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«Marine & Sea Technology and Science»

Diploma Thesis:

“Effective ways to reach EEXI limit for existing vessels and implications”

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Acknowledgments

Abstract

After introducing Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) in 2011, by 62nd session of the Marine Environment Protection Committee (MEPC 62), International Maritime Organization (IMO) pursued its short- and long-term goals to reduce greenhouse gas (GHG) emissions from ships by presenting an Energy Efficiency Existing Ship Index (EEXI). Ships engaged in international voyage will be obliged to comply with the EEXI (MARPOL Annex VI, reg. 23 and 25). In addition, they must satisfy Regulation 28 of the same MARPOL Annex. Regulation 28 prescribes for the reduction of Operational Carbon Intensity through the Carbon Intensity Indicator (CII). The effective date for these changes to become operational is 1 January 2023.

Contrary to EEDI which is used for new ships solely, EEXI and CII is addressing the energy efficiency of already built ships and is set to become formally applicable starting from 2023. Given this, the new regulatory movement of 2021 forces shipowners to demonstrate, by the initial or the next periodic survey, that their ships meet the requirements of EEXI and CII in order for them to receive the International Energy Efficiency Certificate (IEEC) and/or the International Air Pollution Prevention Certificate (IAPPC).

According to DNV, about 80% of the current fleet falling within the EEXI regulations are not compliant and need to take measures by 2023.According to ABS, about 20% of the tanker, 46% of the bulker and 25% of the container fleet are having difficulty to even reach the required EEXI reduction factors, basis their attained values, which will be 15-30% lower than the latest updated EEDI baselines.

This diploma thesis deals with various ways for ships to be EEXI compliant. After IMO strategy and goals regarding energy efficiency, it presented a variety of innovative means through which EEXI requirements could be satisfied. Energy Saving Devices (ESDs) are analyzed and divided into different categories according to their contribution to the EEXI formula.

However, at this moment the easiest and most cost-effective measure for the reduction of EEXI is the Engine Power Limitation or EPL. One of the most serious disadvantages derived from the implementation of EPL is the vessel's speed reduction. In case of large EPL, the vessel's speed will drop dramatically as the main engine power drops and simultaneously changes the operational point of the propeller**.** With a significant reduction of the engine power in order to comply with EEXI regulation, the efficiency factor of the propeller will drop dramatically. Thus, a lot of shipowners will be led to the retrofit or redesign of the propeller.

In this paper is presented case studies with two vessels that will be evaluated on their required and the currently attained EEXI before and after the implementation of ways to reduce it. More specifically, a product/ chemical tanker and a containership will be assessed for EEXI index and an EPL application will be carried out in order to be compliant with the EEXI. An economical feasibility study will then be carried out on the containership by retrofitting its propeller. This retrofit will be evaluated both technically and economically, in order to be shown whether such projects are not only environmentally but also economically feasible and sustainable.

Being compliant with EEXI is a mandatory requirement according to the IMO from 1 January 2023. The implementation of overridable EPL or ShaPoLi is not an investment option. When the ship has to drop its EEXI and engine operating power to a great extent, ESDs cannot achieve this rate without the help of EPL/ShaPoLi. However, with the implementation of ESDs the ship can reach pre-EEXI speeds so that no major changes in the operational profiles of most ships will be observed from 2023. Thus, economic and technical feasibility studies on these issues have been carried out for a long time in shipping companies, in order to achieve fuel savings in addition to the mandatory reduction of emissions, and therefore this new EEXI project to make the companies economically and energetically viable and efficient.

Key Words: attained EEXI, required EEXI, EPL, propeller retrofit, case study, technical and economic feasibility study

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1.0 Introduction

1.1 Generally

In recent years, there has been growing concern in the international community about climate change and its consequences on our planet. The rise in temperature, the greenhouse effect, the degradation of air quality by emitted greenhouse gases and the pollutants are problems that are high on the agenda of governments and international organizations. That is why rules and restrictions have been introduced from time to time on human activities that result in environmental pollution. Shipping could not be excluded from these rules and restrictions.

It was in 1992 when the United Nations Framework Convention on Climate Change (UNFCCC) laid the foundations for stabilizing the Earth's climate by setting limits on certain gaseous pollutants (Greenhouse Gases). Subsequently, the Kyoto Protocol in 1997 agreed to limit specific pollutants such as CO_2, CH_4, N_2O, PFCs, HFCs and SF_6 by industrially developed countries to specific percentages in the period from 2008-2012. The most important pollutants coming from shipping and they are hazardous to the environment are carbon dioxide CO_2, and nitrogen and sulfur oxides, NO_x and SO_x.

Humanity, like every other species that can move, has been contributing to carbon dioxide emissions since time immemorial. This is mainly due to the respiratory nature of our survival, in which we inhale oxygen and exhale carbon dioxide. This production of carbon dioxide has been offset by the photosynthesis effect due to the Earth's dense forest cover, so that a balance has been maintained.

However, as the world in general evolves, respiration is no longer the only source of humanity's carbon footprint. The fuels to cook food, power our industries, run our vehicles and generate electricity have made our lives easier. Unfortunately, this has come at a price; humanity's carbon footprint exploded in the industrial revolution with the advent of factories. In the last 100 years, the average surface temperature of the Earth has increased by about 1°C. This woke up policy makers, as they realized that the threat of climate change is real.

According to the IMO's fourth greenhouse gas study (2018), the transport sector contributes 14% of global greenhouse gas emissions and the shipping industry is responsible for about 2-3% of global carbon dioxide emissions. Although the contribution of the shipping sector is very small compared to other relevant sectors, the International Maritime Organization (IMO) is committed to reducing its carbon footprint by 30% by 2030 and 50% by 2050.

The IMO over the last two decades has revolutionized its environmental protection regulations under the MARPOL annexes. However, the burden of implementing them at ground level falls on the shoulders of the shipowner. This thesis deals with the Energy Efficiency Index for Existing Ships (EEXI), which the IMO adopted as an amendment to MARPOL Annex VI at MEPC 76. However, it is deemed necessary with the EEDI (Energy Efficiency Design Index) to understand the EEXI, which is in line with the IMO's vision with a time horizon of 2050.

EEDI, for new ships, and SEEMP (Ship Energy Efficiency) Management Plan, for all ships, was made mandatory at MEPC 62 (July 2011) with the adoption of amendments to MARPOL Annex VI. These energy efficiency measures apply to ships of 400 gross tonnage and above. Under Annex VI there are both technical and operational measures, to improve energy efficiency of the ship. The EEDI and EEXI come under the spectrum of technical approaches to achieve the energy efficiency of a ship.

Thus, in June 2021, new amendments were adopted to the IMO's MARPOL convention in the Marine Environment Protection Committee (MEPC). The additions included new energy efficiency requirements – Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII). These are part of the global measures to reduce greenhouse gas (GHG) emissions from shipping.

Specifically, the IMO amended MARPOL Annex VI at its MEPC 76 in June 2021. Consequently, ships engaged in international voyage will be obliged to comply with the EEXI (MARPOL Annex VI, reg. 23 and 25). In addition, they must satisfy Regulation 28 of the same MARPOL Annex. Regulation 28 prescribes for the reduction of Operational Carbon Intensity through the CII.

The effective date for these changes to become operational is 1 January 2023. Given this, the new regulatory movement of 2021 forces shipowners to demonstrate, by the initial or the next periodic survey, that their ships meet the requirements of EEXI and CII in order for them to receive the International Energy Efficiency Certificate (IEEC) and/or the International Air Pollution Prevention Certificate (IAPPC).

Accordingly, immediate attention must be given to the implications of EEXI and CII. This means that shipowners must begin to take steps to commence EEXI calculations of their fleet, and to improve energy efficiency by reducing carbon footprints to satisfy EEXI and CII requirements.

1.2 Problem statement and objectives

The shipping industry is facing three major challenges: climate change, increasing bunker fuel price and tightening international rules on pollution and CO_2 emissions. All these challenges can be met by reducing fuel consumption. The energy efficiency of shipping is already very good in comparison with other means of transportation but can still be and must be improved. There exist many technical and operational solutions to that extent. But assessing their true and final impact on fuel consumption is far from easy as ships are complex systems.

By 2050, the maritime transport segment needs to reduce its total annual GHG emissions by 50% compared to 2008 to be in line with the global GHG reduction target to limit the global temperature rise to no more than 2℃ above pre-industrial level.

It is clear that the IMO is trying to decarbonize the maritime sector as soon as possible. In the following decades, the regulations will become more and more stringent and alternative ways of ship propulsion will emerge. Electric propulsion seems to be a very promising alternative as it offers a complete decarbonization and independence of fossil fuels.

In this diploma thesis we will refer to the implementation of operational but mainly technical measures and their impact on the reduction of pollutant emissions. The main objective is to highlight the contribution of each of them, or combinations of them, to fuel savings and whether their application to existing structures is investment-friendly in order to be realized.

According to DNV, about 80% of the current fleet falling within the EEXI regulations are not compliant and need to take measures by 2023. According to ABS, about 20% of the tanker, 46% of the bulker and 25% of the container fleet are having difficulty to even reach the required EEXI reduction factors, based on their attained values, which will be 15-30% lower than the latest updated EEDI baselines.

As regards operational measures, these are measures that can be taken without requiring a change in the mechanical equipment located on board the ship. They are mainly concerned with the management of this equipment; and the way it is operated. They are characterized by the fact that they do not require capital. They are:

- Lower cruising speed.
- Optimization of the voyage in ballast water conditions.
- Maintenance-cleaning of propeller and hull.
- Awareness of energy consumption among staff.

Regarding technical measures, these are measures that require modifications, improvements, possibly additions and changes to the mechanical equipment and are usually quite costly. Some of them are:

- Exhaust gas heat recovery system.
- Use of variable speed pumps and fans.
- Optimization of air conditioning systems using Variable Frequency Drive in pumps, compressors and fans.
- Main Engine optimization for lower specific fuel consumption (SFOC).
- Optimization of ship-propeller cooperation.
- Use of air lubrication system in the hull for reduced friction.
- Engine power limitation
- Change in fuel type from marine diesel oil (MDO) to liquified natural gas (LNG)
- Propeller retrofit-Redesign propeller
- Installation of energy saving devices (e.g.: PBCF, wake equalizing duct)
- Installation of rotor sails
- Increasing transport capacity (deadweight)

In the present thesis, EEXI for two different cases/ships will be calculated in order to make it obvious if EEXI requirements are satisfied. To be more specific, a product/ chemical tanker and a containership will be assessed for their attained EEXI index according to IMO instructions for EEXI formula (MEPC.333(76)). Subsequently, the required EEXI index according to each case will be assessed and be compared to the attained one. As we can predict from the outset, the selected vessels do not comply with the EEXI requirements thus effective, efficient and economically viable methods should be presented.

Some possible measures for the reduction of EEXI are the adoption of the following:

- Engine power limitation.
- Change in fuel type from marine diesel oil (MDO) to liquefied natural gas
- Propeller retrofitting – Redesign propeller: up to 10% fuel savings after EPL
- Installation of energy saving devices (e.g.: PBCF: Propeller boss cap fins, wake equalizing duct): up to 4% fuel savings.
- Installation of a shaft generator → Produce electricity from the operation of the main engine without using extra fuel oil for the operation of auxiliaries.
- Cleaning the hull more frequently & utilize different hull paints quality

The most efficient and fastest measure in order to be reduced the EEXI is the EPL implementation. After the calculation of the necessary EPL for compliance with the EEXI regulation, shipowners should liaise with class and governor maker for calculating the EPL and after that calibration of the engine should be carried out. If a large EPL should be applied, then a study regarding the operational efficiency of the propeller should be done. In case of low efficiency factor of the propeller to the new operational point ($Power_{EPL}$(kW), n_{EPL}(rpm)), a redesigning or retrofitting of the propeller may be investigated.

It is understandable that the adoption of EPL will lead to the reduction of vessel's speed. However, with a retrofit of the propeller, the total efficiency factor of the propeller is increased, as a result for the same output power of the main engine, bigger percentage of the main engine power goes to the propeller so higher vessel speed is achieved. The reduction of vessel's speed due to the EPL will be counterbalanced to a certain degree by the redesigning of the propeller.

Based on the above, such a procedure was also considered in this diploma thesis, in order to be estimated the cost of EPL and new propeller for the under-study vessels. Thus, it could be obvious whether such a project is feasible and economic efficient or not. At this point it should be underlined that the compliance with EEXI is not an investment project but a mandatory one, in order for the ships to be compliant with the last IMO's strict regulations. However, a good shipping company should investigate various ways to be compliant with EEXI in the most energy and cost-efficient possible ways.

1.3 Structure of study

This study is structured as follows:

Chapter 1: Introduction

In the first chapter, after the reference on the climate change and crisis nowadays, a short introduction to the new IMO goals and regulations is carried out. The most important energy efficiency indexes are presented with special reference to EEXI and CII, which will be operational on 1st January 2023. Furthermore, problem statement and objectives, regarding this thesis, are presented in detail.

Chapter 2: Environmental aspect

In the second chapter, the environmental effects of conventionally powered ships are analyzed, in order to highlight the need of switching to alternative fuels and various innovative energy and pollution saving technologies. Specifically, the most common and harmful types of pollutants found on the emissions of diesel engines on ships are listed and their impact on the climate change, the eco-system and the human health are described.

Chapter 3: IMO strategy and goals in relation to energy efficiency

In this chapter the IMO's means, in order to achieve its ambitious goal with zero CO_2 emissions till the end of the century, are presented. A detailed reference is made to the foremost indicators that will play an important role in this achievement. Also, a detailed analysis of EEXI scope, methods of application and its calculation formula is taken place. The calculation of the EEXI of real ships will be shown in more detail in the case studies of this paper, in Appendix 1.

Chapter 4: Technical measures for EEXI improvement

Fourth chapter analyses the available solutions for minimizing EEXI index. EEXI improvement measures if attained EEXI ≥ required EEXI, are presented in detail. EPL, ShaPoLi, ESDs, hull optimization and other innovative and energy efficient means are some of the actions that has a company to do in order to be compliant with IMO regulations from the beginning of 2023.

Chapter 5: Case studies

For the current case study, two vessels will be evaluated on their required EEXI and their currently attained EEXI. It is presented the vessels' speed operational profiles and it is analyzed their speed power curves according to EPL implementation and propeller retrofitting. The cost of retrofitting - propeller change and EPL installation - for the containership which its EEXI index was calculated and discussed in subchapter 5.2, will be calculated. A comparison of the OPEX of the non-compliant EEXI vessel and the corresponding compliant vessel will be made for the same operational speed. The fuel consumption in tones at each speed and totally per year is calculated in order to take place an economical feasibility study for the EPL implementation and propeller retrofit that it will be carried out in order to make it obvious whether this project is not only environmentally sustainable but also economically viable in the long term.

Chapter 6: Discussion

Finally, in chapter 6 conclusions on vessels' case study EEXI compliance by the means that have already been mentioned and recommendations for future investigation are presented.

2.0 Environmental aspect

2.1 Generally

Shipping is the most energy-efficient way of transportation, both for goods and people. The international shipping industry covers almost 90% of total world trade. Since the shipping industry holds a large share of the overall transport chain, as a result it also makes a significant contribution to overall global emissions. From recent studies, it is shown that CO_2, NO_X, SO_2 and PM2.5 emissions from ships correspond to about 3-4%, 15-20%, 4-9% and 3-5% of global anthropogenic emissions, respectively.

Waterborne trade continues to expand, bringing benefits for consumers across the world through competitive freight costs. However, this expansion is accompanied by increased pollution that can be divided into two major groups which are, discharges to the sea which impact the marine environment and fuel emissions to the air that impact the atmosphere.

The International Maritime Organization (IMO) is a special agency under the United Nations intended to regulate international shipping and among other things, has the responsibility to develop a comprehensive framework about the environmental impact of shipping. While IMO had issued regulations concerning the release of oil, sewage and liquid harmful substances with the Annexes I-VI of MARPOL 73/78 since 1973, the regulation of air pollution was adopted much later, in 1997 and was put into force on 19 May 2005. The provisions of Annex VI to MARPOL limit emissions of major pollutants into ships' exhaust gases, namely sulfur oxides (SOx) and nitrogen oxides (NOx), prohibit deliberate emissions of ozone-depleting substances (ODS) and regulate onboard combustion and emissions of volatile organic compounds (VOCs) from tankers.

Lately, IMO has focused on ship's energy efficiency for the purpose of decarbonization of the shipping industry. Since 2013, with the EEDI, a technical measure that requires a minimum level of energy efficiency per ton mile and applies to all new vessels from 400 GT and up, IMO has been urging shipping companies to operate their ships in a more well-regulated and strict manner. The minimum limit of EEDI is gradually tightened every five years, which is valid from 1-1-2015, in order to reduce the required EEDI to push new ships to technically achievable energy adaptations, which will also adequately protect the environment. The EEDI applies to new ships built from 2013, while for the existing ones the EEXI has been approved since June 2021 and is expected to enter into force in 2023, at the same time with CII index, as has already been mentioned in a previous chapter.

2.2 Shipping Emissions

There have been increasing concerns about the adverse impacts on the environment caused by cargo movement in international trade. Different stakeholders ranging from shippers and carriers to government bodies and international communities have expressed worries about the environmental impacts brought by shipping related activities. The pollution and waste created in the shipping processes have imposed environmental burdens and accelerated resource depletion. The air pollution places a heavy burden on the world's oceans, lakes and forests, and it is also considered to be responsible for lung cancer and asthma, among other things. The situation is set to worsen in the face of intensifying trade globalization, which has contributed to sustained growth in international shipping activities. To help protect the environment, many shipping firms have taken the initiative to find ways to lessen the environmental damage of their operations while enhancing their performance.

It is clear that for many decades the use of the Diesel engine has prevailed as the main propulsion system. The main reasons are, the high thermodynamic efficiency level in a wide range of loads, compared to the gas turbine and steam turbine, as well as its ability to operate with very low-quality fuels, resulting in it being proven in an economically viable investment. Maritime sector has been built upon the diesel engines. They are based on a mature technology with more than a century of experience; thus, they are reliable, relatively efficient, with low operating costs and with high maintainability. These engines mainly operate with heavy fuel oil (HFO) and marine diesel oil (MDO). These fuels are inexpensive; however, they are containing in high concentrations substances that are not only harmful for the engine itself but also for the environment. These substances with the process of fuel combustion are being converted into exhaust gases which are released into the atmosphere. These emissions can be grouped into two major categories:

1. Greenhouse Gases (GHGs), emissions contributing in the greenhouse effect,
2. Other emissions.

The first group consists mainly of Carbon Dioxide (CO_2), Methane (CH_4) and Hydrochlorofluorocarbons (HCFCs), whereas the second group consists of emissions such as Sulfur Oxides (SO_x), Nitrogen Oxides (NO_x), Particular Matters (PM_s), Volatile Organic Compounds (VOCs) and Carbon Monoxide (CO).

The above pollutants can further be categorized into two other categories, primary and secondary pollutants. The first come directly from the source (engine) while the later come from the primary that react with the atmosphere, mainly photochemical reactions, in a radius approximately 50 km from the source. These pollutants are mainly ozone, sulfates and nitrates.

Subsequently, the most basic from the main and secondary pollutants will be briefly analyzed:

- CO_2: is the product of the complete combustion of the carbon that a fuel contains. It is found naturally in the Earth's atmosphere, where it regulates the temperature but over the last decades due to its elevated concentrations, the average earth temperature has been increased. It is estimated that the total CO_2 emissions from the maritime sector for 2007 were equal to 1046 million tons, which was equal to 3.3% the total worldwide emissions. In addition to the effects of global warming, high levels of carbon dioxide can cause severe headaches, physical disorders, drowsiness and other symptoms. Furthermore, high CO_2 levels are directly linked to the low productivity, the high predisposition to disease and the transmission of infectious diseases, making it one of the most critical concerns.
- CO: contrary to CO_2, is the product of incomplete combustion of carbonaceous material and therefore it is emitted directly from the funnel of the ship. This is due to insufficient amount of O_2 during the combustion. CO has a lifespan of three months while it slowly oxidizes into CO_2 forming O_3 in the process. It is a colorless, odorless, tasteless and an extremely toxic gas, which is also potentially fatal even in low concentrations.
- O_3: is a secondary pollutant that results from the reactions of hydrocarbons or nitrogen oxides with the sunlight, called photochemical reaction. Ozone can affect sensitive vegetation and ecosystems with effects such as loss of species diversity, changes to habit quality and changes to water and nutrient cycles. Ozone, the main component of smoky fog (urban cloud), is responsible for some of the worst effects of atmospheric pollution. Its presence in the upper atmosphere absorbs dangerous ultraviolet radiation. In the lower atmosphere, where humans breathe and plants grow, ozone has very harmful effects on health and at the same time causes significant damage to forests and crops.
- SO_x: result from the reaction of the high sulfur content with the oxygen during combustion which forms mainly SO_2 and SO_3, with a ratio of 15:1 according to MAN B&W Diesel, 2004. Subsequently SO_3 can react with moisture (H_2O) and create sulfuric acid particles (H_2SO_4). SO_x are being regulated with either the use of low sulfur fuel (mainly LSHFO and MDO) or with the use of scrubbers. The formation of SOx compounds causes a decrease in the pH of the rain and in high concentrations leads to acid rain. Sulfur oxides are formed by the combustion of sulfur-containing fossil fuels. Marine fuels are fuels that primarily contain higher sulfur concentrations than land-based fuels. The health effects are mainly found in pulmonary problems.
- NO_x: are created from the N_2 reaction with the O_2 under high temperature and pressure during the combustion. Under ambient temperature N_2 is chemically inert and does not

react with the O_2. The byproduct is most of the times NO which is rapidly oxidized in the atmosphere to NO_2. NO_x are regulated with improvements at the combustion phase mainly with the Tier II and Tier III standards. They contribute to the creation of photochemical clouds and acid rain.

