Towards sustainable shipping: Development in CII performance of a Bulk Carrier

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Sjöfartsindustrin står för tillfället för en bemärkande del av växthusgasutsläpp, vilket innebär utmaningar då internationella sjöfartsorganisationen, IMO:s mål är en koldioxidneutral sjöfart år 2050. För att uppnå dessa mål är fartygs energieffektivitet samt miljövänlighet i allt större fokus. Syftet med detta slutarbete är att presentera möjligheterna till förbättring av energieffektiviteten och miljöprestandan för ett bulkfartyg inom ramen för det EU-finansierade projektet ”CHEK”. Fokus ligger på att presentera hur designen av fartyget samt olika energibesparande teknologier medverkar i interaktion med varandra och påverkar fartygets koldioxidintensitet, CII. CII är ett mått utvecklat av IMO, för att beskriva fartygs energieffektivitet och koldioxidintensitet. Teoridelen i detta slutarbete ger en överblick över CII, dess beräkningsmetod samt möjliga framtida formeljusteringar. I själva studien studeras flera moderna energibesparande teknologier samt deras påverkan på fartygets miljöprestanda och CII-värde. Teknologier som studerats är till exempel segel, luftsmörjning av skrovet samt återvinning av spillvärme. Resultaten visar flera sammankopplingar mellan olika komponenter i fartygets energisystem och ger därmed värdefulla insikter gällande fartygets miljöprestanda samt dess förbättringspotential. Fartygs energieffektivitet och miljöprestanda spelar en avgörande roll då industrin utvecklas mot ett koldioxidneutralt håll. Resultaten från denna studie ger en inblick i varför det är nödvändigt att undersöka de energibesparande enheterna och därmed förbättra fartygs energieffektivitet, det vill säga, en av nycklarna till en koldioxidneutral sjöfart.

Nyckelord: Energieffektivitet, Sjöfart, CII, Dekarbonisering, Deltamarin

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Abstract:

The maritime industry, a significant greenhouse gas emitter, faces pressure as it must shift towards net-zero emissions. This is leading to a growing importance of energy efficiency and sustainable practices. This thesis presents the improvement in the environmental performance of a kamsarmax size bulk carrier within the context of an EU funded project CHEK. The study focuses especially on presenting how the ship design and various energy-saving technologies work in synergy and affect the rating of the carbon intensity index, developed by the international maritime organization. The theory section of the thesis discusses the development of the carbon intensity index, the calculation method, and potential future adjustments to it. The study considers varied modern technologies such as sails to capture wind energy, hull air lubrication and waste heat recovery systems, that are integrated in the ship design and their effect on the ship's energy efficiency. The results show several interconnections between the different energy system components, giving valuable insight into the environmental performance of the ship as well as its improvement potential. The energy efficiency and environmental performance of ships play a crucial role in advancing towards a zero-emission industry. These results provide a small outlook into the importance of assessing energy-saving devices from an energy system perspective to achieve that.

Keywords: Energy efficiency, Shipping industry, CII, Decarbonization, Deltamarin

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List of abbreviations

List of abbreviations	Meaning
AE	Auxiliary Engine
AER	Annual Efficiency Ratio
ALS	Air Lubrication System
CHEK	deCarbonising sHipping by Enabling Key technology symbiosis on real vessel concept designs
CII	Carbon Intensity Indicator
CPP	Controllable Pitch Propeller
DWT	Deadweight Tonnage
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency eXisting ship Index
ELA	Electric Load Analysis
FPV	Future Proof Vessel
GHG	Green House Gas
GT	Gross Tonnage
HFO	Heavy Fuel Oil
HT	High Temperature
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
kW	kiloWatt
LCA	Life Cycle Assesment
LFO	Light Fuel Oil
LNG	Liquified Natural Gas
LPG	Liquified Propane Gas
MDO	Marine Diesel Oil
ME	Main Engine
MEPC	Marine Environment Protection Committee
nm	nautical mile
OFB	Oil Fired Boiler
ORC	Organic Rankine Cycle
RPM	Revolutions per minute
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
TtW	Tank-to-Wake
WtT	Well-to-Tank
WtW	Well-to-Wake

1 Introduction

At present, decarbonization is one of the key priorities in the shipping industry. The carbon footprint and more broadly, the ship emission footprint is caused by a combination of the ship design, technologies integrated, ship operation, and the types of fuels utilized. Since all these factors are interrelated, the ship design and analysis methods should consider the relevant aspects both at the start of a new ship design process, and when planning a conversion to an existing ship.

This thesis presents a case example of reducing ship environmental impact in the framework of an EU-funded project CHEK. Different energy-saving technologies are simulated in a so-called energy model in MATLAB and Simulink environments, to get a holistic view of the ship's energy system, and the technologies effect on it. With the results from the simulations the technologies impact on the ship's carbon intensity are then analyzed.

1.1 Problem definition

The shipping industry has always been a fundamental part of the global economy and transportation. In our globalized world, we rely on shipping as we import and export more than ever. The shipping industry has been supplying goods during the COVID-19 pandemic as well as during the geopolitical and energy crisis far better than any other transportation method. However, for a long period the energy systems in the maritime industry have been petroleum based, thus having a negative impact on the environment. In 2022 emissions from the maritime sector contribute to about 2% of global energy related Green House Gases (GHG) (International Energy Agency, N.d.).

Since global warming and climate change are one of the biggest challenges that our world is facing, there is a lot of pressure on the shipping industry to decarbonize and reduce its environmental footprint. For example, EU as well as IMO are transitioning to zero-emission technologies with aim to decarbonize shipping completely.

1.2 Aim with thesis

IMO has a strategy for decarbonizing shipping by the year 2050 and the carbon intensity indicator (CII) falls under the scope of IMO's measures for energy efficiency. This thesis focuses on the CII, presenting how the ship design and technologies work in synergy impacting the ship's energy efficiency and CII rating. A more detailed approach of the CII is provided, e.g. the calculation process, what parameters affect it and what the future development of it might look like.

1.3 Delimitation

The focus is on one bulk carrier under an EU funded project called CHEK. Other energy efficiency measures by IMO are not studied, nor the CII of other ship types. The presented formulas and rules for the calculation of CII are based on IMO's Marine Environment Protection Committee and the resolutions from their 78^{th} meeting in 2022 (MEPC.355(78)).

1.4 Commissioner

The commissioner for this thesis was Deltamarin Ltd. Deltamarin is a company in the marine and offshore industry providing ship design, offshore engineering, and construction support services. They manage all design disciplines and stages in newbuilding and offshore projects and have around 400 experts in Finland, Poland, China, and Croatia. The clientele comprises of for example ship owners and operators, shipyards, and offshore constructors. Deltamarin's experts have designed thousands of ship concepts, with hundreds currently sailing across the world's oceans.

1.5 Project CHEK

Project CHEK is a three-year project, with the aim to develop solutions for decarbonizing long-distance shipping and to transform the way ships are both designed and operated. The goal of CHEK is to reduce greenhouse gas emissions by 99%, achieve 40-50% energy savings and reduce black carbon emissions by over 95% compared to a typical reference vessel.

The focus of the development work is in two case vessels – a wind energy optimized bulk carrier and a hydrogen powered cruise ship. Both case vessels will be equipped with a combination of innovative technologies, working in symbiosis to achieve the ambitious targets of the project. The leading principle in CHEK is that technologies are not only stacked on existing ship design, but a unique “Future-proof vessel (FPV) design platform” is developed with goal to maximize the symbiosis between the technologies. The FPV platform will also be used to expand the learnings from the two case vessels to the lobal fleet.

2 Theory

This chapter provides information on the fuel consumption of a ship and an overview of the Carbon Intensity Indicator (CII), including background, explanation of the mathematical formula and how it is implemented in the legislation. The International Maritime Organization is the leading authority for the shipping industry and since the CII is established by them, they serve as primary source for the theory in this thesis.

2.1 Previous research

Emission reduction and energy efficiency are both of high importance in the maritime industry and its development towards decarbonization. Various energy-saving strategies and related technologies as well as ships fuel systems need rapid development in order to reach net-zero emissions, creating a need for research in this domain. CII is one of the latest mandatory measures with accordingly limited research done. However, it is an important part in IMO's vision for decarbonizing the shipping industry and therefore is of interest for several players within the field.

The MCN (Maritime Cluster Northern Germany) Expert Group has developed a guideline in order to assist different stakeholders in the process of improving the efficiency of ships in the light of the new emission related rules, with CII being one of the rules. The first version of the guideline was published in September 2022 with intention to be updated at certain intervals, depending on the development of rules. (Marioth et al., 2023)

Altenbach wrote a research article regarding optimizing CII for ships with refrigerated cargo. The paper discusses the challenges in transport of refrigerated cargo and how to monitor the fuel consumed for the cargo-related electrical consumers in the best way. A sustainable and cost-efficient operation of vessels can be achieved with the Performance Monitoring Systems that the paper presents. (Altenbach, 2023)

Melillo et. al have studied, within the framework of the EU-funded project CHEK, the potential of energy-saving technologies in order to minimize GHG emissions and maximize the energy efficiency of a cruise vessel. Technologies studied are a hydrogen engine, waste heat recovery system, ultrasound antifouling, hull air lubrication and an optimization tool. It can be obtained from the results that considerable improvements in energy savings can be achieved with the studied technologies. (Melillo et. al., 2023)

Ships' energy systems and emission reduction are complex themes. The marine sector is developing fast and is in the need of further research in many fields, to be able to meet the global goals of sustainability.

2.2 A ship's fuel consumption

Ships consume a lot of fuel and ship fuel efficiency is currently a hot topic since the type of fuel used, directly influences the environmental performance of the ship. Currently, the most common fuel types are heavy fuel oil, marine gas oil and natural gas. However, in order for the shipping industry to achieve the goal of decarbonization, it needs to switch from conventional fuels to zero GHG fuels. Luckily carbon neutral fuels are also making their way into the market, e.g. ammonia, methanol and hydrogen. The main factors affecting a vessel's fuel consumption are speed, ship type, size, weather, hull and propeller roughness and engine type. Of these, speed is the most important parameter determining the consumption. (Bialystocki & Konovessis, 2016)

A ship's fuel consumption for propulsion is a result of the energy needed to push the ship through the water at a given speed. The relationship between a vessel's speed and fuel consumption is not linear but exponential. This means that the engine power follows the cube of the speed ($P=S^3$). The fuel consumption is a function of power demand by propulsion, hotel, and the engine efficiency at that specific load. A speed reduction of 10% reduces the fuel consumption by approximately 27%. To assess the fuel savings on a voyage basis the added time it takes to sail the given distance needs to be taken into consideration. As in IMO website, this can result in fuel saving of approximately 19%, however, the sailing duration to cover the same distance has now increased. (IMO, N.d.-a)

2.3 Emissions from ships

For calculating the ship's emissions, the annual fuel consumption is multiplied with a conversion factor between fuel and CO_2 emissions to get the CO_2 emissions emitted. Every fuel type has its own conversion factor, that is dependent on the carbon content. The conversion factor is based on the carbon content of different fuels that gives the CO_2 emissions in grams. Table 2.3-1 below presents the lower calorific values, carbon content and conversion factor for each fuel.

Ships emissions can be calculated based on different perspectives, depending on which part of the lifecycle is considered. IMO divides the Life Cycle Assessment into three categories: Well-to-Tank (WtT), Tank-to-Wake (TtW) and Well-to-Wake (WtW) perspective. Emissions from the Well-to-Wake phase represent GHG emissions from producing and transporting the fuel up to the point of use. Tank-to-Wake accounts the emissions that result from burning or using the fuel once it is already onboard the ship. Well-to-Wake emissions are the sum of the

WtT and TtW emissions and includes emissions from the fuels production until it is burned on a vessel. Figure 2.3-1 presents the Well-to-Wake supply chain that can be found in IMO resolution MEPC.376(80).

