine output must be checked case by case. Concerning biodiesel blends included in Tables 1.2.2, 1.2.3 and 1.2.4 the influence of LHV is however not significant.

Note 2: Liquid biofuels included in the Table 1.3 have a low density, while the capacity of fuel injection system influencing on guaranteed engine output must be checked case by case. Their flash point can, based on specifications, be also lower than 60 °C required for marine applications by SOLAS and Classification societies, which may prevent the use.

Note 3: For Straight and Pure Vegetable oils (SVO and PVO) qualities, depending on Fuel Injection equipment, field follow up / validation may be required. For operation on crude and refined liquid biofuel, dedicated engine retrofit may be required. Wärtsilä must be contacted for further evaluation.

Note 4: The LBF qualities with the properties included in Table 1.2.2, 1.2.3 and 1.3 are acceptable for use. For higher FAME blends please contact Wärtsilä.

Acceptable storage period for liquid biofuels excluding products which belong to the category being presented in Table 1.3 can be significantly shorter than storage periods specified for fossil fuels. Some biodiesel manufacturers are referring e.g. to max. one month storage period. After that acidity starts to increase leading to faster oxidation rate of the fuel.

Blending of different fuel qualities:

Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO) (Table 1.1) must not be mixed with fossil fuels but have to be used as such.

Mixing of Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO) (Table 1.1) and distillate fuel will increase the risk of cavitation in the fuel system, since the required fuel temperature before an engine is normally 80 - 90 °C. At this temperature light fractions of distillate fuel have already started to evaporate.

The use of residual fuel requires much higher operating temperature than the use of Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO), i.e. normally above 100 °C in order to achieve a proper fuel injection viscosity. Thus mixing of Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO) (Table 1.1) with residual fuel will increase the risk of biofuel component polymerization due to elevated temperature.

Liquid bio fuel qualities presented in the Table 1.2.1 and 1.3 can be mixed with fossil distillate fuel and residual fuel with various ratios. Fossil fuel being used as a blending component has to fulfil Wärtsilä’s distillate and residual fuel specification based on the ISO 8217:2017(E) standard. Depending on the bio component type its quality has to meet either the EN 14214:2012 standard included in the Table 1.2.1 or the EN

15940:2016 standard included in the Table 1.3. For biodiesel blend B10 there also exists an EN 16734 standard and for B20 & B30 blends an EN 16709 standard respectively. Biodiesel blend quality has to fulfil the requirements included in those two standards.

Required fuel temperatures:

Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO) (Table 1.1) temperature before an engine is an utmost important operating parameter. Too low temperature will cause solidification of fatty acids leading to clogging of filters, plug formation in the fuel system and even to fuel injection equipment component breakdowns. Too high fuel temperature will increase the risk of polymerization and formation of gummy deposits, especially in the presence of oxygen.

When operating on Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO) (Table 1.1), it is utmost important to maintain a proper fuel temperature before fuel injection pumps in order to ensure safe operation of the engine and fuel system. The recommended fuel operating temperature depends on both the liquid biofuel quality and the degree of processing. E.g. many palm oil qualities require ~ 80 – 90 °C fuel temperature in order to achieve an expected lifetime of fuel injection equipment and to avoid fuel filter clogging. Some refined palm oil qualities are however behaving acceptably also at lower, ~ 70 - 75 °C operating temperature. For other types of Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO) the temperature requirement can be slightly different and must be confirmed before the use.

For fuel qualities included in the Table 1.2.1, 1.2.2, 1.2.3, 1.2.4 and 1.3 fuel temperature before fuel injection pumps is limited to max. 45 °C. If residual fuel is used as a blending component together with HVO or biodiesel, fuel injection viscosity and injection temperature requirements being valid for residual fuels have to be followed.

1.1 Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO)

The specification included in the Table 1.1 is valid for Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO), like palm oil, coconut oil, copra oil, rape seed oil, jatropha oil, fish oil, etc.