- PMs: the particulate matters are solid or liquid in nature and consist of a mixture of organic and non-organic substances, which can be soot, metal oxides and sulfates and small fuel particles that were not burned completely during the combustion phase. Their release into the air leads to the formation of aerosols that can enter deep into the lungs causing respiratory problems, mutations and cancer. PMs as a mixture of many compounds (oxides, solid residues, carbon microparticles) are common causes of cloud formation and low visibility. Especially, particulate matters less than 2.5 μm in diameter can cause serious lung problems. PMs generally comprise a wide range of particles with diameters less than 10 and 2.5 μm, PM10 and PM2.5 respectively. PMs are responsible for about 60000 premature deaths each year worldwide from cardiorespiratory problems and lung cancer, with most occurring off the coasts of Europe, East Asia and South Asia, where there is intense shipping activity with high population density.
- VOCs: Volatile Organic Compounds are organic compounds that have high vapor pressure and low solubility in water. In the maritime industry, VOCs are mainly generated in oil and chemical tankers where cargo splashes in the piping system of the ships from the source to the cargo tanks and from evaporation from the surface of oil and chemicals stored in the tanks.
- $HCFC_s$: Hydrochlorofluorocarbons are a large group of compounds whose structure is very close to that of chlorofluorocarbons (CFC_s). Under normal conditions $HCFC_s$ are liquids or gases which evaporate easily. They are generally stable compounds and do not react. $HCFC_s$ are unlikely to have a direct impact on the environment immediately after their release. They may also be slightly involved in ozone-producing reactions, which can cause damage to plants and materials, but locally.
- CH_4: due to the large involvement of LNG in the shipping industry for years, there is a high worldwide production of methane, which is a chemical gas with a high participation in the greenhouse effect. For a 100-year climate change study, methane is 25 times more active than carbon dioxide in the greenhouse effect, while for a corresponding 20-year study the rate is 76 times that of CO_2.

2.3 Greenhouse Gases

Even though only a tiny amount of the gases in Earth's atmosphere are greenhouse gases, they have a huge effect on climate. Sometime during this century, the amount of the greenhouse gas carbon dioxide in the atmosphere is expected to double. Other greenhouse gases like methane and nitrous oxide are increasing as well. The quantity of greenhouse gases is increasing as fossil fuels are burned, releasing the gases and other air pollutants into the atmosphere. Greenhouse gases also make their way to the atmosphere from other sources. Farm animals, for example, release methane gas as they digest food. As cement is made from limestone, it releases carbon dioxide.

Light is electromagnetic radiation that covers a range of wavelengths. Visible radiation covers the area from red to violet. However, there is also radiation with longer wavelengths, which covers the band beyond the red and is called infrared, as well as with shorter wavelengths, which is emitted in the zone beyond the violet, the ultraviolet radiation. Both infrared and ultraviolet radiation are not visible. Some of the energy emitted by the sun crosses the atmosphere without being absorbed, in the form of mostly visible light, and heats the surface of the earth and the sea. After the earth warms, it emits energy into space, but in the form of infrared radiation.

In the normal composition of the atmosphere there are gases, in very small quantities, such as carbon dioxide, methane and water vapor which are transparent to visible light, so they do not block sun radiation from passing through the atmosphere. But they are not transparent to infrared radiation and absorb most of the energy emitted by the earth before it escapes into space. These gases in turn re-emit infrared radiation, part of which is absorbed by the earth, thus contributing to the rise in temperature of the earth-atmosphere system. In this process the average temperature of earth's surface is about 15°C. These thermoscopic gases are called greenhouse gases. It has been estimated that if it were not for the greenhouse gases in the atmosphere, which eventually trap heat near earth's surface, the average temperature of the earth would be about -18°C.

So, gases that are in the atmosphere and absorb radiation are known GHGs. These gases make up less than 0.1% of the total atmosphere. So, a GHG is a type of gas in the atmosphere, which absorbs and emits radiation within the thermal infrared range, with this process to constitute the primary cause of the greenhouse effect. The main GHGs in earth's atmosphere are, water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and chlorofluorocarbons. (CFCs).

The warming influence of greenhouse gases in the atmosphere has increased substantially over the last several decades. In 2020, the AGGI (Annual Greenhouse Gas Index) was 1.47, representing an increase of 47% since 1990, the base year for the Kyoto Protocol (an international agreement in which countries pledged to reduce greenhouse gas emissions to below 1990 levels). Carbon dioxide (CO_2) is the largest contributor to radiative forcing. Year-to-year variations in how much the AGGI value increases generally correspond to how much CO_2 increases each year, because CO_2 is responsible for about two-thirds of the radiative forcing among all greenhouse gases.

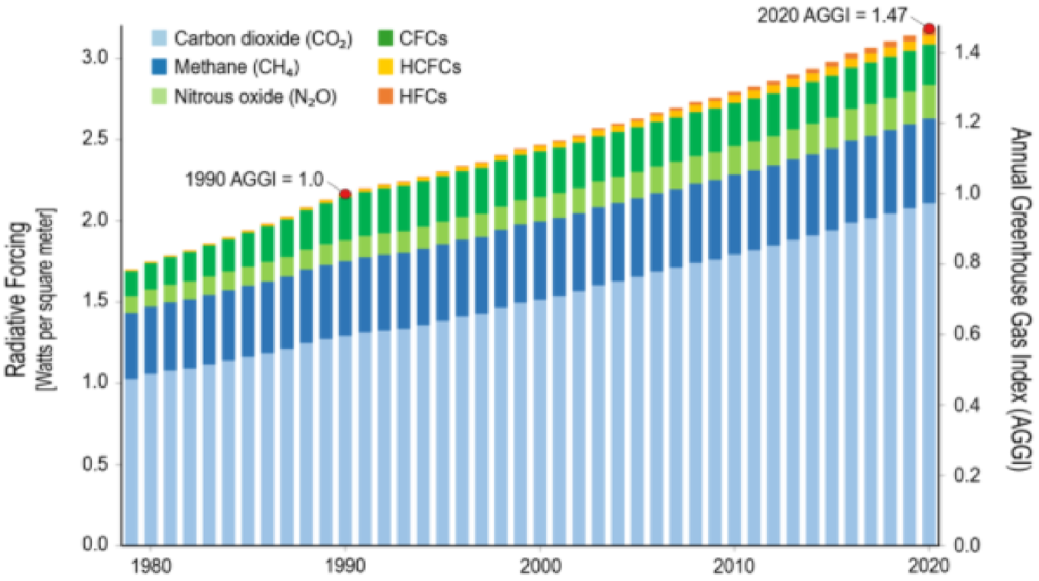

Figure 1:Radiative Forcing and AGGI

Radiative forcing (shown on the left vertical axis of the above figure) is the change in the amount of solar radiation, or energy from the sun, that is trapped by the atmosphere and remains near Earth. When radiative forcing is greater than zero, it has a warming effect; when it is less than zero, it has a cooling effect. In this indicator, radiative forcing from long-lived greenhouse gases is shown relative to the year 1750. The AGGI (shown on the right vertical axis) is an index of radiative forcing normalized to the year 1990 (represented by a red dot); it shows that the warming influence of long-lived greenhouse gases in the atmosphere increased by 47% between 1990 and 2020.

CO_2, in the concentrations we find it in the atmosphere, does not have a direct impact on human health, but it is the main cause for the most important environmental issue of our time, the greenhouse effect.

The increase in atmospheric concentrations of carbon dioxide have caused a significant periodic increase in earth's temperature for many years. As it is shown in the figure below, according to the US National Oceanic and Atmospheric Administration (NOAA), the amount of CO_2 in the atmosphere (blue line) is constantly and significantly increasing, as is human emissions (gray line), since the beginning of the Industrial Revolution in 1750 onwards. After the Industrial Revolution, human activity (fossil fuel combustion) has caused a 40% increase in CO_2 concentrations compared to the pre-industrial era (from 280 ppm in 1750 to 400 ppm in 2015). This increase has been linked to global warming and climate change, that is, to the man-made greenhouse effect.

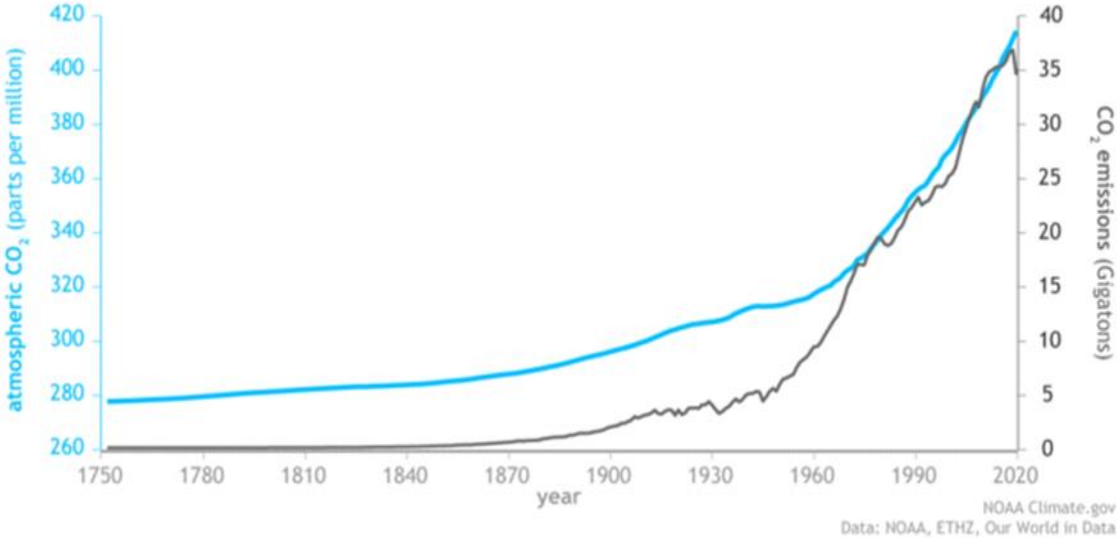

Figure 2:CO_2 in atmosphere and annual emissions

Emissions slowly increased to about 5 billion tonnes per year in the mid-20th century before rising to more than 35 billion tonnes per year by the end of the century. The world average atmospheric CO_2 in 2020 was 412.5 ppm, a level that is higher than ever in at least 800.000 years. A recent measurement in February 2022 showed 419.28 ppm, while in February 2021 was 416.75 ppm. Furthermore, the corresponding average of 2019 was 409.8 ppm, a fact that shows that there is still an increase in CO_2 concentrations in atmosphere every year.

Based on the following figure it is clear that the previous highest concentration of CO_2 was 300 ppm and in that scale the increase at today's level is instantaneous.

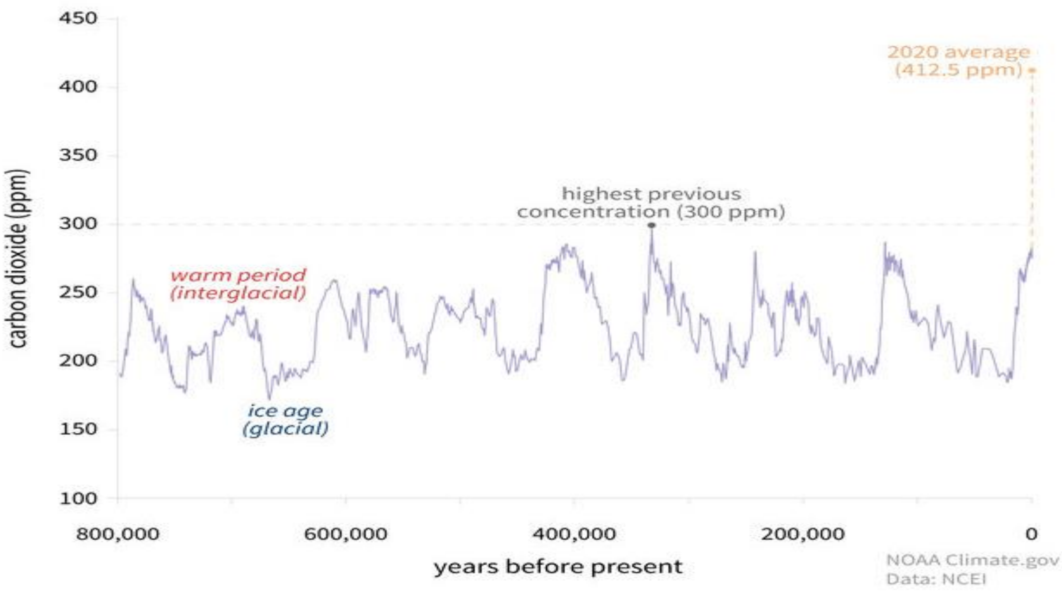

Figure 3:Carbon dioxide (CO_2) levels over the past 800000 years.

The most harmful gases that contribute to the greenhouse effect are CO_2, CH_4 and HCFCs. HCFCs were regulated mainly with the Montreal protocol and ever since are on a declining course. On the other hand, CO_2 is the main greenhouse gas and its regulation is a difficult task because, it is a product of the perfect combustion of fuels that contain carbon. Therefore, the most common methods are either to use alternative fuels that contain less carbon content (such as natural gas) compared to oil or reduce the consumption of oil fuel by a practice called slow steaming. Slow steaming is the practice of operating transoceanic cargo ships, especially container ships, at significantly less than their maximum speed, which reduces fuel consumption and offers cost reductions at shipowners.

The self-regulation of CO_2 levels is a very complicated process not well understood but there is a clear correlation between the industrial growth, based on fossil fuels and the average increase in temperature. The annual increase of global atmospheric CO_2 from 2018 to 2019 was 2.5 ± 0.1 ppm whereas for comparison reasons in the 60s this rate was equal to 0.6 ± 0.1 ppm. Overall, the annual average CO_2 concentration for 2021 was about 416.3 ppm (±0.6). With the annual rise being about 2.5 ppm – even 2020 when emissions fell sharply due to economic impacts of the Covid-19 pandemic – it is clear that 2022 will be the first year with the annual average CO_2 at 50% above pre-industrial levels.

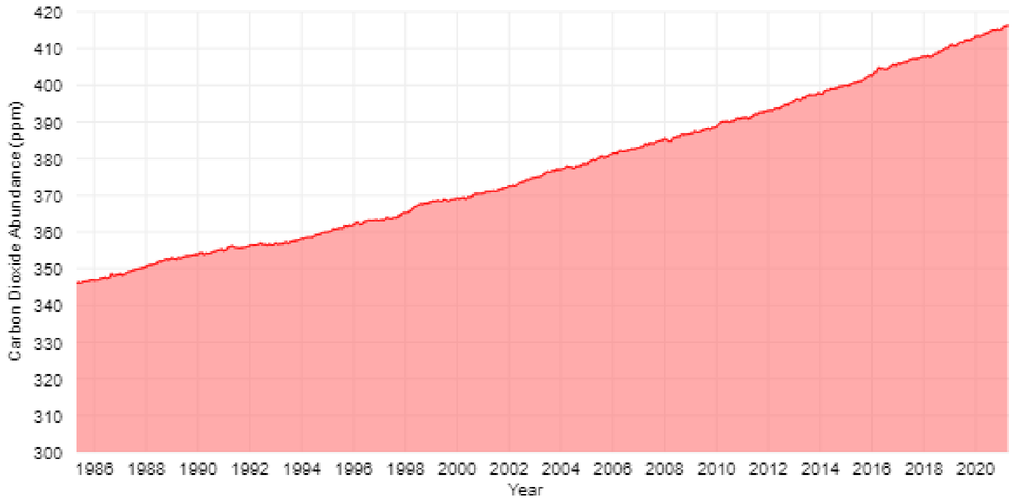

Figure 4:Increase of CO_2 concentrations from 1986.

It is worth-noting again that CO_2 is the most important of earth's long-lived greenhouse gases and whereas it absorbs less heat per molecule compared to CH_4 or N_2O it is more abundant and stays in the atmosphere much longer. Furthermore, compared to H_2O, CO_2 is less abundant but it absorbs wavelengths of thermal energy that water vapor does not, adding to the greenhouse effect in a unique way. Increases in atmospheric CO_2 are responsible for about two-thirds of the total energy imbalance that is causing Earth's temperature to rise.

The following graph from NOAA Climate.gov based on NOAA ESRL data, shows the heat imbalance caused by the main man-made greenhouse gases: carbon dioxide (gray-black, CO2), methane (dark purple, CH4), nitrogen oxide (medium purple, N2O), chlorofluorocarbons (lavender, CFCs), hydrochlorofluorocarbons (HCFCs, blue) and hydrofluorocarbons (HFCs, light blue). Compared to the conditions of 1750, the current atmosphere absorbs more than 3 Watt/m^2 of Earth's surface. Just over 80% of the imbalance is due to the combined effect of carbon dioxide (66%) and methane (16%). Nitrous oxide, which comes from the burning of fossil fuels as well as from various agricultural and industrial activities, including wastewater treatment, accounts for 6.5%. The rest of the heat imbalance is due to chlorofluorocarbons (CFCs) and related halocarbons (compounds containing carbon and halogen atoms) which were widely used in refrigeration systems and as propellant aerosols in the mid-1900s. These substances and their substitutes are now regulated under the Montreal Protocol, but they are extremely long-lived in the atmosphere, so they continue to play a vital role in earth's warming imbalance.

CO_2 concentrations increase do not only affect the average earth temperature but also the ecosystems. It dissolves into the ocean, reacting with molecules producing carbonic acid which lowers the ocean's pH. Since the start of the Industrial Revolution, the pH of the ocean's surface waters has dropped from 8.21 to 8.10, this drop is called ocean acidification. A drop of 0.1 might seem small but pH scale is logarithmic therefore a change of 0.1 means a roughly 30% increase in acidity. This acidity interferes with the ability of marine life to extract calcium from the water to build their shells and skeletons.

The forecasts concerning CO_2 are ominous. Observing the past 270 years there is a correlation between the atmospheric CO_2 and the CO_2 human emissions. The increase in atmospheric CO_2 came along with a rapid increase of manmade emissions, as it has already been mentioned. If global energy demand continues to grow and to be met mostly with fossil fuels, CO_2 is projected to exceed 900 ppm by the end of this century.

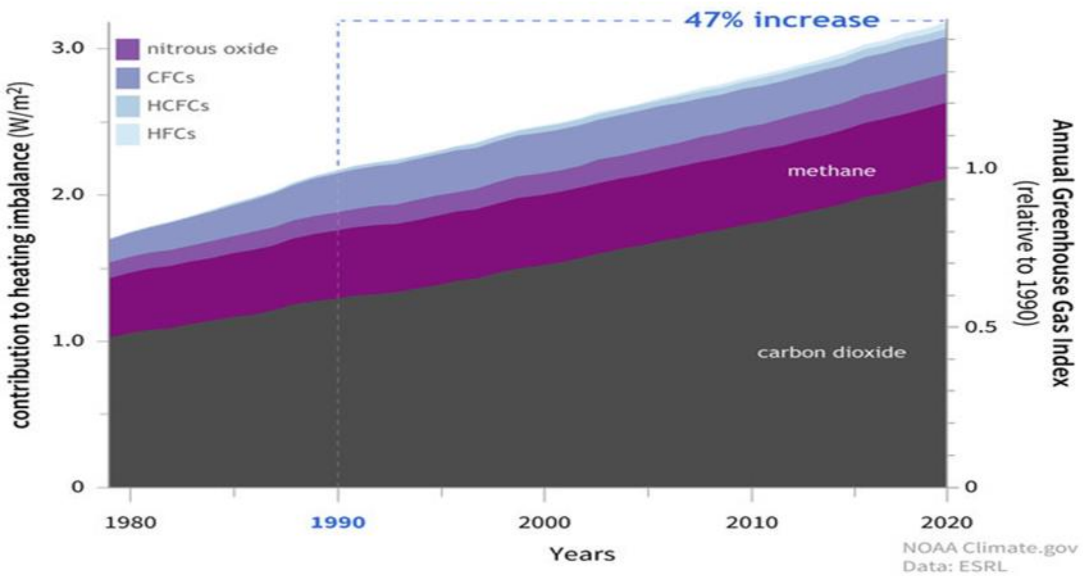

Figure 5:Combined heating influence of greenhouse gases

2.3 Impact of air pollution at eco-system and biodiversity

Ecosystems are impacted by air pollution, particularly sulphur and nitrogen emissions, and ground-level ozone as it affects their ability to function and grow. Emissions of both sulphur dioxide and nitrogen oxides deposit in water, on vegetation and on soils as "acid rain", thereby increasing their acidity with adverse effects on flora and fauna. Ultimately, acidification affects the ability of ecosystems to provide "ecosystem services", such as for example nutrient cycling and carbon cycling, but also water provision, on which the planet and human life is dependent.

Increased ground-level ozone also causes damage to cell membranes on plants inhibiting key processes required for their growth and development. The loss of plant cover affects us all. Trees and other vegetation absorb pollutants such as excessive nitrogen dioxide, ozone and particulate matter, through their leaves and needles and thereby help to improve air quality. Less plant cover thus means less filtering capacity to clean our air.

Eutrophication, the process of accumulation of nutrients, including nitrogen, in water bodies, often results from air pollution. Nutrient overloads in aquatic ecosystems can cause algae blooms and ultimately a loss of oxygen, and of life. As ecosystems are impacted, so is the biological diversity.

Even worse, ultimately human populations are also affected. Harmful concentrations of pollutants may directly enter our drinking water, notably through ground water seepage. Equally, water quality may be deteriorated as air pollution negatively affects vegetation which helps to naturally filter our water systems. Affected vegetation also has negative consequences on another important ecosystem service: that of capturing carbon and thereby reducing the impacts of climate change.

Also, pollutants like NO_x, SO_2 and suspended particulate matters are very harmful to the environment and to human's health as well. SO_2 is converted to sulfuric acid (H_2SO_4), reduces the pH of the rain and in that way acid rain is created. Acid rain depending on the pH and the exposure time, can cause damage on flora (burning of plant leaves), corrode metals and affect building materials as well. For instance, it is known that marble ($CaCO_3$) absorbs SO_2 and is converted to gypsum $CaSO_4$. Gypsum is more water soluble than marble and as a result it is drifted by the rain. Also, the molecular volume of $CaSO_4$ is bigger than $CaCO_3$ which results in cracks on the marble. Those phenomena had been observed in archeological sites such as Acropolis and for this reason not only certain statues had been removed but also regulations were imposed for the reduction of sulfuric content in heating and motor oil in the area of Athens by the 80s.

The most important nitrogen oxides which are being produced during combustion are NO and NO_2. Their main characteristic is that they contribute to the formulation of photochemical smog. Nitrogen oxides are introduced into the atmosphere, which may combine with water to form nitric acid or react with sunlight to produce singular oxygen atoms, which they combine with molecular oxygen to produce ozone. The nitric acid may precipitate to the earth resulting in acid rain as with the case of SO_x. This phenomenon is mostly observed above dense cities mainly the morning hours and is more intense during days of high sunlight. Furthermore, eutrophication, the process of accumulation of nutrients, including nitrogen in water bodies is due to excess NO_x pollutants. Nutrient overloads in aquatic ecosystems can cause algae blooms and ultimately a loss of oxygen. This impacts ecosystems along with the biological diversity.