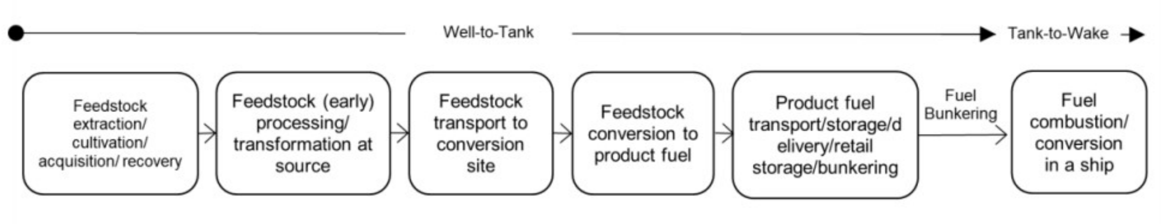


Figure 2.3-1. Well-to-Wake supply chain

Table 2.3-1 Fuel properties (MEPC.308(73))

Type of fuel	**Lower calorific value (kJ/kg)**	**Carbon content**	**Cf (t-CO2/t-fuel)**
MDO	42 700	0.8744	3.206
LFO	41 200	0.8954	3.151
HFO	40 200	0.8493	3.114
LNG	48 000	0.7500	2.750
Methanol	19 900	0.3750	1.375
Ethanol	26 800	0.5217	1.913
LPG (Propane)	46 300	0.8182	3.000
LPG (Butane)	45 700	0.8264	3.030

From the Figure 2.3-1 below, published by IMO in their 4th GHG study in year 2020, the fuel consumption per ship type for each year between 2012-2018 is presented. Containers, bulk carriers, and oil tankers are the dominant vessels for emitting GHG emissions. (IMO, 2020 a) Accordingly, in order to achieve the needed emission reduction these are the most critical vessels to improve the efficiency of.

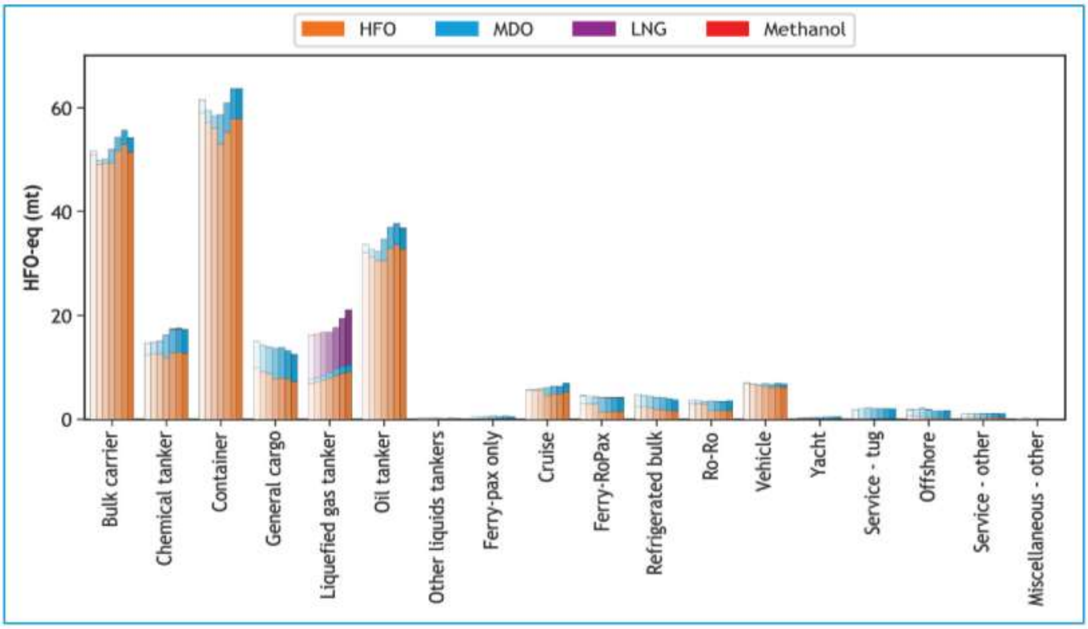


Figure 2.3-1 Fuel consumption per ship type (IMO, 2020)

2.4 Regulatory structure of IMO

The international Maritime Organization, created in 1948, is a standard setting authority for safety, security, and environmental performance of international shipping under the United Nations. One of their main roles is to establish a fair and effective regulatory framework for the global maritime industry. (IMO, N.d.-b) The organization consists of an Assembly, a Council, five main committees and several sub-committees who support the work of the main committees. The structure of IMO is presented in Figure 2.4-1. The Marine Environment Protection Committee (MEPC) regulates affairs concerning the marine environment and GHG emissions.

The International Convention for the Prevention of Pollution from Ships, often referred to as MARPOL is the convention covering the prevention of pollution caused by the marine industry. MARPOL consists of six annexes all aimed at minimizing pollution from ships. The structure of the MARPOL convention is presented in Figure 2.4-2. The MARPOL Annex VI addresses the prevention of air pollution from ships, including GHG emissions. Thus, the MARPOL Annex VI is connected to CII and its regulations. (Andersson, 2022, Chapter 1)

The MARPOL Annex VI consists of the mandatory energy efficiency measures, both operational and technical. The most important energy efficiency measures currently, are the following:

- **Energy Efficiency Design Index (EEDI):** EEDI is a technical measure for all new vessels with main function to promote the usage of energy-saving equipment and machinery. The measure is being gradually adjusted every five years in order to stimulate continuous technical development.
- **Energy Efficiency Operational Index (EEOI):** A technical measure to measure the fuel efficiency of a ship in service.
- **Ship Energy Efficiency Management Plan (SEEMP):** SEEMP provides an approach for shipping companies to manage the energy efficiency performance of ships over time.
- **Energy Efficiency Existing Ship Index (EEXI):** EEXI is similar to EEDI but applicable to all existing vessels regardless of build date.
- **Carbon Intensity Indicator (CII):** The CII measures the energy efficiency of a ship and determines the annual reduction factor needed to ensure continuous improvement of a ship's operational carbon intensity (IMO, N.d.-e).

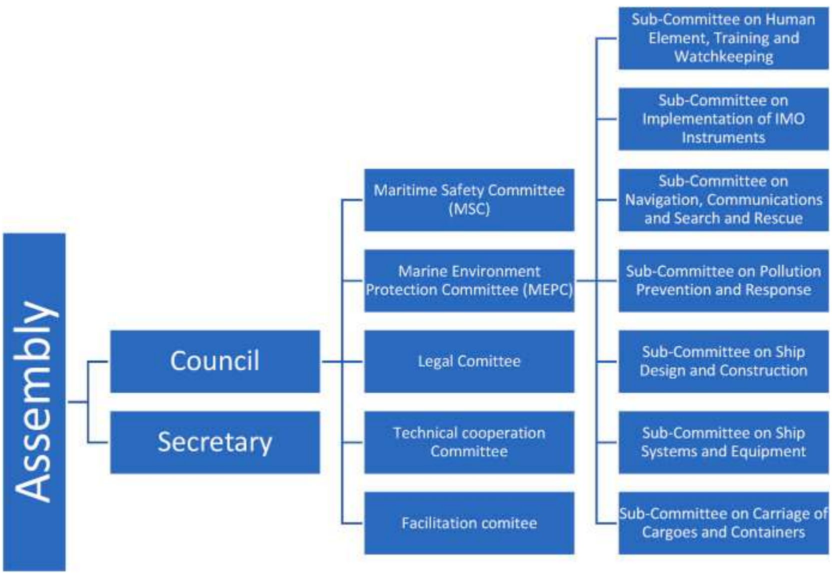


Figure 2.4-1 Structure of IMO (Barreiro, et al., 2022)

Figure 2.4-2 Structure of the MARPOL convention (Barreiro, et al., 2022)

2.5 Introduction to CII

Carbon Intensity Indicator (CII) is a measure for the energy efficiency of ships and applies to all ships over 5000 Gross Tonnage (GT). The CII must be calculated annually, and ships will receive a CII rating, depending on the result. The rating is given in grams of CO_2 emitted divided by the capacity of the ship and nautical miles travelled. The attained CII result must be documented and authenticated against the yearly required CII, set by IMO, to make sure that vessels comply with the regulations. (IMO, 2022-a)

Based on a ship's carbon intensity it will be rated A,B,C,D or E, where A is the best and E as the worst. The goal is for a ship to achieve rating C or better. If a ship is rated D for three ensuing years, or E for one year, it must submit a corrective action plan (SEEMP) to show how rating C or better will be attained. (IMO, 2022-a)

CII regulations in 2023 focus on CO_2 emissions only and the ship's performance from a Tank-to-Wake perspective. This calculation, however, mispresents the total climate impact of the fuel since it does not consider how the fuel is produced and transported to the vessel nor the other greenhouse gases except CO_2. (Comer et al., 2023)

2.5.1 History of CII

The growth in CO_2 emissions and global trade does not go well together with IMO's decarbonization plan and some kind of action was needed to reach a reduction in carbon intensity. Below is an illustrative figure published by IMO regarding the need for the carbon intensity index.

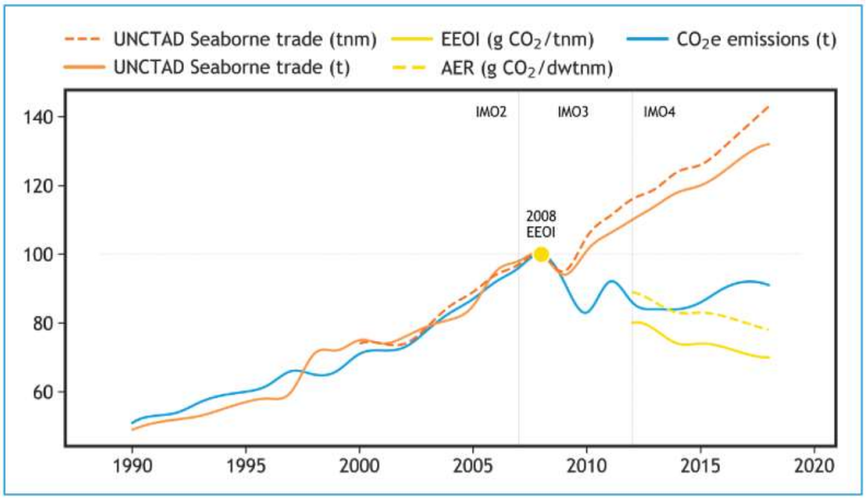


*Figure 2.5-1 Trends in seaborne trade, CII and emissions (*IMO, 2020*)*

As can be seen in the figure the emission growth between years 1990 and 2008 is strongly connected to the growth in seaborne trade. Between years 2008 and 2014 emissions are reducing despite growth in demand, this indicates a rapid reduction in carbon intensity. Between years 2014 and 2018 there is a moderate improvement in carbon intensity. However, a trend in emission growth can be seen, even when accounting for the growth in seaborne trade. (IMO, 2020-a)

The Carbon Intensity index (CII) is a fairly new index with a history going back to 2021. IMO has been committed to reduce GHG emissions and phasing them out from international shipping with total decarbonization as a goal. Their initial GHG strategy in 2018 established GHG reduction targets, in other words targets to reduce ships carbon intensity. The targets then were to reduce the carbon intensity by at least 40% by 2030 and 70% by 2050, compared to 2008 levels. After these targets had been made IMO started developing an index for carbon intensity more ambitiously.

In year 2020 IMO released their fourth greenhouse gas study. The study estimates carbon intensity for the first time and on different levels. Several candidate metrics for the calculation of CII were proposed in this study. They all followed the same concept that is CO_2/transport work. CO_2 has been taken as the numerator in all cases, thus differences lie in the denominator. Potential metrics considered then was energy efficiency operating index (EEOI) (gCO_2/t/nm), annual efficiency ratio (AER) (gCO_2/dwt/nm), DIST (kg CO_2/nm) and TIME (t CO_2/hr). Dwt stands for the ship's deadweight tonnage, NM for the annual distance and "t" the annual hours at sea. (IMO, 2020-b, p.195)

The Marine Environment Protection Committee (MEPC) assembled in June 2021 for their 76th session, discussing the MARPOL Annex VI and adopting amendments on how to reduce GHG emissions in shipping. It was during this session that the formula and guidelines of CII was first introduced. (IMO, 2021)

MEPC had their 78th session in June 2022 where they discussed further the initial GHG strategy and decisions made during session 76. During the session in June 2022 MEPC adopted new guidelines to support measures of reducing ships' carbon intensity. During this session the CII formula introduced in 2021 was corrected. These amendments came into force on 1 November 2022. (IMO,2022-b) And the 1 of January 2023, it became mandatory for ships to report their annual CII.

Table 2.5-1. Timeline for CII (MEPC.377(80))

Date	**Milestone**
MEPC 67 (October 2014)	Approved the Third IMO GHG study 2014, estimated that emissions from shipping in 2012 accounted for about 2% of anthropogenic CO2 emissions.
MEPC 72 (April 2018)	Adopted the Initial IMO GHG strategy, setting out a vision which confirmed IMO's commitment to reduce GHG emissions.
MEPC 76 (June 2021)	IMO introduced the Carbon Intensity Indicator for the first time.
MEPC 78 (June 2022)	Guidelines adopted to support the implementation of CII. e.g. calculational guidelines introduced and initial CII formula corrected.
MEPC 80 (July 2023)	Life Cycle Assessment guidelines and 2023 IMO GHG strategy adopted.