Table 1.1. Liquid biofuel specification for Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO)

Property	Unit	Limit	Test method reference
Viscosity, max.	mm ² /s @ 50 °C	70 ¹⁾	ISO 3104
	mm ² /s @ 80 °C	15 ¹⁾	
Injection viscosity, min.	mm ² /s	1,8 – 2,0 ²⁾	
Injection viscosity, max.	mm ² /s	24	
Density, max.	kg/m ³ @ 15 °C	940	ISO 3675 or 12185
Ignition properties ³⁾		³⁾	FIA-100 FCA test
Sulphur, max.	% m/m	0,05	ISO 8754
Total sediment existent, max.	% m/m	0,05	ISO 10307-1
Water, max. before engine	% v/v	0,20	ISO 3733 /
Micro carbon residue, max.	% m/m	0,50	ISO 10370
Ash, max.	% m/m	0,05	ISO 6245 / LP1001 ⁴⁾
Phosphorus, max.	mg/kg	100	ISO 10478
Silicon, max.	mg/kg	15	ISO 10478

Property	Unit	Limit	Test method reference
Alkali content (Na+K), max.	mg/kg	30	ISO 10478
Flash point (PMCC), min.	°C	60	ISO 2719
Cloud point, max.	°C	⁵⁾	ISO 3015
Cold filter plugging point, max.	°C	⁵⁾	IP 309
Copper strip corrosion, (3 hrs @ 50 °C), max.	Rating	1b	ASTM D130
Steel corrosion (24 / 72 hours @ 20, 60 and 120 °C), max.	Rating	No signs of corrosion	LP 2902
Oxidation stability @ 110 °C, min.	h	17,0 ⁶⁾	EN 14112
Acid number, max.	mg KOH/g	15,0	ASTM D664
Strong acid number, max.	mg KOH/g	0,0	ASTM D664
Iodine number, max.	g iodine /100 g	120 ⁷⁾	ISO 3961
Synthetic polymers	% m/m	Report ⁸⁾	LP 2501
Lower Heating Value (LHV)	MJ/kg	Report	ASTM D240

1. If injection viscosity of max. 24 cSt cannot be achieved with an unheated fuel, fuel system has to be equipped with a heater ($\text{mm}^2/\text{s} = \text{cSt}$).
2. Min. viscosity limit at engine inlet in running conditions; W20: 1,8 cSt, W26, W31, Vasa 32, W32, W32M, W38, W46 with CR, W46F, W50, W20DF, W31DF, W34DF, W46DF and W50DF: 2,0 cSt, W46 with jerk pump and W64: 2,8 cSt ($\text{mm}^2/\text{s} = \text{cSt}$). If a liquid biofuel with lower injection viscosity than 2,8 mm^2/s is desired to be used in the W46 engines equipped with jerk pumps, Wärtsilä Technical Services has to be contacted for further evaluation.
3. Ignition properties have to be equal to or better than the requirements for fossil fuels, i.e., CI min. 35 for LFO and CCAI max. 870 for HFO.
4. Ashing temperatures can vary when different test methods are used having an influence on the test result.
5. Cloud point and cold filter plugging point have to be at least 10 °C below fuel injection temperature and the temperature in the whole fuel system has to be min. 10 – 15 °C higher than cloud point and cold filter plugging point.
6. A lower oxidation stability value down to min. 10 hours can be considered acceptable if other fuel properties, like cloud point, cold filter plugging point and viscosity support that. This needs to be decided case-by-case.
7. Iodine number of soyabean oil is somewhat higher, up to ~ 140, which is acceptable for specific that bio fuel quality.
8. Biofuels originating from food industry can contain synthetic polymers, like e.g. styrene, propene and ethylene used in packing material. Such compounds can cause filter clogging and shall thus not be present in biofuels.

Remark 1: If Selective Catalyst Reduction (SCR) or oxidation catalyst needs to be used, the specification included in the Table 1.1 does not apply, but the fuel quality requirements have to be discussed separately. The specification does not take into consideration Particulate Matter emission limits.