According to Anna Maria Kotrikla, studies on the geographical distribution of maritime traffic have shown that most of the emissions take place in the northern hemisphere, within a well-defined system of international sea routes. It is estimated that 85% of maritime air emissions occur in the northern hemisphere and that 52% affect the North Atlantic and 27% in the North Pacific. It is also prognosticated that approximately 70% of shipping emissions occur within 200 nm, with 44% of these occurring within 50 nm from land (IMO, 2009).

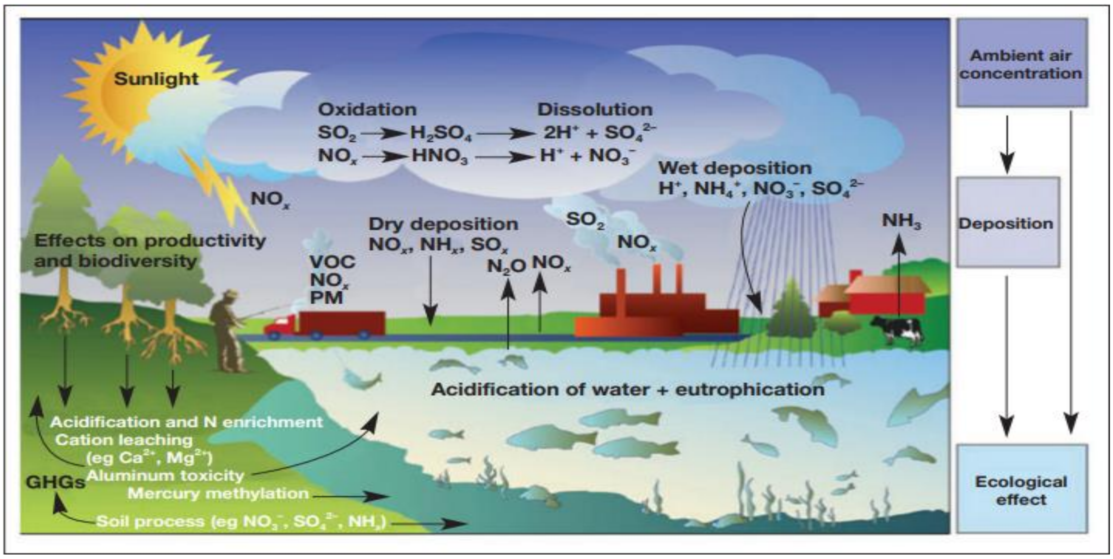

Figure 6: Simplified diagram of the ecological effects caused by nitrogen and sulfur air pollution.

2.4 Impact of air pollution on human health

Exposure to high levels of air pollution can cause a variety of adverse health outcomes. It increases the risk of respiratory infections, heart disease and lung cancer. Both short- and long-term exposure to air pollutants have been associated with health impacts. More severe impacts affect people who are already ill. Children, the elderly and poor people are more susceptible. The most health-harmful pollutants – closely associated with excessive premature mortality – are fine PM2.5 particles that penetrate deep into lung passageways.

Humans come in contact with many different air pollutants primarily via inhalation and ingestion, whereas dermal contact comes as secondary exposure. The contamination of food and water, due to air pollutants as stated previously, makes the ingestion the major route of pollutant intake.

Air pollution contributes to increased mortality and hospital admissions with recent studies stating that this is the largest environmental health risk in developed countries. Human health effects can range from nausea and breathing difficulty to heart diseases and cancer while they can also affect children with birth defects and serious development delays. There are certain groups of people that are more affected than the general population mainly those who live close to Europe's coasts, areas with intense shipping activity.

The most typical health effects of certain pollutants, according to Anna Maria Kotrikla, are:

- SO_x: aggravates asthma and can reduce lung function and inflame the respiratory tract. SO_x can cause headache, general discomfort and anxiety.
- PM: particulate matters with diameter higher than 10μm are trapped into nose and consequently are being removed from the body without any adverse effect. However, smaller particles and mainly those with 2.5 μm diameter are trapped inside the lungs and can cause aggravating cardiovascular and lung diseases, heart attacks and arrythmias and may lead to some forms of cancer. According to a study (Corbett et al., 2007), PMs from shipping activity are responsible for 60000 premature deaths every year from cardiovascular problems and lung cancer.
- NO_x: can cause breathing problems, headaches, chronically reduced lung function and eye irritation. Moreover, NO_x can affect the liver, lung, spleen and blood, and can aggravate lung diseases leading to respiratory symptoms and increased susceptibility to respiratory infection as well.
- CO: is hazardous for humans and impossible to be detected from them as it colorless and odorless. It affects not only the sensitive parts of a society like individuals with respiratory diseases, infants and elderly persons but also healthy individuals. CO enters the body through the lungs and is strongly bound to hemoglobin and therefore reduces the amount of oxygen that it can be transferred to the body's organ and tissues. People that suffer from cardiovascular disease are the most sensitive because further reduction of oxygen to the heart can cause myocardial ischemia. High concentrations of CO can cause asphyxia and eventually death even to a healthy person. Some of the most common effects of a small increase in the level of carbon monoxide are impairing exercise capacity, learning functions, ability to perform complex tasks, affected coordination, difficult concentrating and damaged visual perception.

Summarizing the main effects of air pollutants on environment and human health are:

Table 1: Air pollution and effects on human health and environment.

	SO_2, NO_x, PM, VOCs	**CO_2**
Spatial impact scale	Local, regional	Worldwide
Time impact scale	Short and long term	Mainly long term

Environmental impact	Acid rain, smog, photochemical smog	Greenhouse effect and average temperature rise, sea level rise, extreme weather conditions, impact on agriculture
Human health impact	Direct: respiratory diseases, eye irritation, asthma, chronic bronchitis, cardiovascular diseases	Indirect: rise of average temperature, extreme weather conditions, problem with water resources and agriculture

2.5 Quantitative analysis of shipping caused air pollution

It is estimated that the total CO_2 emissions from the shipping factor for the year of 2007 reached 1046 million tonnes, which represents the 3.3% of the worldwide emissions. From this quantity 870 million (2.7%) are attributed to the international shipping, where the rest is attributed to the domestic sector. Approximately 277 million tons of fuel were consumed by international shipping. Three categories of ship account for almost two-thirds of this consumption. The liquid bulk sector accounts for ~65 million tons fuel/ year, container vessels for~55 million tons fuel/year and the dry bulk sector for ~53 million tons fuel/year.

CO_2 is the most important greenhouse gas emitted both in terms of quantity and on its effect on global warming. Long-term estimations state that in the absence of reduction policies the ship emissions will increase from 150-250% due to the development of maritime sector. However, shipping is the most efficient mean of goods transportation and its CO_2 emissions per unit of energy consumption can only be compared with railway sector.

Apart from CO_2, it is estimated that shipping emitted around 25 million tonnes NO_x, 15 million tonnes SO_x and 1.8 million tonnes PM. The impact of the NO_x on the global warming is debatable because these are neutral with respect to global warming as they neither absorb nor reflect the solar radiation. However, they contribute to chemical reactions in the lower atmosphere creating O_3 which is a greenhouse gas. On the other hand, they also contribute to chemical decomposition reactions of methane (CH_4), which also is a greenhouse gas. Therefore, their contribution to the global warming effect is negligible.

SO_x in the atmosphere form sulphate particles that have the tendency to reflect the incoming solar radiation, reducing the percentage that reaches earth's surface. Furthermore, they have an indirect effect which also cools down the atmosphere. Floating particles in the atmosphere of a polluted area, become condensation cores of water vapor and contribute to the formation of clouds. In these clouds, moisture droplets have a smaller diameter than an unpolluted area. In this way the solar radiation reflected by the clouds increases, the reflectivity of clouds increases. This indirect effect of SO_x has not been quantified but it is estimated that is important.

Moreover, shipping emits soot as a percentage of particulate matter. Soot when located at the atmosphere, due to its black color, amplifies the greenhouse effect, increasing the absorption of solar radiation. This is very important for areas such as the Arctic cycle because this soot is decreasing the reflectivity of the ice, thus contributing in the local warming.

Nowadays, there are views supporting that there is no need for regulations focusing on the reduction of CO_2 and the other pollutants or at least these measures should not be stringent. However, they should take into consideration the fact that CO_2 and for instance SO_2, operate at different time scales. The sulphur particles remain in the atmosphere for only a few days whereas the CO_2 particles have a lifespan of 5 to 200 years. Therefore, the effects of CO_2 on the climate will continue to exist for a much longer period compared to the negating effects of SO_2.

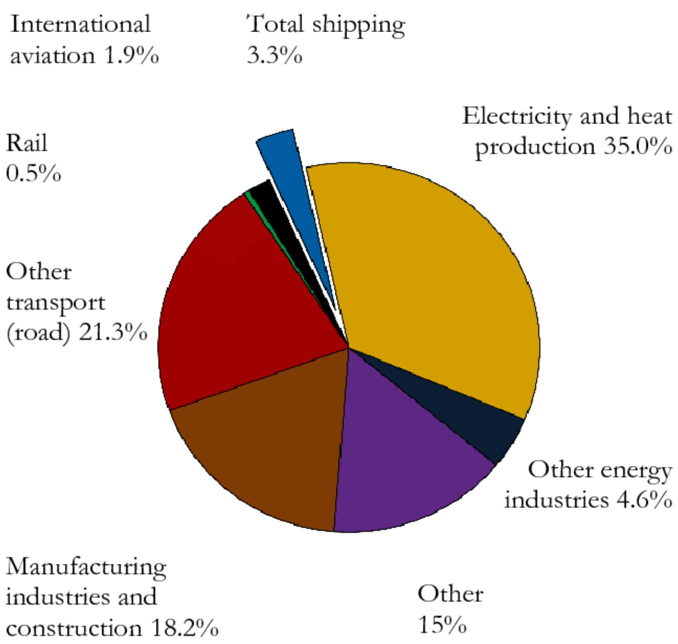

Figure 7: Emissions of CO2 from shipping compared with global total emissions

2.6 Regulations for the prevention of air pollution from ships

Scientists have warned about a potential impact of human activities and in particular of the burning of fossil fuels on the global climate system for several decades before political negotiations started on an international level in the late 1980s. Today, there is a general consensus on the existence of an anthropogenic warming of the global atmosphere and the necessity of an international climate regime to limit the emission of greenhouse gases

Although air pollution from ships does not have the direct cause and effect associated with, for example, an oil spill incident, it causes a cumulative effect that contributes to the overall air quality problems encountered by populations in many areas, and also affects the natural environment, such as tough acid rain.

MARPOL Annex VI, as it has already been mentioned, first adopted in 1997 and limits the main air pollutants contained in ships exhaust gas, including sulphur oxides (SO_x) and nitrous oxides (NO_x), and prohibits deliberate emissions of ozone depleting substances (ODS). MARPOL Annex VI also regulates shipboard incineration, and the emissions of volatile organic compounds (VOC) from tankers.

Following entry into force of MARPOL Annex VI on 19 May 2005, the Marine Environment Protection Committee (MEPC), at its 53rd session (July 2005), agreed to revise MARPOL Annex VI with the aim of significantly strengthening the emission limits in light of technological improvements and implementation experience. As a result of three years examination, MEPC 58 (October 2008) adopted the revised MARPOL Annex VI and the associated NO_x Technical Code 2008, which entered into force on 1 July 2010.

IMO ship pollution rules are contained in the MARPOL 73/78. This international convention initially contained 5 annexes:

i. Regulation for the prevention of pollution by oil, entered into force on October 2, 1983.
ii. Regulation for the control of pollution by noxious liquid substances, entered into force on October 2, 1983.
iii. Regulation for the prevention of pollution by harmful substances carried by sea in packaged form, entered into force in July 1992.
iv. Regulation for the prevention of pollution by sewage from ships, became effective on September 27, 2003.
v. Regulation for the prevention of pollution by garbage from ships, on December 31, 1998.

None of these annexes concerned the regulation of air pollution. For this reason, in 1997 the Annex VI, as has already been mentioned, was introduced which sets limits on NO_x and SO_x emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances from ships of 400 GT and above engages in voyages to ports or offshore terminals under the jurisdiction of countries that have ratified it. The states that have ratified the MARPOL 73/78 are obligated to accept Annexes I and II. Annexes III-VI are optional and require different ratification. Each one of those Annexes enters into force 12 months later, from the moment 15 countries that represent the 50% of world merchant shipping tonnage ratify it. On 18 May 2004, Samoa ratified Annex VI as the 15th country (along with Bahamas, Bangladesh, Barbados, Denmark, Germany, Greece, Liberia, Marshal Islands, Norway, Panama, Singapore, Spain, Sweden and Vanuatu).

The NO_x emission standards are defined in the Annex VI as Tier I-III standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/II standards were introduced by Annex VI amendments adopted in 2008, as follows:

- 1997 Protocol (Tier I): It applies retroactively to new engines greater than 130kW installed on vessels constructed on or after 1 January 2000, or engines which undergo a major conversion after 1 January 2000. The regulation also applies to fixed and floating rigs and to drilling platforms (except for emissions associated directly with exploration and/or handling of sea-bed minerals).
- 2008 Amendments (Tier II/III): Adopted in October 2008 introduced new fuel quality requirements beginning from July 2010, Tier II and III NO_x emission standards for new engines, and Tier I NO_x requirements for existing pre-2000 engines.

As regards, now, the revised Annex VI introduced the ECAs (North American Emission Control Area and the U.S. Caribbean Sea Emission Control Area). An ECA can be designated for SO_x, NO_x, PM or all of them. These areas include:

- Baltic Sea (SO_x: adopted 1997 / entered into force 2005; NO_x: 2016/2021)
- North Sea (SO_x: 2005/2006; NO_x: 2016/2021)
- North American ECA, most of US and Canadian coast (NO_x & SO_x: 2010/2012).
- US Caribbean ECA, including Puerto Rico and the US Virgin Island (NO_x & SO_x: 2011/2014).

Progressive reductions in NO_x emissions from marine diesel engines installed on ships are also included, with a "Tier II" emission limit for engines installed on a ship constructed on or after 1 January 2011; and a more stringent "Tier III" emission limit for engines installed on a ship constructed on or after 1 January 2016 operating in ECAs. Marine diesel engines installed on a ship constructed on or after 1 January 1990 but prior to 1 January 2000 are required to comply with "Tier I" emission limits, if an approved method for that engine has been certified by an Administration.

The revised NO_x Technical Code 2008 includes a new chapter based on the agreed approach for regulation of existing (pre-2000) engines established in MARPOL Annex VI, provisions for a direct measurement and monitoring method, a certification procedure for existing engines and test cycles to be applied to Tier II and Tier III engines.

MEPC 66 (April 2014) adopted amendments to regulation 13 of MARPOL Annex VI regarding the effective date of NO_x Tier III standards.

The amendments provide for the Tier III NO_x standards to be applied to a marine diesel engine that is installed on a ship constructed on or after 1 January 2016 and which operates in the North American Emission Control Area or the U.S. Caribbean Sea Emission Control Area that are designated for the control of NO_x emissions.

In addition, the Tier III requirements would apply to installed marine diesel engines when operated in other emission control areas which might be designated in the future for Tier III NO_x control. Tier III would apply to ships constructed on or after the date of adoption by the Marine Environment Protection Committee of such an emission control area, or a later date as may be specified in the amendment designating the NO_x Tier III emission control area.

Further, the Tier III requirements do not apply to a marine diesel engine installed on a ship constructed prior to 1 January 2021 of less than 500 gross tonnage, of 24 m or over in length, which has been specifically designed and is used solely, for recreational purposes.

Revisions to the regulations for ozone-depleting substances, volatile organic compounds, shipboard incineration, reception facilities and fuel oil quality were also made with regulations on fuel oil availability added.

The revised measures are expected to have a significant beneficial impact on the atmospheric environment and on human health, particularly for those people living in port cities and coastal communities.

The NO_x emission limits apply to each marine diesel engine with a power output of more than 130kW installed on a ship. These limits are set for diesel engines depending on the engine maximum operating speed (n, RPM) as shown in the table below. Tier I and Tier II limits are global whereas the Tier III limits apply only in NO_x Emission Control Areas.

Table 2: NOx emission limits.

Tier	Date	NO_x limit, g/kWh		
		$n < 130$	$130 \le n < 2000$	$n \ge 2000$
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016	3.4	$9 \cdot n^{-0.2}$	1.96

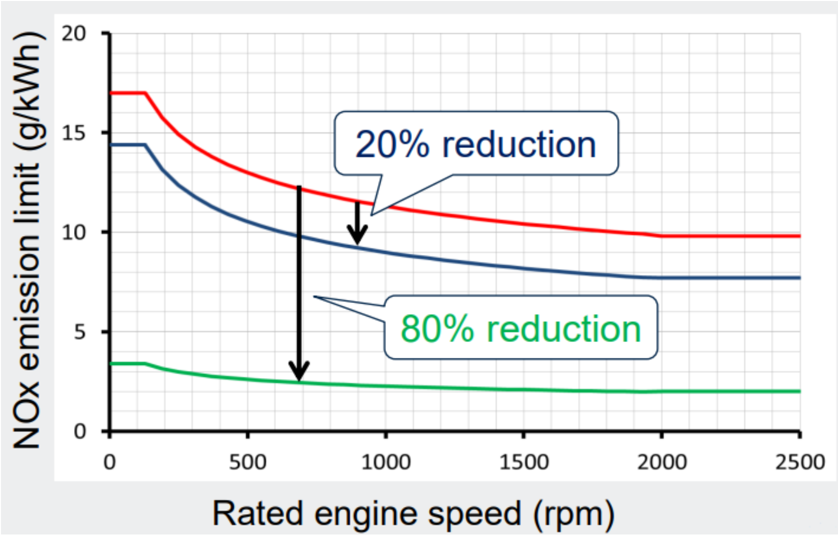

Figure 8: NOx emission limits with respect to engine speed n (RPM).

Annex VI regulations include caps on sulphur content of fuel oil as a measure to control SO_x emissions and indirectly PM (without having explicit PM emission limits). Special fuel quality provisions exist for SO_x Emission Control Areas (SECAs).

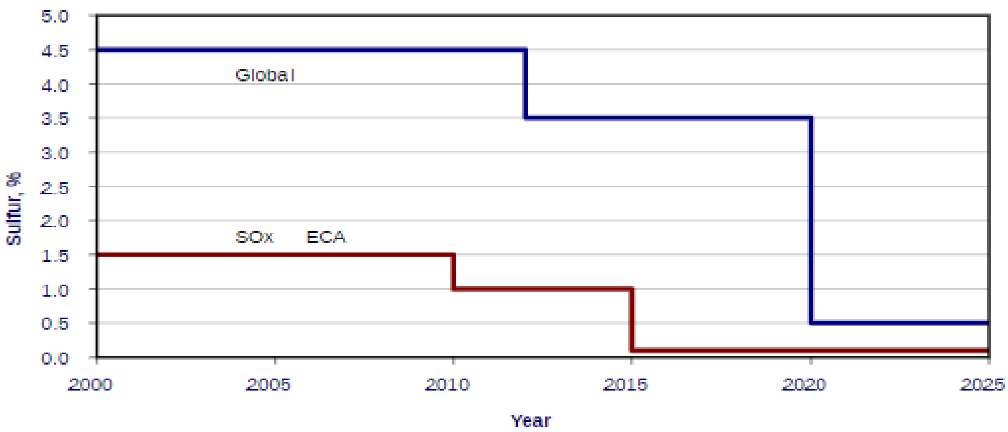

Figure 9: Sulphur emissions limits with respect to years.

Table 3: MARPOL Annex VI fuel sulphur limits.

<table>
<tr><td rowspan="2">Date</td><td colspan="2">Sulphur limit in fuel (% m/m)</td></tr>
<tr><td>SO_x ECA</td><td>Global</td></tr>
<tr><td>2000</td><td>1.5%</td><td rowspan="2">4.5%</td></tr>
<tr><td>2010.07</td><td rowspan="2">1.0%</td></tr>
<tr><td>2012</td><td rowspan="2">3.5%</td></tr>
<tr><td>2015</td><td rowspan="2">0.1%</td></tr>
<tr><td>2020</td><td>0.5%</td></tr>
</table>

In summary, the provisions of MARPOL Annex VI are:

- 2005 Tier1 NOx for new engines post 2000
- 2010 ECA fuel sulphur 1% (currently 1.5%)
- 2011 global Tier 2 NOx for new engines (IMO Tier 1 less 15 to 20%) (engine tuning)
- 2012 global fuel sulphur 3.5% (currently 4.5%)
- 2015 ECA fuel sulphur 0.1%
- 2016 ECA Tier 3 NOx for new engines (IMO Tier 1 less 80%) (exhaust gas aftertreatment)
- 2020 global fuel sulphur 0.5% - if refineries can produce it, review in 2018
- Tier 1 NOx for engines greater than 5MW installed 1990 to 2000 (conversion kits)
- Under Annex VI, exhaust gas scrubbers can be used as an alternative to low sulphur fuel
- Reduced sulphur content will reduce fine particulate emissions significantly.

EEDI and other provisions were adopted at the 62nd MEPC Session, by Resolution MEPC.203(62).

On 1 January 2013, the provisions of the new Chapter 4 of MARPOL Annex VI entered into force, which introduces measures aimed at improving the energy efficiency of shipping in order to reduce fuel consumption and CO2 emissions. Regulation 21 of Chapter 4 introduces the Energy Efficiency Design Index (EEDI), which mainly concerns technical measures and is mandatory for new ships, while Regulation 22 introduces a mandatory Ship Energy Efficiency Management Plan (SEEMP), which mainly concerns operational measures, for all ships (new and existing). In order for a ship to obtain the International Energy Efficiency Certificate (IEEC), it must comply with the requirements for the EEDI and SEEMP.

In conclusion, the 76th session of the IMO’s Marine Environment Protection Committee (MEPC 76) was held remotely with a limited agenda from 10 to 17 June 2021. MEPC 76 adopted technical and operational measures to reduce carbon intensity of international shipping, taking effect from 2023. The measures include the Energy Efficiency Existing Ship Index (EEXI), the enhanced Ship Energy Efficiency Management Plan (SEEMP) and the Carbon Intensity Indicator (CII) rating scheme, which are to be discussed in the next chapter.