2.6 Results from the MEPC 80

The MEPC 80 meeting was held from 3rd to 7th July 2023 in London. During this meeting the 2023 IMO GHG strategy was adopted, with its main goal for the shipping industry to reach net-zero emissions around year 2050. This is an ambitious goal compared to the initial goals that IMO set in 2018. Figure 2.6-1 presents the outline of previous and newly defined ambitions, for the purpose to conduct a comparison between them.

Guidelines for calculating emissions from a lifecycle perspective were also adopted (LCA guidelines) as well as a target to achieve an uptake of energy-saving devices and alternative fuels, representing at least 5% of used energy before 2030. (IMO, 2023)

The LCA guidelines set out methods to calculate emissions from a well-to-wake perspective for all fuels, with the objective to reduce GHG emissions within the boundaries of the shipping sector's energy system and preventing a shift of emissions to other sectors. Preliminary emission factors for various fuels and fuel pathways were set but will be further reviewed and developed. (DNV, 2023-a). In order to reach net-zero emissions by 2050 some indicative checkpoints have been made with the goal to reduce GHG emissions by 20%, striving for 30% by year 2030 and 70%, striving for 80% in year 2040. (IMO, 2023)

There were no immediate changes to the CII framework itself during the MPEC 80 and no further updates will be made until the end of 2025 when the review of the regulation will be completed. However, several challenges with the calculation of CII have been identified and proposals submitted, e.g. regarding implementing new correction factors and developing an alternative CII metric for cruise passenger ships.

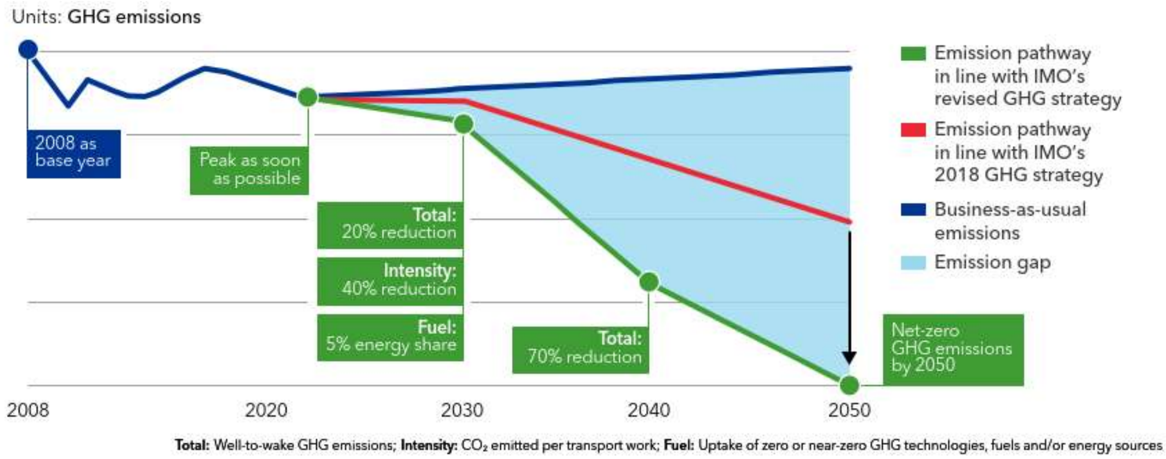


Figure 2.6-1 Emission Projections (DNV, 2023-b)

This new 2023 GHG strategy is a significant strengthening in comparison to the initial strategy, however, it should be noted that despite the ambitious goals the new strategy is not aligned with the IPCC's guidance on what is needed to meet the Paris Agreement that limits the global warming to 1.5 degrees or below. Thus, further work on GHG reduction will be required when the new 2023 strategy will be revised in year 2028. (Smith & Shaw, 2023)

2.7 CII potential impact in the future

Taking into consideration the new goal of reaching net zero GHG emissions by 2050, the CII regulations must be strengthened in order to achieve that. The effectiveness of the CII will be reviewed by 1 January 2026. The review should encompass a comprehensive evaluation of the current regulations, as well as an assessment of how to continue moving towards the net-zero emissions target. This section assesses potential changes that could be expected in the future when calculating CII.

To ensure that the shipping sector reaches these ambitions a “basket of measures”, as IMO calls it, will be implemented. The basket of measures consists of two parts; one technical element which will regulate the reduction of fuel GHG intensity and a second economic element which is a pricing mechanism in some form of GHG emissions. The development of the measures is on-going and will according to the current timeline be adopted in 2025 and enter into force in around 2027. (DNV, 2023-b)

Currently the CII is more of a guideline than a rule since there is no financial penalty for ship owners who do not comply with the rules. Due to the economic element in the “basket of measures” a penalty for not complying with the rules could be stated in the future.
The reduction factor for when calculating CII is yet undetermined by IMO for the years beyond 2026. However, the goal established in 2023 for year 2030 is a 40% reduction in CO_2 emissions. A mathematical prediction of the reduction factor for years 2027-2030 is presented in section 2.9.2.

If the guidelines on LCA will be included into the calculation of CII, it will most likely result in major changes as for example defining new baselines and introducing new fuel/emission factors. Several challenges regarding the current calculation of CII have also been identified, e.g. long port stays and waiting periods. Meaning that depending on the meeting outcomes in 2026 and beyond the calculational formula for CII itself could undergo major changes.

Table 2.7-1 Timeline for development of CII (MEPC.377(80))

Date	**Milestone**
MEPC 81 (Spring 2024)	Finalization of basket of measures
MEPC 83 (Spring 2025)	Approval of measures
MEPC 83 (Autumn 2025)	Adoption of measures & review CII
2026	Entry into force of measures
MEPC 86 (Summer 2027)	Initiate the review of the 2023 GHG strategy
MEPC 88 (Autumn 2028)	Finalization of the review of the 2023 GHG strategy and a possible adoption of the 2028 GHG strategy

2.8 CII for bulk carriers

Bulk carriers are one of the most efficient means of transportation even among ships, as they utilize almost all volume and space available for cargo transport and move at rather slow speeds, using efficient 2-stroke engines. Thus, it may be more difficult than for other type of ships to achieve continuous emission reduction unless they operate on alternative fuels.

When CII is calculated for years 2023 and 2024, between 40-60% of the worldwide bulk carriers will have ratings D or E, meaning improvements must be done to achieve rating C or better. In addition, it is estimated that more than 60% of global bulk carriers will require improvements in energy efficiency in order to remain CII compliant and competitive through to year 2030. The amount can even be higher, depending on IMO's decisions regarding the CII requirements. (Wingrove, 2023)

For bulkers to comply with CII also in the future, improvements and development in energy efficiency needs to be done. Fuel type is the most dominant factor, and for a significant proportion of the existing fleet, switching to low-carbon fuels will be the only solution in the long term to stay compliant with the rules. Of course, this prediction is dependent on several factors, as for example the fuel availability, price as well as future technology and regulations.

Ship owners need to consider reducing fuel consumption and energy use through different methods. For example, changes in logistics, weather routing, speed optimization and energy efficiency devices, to name a few. The CII rating has a significant effect on the vessel's attractiveness. A poor CII rating can result for example in higher port fees, worse financing options, no preferred slot in port and increased insurance premiums.

2.9 Formula for CII

According to latest regulations the CII for weight critical vessels is calculated as the annual efficiency ratio (AER). Equation 1 presents the CII formula in its most simple form and Equation 2 presents the CII formula as it is in IMO guidelines, with correction factors and voyage adjustments applied. All parameters in Table 2.9-1 as well as formulas are based on resolution MEPC.355(78). The equations deviate from the international way to write mathematical equations but are kept in this thesis as they are in IMO resolutions to avoid confusion.

$$CII = AER = \frac{CO_2 \ emissions \ [g]}{DWT \ x \ Annual \ Distance \ travelled \ [nm]} \tag{1}$$

$$\frac{\sum_j C_{Fj} \cdot \left\{FC_j - \left(FC_{voyage,j} + TF_j + (0.75 - 0.03y_i) \cdot \left(FC_{electrical,j} + FC_{boiler,j} + FC_{others,j}\right)\right)\right\}}{f_i \cdot f_m \cdot f_c \cdot f_{iVSE} \cdot Capacity \cdot (D_t - D_x)} \tag{2}$$

Table 2.9-1 Variables in CII formula (MEPC.355(78))

Parameter	Explanation
j	Fuel type
C_{Fj}	Conversion factor, shows how much CO_2 is produced per unit of fuel type
FC_j	Mass of fuel consumed in one year
$FC_{voyage,j}$	Grams of fuel used during the year that can be deducted for voyage periods
TF_j	Fuel removed for STS or shuttle tanker operation
Y_i	A numbering system starting att $y_{2023}= 0$, $y_{2024} = 1$...
$FC_{electrical}$	Fuel used for producing electrical power, which can be deducted
FC_{boiler}	Fuel consumed by the boiler, which may be deducted, used for cargo heating or steam driven cargo pumps
FC_{others}	Fuel consumed by other related devices that may be deducted.
f_i	Capacity correction for ice-classed ships as specified in the EEDI guidelines (MEPC.308(73))
f_m	Factor for ice-classed ships having ice-class IA Super and IA
f_c	Cubic capacity correction factor for chemical tankers
f_{iVSE}	Correction factor for ship-specific voluntary structural enhancement, only applies to self-unloading bulk carriers
Capacity	Given either in deadweight or gross tonnes, as defined for each ship type.
D_t	Total distance travelled in nautical miles
D_x	Distance travelled in nautical miles that can be deducted

2.9.1 Reference line

The reference line coincides with the "world average" calculated performance for each ship type in its weight category. Parameters *a* and *c* are estimated taking the attained CII and capacity of individual ships as sample from IMO's data collecting system based on the year 2019. (MEPC.353(78))

$$CII_{ref} = aCapacity^{-c} \quad (3)$$

2.9.2 Reduction factors

The reduction factor ensures consistent enhancement of a vessel's carbon intensity. The annual achieved CII must be verified against this required CII. To reach IMO's goal of decarbonization the required CII becomes progressively more stringent every year. This section is based on resolution MEPC.338(76).

The required annual operational CII for a ship is calculated as follows:

$$\text{Required annual operational } CII = (1 - Z/100) \times CII_R$$

(4)

Where CII_R is the reference value in year 2019, as explained in the sub-chapter above. Z represents the reduction factors for the required CII between years 2023 and 2030. Factors for the years 2027-2030 are not determined yet and will be further developed and strengthened when the review on CII has been completed. However, according to the new GHG strategy set in 2023 a 40% reduction in carbon intensity needs to be achieved by 2030. IMO has published a formula for calculating the needed improvement by 2030 from the level in 2019, in order to achieve the goal set. The calculation and explanation of parameters is presented below:

$$eR_{shipping,2030} = \frac{40\% - R_{shipping,2019}}{1 - R_{shipping,2019}}$$

(5)

$$\frac{40\% - 23,6\%}{1 - 23,6\%} = 21,5\%$$

(6)

$R_{shipping,2019}$ is the carbon intensity reduction achieved in year 2019 compared to year 2009 and is calculated by IMO to be 23.6%. $R_{shipping,2030}$ is the telling how much improvement is needed by 2030 from the level in 2019, in order to achieve a 40% reduction in CO2 emissions. The calculation gives an $R_{shipping,2030}$ value of 21.5, meaning that at least a 21.5% improvement from 2019 is needed by year 2030.

In order to reach the goal of 21.5% a gap of 10,5% needs to be filled meaning a value of 2.625 % per year for years 2027-2030 to achieve the reduction goal. It should be kept in mind that this is a prediction and the final statement from IMO regarding the reduction factor for those years will be announced in 2026. Table 2.9-2 presents the reduction factor relative to the 2019 reference line.