Remark 2: When analysing the energy content (Higher and Lower Heating Value) of Straight Vegetable Oils (SVO) and Pure Vegetable Oils (PVO) the calculation method included in the ISO 8217 standard can't be used, but the analysis has to be made by following the ASTM D240 standard.

1.2 Fatty acid methyl ester (FAME) / Biodiesel

Renewable refined liquid biofuels which are manufactured by using transesterification processes, can contain both vegetable and / or animal based feedstock and do normally show out very good physical and chemical properties. These fuels can be used provided that the specification included in the Table 1.2.1 is fulfilled. International standards ASTM D 6751-20 or EN 14214:2012 (E) are typically used for specifying biodiesel quality. Further, for biodiesel blend B10 there exists an EN 16734 standard and for B20 & B30 blends an EN 16709 standard respectively. Biodiesel blend quality has to fulfil the requirements included in those two standards. The requirements of B10, B20 and B30 are included in the Table 1.2.2, 1.2.3 and 1.2.4.

Table 1.2.1. Fatty acid methyl ester (FAME) / Biodiesel specification based on the EN 14214:2012 standard

Property	Unit	Limit	Test method reference
Viscosity, min. - max. Injection viscosity, min.	mm ² /s @ 40 °C mm ² /s	3,50 – 5,00 1,8 – 2,0 ¹⁾	EN ISO 3104
Density, min. - max.	kg/m ³ @ 15 °C	860 – 900	EN ISO 3675 / 12185
Celane number, min.	-	51,0	EN ISO 5165
Sulphur content, max.	mg/kg	10,0	EN ISO 20846 / 20884 / 13032
Sulphated ash content, max.	% m/m	0,02	ISO 3987
Total contamination, max.	mg/kg	24	EN 12662
Water content, max.	mg/kg	500	EN ISO 12937
Phosphorus content, max.	mg/kg	4,0	EN 14107
Group I metals (Na+K) content, max.	mg/kg	5,0	EN 14108 / 14109 / 14538
Group II metals (Ca+Mg) content, max.	mg/kg	5,0	EN 14538
Flash point, min.	°C	101	EN ISO 2719A / 3679
Cold filter plugging point, max. (climate dependent requirement)	°C	-20 -> +5 ²⁾	EN 116
Oxidation stability @ 110 °C, min.	h	8,0	EN 14112
Copper strip corrosion (3 hrs @ 50 °C), max.	Rating	Class 1	EN ISO 2160
Acid value, max.	mg KOH/g	0,50	EN 14104
Iodine value, max.	g iodine/100 g	120	EN 14111 / 16300
FAME content, min.	% m/m	96,5	EN 14103
Linolenic acid methyl ester, max.	% m/m	12,0	EN 14103
Polyunsaturated (≥ 4 double bonds) methyl esters, max.	% m/m	1,00	EN 15779
Methanol content, max.	% m/m	0,20	EN 14110
Monoglyceride content, max.	% m/m	0,70	EN 14105
Diglyceride content, max.	% m/m	0,20	EN 14105
Triglyceride content, max.	% m/m	0,20	EN 14105
Free glycerol, max.	% m/m	0,02	EN 14105 / 14106
Total glycerol, max.	% m/m	0,25	EN 14105
Lower Heating Value (LHV)	MJ/kg	Report	ASTM D240

1. Min. viscosity limit at engine inlet in running conditions; W20: 1,8 cSt, W25, W26, W31, Vasa 32, W32, W32M, W38, W46 with CR, W46F, W50, W20DF, W25DF, W31DF, W34DF, W46DF, W46TSDF and W50DF: 2,0 cSt, W46 with jerk pump and W64: 2,8 cSt ($\text{mm}^2/\text{s} = \text{cSt}$). If a liquid biofuel with lower injection viscosity than 2,8 mm^2/s is desired to be used in the W46 engines equipped with jerk pumps, Wärtsilä Technical Services has to be contacted for further evaluation.
2. Cold flow properties of renewable biodiesel can vary based on the geographical location and also based on the feedstock properties, which issues must be taken into account when designing the fuel system. For arctic climates even lower CFPP values down to -44 °C are specified.