3.0 IMO strategy and goals in relation to energy efficiency

3.1 IMO measures

IMO has an ambition to halve GHG emissions by 2050 and a vision to decarbonize shipping as soon as possible within this century. In that order IMO has implemented certain measures. The existing measures are:

- The Energy Efficiency Design Index (EEDI) is applied to new ship designs after 1 January 2013 and it is a performance-based mechanism that requires a certain minimum energy efficiency in new ships. The level is to be tightened incrementally every five years in order to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase. Ship designers and builders are free to choose the technologies to satisfy the EEDI requirements in a specific ship design.
- The Ship Energy Efficiency Management Plan (SEEMP) for all ships above 400 GT in operation – although it contains no explicit and mandatory requirements for content and implementation.
- The Fuel Oil Consumption Data Collection System (DCS), mandating annual reporting of CO_2 emissions and other activity data and ship particulars for all ships above 5000 GT.

As mentioned above, EEDI is applied to new ship designs after 2013, however there is the need for an energy efficiency measurement for existing ships. In that order IMO adopted in June 2021 and will put into force on 1 January 2023 the three following measures:

- The retroactive application of the EEDI to all existing cargo ships above a certain size, known as the Energy Efficiency Design Index for Existing Ships (EEXI). This will impose a requirement equivalent to EEDI Phase 2 or 3 (Phase 2 – ships built between 2021-2025 and Phase 3 2025 – onwards), with some adjustments to all existing ships regardless of year of build and is intended as a one-off certification.
- A mandatory Carbon Intensity Indicator (CII – e.g., Annual Efficiency Ratio [AER – grams of CO_2 per dwt-mile]) and rating scheme where all cargo and cruise ships above 5000 GT are given a rating of A to E every year. The rating thresholds will become increasingly stringent towards 2030. For ships that achieve a D rating for three consecutive years or an E rating a corrective action plan needs to be developed as part of the SEEMP and approved.
- A strengthening of the SEEMP (Enhanced SEEMP) to include mandatory content, such as an implementation plan on how to achieve the CII targets and making it subject to approval.

The ultimate goal of IMO is very clear and that is to reach 100% decarbonization of the shipping industry as quickly as possible and certainly by the end of the century. To set up on this path, IMO has established two intermediate targets. The first is to reduce carbon intensity (tCO_2/ton-mile) by 40% by 2030 with respect to the 2008 baseline, and by 70% by 2050 for individual vessels. The second target is for the total reduction in GHG emissions by 50% from the shipping industry by 2050, also compared with the 2008 baseline. When put in the context of the continuing growth of the world fleet, it seems that achieving the second target would be more challenging than the first. To achieve these intermediate targets, IMO has developed short-term, mid-term and long-term measures.

Until 2023 Short-term measures

- Improvement of EEDI and SEEMP
- Develop technical and operational energy efficiency measures for both new and existing ships with a three step approach (EEDI, EEXI, CII).
- Existing Fleet Improvement Program
- Speed optimization and reduction
- Measures for methane and VOCs
- National Action Plans, Technical cooperation and capacity-building, Port development (AMP etc.), R&D activities, incentives for first movers, Lifecycle guidelines for fuels, GHG study

2023-2030 Mid-term measures

- Program for alternative fuels
- Operational energy efficiency measures for both new and existing ships
- Market Based Measures (MBM), "CO_2 tax"
- Technical cooperation and capacity-building, Feedback mechanism

Beyond 2030 Long-term measures

- Zero-carbon or fossil-free fuels
- Emission Reduction Mechanism

Decarbonization involves alternative fuels and operations that introduce new risks. Moreover, a safe and timely transition to a carbon-neutral future may be compromised if safety risks are not taken into account. The successful introduction of alternative fuels depends on the development of effective safety regulations and the ability to implement a safety culture where all stakeholders take responsibility for handling the new challenges

At this point it should be emphasized that EEXI and CII will be adopted in 2023 and there will not be any delay. As far as we understand these measures will be implemented and shipping companies will have to comply. For those that don't, it is likely that penalties will be applied. In the same way incentives will be given to high-efficiency vessels. This means that it would be the energy-efficiency shipping companies that will survive into the future. And so, the development and adoption of eco-technology is essential.

Currently, new-build vessels must comply with EEDI, which means they must reduce speed and implement low carbon-fuel systems or energy saving devices to reduce their GHGs emissions. However, existing ships are not subject to the same restrictions. This is significant, when we consider that 70% of the current fleet does not need to comply with EEDI. EEXI is being implemented to balance the fleet and to reduce overall GHG emissions. EEDI regulation for new-build vessels were brought into force from phase 0 in 2013, reduction rate 0%, from phase 1 in 2015, reduction rate 10%, from phase 2 in 2020, reduction rate 20% and phase 3 will start 2025, reduction rate 30%.

EEXI will start from 2023 and a reduction rate is set up between phase 2 and phase 3, or 20% to 30%. For Pre-EEDI ships, the gap for reduction rate to target EEXI is 20-30%, and more in order to satisfy target EEXI. As far as EEDI phase 0 ships are concerned, the reduction rate gap to fill is to be within 20-30%. Most of the phase 2 and 3 ships seem to be able to satisfy EEXI.

Technically speaking, it is expected that most pre-EEDI ships may not satisfy EEXI, as doing so requires significant improvements in energy efficiency. It must be noted too that some EEDI ships may also not be able to meet EEXI requirements, and therefore, would need various degrees of improvement.

EEXI is a technical measure, or it means that ships should have good energy performance technically. However, IMO is going a step further and requires the ships actual GHG emissions to be evaluated by means of CII. CII is an operational measure and its calculation based on IMO DCS data or actual fuel consumption over the previous year. Each vessel will then be rated from A to E. The actual fuel consumption will depend on the ship's technical performance and how it is operated.

Corrective actions and SEEMP revision are needed for ships rated as D for 3 consecutive years or rated as E for just one time. The chart shows that the required CII is getting lower and lower every year. Therefore, if a conventional ship begins with a C rating, the same vessel is likely to be ranked with the D rating after a number of years if no additional efficiency improvements have been made. Reducing speed is most likely meant to maintain the rating. However, LNG fuel ships with good energy efficiency and starting out with an A rating, will take many years for the rating to be downgraded to B or C. These vessels will not need to reduce the speed to maintain their good rating. This benefits the shipping business.

3.2 EEDI

The EEDI index is mandatory for all new vessels of 400 GT and above. It is a mathematical formula that expresses the ratio between the cost (i.e., CO_2 emissions) and the profit generated, expressed as the capacity to transport goods, by the operation of the ship. CO_2 emissions are assumed to come from the main engines and auxiliary (secondary) engines, after deducting the emissions attributable to the power offered by the use of the corresponding innovative technologies. The profit generated is considered to be the cargo carried multiplied by the speed of the vessel.

$$\text{EEDI} = \frac{Cost\ for\ the\ environment}{Benefit\ for\ society} = \frac{CO_2\ emissions}{Transport\ work}$$

More specifically, the EEDI can be expressed by the following equation:

$$\text{EEDI} = \frac{P \times SFC \times C_F}{Capacity \times V_{ref}},$$ and now assuming some indeterminate factors:

$$\text{EEDI}=$$

$$\frac{\left(\prod_{j=1}^{M} f_j\right) \sum_{i=1}^{nME} \left(P_{ME_{(i)}} C_{FME_{(i)}} SFC_{ME_{(i)}}\right) + (P_{AE}\, C_{FAE}\, SFC_{AE}) + \{(\prod_{j=1}^{M} f_j \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)}\, P_{AEeff(i)})C_{FAE}\, SFC_{AE}\} - (\sum_{i=1}^{neff} f_{eff(i)}\, P_{eff(i)})C_{FME}}{f_i f_c f_l Capacity v_{ref} f_w}$$

In this equation there are the following parameters relating to the ship's engines:

- P is the power of the ship's main (ME) and auxiliary (AE) engines (in kW). $P_{ME_{(i)}}$ is the power of the main engines at 75% of the MCR (Maximum Continuous Rating). The Regulation specifies that the effect of the shaft motor on Power Take In (PTI) and the shaft generator on Power Take Off (PTO) must be taken into account. $P_{AE_{(i)}}$ is the power of the auxiliary engines.
- $P_{PTI_{(i)}}$ is 75% of installed power for each energy consuming device.
- $P_{eff_{(i)}}$ is 75% of the reduction in engine power (kW) due to innovative energy efficiency engineering technologies.
- $P_{AEeff_{(i)}}$ is the auxiliary engines power reduction due to usage of innovative technologies
- n_{ME} is the number of main engines
- n_{PTI} is the number of energy consuming devices
- n_{eff} is the number of innovative technologies

There are also design parameters of the ship:

- V_{ref} is the speed (by design of the ship) in nautical miles per hour (knots) in the maximum loading condition, assuming deep water, calm sea and no wind.
- Capacity [t] is defined as:
    1. the DWT for bulk carriers, tankers, LPG and LNG carriers, car carriers, general cargo, refrigerated cargo and combined transport vessels,
    2. 70% of DWT, for container ships,
    3. the Gross Tonnage for passenger ships and cruise ships.

There are also parameters relating to CO_2 emissions:

- C_F is a dimensionless emission factor based on the carbon content of the fuel and gives the amount (in g) of CO_2 emitted from the combustion of a quantity of fuel (also in g).
- SFC (Specific Fuel Consumption) (in g/kWh) is the Specific Fuel Consumption, i.e., the amount of fuel consumed by the engine per unit of energy delivered. SFC_{ME} and SFC_{AE} are the specific fuel consumptions in gr/kWh for Main and Auxiliary Engines. The values are derived from the EIAPP certificate in combination with the NOx files of the Engine at 75% of the MCR (Maximum Continuous Rating) for the main engine and 50% for the auxiliaries. If there are engines of different types, then the average is used.

Finally, there are correction or adjustment factors:

- f_j is a dimensionless factor that relates to design features of ships that lead them to show variations in installed propulsion power (e.g., ice-classed ships or shuttle tankers).
- f_w is a dimensionless factor which takes into account the reduction in speed in typical sea conditions, with a given wave height, wave frequency and wind speed.
- $f_{eff(i)}$ is an availability factor for each innovative energy-saving technology, which depends on the percentage of time the technology is available during the cruise.
- f_i is a capacity factor to take into account the limitations in the capacity of a vessel resulting from regulations and technical specificities (e.g., ice-classed vessels).
- f_c is a correction factor for cubic capacity and is considered equal to unity. It is different in the case of ships carrying chemicals or LNG.
- f_l is a factor for general cargo ships equipped with cranes and other loading and unloading machinery, which accounts for the loss of DWT of the ship.

The carbon content of different fuel types and the emission factor CF are given in Table 4.

Obviously, it is desirable to minimize the costs and maximize the benefits of a ship. The EEDI values should therefore be gradually reduced. In order to be able to set a reduction framework, it is necessary to establish:

- The initial EEDI values those ships achieved with the design they had before the MARPOL Annex VI CO_2 emission provisions came into force (i.e., before 1/1/2013). In particular, it is necessary to determine, using statistical methods, the "average values" that the EEDI was obtained for existing ships, for each ship category. To this end, in 2012 the IMO adopted MEPC 215(63) "Guidelines for Calculation of Reference Lines for use with the Energy Efficiency Design Index (EEDI)", which outlines how to calculate the reference lines.
- The required reduction percentages relative to these initial or reference values and how these will vary gradually over time.

Table 4: Carbon content and emission factor for various marine fuels, by MEPC (2014).

Fuel Type	Reference	Carbon content	C_F (tones-CO_2/tonnes-fuel)
Diesel/Gas Oil	ISO 8217 Grades DMX to DMC	0,8744	3,206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA to RMD	0,8594	3,151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME to RMK	0,8493	3,114
Liquefied Petroleum Gases (LPG)	Propane	0,8182	3,000
	Butane	0,8264	3,030
Liquefied Natural Gas (LNG)		0,75	2,750

In order to create the reference EEDI curve, the Lloyds' Register Fairplay database was used for ships that were delivered between 1/1/1999 and 1/1/2009 with gross tonnage above 400 GT. A typical reference EEDI curve for tankers is being displayed below:

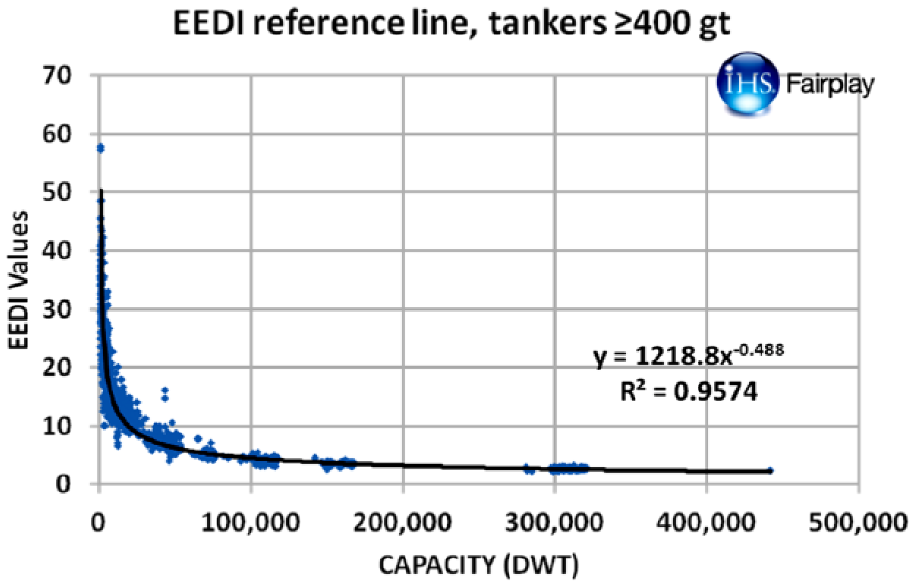

Figure 10: EEDI reference curve for tankers.

There are 3 simple ways to achieve an improved EEDI:

1. Speed reduction. The necessary engine power is proportional to the speed's velocity raised on the third degree ($P = a \cdot V^3$). Thus, a speed reduction can decrease the required power by a lot and consequently the EEDI value.
2. DWT increase. For an increased DWT the required increase in power is not proportional but raised to 2/3. Therefore, the increase in the denominator in the above formula is bigger than the increase in nominator. Also, it must be noted that a vessel with higher capacity might be imposed to a reduced reference EEDI.
3. Application of new technologies which do not affect or impose restrictions in functional or design parameters.

EEDI, as it has already been mentioned, came into force on 1 January 2013 and was followed by an initial two-year phase-out. The IMO calculated the required EEDI values based on baselines developed using average energy efficiency data from ships built between 2000 and 2010. Once a baseline was developed, the required EEDI of a particular ship was calculated using a reduction factor. This reduction was consistent with the IMO's 30% reduction in CO_2 emissions for 2030.

To achieve a smooth transition, the target was set in 3 phases which are shown in the following figure. Under the regulations, every five years the required EEDI level would be further enhanced by reducing the allowable CO_2 emissions per ton per nautical mile. As shown in the graph, various reduction rates have been set until 2025 and beyond, when most ship types will be required to be 30% more efficient compared to the baseline. We can observe that we are currently in phase 2. This means that new ships should be 15-20% more energy efficient than their counterparts built before 2013.

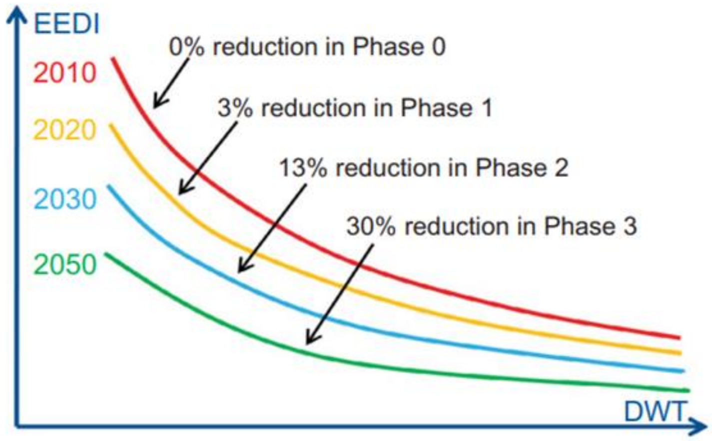

Figure 11: An illustration of the IMO-phased approach for attained EEDI values.

While EEDI is a very useful tool as it is the first attempt to create a measurement that focuses on the CO_2 emissions from a certain mean of transportation it has certain disadvantages. First of all, it is debatable to what extent the reference curves are valid, since it is not mandatory for the shipowners to provide data concerning the operation of their vessels. There is the possibility that a new database might be created with valid data from the shipowners, the classification societies and the shipyards. Furthermore, the initial EEDI (phase 0) was not stringent enough and the vessels that were created during that phase will approximately operate until 2040, assuming a mean lifespan of 25 years. Therefore, the real benefit from the EEDI might require one to two decades to be observable. Finally, the third problem is that the developing countries (mainly China, Brazil, India, South Africa and Saudi Arabia) have expressed their objections concerning the universal adoption of a common index. They express that the developed countries are responsible for the higher percentage of CO_2 emissions and thus they require to be excluded from the developing EEDI framework, or adopt it with more favorable terms. However, an emission reduction strategy with different criteria per country is ineffective for shipping, as ships can easily change flags.

3.3 SEEMP

The Ship Energy Efficiency Management Plan is a mandatory operational measure which establishes a mechanism to improve the energy efficiency of the ship in a cost-effective manner. SEEMP was made mandatory by IMO for all ships over 400 GT in international voyages as of 1/1/2013 and is required for the issuance of the International Energy Efficiency Certificate (IEEC).

Each ship will be required to have an on-board SEEMP, which will have been developed taking into account the specific characteristics. The SEEMP should not be seen as just another bureaucratic procedure, but as an ideal opportunity for the ship operator to reduce fuel costs by improving the energy efficiency of the ship.

The development and implementation of the SEEMP is a cyclical process involving four main stages:

- design
- implementation
- monitoring
- self-evaluation and improvement

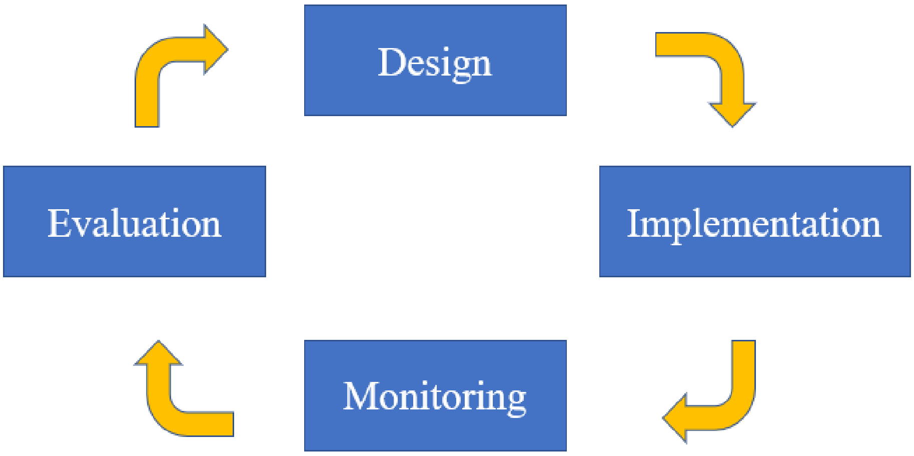

Figure 12: The stages of SEEMP development and implementation.

In what has to do with SEEMP requirements (New Reg. 26), on or before 1 January 2023 the ship list presented in the sub-chapter 3.6 with the addition of cruise having conventional propulsion of 5000 GT and above engaged in international voyages shall include in the SEEMP:

- a description of the methodology that will be used to calculate the ship's Attained annual operational Carbon Intensity Indicator (CII) and the processes that will be used to report this value to the ship's flag Administration
- required annual operational CII for the next 3 years
- an implementation plan documenting how the Required annual operational CII will be achieved during the next 3 years, and
- a procedure for self-evaluation and improvement

Confirmation of compliance shall be provided by the Administration/RO and retained onboard prior to 1 January 2023.

The SEEMP of these ships shall be subject to verification and Company audits taking into account the Guidelines which are still to be developed

3.4 EEOI

The Energy Efficiency Operational Indicator (EEOI) is proposed to monitor the energy efficiency of the ship. It is obvious that a 30% decrease in EEDI cannot singlehandedly achieve the required 50% reduction, therefore operational indexes are going to be used to cover the rest of the distance. EEOI and CII are both indexes that contain operational data from the ship. The EEOI is a voluntary indicator that can be used to monitor the SEEMP. The EEOI can be affected by changes in ship operations, unlike the EEDI, which is related to ship design features. Specifically, EEOI uses the actual CO_2 emissions and the actual ship's transport workload during a voyage. Since it is possible that a voyage may be energy wasteful, the index can be calculated by taking a number of voyages into account to obtain an average.

EEOI is an operational index that is usually measured on a yearly basis. EEOI, as it mentioned above, is equal to the emitted CO_2 divided by the product of the transported cargo with the transported distance. This index is the one most accurately representing ship efficiency, but it is the one harder to implement and regulate. This index is highly fluctuating according to the chartering profile of the ship and thus it involves the cooperation of two interested parties in shipping, making it harder to regulate. EEOI analytic formula is the following:

$$\text{EEOI} = \frac{\Sigma_{CO_2} emmited}{\Sigma_{cargo\ trasported}\ distance\ travelled}$$

The lower the index, the more energy efficient the operation of a ship. More specifically, for a voyage, the EEOI is calculated on the basis of the following equation:

$$\text{EEOI} = \frac{\Sigma_j FC_j C_{Fj}}{m_{cargo} D}$$

Where:

- j is the fuel type,
- FC_j is the mass of fuel consumed on the journey (in tonnes)
- C_{Fj} is the emission factor representing the mass of CO_2 emitted from the combustion of a given mass of fuel (dimensionless quantity, in tonnes CO_2/tonnes of fuel)
- m_{cargo} is the cargo carried on the voyage (in tonnes) or the work performed (number of TEU or passengers) or GT for passenger ships
- D is the distance in nautical miles for the cargo carried on the voyage or the work performed

The EEOI units depend on the cargo transported or the work performed and can be tonnes CO_2/ (tonnes 🕐 nm), tonnes CO_2/ (TEU 🕐 nm), tonnes CO_2/ (person 🕐 nm) etc.

The main difference with the EEDI index is that it is now captured in real numbers consumption figures to show how efficient a ship is and not the theoretical consumption values of the main engine and generators. The influence of weather conditions is now actually reflected in the consumption and not by correction factors. These differences are capable of leading to large discrepancies between the two indicators.