Table 2.9-2 reduction factor Z (MEPC.338(76))

Year	**Reduction factor (Z) relative to 2019**
2023	5%
2024	7%
2025	9%
2026	11%
2027	2,625%*
2028	2,625%*
2029	2,625%*
2030	2,625%*

*The value is only an estimation and not a final value given by IMO

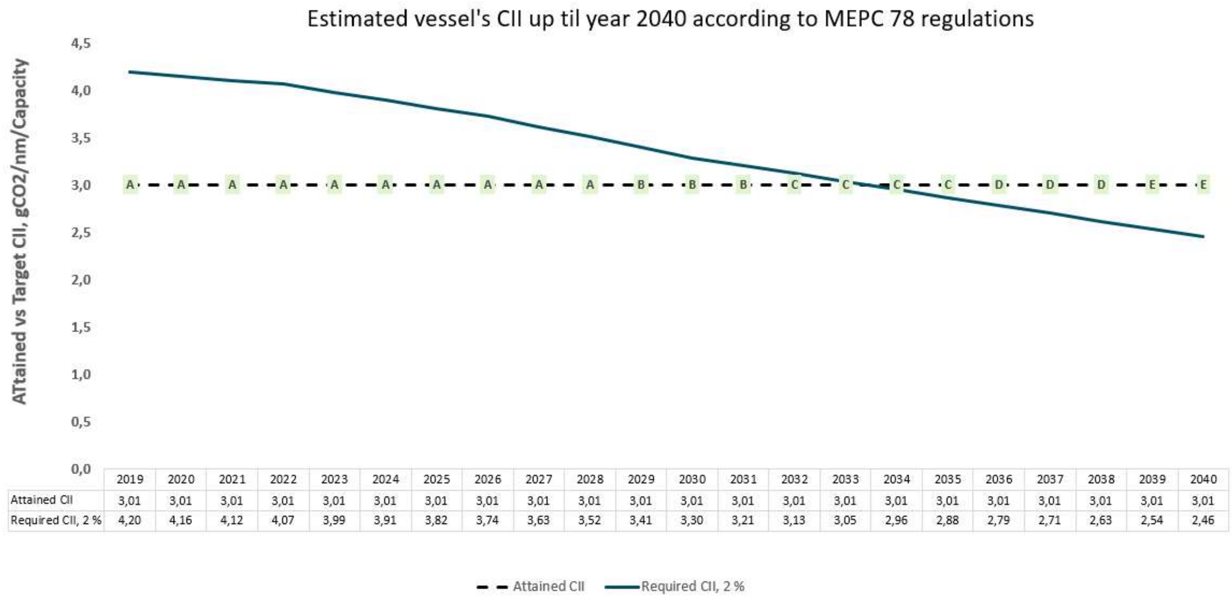


Figure 2.9-1 Example case of required CII vs years

2.9.3 Rating guidelines

Four boundaries are defined for each year from 2023 to 2030, in order to give a ship its CII rating. A rating can be determined by comparing the attained annual CII with the boundary values. This sub-chapter is referring to resolution MEPC.354(78).

The rating boundaries are set expecting that 30 % of all rated ships are assigned value C. The upper 20 % and further upper 15 % are expectedly assigned ratings D and E respectively, and the lower 20 % and further lower 15 % are assigned rating B and A, respectively. The boundaries are presented in Figure 2.9-2. A ship rated E belongs to the inferior boundary, while D rated ships are linked to the upper boundary. B and A rated ships belong to lower and superior boundaries respectively.

The ratings may not always be identical to the expected scenario, for example one year 20% instead of 15% may achieve rating A. The boundaries are defined based on the required CII, along with vectors indicating both the direction and distance of deviation from the required value. This is illustrated in Figure 2.9-3.

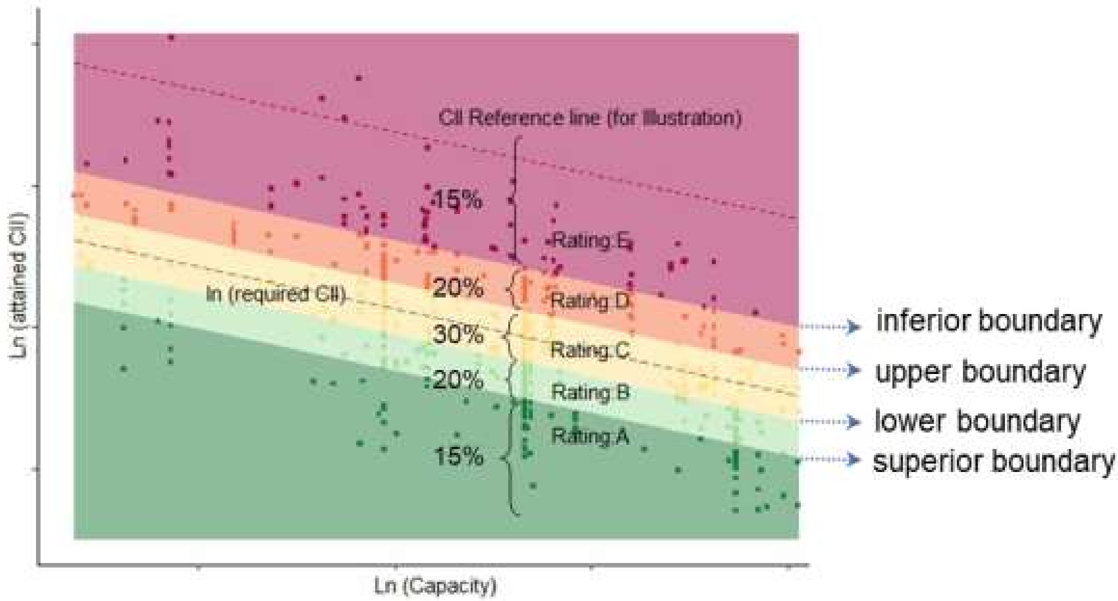


Figure 2.9-2 CII Boundaries (MEPC.354(78))

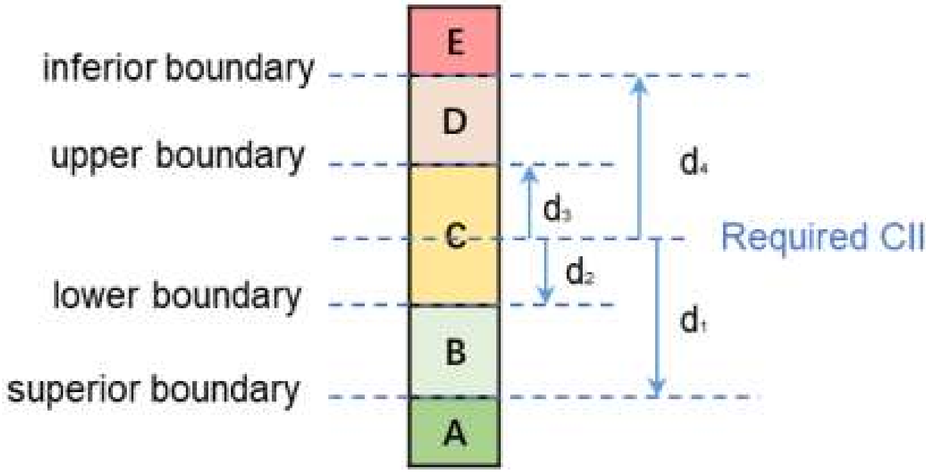


Figure 2.9-3 CII vectors (MEPC.354(78))

3 Methodology

This section covers the methods on how data was gathered as well as analyzed and calculated. The main parts of the simulation model and assumptions of simulated energy-saving devices are explained.

The data in this section is based on a conference paper presented by me at the HIPER Conference 15th symposium in September 2023 in Bernried, Germany. (Sandberg et al., 2023)

3.1 Analysis method

The study presented how different energy-saving technologies affect the CII rating of a kamsarmax sized bulk carrier (bulk carriers which have a maximum length overall of 229 m). The energy model is implemented in MATLAB and Simulink environments. The necessary input for the energy model is the ship's operational profile, the machinery configuration, fuel data and the ship energy consumption. Other equipment such as batteries and other energy-saving devices will also have to be configured if they are included in the modelled system, as they are in this study. Input values such as electrical load analysis, speed-power table and heat balances are calculated by other engineers that are experts in their field and the calculated data is then integrated in the energy model in order to analyze how the different parameters affect the CII and energy efficiency of the studied vessel.

By integrating insights and information from other experts into the energy model a more accurate analysis of the ship's energy efficiency can be achieved. A collaborative approach and the model thus developed contributes to a more holistic understanding of the whole energy system and the different interconnections within it. Incorporating, in some cases complex data, from different engineering domains demands an understanding of each field and communication between engineers, in order to ensure a precise and accurate approach when building the energy model.

The propulsion power can be inserted in the energy model in form of simplified speed-power curves including relevant marginals. The ship's heat balance, electrical load analyses and parameters for the mechanical system are important parameters affecting the energy efficiency and are therefore crucial inputs in the model. SFOC (Specific Fuel Consumption) values, temperature, and mass flow for the exhaust gas, for both main- and auxiliary engines are included in the "machinery data" section, as input to the model. The typical output of the energy model is the energy distribution within the ship and various key performance indicators (KPI). In Figure 3.1-1 the components of the energy model on a large scale are showed. Energy consumers and machinery data represent the inputs and KPI: s represent energy model outputs. Due to confidential reasons more detailed pictures of the model configuration in the Simulink environment are not shown. Figure 3.1-2 shows an example of the energy flow simulation tool. There a more graphical presentation of the parameters is shown. With the energy simulation tool, the best and most profitable technology and energy efficiency solutions for each ship can be discovered as well as the most logical focus point depending on the ship type and project.

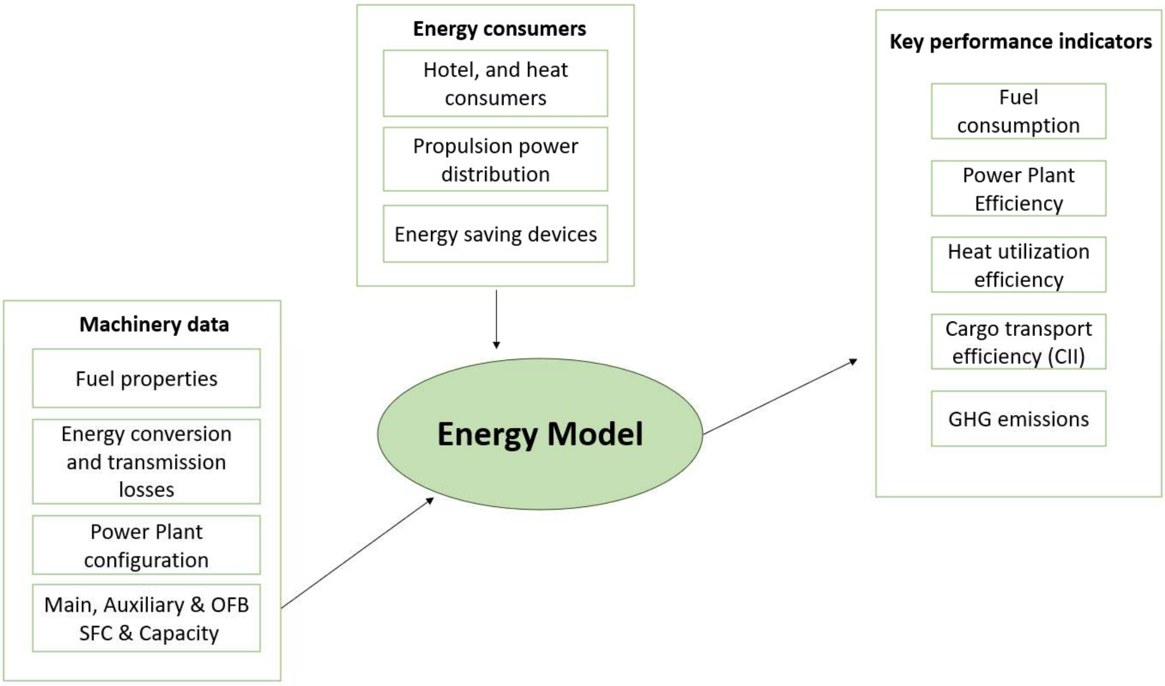


Figure 3.1-1 Main components of energy model

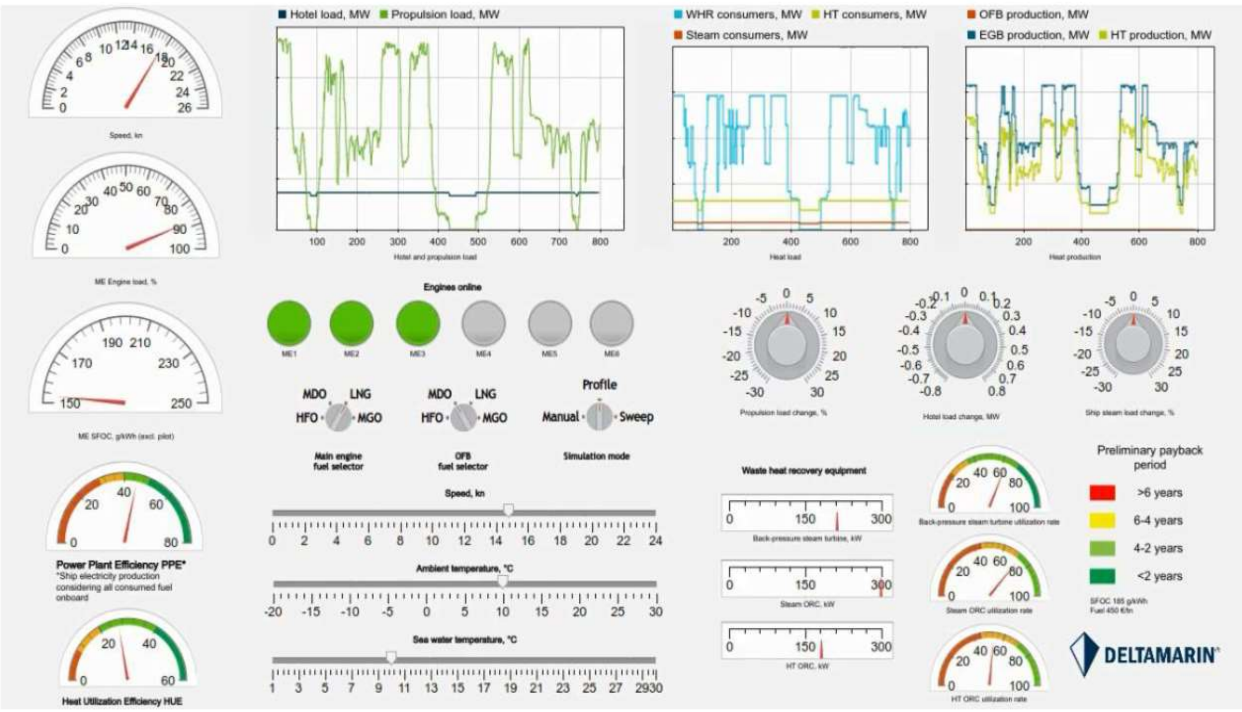


Figure 3.1-2 : Example of Deltamarins energy flow simulation tool (Deltamarin, 2017)