Remark 1: When analysing the energy content (Higher and Lower Heating Value) of Biodiesel the calculation method included in the ISO 8217 standard can't be used, but the analysis has to be made by following the ASTM D240 standard.

Table 1.2.2. Automotive B10 diesel fuel – Requirements and test methods based on the EN 16734:2016 standard

Property	Unit	Limit	Test method reference
Viscosity, min. - max. Injection viscosity, min.	mm^2/s @ 40°C mm^2/s	2,000 – 4,500 1,8 – 2,0 ¹⁾	EN ISO 3104
Density, min. - max.	kg/m^3 @ 15 °C	820 – 845	EN ISO 3675
Sulphur content, max.	mg/kg	10,0	EN ISO 20846 / 20884 / 13032
Ash content, max.	% m/m	0,010	ISO 6245
Total contamination, max.	mg/kg	24	EN 12662
Water content, max.	% m/m	0,020	EN ISO 12937
Manganese content, max.	mg/l	2,0	EN 16576
Cold filter plugging point, max. (climate dependent requirement)	°C	-20 -> +5 ²⁾	EN 116 / 16329
Flash point, min.	°C	55 ³⁾	EN ISO 2719
Oxidation stability min.	h	20,0	EN 15751
Oxidation stability max.	g/m^3	25	EN 12205
Polycyclic aromatic hydrocarbons, max.	% m/m	8,0	EN 12916
Carbon residue (on 10% distillation residue), max.	% m/m	0,30	EN ISO 10370
Copper strip corrosion (3 h at 50 °C), max.	Rating	Class 1	EN ISO 2160
Lubricity, wear scar diameter at 60 °C, max.	μm	460	EN ISO 12156-1
Distillation			EN ISO 3405 / 3924
- % v/v recovered at 250 °C, max.	% v/v	< 65	
- % v/v recovered at 350 °C, min	% v/v	85	
- 95% v/v recovered at, max.	°C	360	
FAME content, min.	% v/v	10,0	EN 14078

1. Min. viscosity limit at engine inlet in running conditions; W20: 1,8 cSt, W25, W26, W31, Vasa 32, W32, W32M, W38, W46 with CR, W46F, W50, W20DF, W25DF, W31DF, W34DF, W46DF, W46TSDF and W50DF: 2,0 cSt, W46 with jerk pump and W64: 2,8 cSt ($\text{mm}^2/\text{s} = \text{cSt}$). If a liquid biofuel with lower injection viscosity than 2,8 mm^2/s is desired to be used in the W46 engines equipped with jerk pumps, Wärtsilä Technical Services has to be contacted for further evaluation.

2. Cold flow properties of renewable biodiesel can vary based on the geographical location and also based on the feedstock properties, which issues must be taken into account when designing the fuel system. For arctic climates even lower CFPP values down to -44 °C are specified.
3. The use in marine applications is allowed provided that a fuel supplier can guarantee min. flash point of 60 °C.

Table 1.2.3. High FAME diesel fuel (B20) – Requirements and test methods based on the EN 16709:2015 standard