3.5 CII

The Carbon Intensity Indicator, known and referred to by the acronym CII, and the according rating scheme are requirements addressing to the operational efficiency and applying to all cargo, Ro-Ro Pax and cruise ships of 5000 gross tonnage (GT) and above trading internationally, already subject to the requirement of the IMO Data Collection System (DCS) for fuel oil consumption of ships. The calculation of CII is performed annually, starting in 2023, based on the reported IMO Data Collection System and the performance level should be recorded in the ship's SEEMP. The International Maritime Organization (IMO) has adopted 4 sets of guidelines for the proper implementation of CII concerning the operational Carbon Intensity Indicators and the calculation methods (G1), the reference lines for use with operational Carbon Intensity Indicators (G2), the operational Carbon Intensity reduction factors relative to reference lines (G3) and eventually the operational Carbon Intensity rating of ships (G4).

So, CII is a measure of a vessel's operational efficiency or how efficient is being operated based on the actual amount of fuel consumed per year. It is a calculated score and is measured with two potential ways: 1) the AER (Annual Efficiency Ratio) for cargo vessels or 2) the cgDist (Capacity gross-tonnage Distance) for passenger or non-cargo carrying vessels.

The units of score are the same as that for the EEXI which are grams CO_2 per ton-Nautical mile (gCO_2/t. Nm), effectively measures the amount of CO_2 created per unit of cargo carried certain distance. This score, which is shown below, is actually calculated from the consumption and distance traveled data provided to the IMO DCS every year and this DCS is a requirement which is in force since 2019.

So, the difference between EEXI and CII is a difference between theoretical amount of CO_2 a vessel might produces based on design, and the actual amount based on the fuel it has consumed ant it is following the basic formula for it:

$$\text{CII} = \frac{Annual\ CO_2\ mass}{Distance\ x\ DWT}$$

CII which is based on AER calculation is similar to EEOI, where it was previously analyzed, but there is a key difference. Below comparing the two scores, where we can see that fuel consumed fuel type distance traveled, that data is all the same and we have taken the information from DCS. But the key difference is that EEOI uses the actual amount of cargo carried as the capacity, but on the other hand CII uses the vessel's deadweight. So EEOI is more accurate in terms of carbon produced, but the CII is easier to calculate. The EEOI is in use as a measure of efficiency with non-regulatory organizations and it is not a statutory requirement, where CII is a statutory requirement and is in force through the flag states on the recognized organizations. In the last row of the table below we can see an example difference of the attained EEOI and the attained CII score for a vessel.

Table 5: EEOI vs CII

EEOI	**CII**
Fuel consumed Fuel type Distance traveled	Fuel consumed Fuel type Distance traveled
Total cargo carried	Vessel deadweight
Non – regulatory companies / Organization Not a statutory requirement	IMO a statutory requirement
Example: 7.43 gCO_2/ t. nm	Example: 3.22 gCO_2/ t. nm

To summarize what the CII index is all about, in essence the ship is given an annual rating ranging from A to E, whereby the lower assessment thresholds will become increasingly stringent towards 2030. The CII applies to all cargo, Ro-pax and cruise ships over 5000 GT. A ship rated D or E for three consecutive years will be required to submit a corrective action plan to show how the required index (C or higher) will be achieved. The draft agreement also provides that the IMO will review the effectiveness of the implementation of the CII and EEXI requirements no later than 2026 and, if necessary, develop and adopt further

Now in what has to do with the operational carbon intensity – indicators and rating (New Reg. 29) the ship list presented in the sub-chapter 3.6 with the addition of cruise having conventional propulsion of 5000 GT and above shall:

- from 2023, after the end of each calendar year, calculate the Attained annual operational CII over a 12-month period from 1 January to 31 December in that calendar year and electronically report to its Administration/ RO within March of each calendar year; and

- calculate the Required annual operational CII as (1-Z/100) x CIIR, where the annual reduction factor Z is a flat rate for all ship types (i.e., 5% for 2023; 7% for 2024; 9% for 2025; 11% for 2026 and % still to be decided for 2027-2030) and the reference values CIIR are calculated according to the IMO Guidelines.

The administration/RO shall verify the Attained annual operational CII against the Required annual operational CII to determine operational carbon intensity rating A, B, C, D or E. The middle point of rating level C shall be the value equivalent to the required annual operational CII.

As it has already been mentioned, a ship rated D for 3 consecutive years or rated as E shall develop a corrective action plan to achieve the required annual operational CII. Such a plan shall be included in the SEEMP which shall be submitted to the Administration/RO for verification within 1 month after reporting the Attained annual operational CII.

3.6 EEXI

The Energy Efficiency Existing Ship Index (EEXI), which is one of the two major regulatory changes approved by IMO at MEPC June 2021, as has already been mentioned, measures CO_2 emissions per transport work, purely considering the ship's design parameters. EEXI does not require any measurement or reporting of true CO_2 emissions while the ship is in operation. EEXI is similar to EEDI, which has been in force since 2013. These indexes measure the same in practice; however, EEDI is applied to new ships while EEXI applies to existing vessels. EEXI regulation is one of the most significant measures by the IMO to promote more environmentally friendly technologies and reduce the shipping industry's carbon footprint.

The EEXI is considered to be the extension of EEDI for existing ships, regardless of their delivery date. In addition, the simplified version of the EEXI mathematical formula also depicts the ratio of CO_2 emissions per unit of transport work. In particular, the EEXI is a design index that determines the standardized CO_2 emissions related to installed engine power, transport capacity and ship speed (DNV).

EEXI is a calculated score to measure the overall energy efficiency of a vessel's design. It only applies to vessel designs. It has to do with the technology and equipment on board and not how it goes. As previously stated, it is the same as EEDI, but retrospectively applies to all vessels. The smaller the EEXI the more energy efficient the design of the vessel.

The IMO have agreed on amendments to Marpol that require all vessels above 400 GT to:

- Calculate the EEXI and develop an EEXI technical file for the vessel. This calculated EEXI will be known as the “Attained EEXI”.
- Have the calculation verified by the flag administration or a recognized organization.
- Ensure the Attained EEXI is below the Required EEXI, as defined by vessel’s type and size. If the vessel’s Attained EEXI is greater than the Required EEXI, then the vessel will likely require additional technology installed in order to reduce the vessel’s Attained EEXI and to remain in compliance.
- Have the Energy Efficiency Certificate (IEEC) re-issued?

The EEXI calculation must be done, and the technical file approved by the recognized organization by the vessel’s first annual, intermediate or full renewal of the Air Pollution Prevention Certificate after the 1st January 2023. The exact timeline of the crucial phases of the EEXI implementation is presented in the following figure.

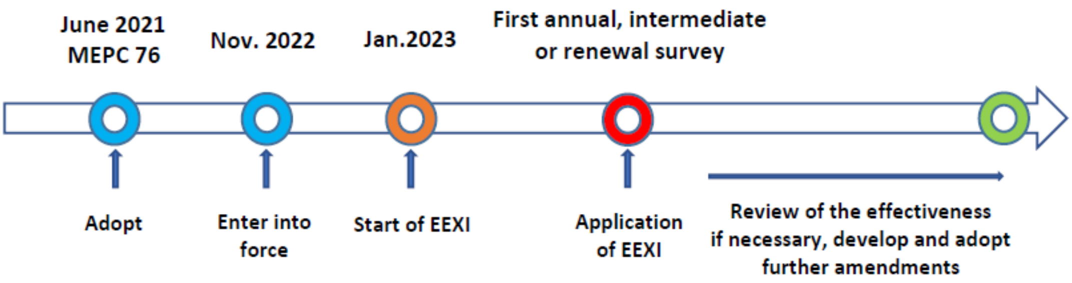

Figure 13: EEXI implementation timeline (ClassNK, 2021).

The method of calculation is similar to that of EEDI, since the value of EEXI should also be calculated for each individual ship resulting in the Attained EEXI of the vessel. In accordance with EEDI philosophy, a Required EEXI is also imposed, setting the limit for the minimum level of the new index, specified for each ship type and size. It is easily understood based on previous analysis for the EEDI that the Attained EEXI should also be equal or less to the required EEXI, utilizing EEDI reference lines and reduction factors for ships with a certain size of a specified ship type, related to Phases 2 and 3 of EEDI.

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

- Main engine part
- Auxiliary engine part
- Shaft motor
- Innovative energy efficiency technology for reduction of main engine power
- Innovative energy efficiency technology for reduction of auxiliary engine power
- Ship-type specific correction factors

Figure 14: EEXI Mathematical Formula (DNV)

Ships falling within the scope of the EEDI requirement may use the EEDI (calculated in accordance with the 2018 guidelines on the method for calculating the achieved EEDI for new ships (Resolution MEPC.308(73))) as an EEXI indicator provided that the value of the EEDI is equal to or less than that of the required EEXI.

The terms of the above formula were analyzed in subchapter 3.2, since this formula is identical to that of the EEDI, so they need not be mentioned again. However, it is necessary, in the next subchapter 3.7, to analyze to a considerable extent the calculation of the EEXI formula terms.

- Attained EEXI ≤ Required EEXI
- Required EEXI = (1-Y/100) × EEDI Reference line value

Where Y is specified in below table:

Table 6: Reduction factors (in percentage) for the EEXI relative to the EEDI reference line

Ship type	**Size**	**Reduction factor**
Bulk carrier	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	10,000 and above but less than 20,000 DWT	0-20
Gas carrier	15,000 DWT and above	30
	10,000 and above but less than 15,000 DWT	20

	2,000 and above but less than 10,000 DWT	0-20
Tanker	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	4,000 and above but less than 20,000 DWT	0-20
Containership	200,000 DWT and above	50
	120,000 and above but less than 200,000 DWT	45
	80,000 and above but less than 120,000 DWT	35
	40,000 and above but less than 80,000 DWT	30
	15,000 and above but less than 40,000 DWT	20
	10,000 and above but less than 15,000 DWT	0-20
General cargo ship	15,000 DWT and above	30
	3,000 and above but less than 15,000 DWT	0-30
Refrigerated cargo carrier	5,000 DWT and above	15
	3,000 and above but less than 5,000 DWT	0-15
Combination carrier	20,000 DWT and above	20
	4,000 and above but less than 20,000 DWT	0-20
LNG carrier	10,000 DWT and above	30
Ro-ro cargo ship (vehicle carrier)	10,000 DWT and above	15
Ro-ro cargo ship	2,000 DWT and above	5
	1,000 and above but less than 2,000 DWT	0-5
Ro-ro passenger ship	1,000 DWT and above	5
	250 and above but less than 1,000 DWT	0-5

Cruise passenger ship having non-conventional propulsion	85,000 GT and above	30
	25,000 and above but less than 85,000 GT	0-30

As shown above, bulk carriers, combination carriers, container ships, cruise passenger ships having non-conventional propulsion, gas carriers, general cargo ships, refrigerated cargo carriers, LNG carriers, ro-ro cargo ships, ro-ro cargo ships (vehicle carrier), ro-ro passenger ships and tankers of 400 GT and above engaged in international voyages shall calculate the Attained EEXI and this shall result equal or less than the Required EEXI, calculated as $(1-Y/100) \times EEDI$.

In what it has to do with the reference line value, the reduction factors Y are specific for each ship type. The verification of the ship's Attained EEXI shall take place at the first annual, intermediate or renewal survey of the IAPP Certificate or the initial survey of the IEEC Certificate, whichever is the first, on or after 1 January 2023.

For those ships already having a verified attained EEDI, this value may be taken as the Attained EEXI if it is equal to or less than the required EEXI. In this case, the Attained EEXI shall be verified based on the EEDI Technical File.

An EEXI Technical file, containing all basic information required for the calculation of EEXI, must be issued to be submitted to the Administration and/or any other organization duly authorized by it in order to be verified and the IEE Certificate to be re-issued. In case of ships already complying with EEDI phase 2 and 3 and this value is equal to or less to the Required EEXI, an EEXI Technical File is not necessary and the IEE Certificate shall be renewed without any further approval.

As we can understand, there are various technical options for a shipowner to improve EEXI with the most common ones so far being:

- Engine power limitation: ≈37%
- Change in fuel type from marine diesel oil (MDO) to liquified natural gas (LNG): 25%
- Propeller retrofit-Redesign propeller 10%
- Installation of energy saving devices (e.g.: PBCF, wake equalizing duct): up to 4%
- Installation of rotor sails: 3.8%
- 10% increase in transport capacity (deadweight): 3%

So, based on what we have seen above, engine power limitation will be the key measure to improve EEXI and comply more easily to the requirements. However, besides the desired effect of reduced fuel oil consumption, throttling will also result in a lower maximum speed of the vessel. To counteract this effect, a retrofit of the propeller is to be recommended. The retrofit propeller will be precisely designed for the new operating point of the engine. This will further reduce fuel consumption by up to 14% or increase the reference speed of your ship and thus improve the EEXI value of your vessel. This even opens the possibility to reduce the engine power limitation slightly, if desired.

In more detail, the options and available tools required to change the EEXI value will be presented in detail in the next chapter.

3.7 EEXI CALCULATION

Let us now see how the calculation of the achieved EEXI is carried out, by analyzing the terms of figure's 13 formula, since this is something that will concern us in the case studies of this thesis:

$P_{ME_{(i)}}$: power of the main engines at 75% of the MCR

For LNG carriers equipped with a diesel electric propulsion system, the $P_{ME_{(i)}}$ shall be calculated from the following formula:

$P_{ME_{(i)}} = 0.83 \times MPPmotor(i) / \eta(i)$

Where $MPPmotor(i)$ is the nominal motor output specified in the certified document, η(i) shall be taken as the product of the electrical efficiency of the generator, transformer, converter and motor, taking into account the weighted average as required.

The electrical efficiency, η(i), shall be taken as 91.3 % for the calculation of the EEDI. Alternatively, if a value greater than 91.3 % is to be applied, η(i) shall be obtained by measurement and verification by a method approved by a verifier.

For LNG carriers equipped with steam turbine propulsion systems, $P_{ME_{(i)}}$ shall be 83% of the nominal installed power ($MCR_{SteamTurbine}$) for each steam turbine.

In cases where overridable Shaft/Engine Power Limitation is installed (in accordance with the 2021 Guidelines on Shaft/Engine Power Limitation for EEXI compliance and use of power reserve requirements (MEPC.335(76) analysis)), $P_{ME_{(i)}}$ shall be 83% of the limited power (MCR_{lim}) or 75% of the original installed power (MCR), whichever is lower, for each main engine.

$\mathbf{P_{PTO}}$: shaft generator

Where shaft generators are installed, $P_{PTO(i)}$ is 75% of the rated electrical output power of each shaft generator. In case the shaft generators are installed in a steam turbine, the $P_{PTO(i)}$ is 83% of the rated electrical output power and the factor of 0.75 should be replaced to 0.83.

Two options are available for calculating the effect of shaft generators:

Option 1:

The maximum allowable reduction for the calculation of $\Sigma P_{ME(i)}$ shall not exceed P_{AE}. For this case, $\Sigma P_{ME(i)}$ shall be calculated as:

$$\sum_{i=1}^{nME} P_{ME(i)} = 0.75 \times \left(\sum MCR_{ME(i)} - \sum P_{PTO(i)}\right) \text{ with } 0.75 \times \sum P_{PTO(i)} \leq P_{AE}$$

Option 2:

When an engine is installed with a higher rated output power than that of the propulsion and limited by verified technical means, then the value of $P_{ME(i)}$ shall be 75% of this limited power for determining the reference speed, V_{ref}. The figure below provides guidance for the determination of $\Sigma P_{ME(i)}$:

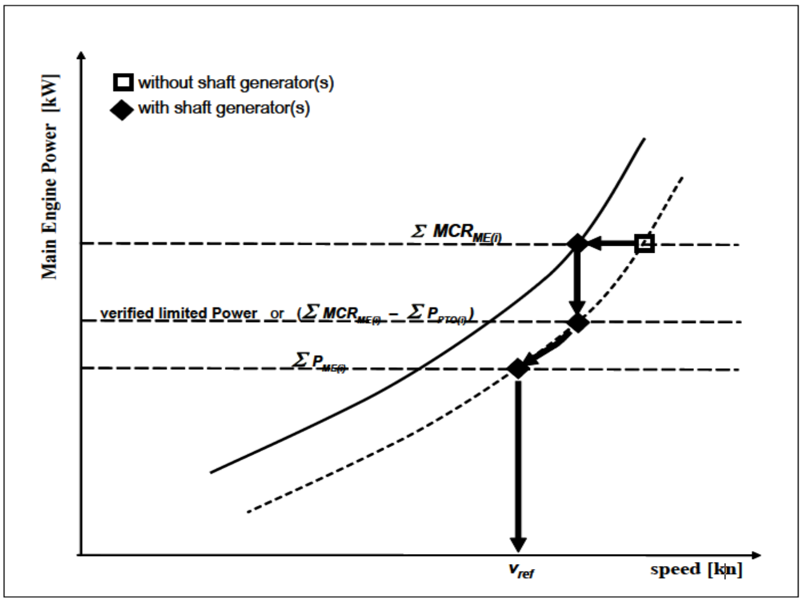

Figure 15: Determination of $\Sigma P_{ME(i)}$

P_{PTI}(i): Shaft motor

Where shaft motors are installed, the PPTI(i) shall be 75% of the rated power consumption of each shaft motor divided by the weighted average efficiency of the generator(s), as follows:

$$\sum \quad P_{PTI(i)} = \frac{\sum \quad 0.75 \times PS_{SMmax(i)}}{\eta_{\underline{gen}}}$$

Where:

$PS_{SMmax(i)}$: is the nominal power consumption of each axis motor

$\eta_{\underline{gen}}$: is the weighted average efficiency of the generator(s)

In case the shaft motors are installed in a steam turbine, the PPTI(i) is 83% of the rated power consumption and the factor of 0.75 should be replaced to 0.83.

The propulsion power at which V_{ref} is measured is:

$$\sum \quad P_{ME(i)} + \sum \quad P_{PTI(i),Shaft}$$

Where:

$$\sum \quad P_{PTI(i),Shaft} = \sum \quad (0.75 \times \ P_{SM,(i)} \ \times \eta_{PTI(i)}$$

$\eta_{PTI(i)}$: is the performance of each shaft motor installed.

Where the total propulsion power, as defined to the above sum, is greater than 75% of the propulsion system power which is limited by verified technical means, then 75% of the limited power shall be used as the total propulsion power to determine the reference speed, Vref.

In the case of a PTI/PTO combination, the normal mode of operation at sea will determine which of these will be used in the calculation.

$\mathbf{P_{eff(i)}}$: Innovative mechanical energy efficient technology for main engine

$\mathbf{P_{eff(i)}}$ is the performance of the innovative mechanical energy efficient technology for propulsion at 75% of main engine power. The mechanically recovered energy directly linked to shafts does not need to be measured, since the effect of the technology is directly reflected in the Vref. In the case of a ship equipped with a number of engines, CF and SFC should be the weighted average of all main engines.

$\mathbf{P_{AEeff}}$: Innovative mechanical energy efficient technology for auxiliary engine

Correspondingly $\mathbf{P_{AE}}$: Auxiliary engine power

P_{AE} is the required auxiliary engine power to provide the maximum load at sea, including the power required for the propulsion machinery/systems and the anchorage, e.g., main engine pumps, navigation systems and on-board living arrangements, but not including power for machinery/systems not used for propulsion, e.g., thrusters, cargo pumps, cranes, ballast pumps, cargo containment, e.g., refrigeration and cargo hold fans, when the ship is under way at speed (V_{ref}).

For vessels with a total propulsion power $\sum MCR_{ME(i)} + \frac{\sum P_{PTI(i)}}{0.75}$ equal to or greater than 10,000 KW, the P_{AE} is determined as follows:

$$P_{AE_{\sum MCR_{ME(i)} \geq 10{,}000kW}} = \left(0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right)\right) + 250$$

For vessels with a total propulsion power $\sum MCR_{ME(i)} + \frac{\sum P_{PTI(i)}}{0.75}$ below 10,000 KW, the P_{AE} is determined as follows:

$$P_{AE_{\sum MCR_{ME(i)} < 10{,}000kW}} = \left(0.05 \times \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right)\right)$$

Concerning now **SFC** for main and auxiliary engines:

The indicators ME(i) and AE(i) refer to the main and auxiliary engine(s), respectively. For engines certified to test cycles E2 or E3 of the 2008 NO_X Technical Code, the specific engine fuel consumption ($SFC_{ME(i)}$) is that recorded in the test report included in the NO_X technical file for the engine(s) at 75% of the MCR power of its rated torque. For engines certified for the D2 or C1 test cycles of the 2008 NO_X Technical Code, the Specific Fuel Consumption of the engine (SFC_{AE}(i)) is that recorded in the test report included in the NO_X technical file for the engine(s) at 50% of the MCR power of its rated torque. The SFC shall be corrected to the value corresponding to the ISO reference conditions using the standard lower heating value of oil (42,700 kJ/kg) according to ISO 15550:2002 and ISO 3046-1:2002.

The SFC_{AE} is the weighted average power between the $SFC_{AE(i)}$ of the respective engines i. For engines that do not have a test reference included in a NO_X technical file because their power is below 130 kW, the SFC specified by the manufacturer and approved by a competent authority shall be used. At the design stage, if the test reference is not available in the NO_X file, the SFC specified by the manufacturer and approved by a competent authority shall be used.

For those engines where no test records are available in the NOx technical file and no specific consumption has been given by the manufacturer or verified by the verifier, the specific consumption shall be approximated as follows:

SFC_{ME}=190 [g/kWh].

SFC_{AE}=215 [g/kWh]

For LNG fuelled engines whose SFC is measured in kJ/kWh it shall be corrected to the SFC value of g/kWh using the standard lower calorific value of LNG (48,000 kJ/kg), in accordance with the 2006 IPCC Guidelines.

The lower calorific values of reference additional fuels are given in the table below. The lowest reference calorific value corresponding to the conversion factor of the respective fuel should be used for the calculation.

Table 7: Calorific reference values of additional fuels

Type of fuel	Reference	Lower calorific value (kJ/kg)	Carbon content	C_F (t-CO_2/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
Liquified Petroleum Gas (LPG)	Propane	46,300	0.8182	3.000
	Butane	45,700	0.8264	3.030
Liquified Natural Gas (LNG)		48,000	0,7500	2,750
Methanol		19,900	0,3750	1,375
Ethanol		26,800	0,5217	1,913

For those engines where there are no test records in the NO_X technical file and the specific consumption has not been determined by the manufacturer the C_f factor corresponding to the SFC is determined as follows:

C_f = 3.114 [t CO_2/t fuel] for diesel ships including HFO if used in practice

f_j: correction index based on the design of the ship concerned, categorized as follows:

Power correction factor for ships sailing on ice

The power correction factor f_j for ships navigating on ice shall be taken as the greater of f_{j0} and $f_{j,\,min}$ as shown in the table below but not greater than $f_{j,\,max} = 1$.