3.2 General design data of ship

A Kamsarmax sized bulk carrier was used as a reference hull and the ship design for this particular vessel has been developed by Deltamarin Ltd.

Table 3.2-1 Basic particulars of Kamsarmax bulk carrier (Krishnan et al. (2023).

Length overall (LOA)	229.00 m
Length between perpendiculars (LPP)	225.06 m
Breadth	32.26 m
Deadweight and draft	80 900 MT at 14.475 m
Laden- service speed and shaft power	14 knots at 80% MCR

3.3 Operating profile & Weather data

The operating profiles are based on propulsion power profiles calculated for each month of the year. Hotel and heat power demands are modelled according to operating mode of the vessel. Sea water temperature is modelled at constant 25 degrees Celsius, due to restrictions in inputs available to the model. However, the sea water mainly influences the heat balance of the ship and the technology related to the waste heat recovery system.

It should be noted that the model does not take correct sequence of port stops into consideration. Nevertheless, port stops contribute to <5 % of total energy consumption and majority of simulations are not affected by the order of operating modes. A clean hull is assumed by default in all simulation cases, in order to achieve a fair comparison.

Based on information by the ship charterer six different routes were selected based on realistic operations for this size of bulk carrier. These are presented in Table 3.3-1. It is assumed that the ship sails along each of the routes 12 times, starting on the first day of each month. Based on the vessel’s position and assumed time the wind and wave parameters are gathered from a weather database. The databases are provided by the European Commission initiative called Copernicus that aggregates data provided by European meteorological institutes.

Table 3.3-1 Operational routes (Krishnan et al. (2023).)

	Departure	Arrival	Via	Length
A	Brazil	China	Cape of Good Hope	11220 nm
B	China	Australia (Newcastle)		4812 nm
C	Australia (Newcastle)	Brazil	Cape Horn	7243 nm
D	Australia (Newcastle)	Brazil	Cape of Good Hope	8698 nm
E	Rotterdam	Baltimore		3646 nm
F	Baltimore	Brazil		5002 nm

Hotel and heat power demands are modelled according to the operating mode of the vessel. The operation mode distribution is presented in Figure 3.3-1 and the details are outlined in sections below. A ship is maneuvering when it is actively adjusting its speed, course or position, often when entering or exiting a port. The other modes presented in the figure are self-explanatory.

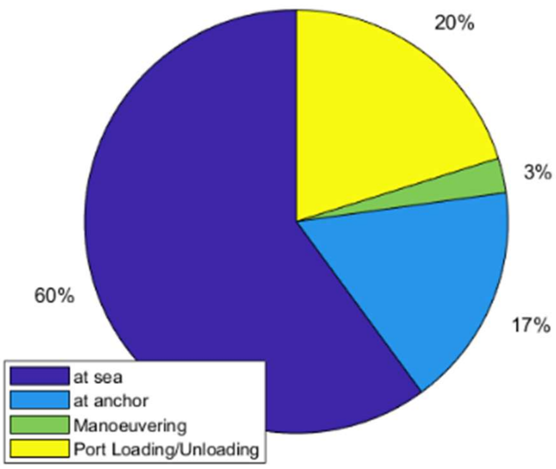


Figure 3.3-1 Operation mode distribution (Molchanov, 2022)

3.4 Key machinery components

3.4.1 Fuel type used and fuel properties

This section discusses fuel types and parameters that have been used in the simulations. Heavy fuel oil (HFO) is considered as the main fuel type for cases with 2-stroke engine. For cases with 4-stroke engine Marine diesel oil (MDO) or liquified biogas (LBG) are assumed as primary fuel. Fuel properties assumed for the energy model are shown in Table 3.4-1 below.

This thesis provides an estimation of the potential impact of reducing ship carbon emissions by also applying for the LBG fuel a simplified carbon factor of "0", regarding the well-to-wake emissions. It should be noted that during the time of writing, the fuel carbon factors and guidelines for calculating in a well-to-wake perspective, had not yet been set up in a satisfactory manner. Therefore, the results calculated with a carbon factor of 0 are only estimations with aim to show the potential in emission reductions.

Table 3.4-1 Fuel properties

Energy source	**LHV, MJ/kg**	**Density (kg/m^3)**	**Carbon factor**
HFO	40 200	0.991	3.114
MDO	42 700	0.920	3.206
LBG (Tank to Wake)	49 700	0.450	2.750
LBG (Well to Wake)	49 700	0.450	0

3.4.2 2-stroke engine configuration

For simulations with 2-stroke engine the MAN engine 5S60ME-C8.5 PL-EGB (8800 kW) was used. The 2-stroke engine configuration is directly coupled to a fixed-pitch (FP) propeller and represents a typical baseline machinery for a bulk carrier. In all machinery configurations the exhaust gas heat is recovered from the main engines, but not from the auxiliary engines.

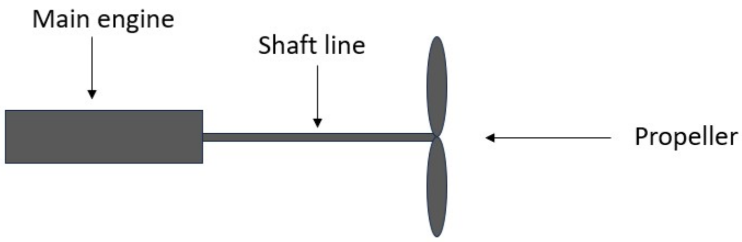


Figure 3.4-1 2-stroke engine configuration

3.4.3 4-stroke engine configuration

Wärtsilä's W8V31 engine (5200 kW) was simulated when a 4-stroke engine was used and MDO was considered as the primary fuel. Conversely, Wärtsilä's W8V31DF engine (4800 kW) was chosen for applications where a 4-stroke engine was employed, and LBG assumed as the primary fuel. Figure 3.4-2 presents a so-called fuel-flexible 4-stroke engine with shaft generators mounted on gearbox and a controllable-pitch propeller (CPP). For the simulations in the 4-stroke machinery a fixed loss of 1% was included for the shaft line and 2% additional losses included due to the gearbox.

When 4-stroke engines are utilized the powerplant will have one auxiliary engine installed. The auxiliary engine assumed is Wärtsilä's 6L20DF engine (960 kW, 1000 RPM). Conversely, three Yanmar gensets (3 x 500 kW, 900 RPM) are installed when generating electricity for cases with 2-stroke engine. The auxiliary engine in the 4-stroke configuration will have a somewhat small impact on the total energy efficiency, due to the usage of shaft generators at sea and a small share of annual energy consumed in ports. In simulations with 2-stroke engine no shaft generator is considered. Exhaust heat is recovered from the main engine, but not from auxiliary engines in all machinery configurations.

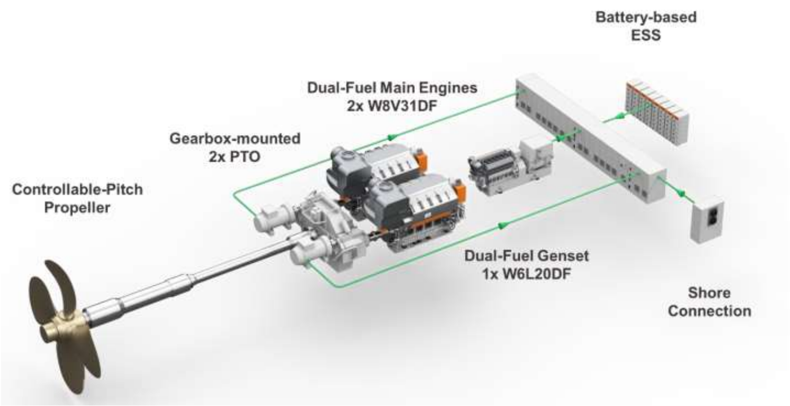


Figure 3.4-2 4-stroke engine configuration including batteries and shore power (Molchanov, 2022)

3.5 Power demand

The power demand for various speeds is shown in Table 3.5-1, for design draft with a 15% sea margin included. The sea margin describes how much added power is required when operating, meaning it takes into account resistance caused by e.g. wind and fouled hull/propeller. Losses in energy between engine and consumers are not included.

Table 3.5-1 Power demand (kW) for design draft for various speeds (Molchanov, 2022)

Speed	11kn	14kn	16kn
Power	1756 kW	3266 kW	4860 kW

To display the differences in hotel load consumers between 2- and 4-stroke machinery concepts for bulkers, a set of reference electrical load analyses (ELA) have been analyzed. The results are presented in Figure 3.5-1.

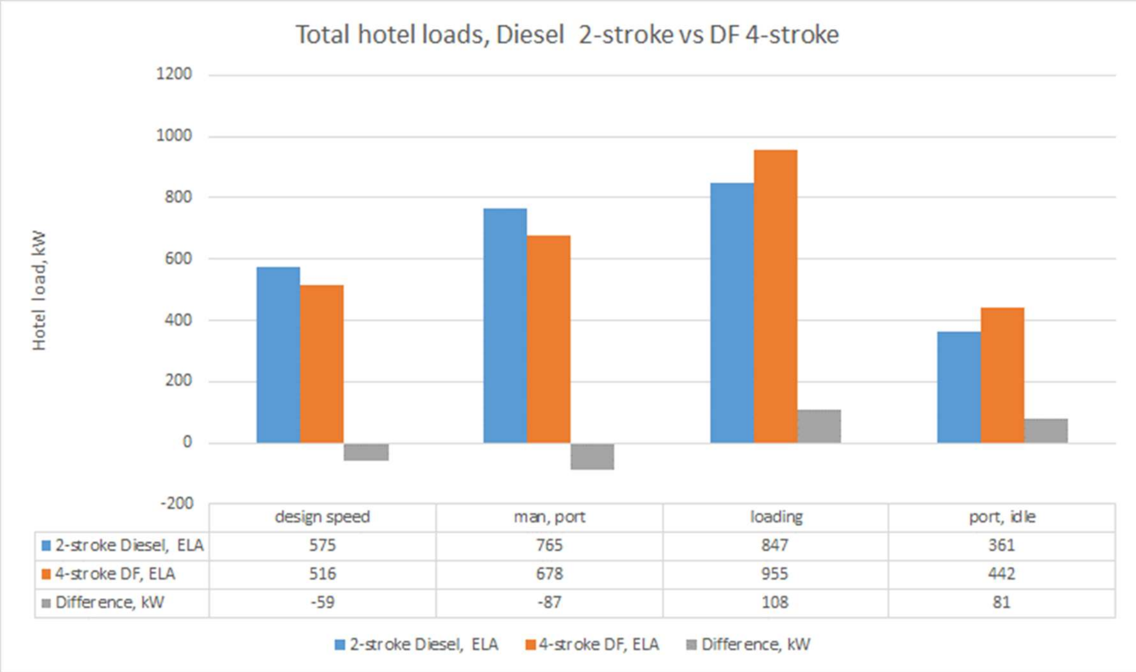


Figure 3.5-1 Indicative differences in hotel load with a 2- and 4-stroke machinery (Molchanov, 2022).