Property	Unit	Limit	Test method reference
Viscosity, min. - max. Injection viscosity, min.	mm ² /s @ 40°C mm ² /s	2,000 – 4,620 1,8 – 2,0 ¹⁾	EN ISO 3104
Density, min. - max.	kg/m ³ @ 15 °C	820 – 860	EN ISO 3675
Cetane number, min.	-	51,0	EN ISO 5165, EN 15195 / 16144 / 16715 / 16906
Sulphur content, max.	mg/kg	10,0	EN ISO 20846 / 20884 / 13032
Ash content, max.	% m/m	0,010	ISO 6245
Total contamination, max.	mg/kg	24	EN 12662
Water content, max.	% m/m	0,026	EN ISO 12937
Manganese content, max.	mg/l	2,0	EN 16576
Cold filter plugging point, max. (climate dependent requirement)	°C	-20 -> +5 ²⁾	EN 116 / 16329
Flash point, min.	°C	55 ³⁾	EN ISO 2719
Oxidation stability min.	h	20,0	EN 15751
Polycyclic aromatic hydrocarbons, max.	% m/m	8,0	EN 12916
Distillation			EN ISO 3405 / 3924
- % v/v recovered at 250 °C, max.	% v/v	< 65	
- % v/v recovered at 350 °C, min	% v/v	85	
- 95% v/v recovered at, max.	°C	360	
FAME content, min. – max.	% v/v	14,0 – 20,0	EN 14078

1. Min. viscosity limit at engine inlet in running conditions; W20: 1,8 cSt, W25, W26, W31, Vasa 32, W32, W32M, W38, W46 with CR, W46F, W50, W20DF, W25DF, W31DF, W34DF, W46DF, W46TSDF and W50DF: 2,0 cSt, W46 with jerk pump and W64: 2,8 cSt (mm²/s = cSt). If a liquid biofuel with lower injection viscosity than 2,8 mm²/s is desired to be used in the W46 engines equipped with jerk pumps, Wärtsilä Technical Services has to be contacted for further evaluation.
2. Cold flow properties of renewable biodiesel can vary based on the geographical location and also based on the feedstock properties, which issues must be taken into account when designing the fuel system. For arctic climates even lower CFPP values down to -44 °C are specified.
3. The use in marine applications is allowed provided that a fuel supplier can guarantee min. flash point of 60 °C.

Table 1.2.4. High FAME diesel fuel (B30) – Requirements and test methods based on the EN 16709:2015 standard

Property	Unit	Limit	Test method reference
Viscosity, min. - max. Injection viscosity, min.	mm ² /s @ 40°C mm ² /s	2,000 – 4,620 1,8 – 2,0 ¹⁾	EN ISO 3104
Density, min. - max.	kg/m ³ @ 15 °C	825 – 865	EN ISO 3675
Cetane number, min.	-	51,0	EN ISO 5165, EN 15195 / 16144 / 16715 / 16906
Sulphur content, max.	mg/kg	10,0	EN ISO 20846 / 20884 / 13032
Ash content, max.	% m/m	0,010	ISO 6245
Total contamination, max.	mg/kg	24	EN 12662
Water content, max.	% m/m	0,029	EN ISO 12937
Manganese content, max.	mg/l	2,0	EN 16576
Cold filter plugging point, max. (climate dependent requirement)	°C	-20 -> +5 ²⁾	EN 116 / 16329
Flash point, min.	°C	55 ³⁾	EN ISO 2719
Oxidation stability min.	h	20,0	EN 15751
Polycyclic aromatic hydrocarbons, max.	% m/m	8,0	EN 12916
Distillation			EN ISO 3405 / 3924
- % v/v recovered at 250 °C, max.	% v/v	< 65	
- % v/v recovered at 350 °C, min	% v/v	85	
- 95% v/v recovered at, max.	°C	360	
FAME content, min. – max.	% v/v	24,0 – 30,0	EN 14078

1. Min. viscosity limit at engine inlet in running conditions; W20: 1,8 cSt, W25, W26, W31, Vasa 32, W32, W32M, W38, W46 with CR, W46F, W50, W20DF, W25DF, W31DF, W34DF, W46DF, W46TSDF and W50DF: 2,0 cSt, W46 with jerk pump and W64: 2,8 cSt (mm²/s = cSt). If a liquid biofuel with lower injection viscosity than 2,8 mm²/s is desired to be used in the W46 engines equipped with jerk pumps, Wärtsilä Technical Services has to be contacted for further evaluation.
2. Cold flow properties of renewable biodiesel can vary based on the geographical location and also based on the feedstock properties, which issues must be taken into account when designing the fuel system. For arctic climates even lower CFPP values down to -44 °C are specified.
3. The use in marine applications is allowed provided that a fuel supplier can guarantee min. flash point of 60 °C.