Table 8: Calculation of the design-based correction index

Ship type	f_{j0}	$f_{j,min}$ depending on the ice class			
		IA Super	IA	IB	IC
Tanker	$\frac{17.444 \cdot DWT^{0.5766}}{\sum_{i=1}^{nME} MCR_{ME(i)}}$	$0.2488 \cdot DWT^{0.0903}$	$0.4541 \cdot DWT^{0.0524}$	$0.7783 \cdot DWT^{0.0145}$	$0.8741 \cdot DWT^{0.0079}$
Bulk carrier	$\frac{17.207 \cdot DWT^{0.5705}}{\sum_{i=1}^{nME} MCR_{ME(i)}}$	$0.2515 \cdot DWT^{0.0851}$	$0.3918 \cdot DWT^{0.0556}$	$0.8075 \cdot DWT^{0.0071}$	$0.8573 \cdot DWT^{0.0087}$
General cargo ship	$\frac{1.974 \cdot DWT^{0.7987}}{\sum_{i=1}^{nME} MCR_{ME(i)}}$	$0.1381 \cdot DWT^{0.1435}$	$0.1574 \cdot DWT^{0.144}$	$0.3256 \cdot DWT^{0.0922}$	$0.4966 \cdot DWT^{0.0583}$
Refrigerated cargo ship	$\frac{5.598 \cdot DWT^{0.696}}{\sum_{i=1}^{nME} MCR_{ME(i)}}$	$0.5254 \cdot DWT^{0.0357}$	$0.6325 \cdot DWT^{0.0278}$	$0.7670 \cdot DWT^{0.0159}$	$0.8918 \cdot DWT^{0.0079}$

The power correction factor for general cargo ships shall be calculated as follows:

$$Fj = \frac{0.174}{Fn_\nabla^{2.3} \times C_b^{0.3}}$$

If $f_j > 1$ then $f_j = 1$

Where:

$$Fn_\nabla = \frac{0.5144 \times Vref}{\sqrt{g \times \nabla^{1/3}}}$$

If $Fn > 0.6 \; then \; Fn = 0.6$ and $Cb = \frac{\nabla}{Lpp \times Bs \times Ds}$

For all other types of ships fj is considered equal to 1

$\mathbf{f_w}$: factor for speed reduction at sea

f_w is a dimensionless coefficient indicating the decrease of speed in representative sea conditions of wave height, wave frequency and wind speed (e.g., Beaufort scale 6) and is considered equal to 1 in accordance with MARPOL Annex VI Regulations 20 and 21. For other cases it may be calculated by carrying out a specific simulation of its performance in representative sea conditions.

f_w can be determined by conducting the ship specific simulation on its performance at representative sea conditions. The simulation methodology should be based on the Guidelines developed by the Organization and the method and outcome for an individual ship should be verified by the Administration or an organization recognized by the Administration; and

In cases where a simulation is not conducted, fw should be taken from the "Standard fw " table/curve. A "Standard fw " table/curve is provided in the Guidelines for each ship type defined in regulation 2 of MARPOL Annex VI, and expressed as a function of capacity (e.g. deadweight). The "Standard fw " table/curve is based on data of actual speed reduction of as many existing ships as possible under the representative sea condition.

fw and attained $EEDI_{weather}$, if calculated, with the representative sea conditions under which those values are determined, should be indicated in the EEDI Technical File to distinguish it from the attained EEDI calculated under regulations 20 and 21 of MARPOL Annex VI.

f_i: capacity factor for technical/regulatory capacity limitation

f_i is the capacity factor used in any technical or regulatory capacity limitation. In case it is not necessary it is considered equal to 1.

The capacity factor for ships navigating on ice shall be calculated as follows:

$$f_i = f_{i(ice\ class)} \cdot f_{iCb}$$

Where $f_{i(ice\ class)}$ is the capacity factor for the ice strengthening of the ship which can be obtained from table 9 and f_{iCb} is the capacity factor for the improved ice navigation capability and cannot be considered less than 1 and is calculated as follows:

$$f_{iCb} = \frac{C_{b\ reference\ design}}{C_b}$$

Where $C_{b\ reference\ design}$ is the average displacement factor for each type of ship, which can be obtained from table 10 for bulk carriers, tankers and general cargo ships, while C_b is the displacement factor of the ship. For other categories of ships $f_{iCb} = 1$.

Table 9: Capacity correction factor for ice-strengthening of the hull

Ice class	$f_{i(ice\ class)}$
IC	$f_{i(IC)} = 1.0041+58.5/DWT$
IB	$f_{i(IB)} = 1.0067+62.7/DWT$
IA	$f_{i(IA)} = 1.0099+95.1/DWT$
IA Super	$f_{i(IAS)} = 1.0151+228.7/DWT$

Table 10: Average block coefficients Cb reference design for bulk carriers, tankers and general cargo ships

	Size categories				
Ship type	below 10,000 DWT	10,000-25,000 DWT	25,000-55,000 DWT	55,000-75,000 DWT	above 75,000 DWT
Bulk carrier	0.78	0.8	0.82	0.86	0.86
Taker	0.78	0.78	0.8	0.83	0.83
General cargo ship	0.8				

f_{iCSR}: Ships under the Common Structural Rules (CSR)

For bulk carriers and oil tankers, built in accordance with the Common Structural Rules (CSR) adopted by the registrants and having the class notation CSR, the following correction factor shall be used:

$f_{iCSR} = 1+ (0.08 \cdot LWT_{CSR} / DWT_{CSR})$

Where DWT_{CSR} is the deadweight of the ship and LWT_{CSR} is the light weight; for other types of ships f_i is equal to 1.

f_c: Cubic capacity correction factor

If no cubic capacity correction factor is necessary it is considered equal to 1.

f_c for chemical tankers

For chemical tankers, in accordance with Regulation 1.16.1 of MARPOL Annex II, the following correction factor shall be used:

$f_c = R^{-0.7} - 0.014$, where R is less than 0,98

Or

$f_c = 1.000$, where R is more than 0,98

R is the capacity ratio of the deadweight of the ship (tonnes) divided by the total cubic capacity of the cargo tanks of the ship (m^3).

f_c for gas carriers

for gas carriers having direct diesel driven propulsion system constructed or adapted and used for the carriage in bulk of liquefied natural gas, the following cubic capacity correction factor

$f_{cLNG} = R^{-0.56}$

f_c for ro-ro passenger ships (f_{cRoPax})

for ro-ro passenger ships having a DWT/GT-ratio of less than 0.25, the following cubic capacity correction factor, f_{cRoPax}, should apply:

$f_{cRoPax} = ((DWT/GT)/0.25)^{-0.8}$

Where DWT is the Capacity and GT is the gross tonnage in accordance with the International Convention of Tonnage Measurement of Ships 1969, annex I, regulation 3**.**

f_c for bulk carriers having R of less than 0.55 ($f_{c\ \text{bulk carriers designed to carry light cargoes}}$**)**

for bulk carriers having R of less than 0.55 (e.g. wood chip carriers), the following cubic capacity correction factor, $f_{c\ \text{bulk carriers designed to carry light cargoes}}$, should apply:

$f_{c\ \text{bulk carriers designed to carry light cargoes}} = R^{-0.15}$

f_l: factor for general cargo ships equipped with cranes

The f_l factor for general cargo ships equipped with cranes or systems related to cargo transport compensates for the loss in deadweight of the ship.

$f_l = f_{cranes} \cdot f_{sideloader} \cdot f_{RoRo}$

f_{cranes}=1, if there are no cranes

$f_{sideloader}$=1, if there are no sideloaders

f_{RoRo}=1, if there is no ro-ro ramp

Definition of the f_{cranes} factor:

$$f_{cranes} = 1 + \frac{\sum_{n=1}^{n} (0.0519\ SWL_n\ Reach_n + 32.11}{Capacity}$$

Where,

SWL = safe working load, as specified by the crane manufacturer in metric tonnes

Reach=reach to which the SWL applies

n = number of cranes

For other load handling systems, the coefficient is defined as follows:

$$f_{sideloader} = \frac{Capacity_{\ No\ RoRo}}{Capacity_{RoRo}}$$

$$f_{roro} = \frac{Capacity_{\ No\ sideloaders}}{Capacity_{sideloaders}}$$

V_{ref}: vessel reference speed

The ship's speed can be obtained as appropriate in the following five ways:

1. For ships falling within the scope of the EEDI requirement, the ship's speed Vref should be taken from the approved speed-power curve as defined in the Guidelines for the calculation of EEDI (MEPC.254(67)).
2. For ships not within the scope of the EEDI requirement, the ship's speed Vref should be taken from an estimated speed-power curve as defined in the 2021 Guidelines (Resolution MEPC.334(76)), which is provided by the shipyard after construction in accordance with the tank test.
3. For ships that are not within the scope of the EEDI requirement but whose sea trial has been calculated under the EEDI draught meaning that it is corrected for wind and waves as defined by the EEDI calculation guidelines, the ship's speed Vref may be obtained from the sea trial report: $V_{ref} = V_{S,EEDI} \times \left[\frac{P_{ME}}{P_{S,EEDI}}\right]^{\frac{1}{3}}$ (knot), Where $V_{S,EEDI}$ is the service speed for the EEDI draught and $P_{S,EEDI}$ is the power of the main engine corresponding to the speed $V_{S,EEDI}$.
4. For container ships, bulk carriers or tankers which are not within the scope of EEDI but whose sea trial results (which may have been calibrated from the tank test) are included in the sea trial report under design load draught while the sea state is corrected for wind and waves as defined by the EEDI calculation guidelines, the ship's speed V_{ref} may be obtained as follows:

   $V_{ref} = k^{\frac{1}{3}} \times \left(\frac{DWT_{s,service}}{Capacity}\right)^{\frac{2}{9}} \times V_{S,service} \times \left[\frac{P_{ME}}{P_{S,service}}\right]^{\frac{1}{3}}$ (knot), Where, $V_{S,service}$ is the service speed at design load draught, $DWT_{s,service}$ is the deadweight at the loading draught, $P_{S,service}$ is the main engine power for the speed $V_{S,service}$

   k is the scale factor which is selected as follows:

   a. 0,95 for container ships of 120 000 DWT or less
   b. 0,93 for container ships of more than 120 000 DWT
   c. 0,97 for bulk carriers of 200 000 DWT or less.
   d. 1,00 for bulk carriers with more than 200,000 DWT
   e. 0,97 for tankers of 100 000 DWT or less; and
   f. 1.00 for tankers of more than 100,000 DWT.

5. In cases where the speed-power curve is not available or the sea trial report does not contain the EEDI or design load draught condition, the ship's speed Vref may be

calculated from the statistical average of the ship's speed and engine power distribution as defined below:

$V_{ref} = (V_{ref,avg} - m_v) \times \left[\frac{\sum \quad P_{ME}}{MCR_{avg}}\right]^{\frac{1}{3}}$ (knot), where $V_{ref,avg}$ is a statistical average of the distribution of ship speed for a given type and size of ship, calculated as follows: $V_{ref,avg} = A \times B^C$. A, B and C are the parameters given in the figure below, m_v is the margin of performance of a ship, which should be 5 % of $V_{ref,avg}$ or 1 knot, whichever is lower.

MCR_{avg} is a statistical average of the distribution of MCRs for main engines calculated as follows?

MCR_{avg}= D x E^F

where D, E and F are also given in the next figure.

Parameters to calculate $V_{ref,avg}$

Ship type	A	B	C
Bulk carrier	10.6585	DWT of the ship	0.02706
Gas carrier	7.4462	DWT of the ship	0.07604
Tanker	8.1358	DWT of the ship	0.05383
Containership	3.2395	DWT of the ship where DWT ≤ 80,000 80,000 where DWT > 80,000	0.18294
General cargo ship	2.4538	DWT of the ship	0.18832
Refrigerated cargo carrier	1.0600	DWT of the ship	0.31518
Combination carrier	8.1391	DWT of the ship	0.05378
LNG carrier	11.0536	DWT of the ship	0.05030
Ro-ro cargo ship (vehicle carrier)	16.6773	DWT of the ship	0.01802
Ro-ro cargo ship	8.0793	DWT of the ship	0.09123
Ro-ro passenger ship	4.1140	DWT of the ship	0.19863
Cruise passenger ship having non-conventional propulsion	5.1240	GT of the ship	0.12714

Parameters to calculate MCR_{avg} or MPP_{avg} (= D x E^F)

Ship type	D	E	F
Bulk carrier	23.7510	DWT of the ship	0.54087
Gas carrier	21.4704	DWT of the ship	0.59522
Tanker	22.8415	DWT of the ship	0.55826
Containership	0.5042	DWT of the ship where DWT ≤ 95,000 95,000 where DWT > 95,000	1.03046
General cargo ship	0.8816	DWT of the ship	0.92050
Refrigerated cargo carrier	0.0272	DWT of the ship	1.38634
Combination carrier	22.8536	DWT of the ship	0.55820
LNG carrier	20.7096	DWT of the ship	0.63477
Ro-ro cargo ship (vehicle carrier)	262.7693	DWT of the ship	0.39973
Ro-ro cargo ship	37.7708	DWT of the ship	0.63450
Ro-ro passenger ship	9.1338	DWT of the ship	0.91116
Cruise passenger ship having non-conventional propulsion	1.3550	GT of the ship	0.88664

Figure 16: Parameters to calculate $V_{ref,avg}$ and MCR_{avg}

4.0 Technical measures for EEXI improvement

According to DNV GL approximately 6500 ships in DNV class will have to comply with EEXI by the end of 2023. Majority of ships will have to apply engine power limitation (EPL) to comply. More generally the plurality of ships will have to install some kind of improvement measure for their energy efficiency. These measures for a shipowner might either be EPL, ShaPoli, ESDs, hull optimization (installation of sails, flettner rotors, bulbous bow), or at the worst case they might even have to replace their ships with new vessels. EPL and ShaPoli are currently covered by DNV's EEXI calculator.

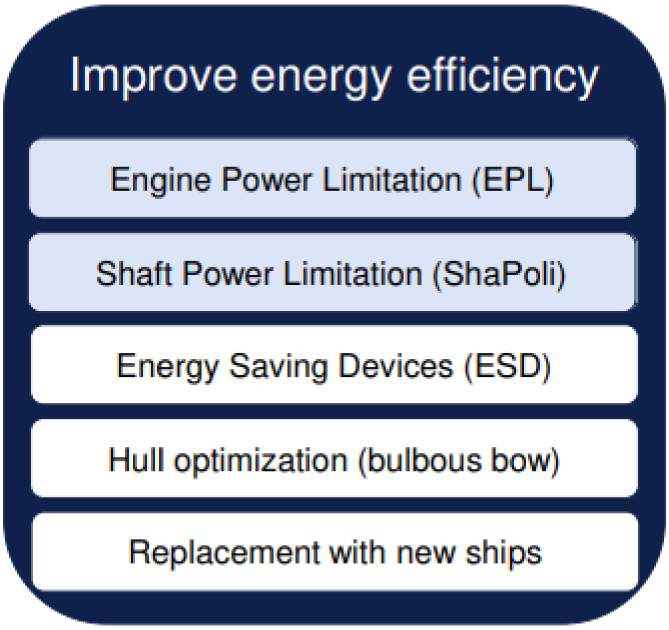

Figure 17: EEXI improvement measures if attained EEXI ≥ required EEXI (DNV GL)

In case someone has calculated EEXI and EEXI is actually higher than the required value, they will have to come up with mitigating actions, which might either be a simple Engine Power Limitation, which is illustrated to the following figure, or a more complex solution such as the installation of Energy Saving Devices. In case of a simple power reduction they also need to provide the related information and form of an approved onboard management manual. After recalculation of EEXI and in case of compliance with the required values they can directly send the approval documentation, so the EEXI technical file and the OMM (in case of EPL) for approval and can directly get a statement of compliance. This statement will be issued before the IEE certificate. DNV can only issue the certificate on the first periodical survey after entry into force that it will be in 2023 and if the approval documentation is aligned with the installation the DNV surveyors will issue the IEEC. In case someone goes for more complex alterations, actually, then a more challenging and advanced approval process might be needed and in some cases a survey is appropriate after the installation of e.g. flettner rotors.

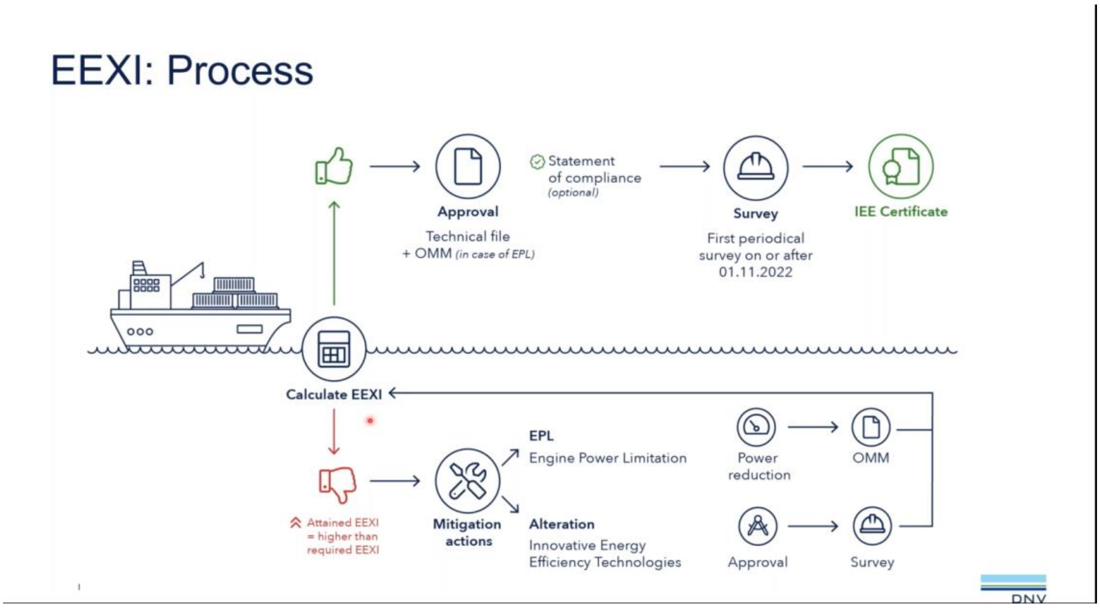

Figure 18: Procedure for issuing a certificate of conformity

4.1 Energy saving devices for EEXI improvements

First of all, we need to know how Energy Saving Devices (ESDs) are categorized according to MEPC.1/Circ.815. ESDs are classified as A, B and C according to the terms that the device contributes to the EEXI formula, as it is shown below. For example, devices that can increase reference velocity are in category A, devices that can improve main engine energy efficiency fall within category B, and devices that can improve auxiliary engine energy savings belong to category C. These categories are further subdivided into Category B-1, B-2, Category C-1, and C-2 according to weather dependency of the ESDs, as we can see in figure 17.

Main engine emissions | Aux. engine emissions | Aux. energy engine savings | Main engine energy engine savings

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

Transportation

Figure 19: Formula for calculating the EEXI (KR)

Reduction of Main Engine Power			Reduction of Auxiliary Power	
Category A	**Category B-1**	**Category B-2**	**Category C-1**	**Category C-2**
Cannot be separated from the overall performance of vessel	Can be treated separately from the overall performance of vessels $f_{eff}=1$	Can be treated separately from the overall performance of vessels $f_{eff}<1$	Effective at all time $f_{eff}=1$	Depending on ambient environment $f_{eff}<1$
· Low friction coating · Bare optimization · Rudder resistance · Propeller design	· Hull air lubrication system (air cavity via air injection to reduce ship resistance) can be switched off	· Wind assistance (Sails, Flettner Rotors, Kites)	· Waste heat recovery system (exhausts gas heat recovery and conversion to electric power)	· Photovoltaic cells

Figure 20: Innovative energy efficiency technologies (KR)

4.2 ESDs in Category A

ESDs in category A are some technologies that can improve the speed-power performance of the ship, which means these devices can increase the reference speed (V_{ref}) at the same power (P_{ME}). These ESDs cannot be separated from the overall performance of the ship. These devices have some advantages: they are relatively inexpensive, simple to install and require a short engineering period compared to other ESDs. However, it is rather difficult to expect a dramatic improvement in the EEXI rating, because these effects are reflected as reference speed, the speed is in proportion to the cube root of power saving ratio. For example, if you install ESD A, which can save 10% main engine power, you can expect about a 3.5% decrease in EEXI rating.

Power Saving due to ESD	2%	4%	6%	8%	10%
EEXI (velocity) Improvement	0.7%	1.3%	2.1%	2.8%	3.5%

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

Figure 21: Effect of ESDs A to EEXI rating (KR)

Interpreted more positively from the perspective of securing the available speed within the EEXI regulation. For example, if we assume a speed-power curve of the ship, as it is shown below, here is reference power normally 75% of MCR. If we check the EEXI requirement for every point on the curve, it is shown as blue if the EEXI requirement is satisfied and red if it is not satisfied. Then we can find an intersection point of blue and red. This point is the optimized EPL level of the original ship, which means the ship cannot operate above this level. However, some ship owners may require a higher ship speed for some reason such as contractive speed with shipper, then the ESD should be considered.

Here, if we consider ESD which has a 10% main engine power reduction effect the curve can be expressed like the dotted one on the right. Then, there is the point B_0 which has 3.5% lower EEXI than point A. But B_0 is not an optimal point for this ship. The maximum speed with satisfying EEXI is point B. Then, point A and B have the same EEXI value, with point B as 5.4% more margin than point A in terms of speed and power. So, the 10% of ESD makes 5% of velocity margin.