Significant changes in heat balance will be seen when the ship transitions from HFO fuel to LBG fuel. In order to keep the fuel storage tanks pumpable and avoid wax formation when HFO is used a lot of heat is required. These differences in tank heating requirements will be the dominating parameter for changes in heat balance.

Additionally, heat consumers that require lower grade heat, as for example, space heating, potable water heating and preheating of AC air, have been assigned to engine high temperature (HT) cooling water instead of steam. Resulting in a further optimized heat system. Figure 3.5-2 illustrates the heat balance comparison between the main fuels, based on preliminary heat balance for the vessel as a function of the environmental temperature.

	VLSFO Version					
	AT SEA			IN PORT		
Temperature	**-10**	**25**	**35**	**-10**	**25**	**35**
Steam consumers	632	392	264	594	360	175
HT consumers	247	19	17	248	37	33
SUM, kW	**879**	**411**	**281**	**842**	**397**	**208**

	LBG Version + Optional savings					
	AT SEA			IN PORT		
Temperature	**-10**	**25**	**35**	**-10**	**25**	**35**
Steam consumers	359	64	40	357	60	40
HT consumers	237	9	7	309	62	38
SUM, kW	**596**	**73**	**47**	**666**	**122**	**78**
Improvement relative to VLSFO	**-32 %**	**-82 %**	**-83 %**	**-21 %**	**-69 %**	**-62 %**

Figure 3.5-2 Heat balance comparison between VLSFO and LBG-fueled bulker (Molchanov, 2022)

3.6 Energy-saving devices

This section presents the studied energy-saving devices/methods in project CHEK for the specific bulk carrier used as case ship.

3.6.1 Shore power

Even when ships are docking and there is no need for propulsion, several of the ship functions are still operating. These are for example, control and cargo handling systems, ventilation, heating, cooling and pumps. When consuming energy in port the generators are running, resulting in GHG emissions. Instead of generating electricity on board using generators the electricity can come from shore power. An explanation of the working principle is in Figure 3.6-1. The reduction potential in port for the electrical motors on board is from 50% up to 100%. (IMO, N.d.-c)

In the simulations where shore power is utilized it is either available in all ports or not accessible at all. In the cases where shore power is applied it is assumed that shore power is available with a maximum power of 1500 kW.

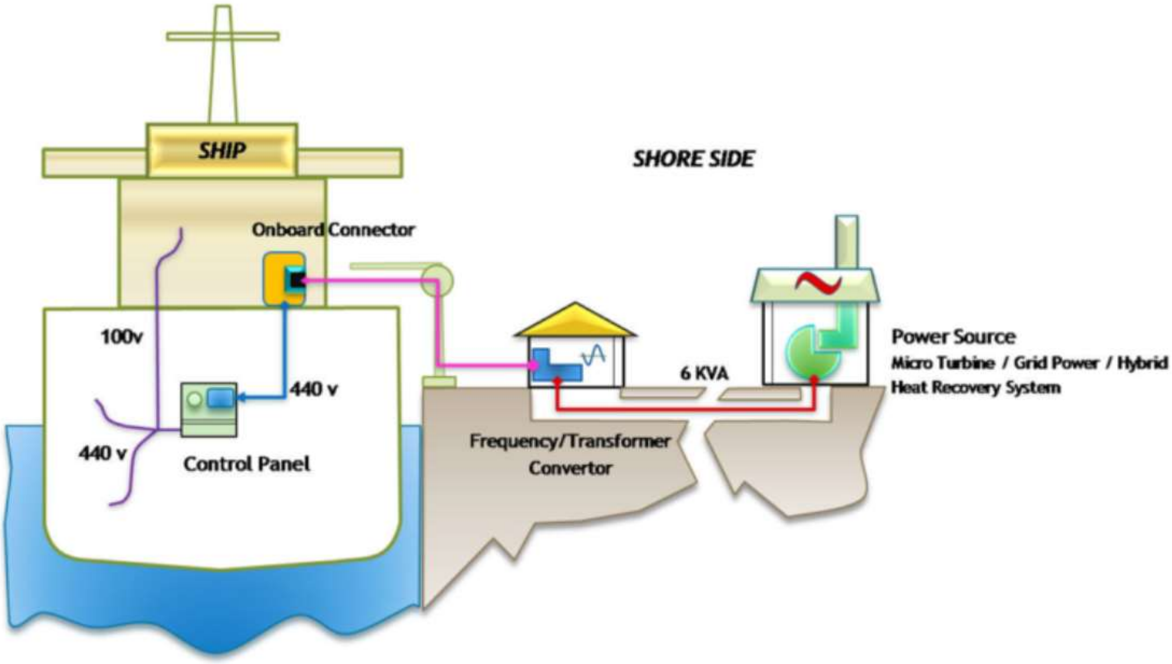


Figure 3.6-1 Schematic of shore power (IMO, N.d.-c)

3.6.2 Batteries

In this study when batteries are assumed they act as a passive energy-saving device, also called spinning reserves. Meaning they enable auxiliary and main engines to operate in higher efficient loads without safety concerns and at the same time supply power to propulsion shaft and shaft generator. The spinning reserve enables auxiliary generators to run up to a 95% load without having to turn on additional generators. This leads to savings on fuel efficiency and engine maintenance.

It is assumed in the model that main engines are allowed to run at 100%, supplying power to the propulsion shaft and shaft generators when the battery is installed. Without batteries auxiliary generators take over when main engine reaches a load of 90%, resulting in disabled shaft generators.

3.6.3 Organic Rankine Cycle (ORC)

An ORC system uses heat energy to generate electricity. Typically, a thermal energy source feeds an evaporator to drive an expander which generates the electricity. The provider of heat can for example be a waste heat source. This makes it possible to use existing heat energy that would otherwise be lost. (Alfalaval, N.d.) The working principle of an ORC unit is displayed in Figure 3.6-2.

The working principle of ORC is similar to a traditional Rankine cycle, where pressurized water is evaporated and expanded through a steam turbine. The main difference compared to the Rankine cycle is that ORC uses an organic fluid as working fluid instead of water.
Two ORC units, 2 x 150 kWe are "installed" onboard, with performance figures received from Climeon. In this case the ORCs are connected to a separate waste heat recovery loop, which collects energy both from the engine's HT cooling water as well as exhaust heat through a steam booster. It is estimated that one unit will be used almost continuously, and the 2nd unit will generate additional electricity when enough waste heat is available, usually in high load scenarios.

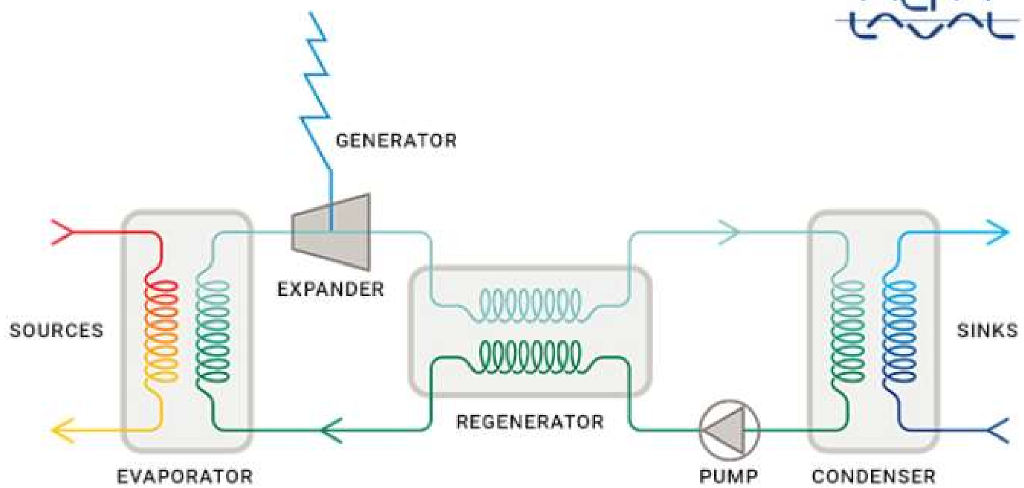


Figure 3.6-2. Schematic of the ORC working principle (Alfalaval, N.d.)

3.6.4 Air lubrication

Air Lubrication System (ALS) is a proven technology to reduce fuel consumption and emissions, by up to 10%. The working principle of an ALS system is following: the system creates a carpet of microbubbles on the hull of the ship and thereby reduces the frictional resistance and results in more efficient propulsion. The system works in all sea conditions, is not weather dependent and does not have an impact on the vessel's operational profile. (Wärtsilä, N.d.-a)

Air lubrication was modelled according to estimations made by the company Silverstream Technologies for the Silverstream® System. Estimations in power savings are based on a result of the achieved drag reduction and electrical power demand needed to run the system. In the simulation with air lubrication the air lubrication system is considered by using a percentage reduction in final shaft power demand, while including the electrical load in the vessel's hotel load.

3.6.5 Sails

Sails can use the wind to replace a part of the required propulsion power. Modern sails are fixed installations on the ship in different forms. Naturally energy savings due to sails are highly dependent on operating profiles and wind conditions. (IMO, N.d.-d)

In the simulation cases where sails are installed the particulars of the sails are provided by BAR Technologies. Two sails, assisting in the propulsion are assumed. The span and chord of each sail is 37.5m and 20m respectively. Air density is considered as 1.225 kg/m^3. The wind conditions are calculated by using wind data and the vessel speed. The wind conditions will be used in calculating the lift and drag forces generated by the sails for various angles. It is in the calculation assumed that the sails perform best around 40 to 135 deg relative wind angles, and thus, at this angular range, produce maximum lift. When the effect of two sails is calculated it should be noted that the forces do not double as there is an interaction between the sails. (Hydronav, 202, p 46)

3.6.6 Gate rudder

A gate rudder improves the thrust performance and maneuverability of the ship, resulting in reduced fuel consumption. The gate rudder is a device consisting of two foils on respective sides of the propeller. The result of reduction in fuel consumption depends on the vessel type, its operational profile as well as the propeller and rudder. (Wärtsilä, N.d.-b)

Since no actual gate rudder simulation results were established when writing this thesis, the results are based on 8% constant propulsion power savings in simulations where gate rudder is applied.

3.7 Simulation matrix of used technologies.

Table 3.7-1 lists all of the simulated cases. Each simulation is performed for each month of the year.

Table 3.7-1 Simulation matrix

Case #1	**2S Benchmark**	2-stroke benchmark, no additional energy-saving improvements.
Case #2	2S fouling	2-stroke benchmark + 20 % increase in propulsion power due to fouling
Case #3	**4S Benchmark**	New benchmark with the 4-stroke configuration (incl. shaft generator)
Case #4	Shore Power	4-stroke benchmark + shore power (1500 kW) available in all ports
Case #5	ORCs	4-stroke benchmark + 2 x 150 kWe waste heat to power modules installed in the system
Case #6	ALS	4-stroke benchmark + air lubrication savings estimated from Silverstream
Case #7	Sails	4-stroke benchmark + 2 sails provided from BAR technologies
Case #8	Gate Rudder	4-stroke benchmark + 8 % constant propulsion power savings.
Case #9	4S LBG	4-stroke benchmark + LBG as primary fuel.
Case #10	CHEK Combo	All the above energy savings measures combined except gate rudder and including battery as spinning reserve.
Case #11	LBG Combo (TtW)	All the above energy savings measures combined except gate

		rudder. Also battery included. LBG as main fuel. Results presented on Tank-to-Wake basis.
Case #12	LBG Combo (WtW)	All the above energy savings measures combined except gate rudder. Also battery included. LBG as main fuel. Results presented on Well-to-Wake basis.

4 Results

In this section a summary of the results of the energy model as well as the improvement in CII based on different energy-saving strategies is presented.

4.1 Energy model results

Table 4.1-1 and Table 4.1-2 results from the energy model are presented in more detail. In all simulation cases a clean hull is assumed by default except in case “2s fouling” where a 20% increase in propulsion power is considered, to count the effect of fouling. A fouled hull results in increased fuel consumption by 714 tons or 17,7% for the considered journey. Therefore, a clean hull means savings in fuel cost as well as in emissions and is of significant matter to the ship owner.