1.3 Paraffinic diesel fuels from synthesis and hydrotreatment

Paraffinic renewable distillate fuels originating from synthesis or hydrotreatment are high quality distillate fuels and their composition and physical & chemical properties do differ from transesterified biodiesel. The quality of paraffinic diesel shall meet the EN 15940:2016 Class A requirements included in the Table 1.3. For arctic or severe winter climates additional or more stringent requirements are set concerning cold filter plugging point, cloud point, viscosity and distillation properties.

Table 1.3. Requirements for paraffinic diesel from synthesis or hydrotreatment based on the EN15940:2016 standard

Property	Unit	Limit	Test method reference
Viscosity, min. - max. Injection viscosity, min.	mm ² /s @ 40°C mm ² /s	2,000 – 4,500 1,8 – 2,0 ¹⁾	EN ISO 3104
Density, min. - max.	kg/m ³ @ 15 °C	765,0 – 800,0 ²⁾	EN ISO 3675 / 12185
Cetane number, min.	-	70,0	EN 15195 / EN ISO 5165
Sulphur content, max.	mg/kg	5,0	ISO 20846 / 20884
Ash content, max.	% m/m	0,010	EN ISO 6245
Total contamination, max.	mg/kg	24	EN 12662
Water content, max.	mg/kg	200	EN ISO 12937
Total aromatics, max.	% m/m	1,1	EN 12916
Carbon residue on 10% distillation residue, max.	% m/m	0,30	EN ISO 10370
Lubricity, max.	µm	460	EN ISO 12156-1
Flash point, min.	°C	55 ³⁾	EN ISO 2719
Cold filter plugging point, max. (climate dependent requirement)	°C	-20 -> +5 ⁴⁾	EN 116 / 16329
Oxidation stability, max.	g/m ³	25	EN ISO 12205
Oxidation stability, min.	h	20 ⁵⁾	EN 15751
Copper strip corrosion (3 hrs @ 50 °C), max.	Rating	Class 1	EN ISO 2160
Distillation			EN ISO 3405 / 3924
- % v/v recovered @ 250 °C, max.	% v/v	< 65	
- % v/v recovered @ 350 °C, min.	% v/v	85	
- 95 % v/v recovered at, max.	°C	360	
FAME content, max.	% v/v	7,0	EN 14078

1. Min. viscosity limit at engine inlet in running conditions; W20: 1,8 cSt, W25, W26, W31, Vasa 32, W32, W32M, W38, W46 with CR, W46F, W50, W20DF, W25DF, W31DF, W34DF, W46DF, W46TSDF and W50DF: 2,0 cSt, W46 with jerk pump and W64: 2,8 cSt (mm²/s = cSt). If a liquid biofuel with lower injection viscosity than 2,8 mm²/s is desired to be used in the W46 engines equipped with jerk pumps, Wärtsilä Technical Services has to be contacted for further evaluation.
2. Due to low density the guaranteed engine output of pure hydrotreated fuel / GTL has to be confirmed case by case.
3. The use in marine applications is allowed provided that a fuel supplier can guarantee min. flash point of 60 °C.
4. Cold flow properties of renewable biodiesel can vary based on the geographical location and also based on the feedstock properties, which issues must be taken into account when designing the fuel system. For arctic or severe winter climates even lower CFPP values down to -44 °C are specified.
5. Additional requirement if the fuel contains > 2,0 % v/v of FAME.

Remark 1: When analysing the energy content (Higher and Lower Heating Value) of paraffinic diesel the calculation method included in the ISO 8217 standard can't be used, but the analysis has to be made by following the ASTM D240 standard.

Contact

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