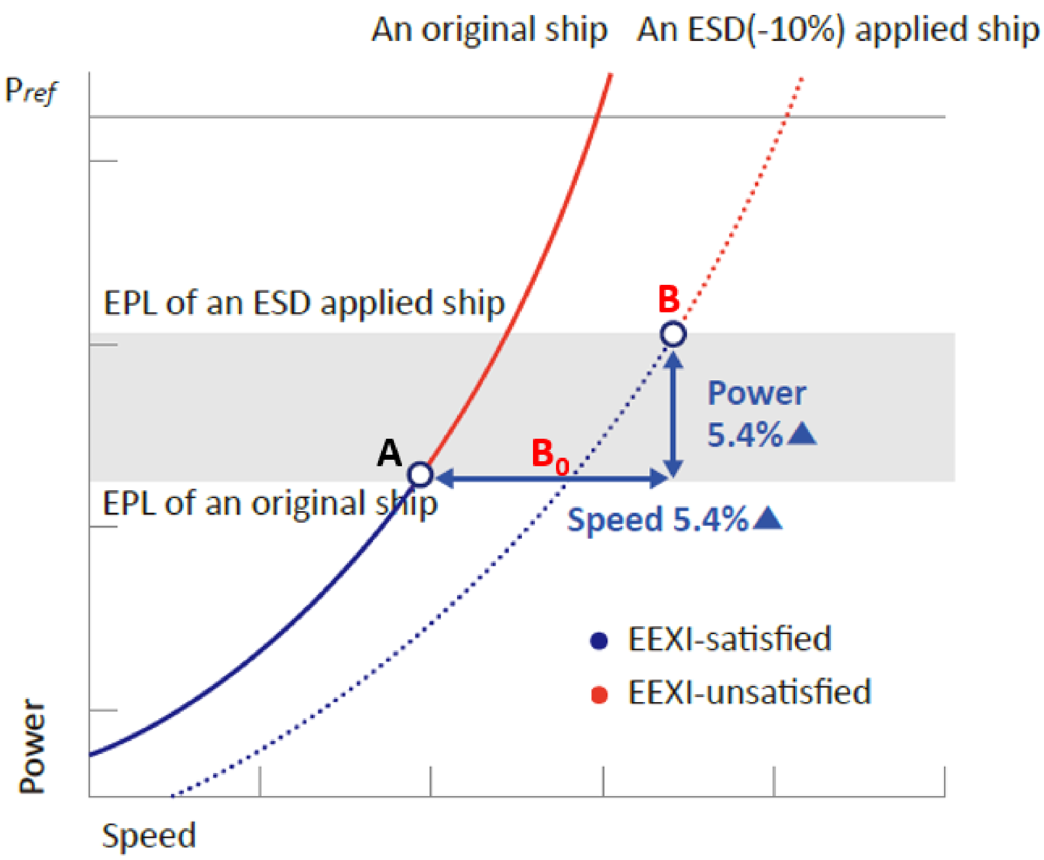

Figure 22:ESD to maximize available speed

Although an ESD with 10% efficiency lowers the EEXI only by as much as 3.5%. This can be more positively interpreted from the perspective of securing the available speed within the EEXI regulation.

Some ESDs which are commercialized on the market and can reduce ship's resistance are:

- Bulbous bow retrofit, which can reduce wave making resistance
- Vortex flow control fins, that can reduce hull's friction resistance
- Hull coating technique, which can reduce hull's friction resistance

Figure 23: Ship's wave making and friction resistance reduction methods (KR)

On the other hand, there are a lot of propulsion improving devices, called PID, on the market. These devices are designed to be installed near the propellers or near the rotor in order to increase propulsion power. Some devices prevent propulsion loss due to rotational flow occurring behind the propeller, for example, swirl recovery vanes, pre-swirl stator (duct, fin) and contra-rotating propellers (CRP), figure 21. While rudder bulbs and propeller boss cap fins can prevent the generation of a hub vortex behind the propeller, which can reduce propeller's energy loss, figure 22. Rudder fins can also convert the lift force to thrust and increase power performance. In figure 23, it is shown Kawasaki RBS-F" (patented), which is an energy saving device installed on a rudder. It consists of a streamline-shaped rudder bulb and airfoil-shaped fins. The rudder bulb brings smooth inflows to the propeller, and the fins produce thrusts in the rotational flows generated by the propeller. As a result, Kawasaki RBS-F reduces the required propulsive power by 2% to 7%. Kawasaki RBS-F has been installed on more than 100 ships including LNG Carriers, LPG carriers and bulk carriers.

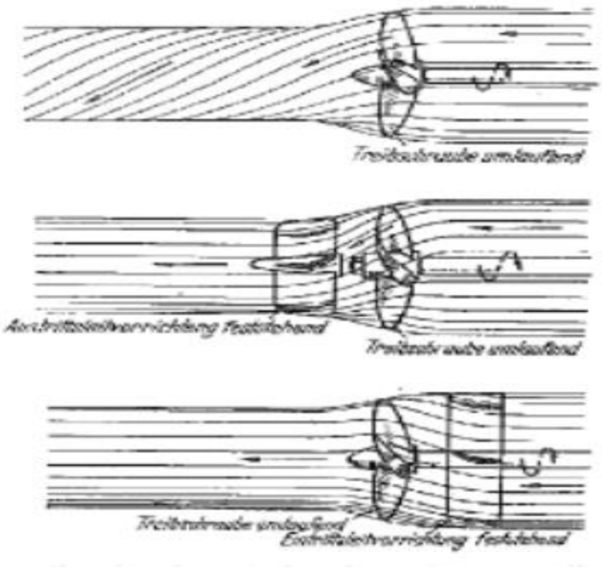

Figure 24: Saving rotational flow losses (14).

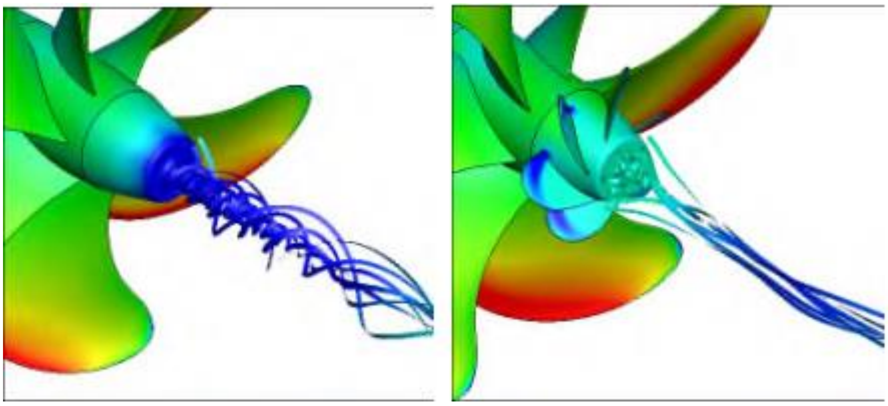

Figure 25: Influence of PBCF on stream line (15)

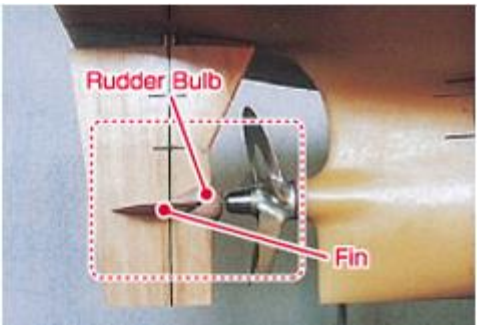

Figure 26: Kawasaki RBS-F (Rudder Bulb System with Fins)

Continuing to look at the propulsion improving devices, both the NPT (New Profile Technology) and CLT (Contracted-Loaded Tip) propeller are direct changes to the propeller. NPT propellers offer:

- 2-4% efficiency gain,
- smaller optimum diameter,
- smaller blade surface, significant weight and inertia reduction,
- lower pressure pulses,
- and all of them cost the same cost as conventional propellers.

How NPT propellers work;

- reduced pressure peak on section
- blade surface area reduced
- viscous drag reduced = improved efficiency

On the other hand, the advantages of CLT propellers over conventional propellers resulting from full scale installations and from several comparative full-scale trials and long-term observation are the following:

• Higher efficiency (between 5 - 8%)

1. Fuel saving
2. Reduced emissions
3. Saving on MM/EE maintenance
4. Higher top speed
5. Greater range

• Inhibition of cavitation and of the tip vortex

1. Less noise
2. Less vibrations
3. Lower pressure pulses
4. Lower area ratio

• Greater thrust

1. Smaller optimum propeller diameter
2. Better maneuverability

Similarly, a propeller nozzle and duct which is installed near the propeller helps to improve propulsion power by controlling the propeller inflow. The steerable nozzle, figure 26 demonstrates greatly improved maneuvering performance by generating higher lateral forces. Less space is needed for the overall propulsion arrangement and better efficiency is achieved by placing the propeller further to the rear than the fixed nozzle. The steerable nozzle guarantees the highest pull combined with excellent maneuvering performance. Becker Nozzle products are fully compliant with DP regulations and can be used as a part of the DP system. Due to the excellent rudder forces at lower speeds and in BP mode, the Becker Steering Nozzle demonstrates excellent station keeping results in DP and is therefore the perfect choice for vessels operating in DP.

Figure 27: NPT propeller

Figure 28:A CP CLT propeller installed in a modern Ro-Pax.

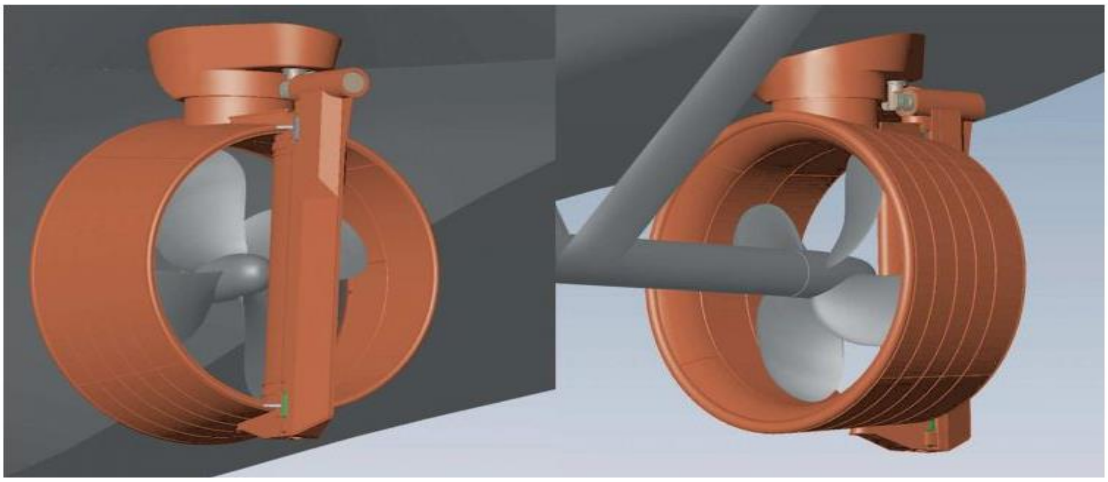

Figure 29: Becker nozzle

4.3 ESDs in Category B

The ESDs in category B are technologies that can firstly reduce the propulsion power and there may be consideration of power reduction (P_{eff}) and availability factor (f_{eff}). Moreover, it can be treated separately from the overall performance of the ship, which means those devices can be turned on and off. Unlike ESD category A, ESD category B can reduce the EEXI rating almost proportional to the power saving rate, because ESD category B power reduction terms are directly reflected in the numerator in EEXI formula, as we can see below in figure 28. One main drawback is that these devices are rather expensive and require long engineering time.

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

Figure 30: Effect of ESDs in category B in EEXI formula.

Examples of ESDs in category B commercialized on the market are air lubrication systems and wind assistance systems. The air lubrication system spares air bubbles at the bottom of the ship, which change the fluid density in the boundary layer. This system also reduces the hull's friction resistance. These devices are applicable, only, to ships with a flat bottom and small draught, because they are effective when the bubble sheet continuously maintains at the bottom of the hull.

Figure 31: Air lubrication system (20)

On the other hand, a wind assistance system describes a device that can increase propulsion power by using wind (weather dependent, f_{eff}) e.g., rotors, sails, kites. The effectiveness of every wind assistance system is dependent on the environmental conditions, so the weather effect is also included in the EEXI formula as f_{eff}.

Figure 32: Rotors, sails and kites (18,19)

4.4 ESDs in Category C

The ESDs in this category are technologies that can generate additional electricity. The saved energy is counted as effective auxiliary power (P_{AEeff}). The ESDs C can also reduce EEXI rating almost proportional to the power saving rate. But these devices are also very expensive and require a prolonged engineering time and few have a proven track record.

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

Figure 33: Effect of ESDs in category C in EEXI formula.

Examples of ESDs C which are commercialized and on the market are waste heat recovery systems, which are effective at all time, and solar cells, which are dependent on the weather. A waste heat recovery system can increase the efficiency of the utilization of the energy generated from fuel combustion in the engine through recovering the thermal energy of exhaust gas, cooling water, etc. Solar cells also make additional electric power from solar energy, figure 32.

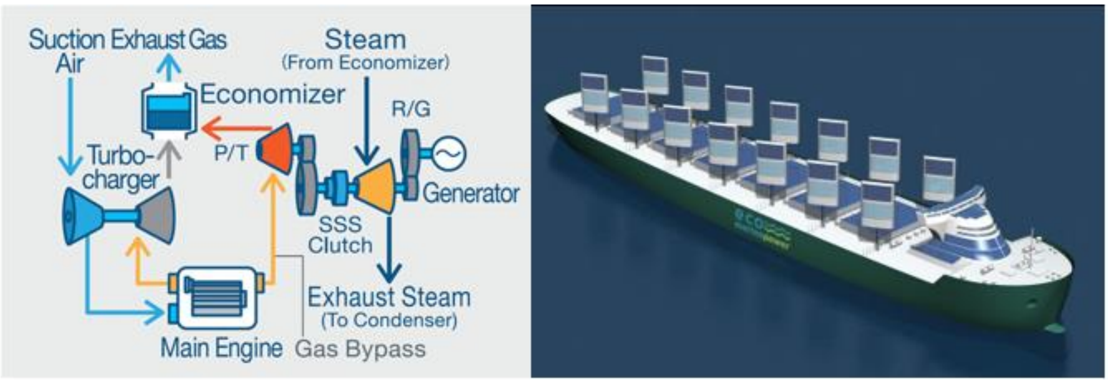

Figure 34: Waste heat recovery system (21) on the left and marine solar cells on the right (22).

In conclusion, if you want to install an ESD you should first decide on your marginal chartering speed and then you can check the required power saving ratio you have to make through the ESD. You will require a number of EEXI calculations, then you will be able to select an appropriate ESD considering the CAPEX, the verification cost and the payback time. In the worst case it may be necessary to scrap the current ship and build a new ship with high energy efficiency.

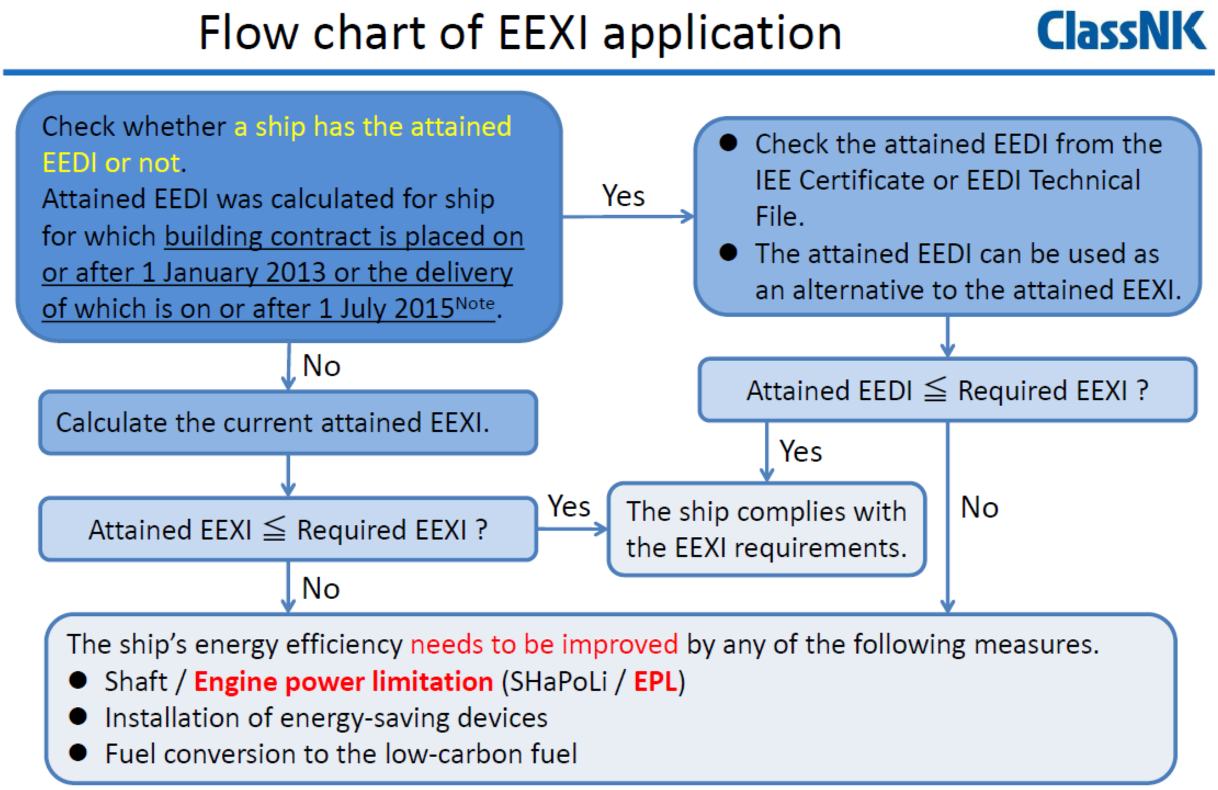

Figure 35: Flow chart of EEXI application

4.2 Alternative fuels

An important factor of the EEXI formula is the C_F. It is a factor that indicates the carbon content of the fuel. LNG, LPG, biofuel, methanol, ammonia and hydrogen as well as the usage of fuel cells and batteries are some of the main options for energy storage. However, there is no one-size-fits-all solution and a lot of considerations will go into selecting the appropriate option based on ship type/age, trading area, retrofitting and operations costs along with safety issues.

There are numerous challenges concerning the green alternative fuels. For instance, biofuel, a carbon neutral fuel, being produced from biologically renewable resources has the issue of oxidation stability, cold flow properties, risk of microbial growth, increased engine deposits and hence requires careful handling.

Handling of other alternative fuels is complex and requires a highly trained crew, since most gases in liquid form require storage at cryogenic temperature and much higher safety standards compared to the traditional fuels, for instance hydrogen has a wide flammability range, while ammonia is highly toxic.

Hydrogen is a clean fuel; however till now manufacturing green hydrogen is energy-intensive and has carbon by-products. Hydrogen can be categorized in several categories, brown, gray, blue and green. Brown hydrogen is created through coal gasification, gray from natural gas by throwing off carbon waste, whereas blue from carbon capture and storage and green hydrogen which is the ultimate clean hydrogen resource uses renewable energy which at the moment is quite expensive.

Similarly, to green hydrogen, green ammonia requires two to four times the cost of producing it with respect to conventional one. Green and blue ammonia value chains differ from the hydrogen production method used; since green ammonia is generated from water electrolysis and blue one from a conventional pathway by combining natural gas with the carbon capture.

Storage capacity and energy density/calorific value are other important aspects to be considered, since fuels with lower energy density compared to the traditional ones at the moment will require more storage space. Hydrogen, ammonia and methanol fall into that category.

Last but not least, for a fuel to become widely used, it must have scalability which is translated into both available infrastructure and demand. This can be quite easily achieved on liner routes, but not for ships traveling between ports. Below the pros and cons of the prevailing alternative fuels are being evaluated.

Table 11: Pros and cons of alternative fuels

Alternative Fuels	Pros	Cons
Liquified Natural Gas (LNG)	• Already implemented and tested • Infrastructure currently under development • High energy density • Requires specific regulations prescribed in IMO's (IGF Code)	• Offers limited benefits since it is known as a 'transition fuel' • Requires a temperature of -162C to stay in liquid state • Low volumetric density, requires twice the storage compared to transitional marine fuels • Bunkering, storage and handling requires much more care • Methane slip (25 times greater impact in GHG emissions)
Liquified Petroleum Gas (LPG)	• Lower in cost compared to traditional marine fuel	• Similar to LNG, CO_2 reduction is limited • LPG requires larger storage tanks • Limited operational experience • Slippage factor (4 times greater impact in GHG emissions) • Not widespread development of bunkering infrastructure
Biofuels	• Carbon neutral, developed from biologically renewable resources	• Higher in cost compared to many fossil fuels • Technical issues that can affect machinery, for instance

	• Usually blended with traditional marine fuels	biofouling, plugging of filters and engine deposits • Limited production and availability
Hydrogen (H_2)	• Zero carbon emissions • Can be produced by renewable sources with electrolysis • Green hydrogen production costs can be reduced by the falling cost of renewable energy	• Low energy density • Green production currently expensive • Large fuel volume (requires 8 times more volume than fuel oils for the same power output) • Requires a temperature of -253C to stay in liquid state • Highly combustible and explosive, safety issues • Combustion happens in high temperatures, producing NOx emissions
Ammonia (NH_3)	• No CO_2 emissions • Cheap conversion process • ‘Green’ production possible using green hydrogen and renewable power • Higher energy density that hydrogen, requires only refrigeration for storage • Already produced for chemical industry	• Currently made using natural gas • Requires energy for refrigeration • Large fuel volume, 2.7 times that of HFO • Has NOx emissions (GHG impact 300 times greater than CO_2 • Highly toxic • Low flammability without pilot fuels
Methanol (CH_3OH)	• Liquid at ambient temperatures • Easy to store and handle • Low cost for conversion of existing engines • Biodegradable, with lower impact on the environment	• Produced mainly from natural gas or coal, reduction of CO_2 is limited • Lower energy density than fuel oil • Requires 2.4 times the storage space compared to HFO • Low flash point, increased fire risk • Toxic when inhaled or handled • Increased corrosion risks

4.3 Engine Power Limitation (EPL) / Shaft Power Limitation (ShaPoLi)

Most of the existing vessels' EEXI score is much higher than the required limit and the aforementioned ESDs either cannot offer significant EEXI improvements or their retrofit/installation is much costlier for an existing vessel, with a remaining operational life of 10 years.

EPL is likely to be the easiest way for older ships to comply with the EEXI requirements as it requires minimal changes to the ship and does not change the underlying performance of the engine. EPL establishes a semi-permanent, overridable limit on a ship's maximum power thus affecting speed. For mechanically controlled engines, this would take the form of a mechanical stop screw sealed by a wire that limits the amount of fuel that can enter an engine, as it is displayed below, whereas for newer, electronically controlled engines, EPL would be applied via a password protected software fuel limiter. EPL can be overridable if a ship is operating under adverse weather conditions and requires extra engine power for safety reasons, in that case the override should be recorded and reported to the appropriate regulatory authority.