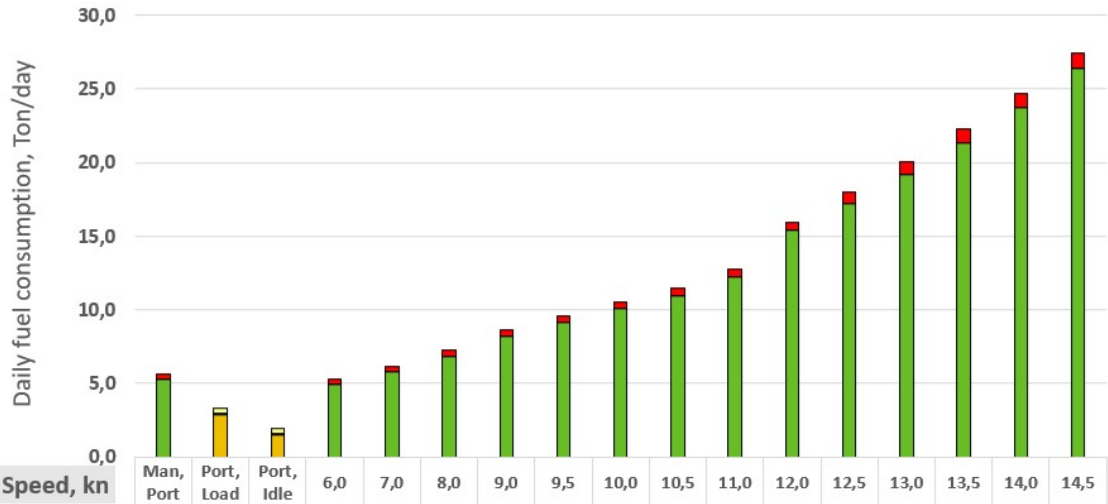
In Figure 4.1-1 it can be noted how the speed affects the fuel consumption almost exponentially. The fuel consumption is presented in ton/day for main- and auxiliary engine as well as for boiler, in various speeds.

Table 4.1-1 Energy model results a)

Name	2S New Benchmark	2S Fouling	4S New Benchmark	Shore Power	ORCs	ALS
Amount of months	12	12	12	12	12	12
Main Engine fuel, t	4026	4740	4561	4561	4312	4170
Main engine pilot fuel, t	0	0	0	0	0	0
Auxiliary engine fuel, t	896	896	390	135	390	390
Auxiliary engine pilot fuel, t	0	0	0	0	0	0
Oil-fired boiler fuel, t	186	212	54	54	54	54
Cold Iron MWh	0	0	0	1179	0	0
Total fuel cons, MWh	**57107**	**65383**	**59363**	**56338**	**56412**	**54734**
PP efficiency avg. %	47,6 %	48,4 %	44,5 %	44,8 %	46,8 %	45,4 %
AE load, avg %	48,5 %	48,5 %	55,1 %	36,7 %	55,1 %	55,1 %
ME load, avg %	49,0 %	58,4 %	45,8 %	45,8 %	78,0 %	77,4 %
ME total run-hours	5266	5266	10470	10470	6193	5933
AEs total run-hours	16022	16022	3494	1730	3494	3494
SG total run-hours	0	0	5266	5266	5266	5266
Prop MWh	22468	26784	22468	22468	22468	19550
Hotel MWh	3669	3669	3656	3656	3656	4999
CO_2 Emissions, tons	15905	18210	16040	15228	15248	14794

Table 4.1-2 Energy model results b)

Name	Sails	Gate Rudder	4S LBG	CHEK Combo	LBG Combo (TtW)	LBG Combo (WtW)*
Amount of months	12	12	12	12	12	12
Main Engine fuel, t	3864	4124	3729	3540	2942	2942
Main engine pilot fuel, t	0	0	183	0	117	117
Auxiliary engine fuel, t	390	390	331	135	113	113
Auxiliary engine pilot fuel, t	0	0	16	0	9	9
Oil-fired boiler fuel, t	54	54	47	54	47	47
Cold Iron MWh	0	0	0	1179	1179	1179
Total fuel cons, MWh	**51104**	**54185**	**58938**	**44227**	**44225**	**44225**
PP efficiency avg. %	45,3 %	45,4 %	44,8 %	46,1 %	46,1 %	46,1 %
AE load, avg %	55,1 %	55,1 %	54,7 %	36,7 %	36,7 %	36,7 %
ME load, avg %	71,3 %	77,0 %	48,9 %	66,7 %	70,5 %	70,5 %
ME total run-hours	5919	5897	10532	5721	5882	5882
AEs total run-hours	3494	3494	3590	1730	1730	1730
SG total run-hours	5266	5266	5170	5266	5266	5266
Prop MWh	19182	20670	22468	16264	16264	16264
Hotel MWh	3656	3656	3656	4999	4999	4999
CO_2 Emissions, tons	13813	14646	11931	11954	8932	401



Speed, kn	Man, Port	Port, Load	Port, Idle	6,0	7,0	8,0	9,0	9,5	10,0	10,5	11,0	12,0	12,5	13,0	13,5	14,0	14,5
OFB fuel	0,0	0,3	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Auxiliary engine pilot fuel	0,0	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Auxiliary engine fuel	0,0	2,9	1,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Main engine pilot fuel	0,3	0,0	0,0	0,3	0,3	0,4	0,4	0,4	0,5	0,5	0,5	0,5	0,8	0,9	0,9	1,0	1,0
Main Engine fuel	5,3	0,0	0,0	5,0	5,8	6,8	8,2	9,1	10,1	11,0	12,3	15,4	17,2	19,2	21,4	23,7	26,4

Figure 4.1-1 Fuel consumption ton/day

4.2 CII results

In Figure 4.2-1 it is presented how the different technologies used affect the CII. The grey color represents cases with 2-stroke engines, the green and blue colors represent cases with 4-stroke engines in MDO and LBG fuel respectively. The CII results are based on decisions from MEPC 78 (commenced in June 2022). The reduction of the reference line is assumed to be 2,625% between the years 2026 and 2030 to meet the goals set by IMO, following with annual 2% until year 2040. The alternative “CHEK combo” will stay in superior rating most of its lifetime and comply with CII regulations in their current form until at least year 2040. In Figure 4.2-2 the attained CII vs speed is presented to graphically show that a higher speed of the ship and thereby increased fuel consumption, affects the rating negatively.

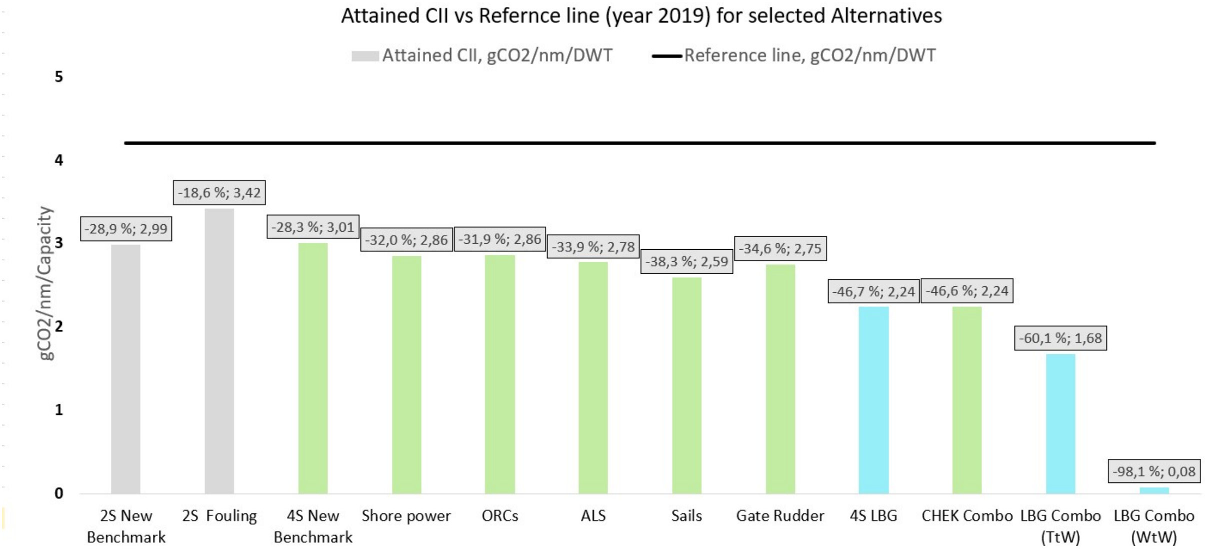
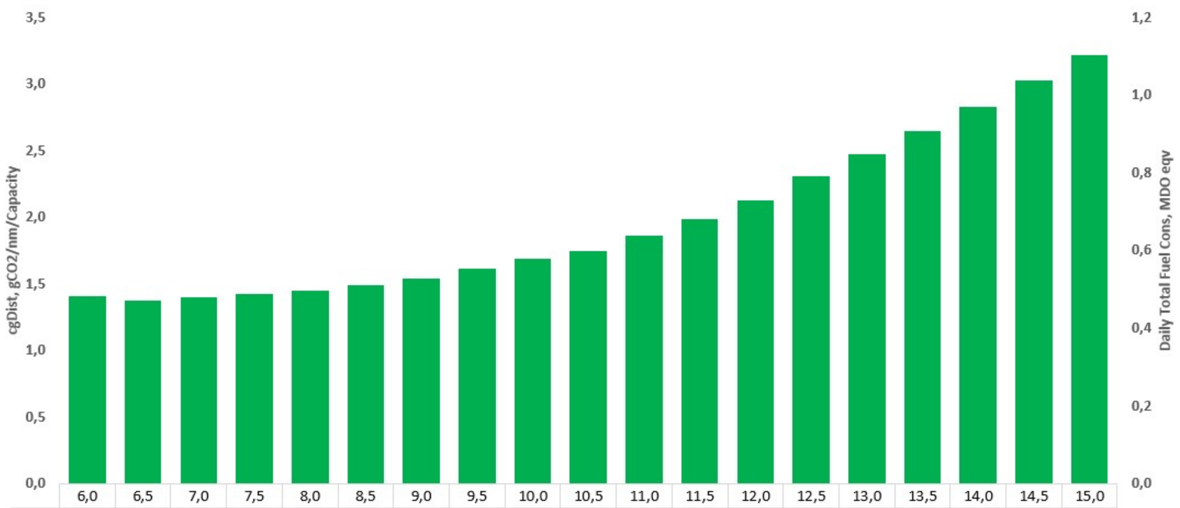


Figure 4.2-1 Attained CII for all simulations



	6,0	6,5	7,0	7,5	8,0	8,5	9,0	9,5	10,0	10,5	11,0	11,5	12,0	12,5	13,0	13,5	14,0	14,5	15,0
AER	1,4	1,4	1,4	1,4	1,4	1,5	1,5	1,6	1,7	1,7	1,9	2,0	2,1	2,3	2,5	2,6	2,8	3,0	3,2

Figure 4.2-2 Attained CII vs Speed

5 Discussion

The results indicate that a combination of various energy-saving technologies that can be integrated in the ship design can make a huge increase in energy efficiency. It should be noted that in the presented results the rather restricted operational profile included only 60% of the time operation at sea. The operational profile plays a key role for technologies such as sails and/or wind-assisted propulsion, since benefits are achieved when the ship is sailing. It can be observed from the results that sails result in great savings, meaning that already a single technology can have a considerable impact on the ship's energy efficiency. Shore Power connection on both ends and in all ports can save up to 5% of total energy consumption, therefore being another example of the impact one technology can have. However, all technologies come with downsides and one thing to consider regarding for example shore power is that it might come at a higher cost than fuel and fluctuating electricity prices naturally affect the cost of shore power in addition to fuel prices and investments in port infrastructure.

Even if only one energy-saving device is simulated, various interconnections between the equipment onboard can be observed. For example, consider sails: the impact of sails is mainly regarding the reduced power needed for propulsion. Nevertheless, reduced propulsion power results in changed engine utilization that leads to larger total saving. This is because of improved power plant efficiency, increased engine load and reduction in engine running hours.

The Organic Rankine Cycle results in almost 5% savings in energy consumption. However, the pure power production by the ORC itself covers less than 3% of the energy requirements. In this particular ORC simulation, the ORC units are able to reduce the ship's electrical load which would typically be handled by the shaft generators. This results in a switched engine configuration, where now one main engine runs on a relatively high load, instead of two main engines on a relatively low load. This altogether leads to reduced fuel consumption, due to the improved efficiency in power conversion from fuel to power.

It is important to simulate the impact of the design variations in the current rule framework, such as the CII. Nevertheless, in order to achieve the set goals of shipping decarbonization, the rules must be developed in the future, which might include adjusting the baselines and introducing various correction factors. When calculating only the Tank-to-Wake emissions as stated in the current regulations, a combination of various energy-saving methods produce almost equal reduction in CII result as fuel change to gas from MDO.

In order for ships to be able to adjust for strengthening rules and emission limits, it is important to calculate the absolute reductions in fuel consumption and emissions and simulate the ship along with realistic operational profiles. This gives ship owners the possibility to choose a strategically wise combination of design features and technologies for their ship right from the start. By preparing for certain future upgrades already in an early stage, complying with future required rules and clean fuel infrastructure is going to be more accessible for the ship owners.

6 Conclusion

This thesis presented the method of calculating CII and a set of results regarding the impact of different technologies and their combination on a bulk carrier's energy efficiency, carbon emissions and CII on a typical operating route.

CII is one of IMO's short-term measures and measures the energy efficiency of a ship. The CII is given in CO_2 emitted per cargo capacity and nautical mile, and is mandatory to calculate for all ships above 5000 GT. The marine sector is developing rapidly since IMO has set ambitious targets in order to reach net-zero emissions by or around year 2050. The uncertainty regarding the development of CII rules and future legislation highlights the importance of energy efficiency in the industry.

Due to interconnections between various energy system components in the energy model, surprising observations could be made, even when simulating only one individual change. For instance, the sails alone reduce the ship engine loads considerably, which results in less waste heat available for Organic Rankine Cycles. Modelling the impact of several technologies even on a rough level, gives a valuable insight into the environmental performance of the ship and its improvement potential. These results provide a small outlook into the benefits and necessity to valuate energy-saving devices and design choices from an energy system perspective.

7 Extended abstract in Swedish

Den globala uppvärmningen är ett av de största hoten mot nuvarande ekologiska system och mänsklig civilisation, och inom flera sektorer prioriteras dekarbonisering i allt högre grad, i hopp om minimering av växthusgasutsläpp. Dekarbonisering är en nödvändig åtgärd för att minska de globala utsläppen av växthusgaser samt för att bekämpa klimatförändringarna. Inom sjöfarten kan dekarbonisering innebära till exempel en övergång från fossila bränslen som tjockolja och diesel till alternativa bränslen med låga koldioxidutsläpp och/eller koldioxidneutrala bränslen utan utsläpp. Även energibesparande teknologier med syfte att öka på fartygs energieffektivitet och därmed minimera utsläppen är också bra exempel på sätt att dekarbonisera. För att främja dekarboniseringen på en global nivå krävs internationella överenskommelser såväl som politiska åtgärder

Marinindustrin stod år 2022 för ca 2% av de globala energirelaterade växthusgaserna (International Energy Agency, N.d.). Höga mängder utsläpp beror främst på att sjöfarten länge använt sig av fossila bränslen och därmed bidragit till utsläpp av växthusgaser. Eftersom sjöfarten står för en betydande del av de globala växthusgasutsläppen, och förändringar krävs för att i framtiden kunna uppnå en koldioxidneutral sjöfart, befinner sig industrin under en stor press. Till exempel har både International Martitime Organization (IMO) och Europeiska unionen (EU) satt upp diverse del mål, i hopp om att slutligen nå en koldioxidneutral sjöfart, vilket kommer att innebära stora förändringar inom hela industrin. Sjöfarten är en fundamental del inom den globala ekonomin och handeln. Under Covid-19 pandemin, energi- och geopolitiska kriser har transporten av varor skett överlägset mera energisnålt och tryggare via sjöss än via landvägar. Därav är det viktigt att arbeta för dekarbonisering av industrin.

IMO har som mål en koldioxidneutral sjöfart år 2050 och deras mått på fartygs koldioxidintensitet (CII) faller under deras mått för fartygs energieffektivitet. Till de måtten hör även Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI) och Energy Efficiency Operating Index (EEOI) och Ship Energy Efficiency Management Plan (SEEMP). Detta slutarbete fokuserar på måttet CII samt hur designen av fartyg och integreringen av koldioxidneutrala teknologier fungerar i symbios med påverkan på ett fartygs energieffektivitet samt CII-värde. Arbetet fokuserar på endast ett fartyg (ett bulker fartyg) och är skriven inom ramarna för ett EU finansierat projekt ”CHEK”. Som uppdragsgivare för arbetet fungerar företaget Deltamarin, ett ingenjörsföretag inom sjöfartsindustrin.

CII är ett relativt nytt mått och trädde i kraft år 2023. Därav finns det för tillfället endast fåtal undersökningar gjorda gällande ämnet. Eftersom IMO står bakom CII baserar sig arbetes teoridel främst på deras källor samt resolutioner från IMO:s marinskydds kommittés (MEPC) möte från juni år 2022.

Fartygens bränsletyp och energi-innehåll påverkar direkt dess miljövänlighet samt mängden växthusgaser. Användandet av koldioxidneutrala bränslen är ett kriterium som måste uppfyllas ifall det globala hållbarhetsmålen ska uppnås. Då man räknar mängden växthusgaser ett fartyg producerar, använder man en så kallad koldioxid (CO_2) faktor för att få fram mängden koldioxidutsläpp. Varje bränsle har sin egen CO_2 faktor med ett värde beroende på mängden kol bränslet innehåller. Utsläppen kan räknas ur flera olika perspektiv. För tillfället räknas utsläppen endast baserat på mängden utsläpp fartyget producerar under drift även kallat Tank-to-Wake perspektiv. Då IMO:s mål är en koldioxidneutral sjöfart år 2050, är det sannolikt att CII i framtiden kommer att räknas ur ett livscykelperspektiv, dvs. Well-to-Wake perspektiv, alltså skulle produktionen av bränslet även tas i beaktandet (Well-to-Tank). CII:s effektivitet kommer att behandlas av IMO senast 1 januari år 2026.

CII är som nämnt ett mått för fartygs energieffektivitet och skall beräknas för alla fartyg över 5000 GT. CII ges i mängden CO_2 dividerat med fartygets kapacitet och resta sjömil. Alla fartyg över 5000 GT är tvungna att räkna sitt CII värde årligen och baserat på resultatet får det ett betyg från A till E där A står för utmärkt. Ifall fartyget får betyget D i tre påföljande år eller E i ett år måste rederiet göra upp en plan för hur betyg C eller bättre ska uppnås.

Detta slutarbete visar hur olika energisparande teknologier påverkar CII värdet för ett Kamsarmax storleks Bulker fartyg, dvs. bulker fartyg med en maximum längd på 229 meter. Energimodellen är konfigurerard i MATLAB samt Simulink miljöer och består av fartygets operationsprofil, maskinkonfiguration, data över bränslekonsumtion och fartygets energiförbrukning. Delar av modellen är baserade på till exempel el- och värmebalanser är beräknade av andra ingenjörer och sedan integrerade i energimodellen för att analysera hur de undersökta parametrarna påverkar skeppets CII och därmed också energieffektivitet. Resultaten som modellen genererar är fartygets energidistribution samt de mest betydande indikatorerna för fartygets miljöprestanda.

Två olika maskinkonfigurationer studeras, både en 2 takts motor från MAN där tjockolja antas som bränsle och en 4 takts motor från Wärtsilä där antingen dieselolja eller biogas antas som bränsle. De olika energisparande teknologierna som studeras är följande: landström, batterier, organisk rankine cykel, luftsmörjning, segel samt ett portroder. De olika teknologierna beskrivs kort i följande stycken.

Även då fartyg står i hamn är de stora energiförbrukare som följd av att flera av system fortfarande måste vara i gång. Med dessa system menas till exempel olika kontroll-, ventilation samt uppvärmning och kylsystem. I stället för att fartyget själv genererar sin el och konsumerar bränsle då det står i hamn kan det ansluta till landström och därmed konsumera mindre energi eftersom generatorerna ombord då inte behöver generera all el. I simulationerna där landström applicerats antas det finnas tillgängligt i alla hamnar med en maximum effekt på 1500 kW.

Batterierna antas fungera som passiva energibesparande enheter. Dvs, de tillåter huvud- och hjälpmotorerna att arbeta vid högre last vilket leder till högre effektivitet och minskad energikonsumtion. Organisk Rankine Cykel (ORC) använder sig av värmeenergi för att generera elektricitet. Den använda värmeenergin är ofta spillvärme, dvs. värmeenergi som annars skulle gå förlorad. I simulationerna där ORC är applicerad, förväntas den använda värmeenergin från motorns högtemperatur kylvatten samt avgashetta.

Luftsmörjning minskar ett fartygs bränslekonsumtion samt utsläpp avsevärt. Funktionsprincipen för ett luftsmörjningsystem är följande: en så kallad ”matta” av mikrobubblor bildas på fartygets skrov och resulterar därmed i mindre friktion och en mera effektiv propulsion. I detta arbete var luftsmörjning simulerad enligt estimationer gjorda av företaget Silverstram Technologies.

Segel använder sig av vinden för att minska på den behövda propulsionskraften. Moderna segel är fasta installationer på fartyg. Besparingarna är goda men naturligtvis starkt beroende av fartygets operationsprofil samt väderförhållanden. I simulationer där segel är applicerade är dess parametrar estimerade av företaget BAR Technologies.

Ett portroder förbättrar manövreringen samt fartygets framdrivning. Portrodern är en enhet som appliceras på propellern och resulterar i minskad bränslekonsumtion. I simulationer där portrodern är applicerad antas 8% konstant besparing i den behövda propulsionskraften. Detta eftersom inga riktiga simuleringar med portroder utförts då detta arbete skrevs.

Sammanlagt kördes 12 olika simuleringar för detta arbete. 2 simuleringar kördes med 2 takts motorn varav ena fungerade som referenspunkt och den andra antog 20% ökning i propulsionskraften för att visa effekten av ett smutsigt skrov. I de resterande simuleringarna fungerade 4 takts motorn med diesel som referenspunkt och simuleringarna med de olika energibesparande enheterna jämfördes med den. För att visa vilken påverkan val av bränsle har simulerades ett fall enligt referenspunkten för 4 takts motorn med diesel men bränslet antogs vara biogas. Även 2 så kallade ”combo” simuleringar kördes där olika energibesparande enheter kombinerades för att visa synergier mellan olika teknologier, dessa simuleringar kallas ”combo” fall. I ett av fallen antogs diesel som bränsle och i det andra biogas. Resultaten för ”combo” fallet med biogas presenteras både ur Tank-to-Wake persepktiv och Well-to-Wake perspektiv. I beräknandet av utsläppen ur ett Well-to-Wake perspektiv användes en CO_2 faktor med värdet 0, med syfte att visa förbättringspotentialet. Dock är detta en estimering eftersom IMO under tiden då detta arbetet skrevs inte kommit ut med officiella riktlinjer gällande CII beräkningar ur ett livscykel perspektiv.

Resultaten visar hur både enskilda energibesparande teknologier samt kombinationer av dem kan spela en betydande roll för fartygets energieffektivitet. Även om bara en teknologi simulerats kan samband mellan olika enheter ombord observeras. Ett exempel på detta är seglen: segel påverkar i förstahand propulsionskraften. Dock resulterar ett reducerat behov i propulsionskraft i till exempel en förbättrad maskinkonfiguration och högre motorbelastning vilket leder till ännu större besparingar. Samtidigt leder också den förändrade maskinkonfigurationen till att mindre spillvärme finns för den organiska rankine cykeln att ta tillvara.

För att fartyg även i framtiden ska uppfylla miljökriterierna är det viktigt att analysera deras energisystem och simulera fartygen enligt deras verkliga operationsprofil. Då man gör detta ordentligt ger det skeppsägarna möjligheter att i allt tidigare skeden göra strategiska val angående design och olika teknologier för deras fartyg. Genom att göra strategiska och miljövänliga val redan i ett tidigt skede kommer uppfyllandet av de framtida miljökraven vara enklare.

Detta slutarbete presenterar metoder för att räkna fartygs koldioxidintensitet, dvs. CII och inverkan olika energibesparande teknologier har på ett bulker fartygs energieffektivitet, koldioxidutsläpp och CII betyg. CII hör till IMO:s mått för fartygs energieffektivitet och ges i CO_2 utsläpp dividerat med fartygets kapacitet och operationsrutt i sjömil. Osäkerheten gällande utvecklingen av CII, stiftandet av framtida miljölagar samt de globala målen för koldioxidneutralitet påvisar den betydande roll som energieffektivitet inom sjöfarten har. De olika simuleringsresultaten visar enskilda teknologiers besparingar samt hur integrerade de olika systemen är med varandra. Simuleringar över fartygs energisystem samt olika koldioxidneutrala teknologier ger värdefulla inblickar över fartygs miljövänlighet samt förbättringspotential. Resultaten i detta slutarbete ger en inblick i förmånerna och betydelsen av att analysera olika teknologiska lösningar och designelement ur ett energiperspektiv.

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