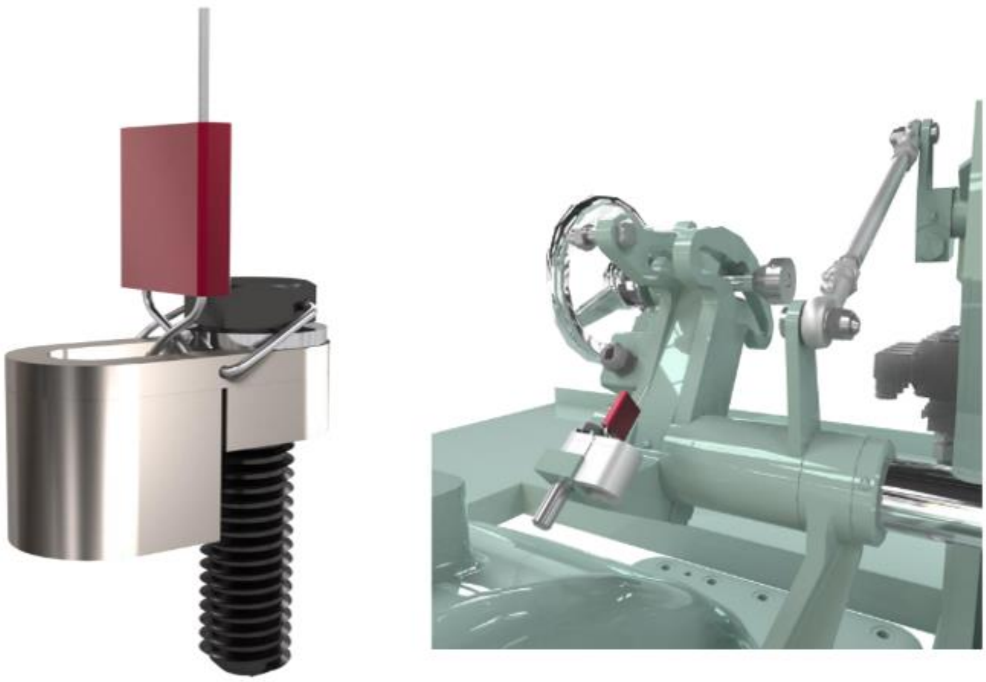

Figure 36: MAN overridable power limitation for MC engines.

According to MEPC.335(76) For EPL for the mechanically controlled engine, the sealing device should either:

1. visibly indicate removal of the sealing when the ship's engine power exceeds the limited engine power as stated in the OMM for EPL or in any case of system malfunction; or
2. be equipped with other systems such as an alert-monitoring system which can indicate when the ship's engine power exceeds the limited engine power as stated in the OMM for EPL or in any case of system malfunction and recording the use of unlimited mode, verified by the Administration or the RO.

EPL can reduce the CO_2 emissions and the fuel used by a significant amount, since the engine load is proportional to the cube of the vessel's speed. For instance a 10% decrease in vessel's speed can decrease the hourly fuel used by 30%. EPL is the most widespread measure to comply with the EEXI required value, however its impact on the GHG emissions is questionable.

As mentioned EEXI will be into force by 2023 and IMO has the goal to reduce the CO_2 intensity of international shipping by at least 40% from 2008 levels by 2030. However, when this strategy was agreed an estimated 30% reduction had already been achieved due to widespread slow steaming by ship operators, according to the following figure.

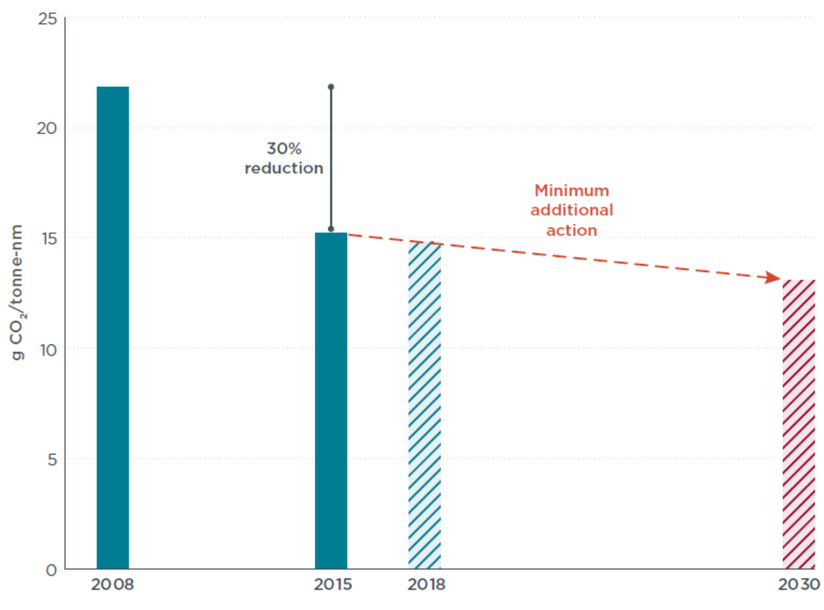

Figure 37: CO_2 intensity of international shipping, 2008 to 2030

According to a paper by Dan Rutherford et al [23], an EPL of 40-50% would reduce CO_2 emissions modestly, between 1% and 4%. Furthermore, an EPL scenario of 60% would reduce this emissions fleetwide in 2030 by 6%, if applied only to ships already in service in 2018 whereas for newer ships this reduction can be tripled.

Now, as for the overridable Shaft Power Limitation (SHaPoLi) system, it has to do with a verified and approved system for the limitation of the maximum shaft power by technical means that can only be overridden by the ship's master or the officer in charge of navigational watch (OICNW) for the purpose of securing the safety of a ship or saving life at sea.

Shaft power means the mechanical power transmitted by the propeller shaft to the propeller hub. It is the product of the shaft torque and the shaft rotational speed. In case of multiple propeller shafts, the shaft power means the sum of the power transmitted to all propeller shafts.

According to MEPC.335(76) SHaPoLi system should consist of the following main arrangements:

1. sensors for measuring the torque and rotational speed delivered to the propeller(s) of the ship. The system includes the amplifier and the analogue to the digital converter;
2. a data recording and processing device for tracking and calculation of the data as given in paragraph 2.2.5.1 of these Guidelines; and
3. a control unit for calculation and limitation of the power transmitted by the shaft to the propeller(s).

5.0 Case Studies

For the current case study, two vessels will be evaluated on their required EEXI and their currently attained EEXI. For confidentiality reasons, these vessels will be named Ship 1 and Ship 2 respectively. Their characteristics are displayed below:

Table 12: Investigated ships' characteristics

	Ship 1	Ship 2
Ship type	Product/Chemical Tanker	Containership
Built	2012 (CSR)	2002
Lpp [m]	174	286.56
B [m]	32.2	40
D [m]	19.1	24.2
Design Draft [m]	11.0	12.0
Scantling Draft [m]	13.06	14.5
LWT [t]	10933.51	26795.8
Displacement summer [t]	60925.7	112639.5
Displacement Design [t]	50227.1	87869
DWT summer [t]	49992.19	85881.7
DWT design [t]	39293.59	61073.2
MCR [kW]	9960	57074

Initially, the attained along with the required EEXI for each one of the two vessels is calculated. The calculations can be found in Appendix 1.

5.1 Ship 1 EEXI calculation and EPL

According to Appendix 1 calculations the attained EEXI for Ship 1 is equal to:

$$attained\ EEXI = 6.04\ gCO_2/t \cdot nm$$

The required EEXI is equal to:

$$required\ EEXI = 4.97\ gCO_2/t \cdot nm$$

Therefore, the attained EEXI is 21.56% above the required EEXI. In that order, the solution of Engine Power Limitation will be investigated.

EPL is applied by reducing the MCR until the calculated EEXI falls below the required value. In that order, it is a trial-and-error procedure since, by reducing incrementally the MCR the new values of SFOC and V_{ref} are calculated, using the cubic polynomials of the interpolated values from the ME's shop test along with the speed-power curve from the model test. According to the calculations at Appendix 1, it was found that for a decrease in EEXI value of 21.56%, the MCR must be reduced by 39%. Therefore, the limited MCR will be equal to:

$$MCR_{limited} = 6080 \text{ kW}$$

The new attained EEXI is equal to:

$$attained\ EEXI = 4.96\ gCO_2/t \cdot nm$$

The vessel's speed V_{ref} is reduced from 14.77 kn to 12.99 kn. Applying EPL might be one of the easiest ways to comply with IMO's standards; however, there is an impact on the vessel's speed since there is an upper limit set on the vessel's MCR. According to data collected for years 2019 - 2021, representing the % of total time the vessel spent at each speed, at laden draft, it is clear that the vessel was operating at 8.3% of total time at speeds that will no longer be achievable due to the application of the EPL. Below the histogram of % time at speeds, a laden draft is presented where the red area indicates the speeds that will no longer be achievable due to the application of EPL.

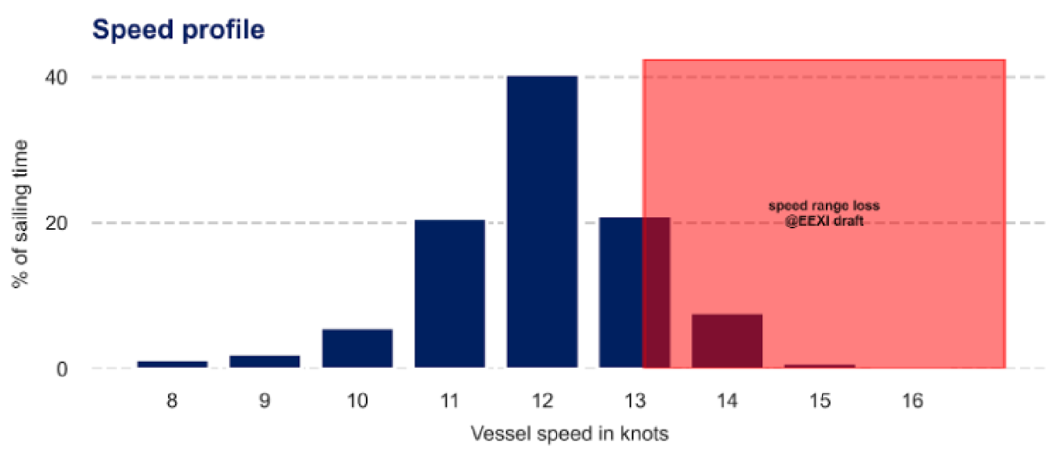

Figure 38: Speed range loss due to MCR reduction at 6080 kW

5.2 Ship 2 EEXI calculation, EPL and propeller redesign

According to Appendix 1 (7.2 - Ship 2 calculations) the attained EEXI for Ship 2 is equal to:

$$attained\ EEXI = 16.15\ gCO_2/t \cdot nm$$

The required EEXI is equal to:

$$required\ EEXI = 11.54\ gCO_2/t \cdot nm$$

Therefore, the attained EEXI is 28.54% above the required EEXI. In that order, the solution of Engine Power Limitation will be investigated. In order to operate the ship at higher speeds and the smallest possible reduction in power, was carried out after CFD analysis a propeller redesign.

At the initial stage, EPL is applied by reducing the MCR until the calculated EEXI falls below the required value. In that order, it is a trial-and-error procedure, which has already been analyzed in the previous case of the tanker. According to the calculations at Appendix 1, it was found that for a decrease in EEXI value of 28.54%, the MCR must be reduced by 48.66%. Therefore, the limited MCR will be equal to:

$$MCR_{limited} = 29300 \text{ kW}$$

The new attained EEXI is equal to:

$$attained\ EEXI = 11.53\ gCO_2/t \cdot nm$$

Since the old propeller does not anymore operate on the optimum point, it was redesigned with respect to the new $MCR_{Limited}$. According to the calculations at Appendix 1 it was found that for a decrease in EEXI value of 28.54%, the MCR must be reduced now, less than before, by 45.94%

Therefore, the limited MCR will be equal to:

$$MCR_{limited} = 30850 \text{ kW}$$

The new attained EEXI is equal to:

$$attained\ EEXI = 11.53\ gCO_2/t \cdot nm$$

The propeller's redesign impact can be easily understood based on the following two histograms. By applying EPL without changing the propeller, the vessel's speed at 100% of the MCR, was calculated equal to 23.04 kn, a speed above which the vessel operated 0.6% of the total time for years 2019 - 2021. For the case of the redesigned propeller the maximum achievable speed was calculated equal to 23.93 kn. Therefore, by redesigning the propeller based on the new $MCR_{Limited}$, the required EEXI was achieved with a speed gain of 0.88 kn.

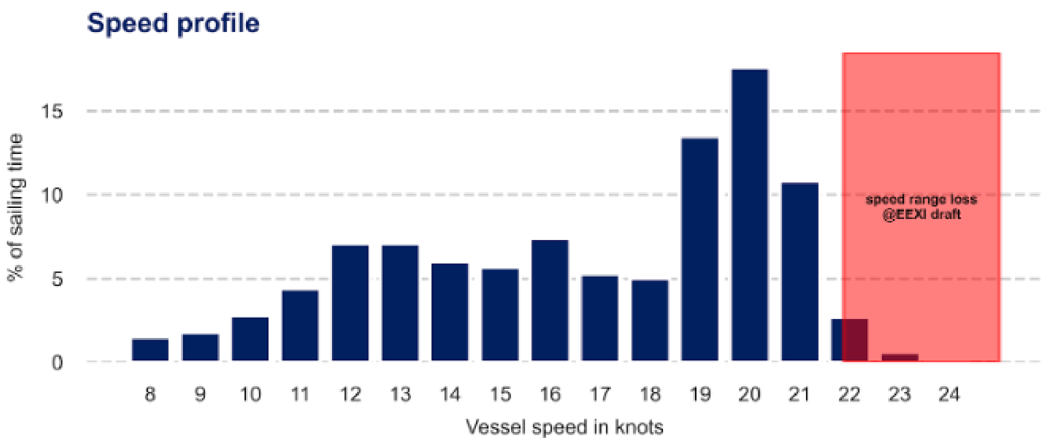

Figure 39: Speed range loss due to MCR reduction at 29300 kW, with the old propeller

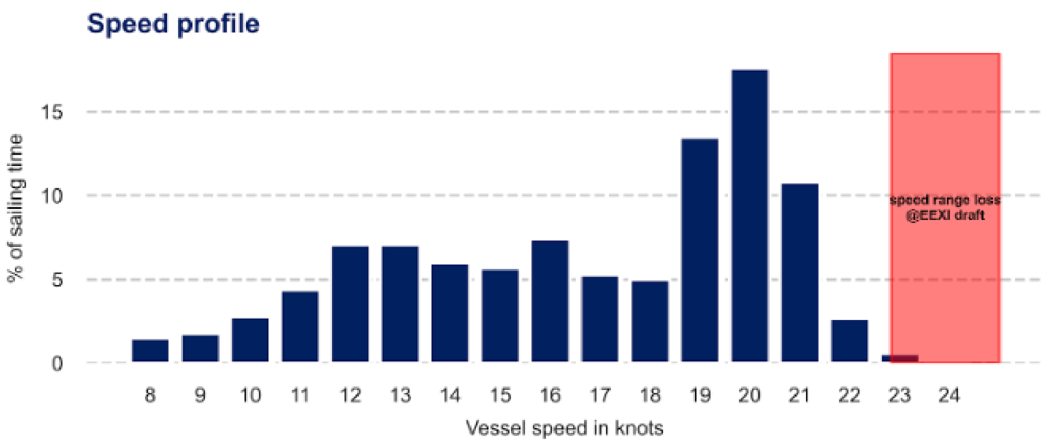

Figure 40: Speed range loss due to MCR reduction at 30850 kW, with the new propeller

5.3 Economical study

Now, the cost of retrofitting - propeller change and EPL installation - for the containership which its EEXI index was calculated and discussed in subchapter 5.2, will be calculated. A comparison of the operating costs (OPEX) of the non-compliant EEXI vessel and the corresponding compliant vessel will be made for the same operational speed. In addition, an economical study will be carried out in order to make it obvious whether this project is not only environmentally sustainable but also economically viable in the long term.

At this point it is worth noting that for both vessels, the necessary reduction percentage of EEXI was more than 20% in order to be compliant. Taking into consideration also that the vessels were quite aged, the containership for instance had 20 years in operation, the choice of EPL seems like the best one, both in terms of cost and in terms of applicability. On the other hand, in order to reach that reduction percentages with ESDs would be difficult because none of them can offer a great reduction - it would require the application of several of them, for instance air lubrication systems & wind assistance systems etc. - which are also much more expensive and still their effectiveness is questionable. So, the EPL choice seems the most favorable.

The case of containership is more interesting since these vessels operate at higher speeds even in the slow steaming era. It can be seen from both Figures 36, 37 that the average speed of Ship 2 was 20 knots during the years 19-21. After the application of the EPL, it is expected that the vessel will still operate in that speed window therefore, the propeller retrofit that was evaluated also seems like an interesting alternative because it can offer several fuel savings, but with a considerable CAPEX. Furthermore, any fuel savings are important not only for the reduced OPEX but also because of the implementation of the CII under by 2023 which will evaluate the operational performance of vessels. Therefore, the economic study will examine whether or not the propeller retrofit along with the EPL application is a viable choice.

The average lifespan of a containership is around 30 years. Since the investigated ship was built in 2002 it is assumed that it still has 10 years of operation. The economic viability of the propeller retrofit will be assessed based on two metrics, the Net Present Value (NPV) and the Financial Rate of Return (FRR). The NPV will be assessed for a discount rate range 4-10%.

The study will take into consideration the speed profile of Figure 36 for the speed distribution. From AIS data it is found that the Ship 2 operated totally 22032 hours during the years 2019-2021, so for a year it is estimated that the vessel operates around 7344 hours.

Table 13: Speed profile of Ship 2 during years 2019 - 2021

Total hours per year traveling: 7344														
Speed [knots]	8	9	10	11	12	13	14	15	16	17	18	19	20	21
% Time	1.5	1.8	2.8	4.4	7.1	7.1	6	5.7	7.4	5.3	5	13.5	17.6	10.8
hours	110	132	206	323	521	521	441	419	543	389	367	991	1293	793

Using the Speed - Power curves for both the new and old propeller, the Power - hours distribution will be calculated. In order to have an equation for Speed – Power for both old and new propeller, the data from Sea Trials were fitted into an exponential curve. For the old propeller this curve is equal to:

$$Power\ [kW] = 0.157586 \cdot e^{6.656646 \cdot Speed\ [knots]}$$

For the new propeller this curve is equal to:

$$Power\ [kW] = 0.157588 \cdot e^{6.573215 \cdot Speed\ [knots]}$$

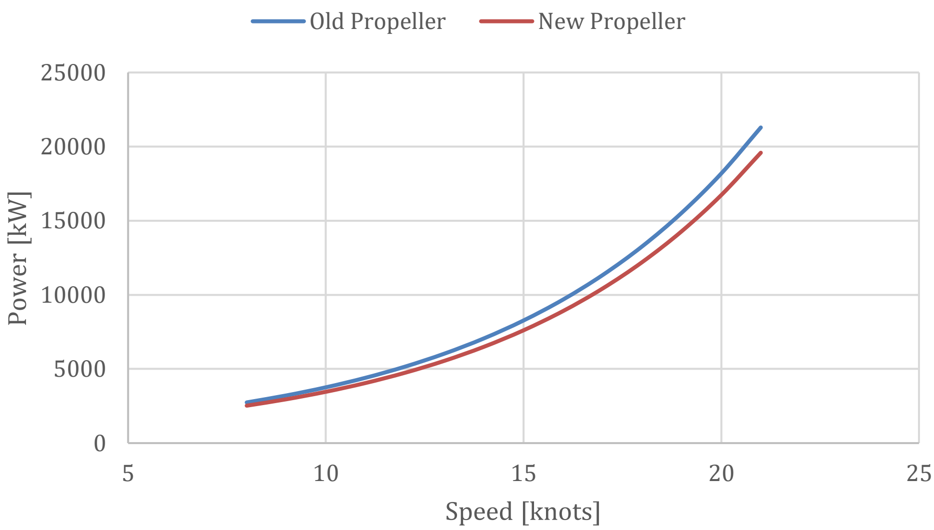

Figure 41: Speed – Power curves for old and new propeller, Ship 2

Subsequently, based on the estimated Power the SFC will be calculated from the SFC - Power curve at Figures 47/49. From the following formula the total fuel consumption per year, in tones, can be calculated:

$$Fuel\ [tons] = \frac{SFC\left[\frac{gr}{kW} \cdot h\right] \cdot Power[kW] \cdot Time[hours]}{10^6}$$

Therefore, the fuel consumption in tones at each speed and totally per year is calculated in the following table:

Table 14: Annual fuel consumption of Ship 2, without propeller retrofit

Without propeller retrofit														
Speed [knots]	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Power [kW]	2744	3213	3761	4403	5155	6035	7065	8270	9682	11335	13269	15534	18185	21289
SFC [gr/kWh]	205.3	204.5	203.6	202.6	201.4	200.0	198.5	196.7	194.8	192.6	190.1	187.5	184.7	181.8
Time [hours]	110	132	206	323	521	521	441	419	543	389	367	991	1293	793
Fuel [tons]	62.0	86.7	157.8	288.1	540.9	628.9	618.4	681.8	1024.0	849.1	926.0	2886.5	4342.8	3068.7

Table 15:Annual fuel consumption of Ship 2, with propeller retrofit

With propeller retrofit														
Speed [knots]	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Power [kW]	2525	2956	3460	4051	4742	5552	6499	7609	8907	10428	12208	14291	16731	19586
SFC [gr/kWh]	205.7	204.9	204.1	203.1	202.0	200.8	199.3	197.7	195.8	193.8	191.5	188.9	186.2	183.3
Time [hours]	110	132	206	323	521	521	441	419	543	389	367	991	1293	793
Fuel [tons]	57.1	80.0	145.5	265.8	499.2	580.8	571.4	630.3	947.3	786.0	857.8	2675.7	4028.0	2847.3

So, before the propeller retrofit the annual fuel consumption in tones is calculated equal to:

$$Fuel\ [tones]_{old\ prop} = 16161.7$$

And after the new propeller retrofit the fuel consumption is equal to:

$$Fuel\ [tones]_{new\ prop} = 14972.0$$

The annual fuel savings are calculated equal to:

$$\boldsymbol{Fuel\ savings\ [tones] = 1189.7\ tones}$$

At this point in this thesis the following should be noted:

- The NPV (Net Present Value) will be calculated for a discount rate range from 4% to 10%.
- Below are presented the economic calculations of the benefits and the amount of return on investment over a time horizon of 7 years from the date of investment taking into account the age of the vessel.
- The Financial Net Present Value (FNPV) of the project and the Financial Rate of Return (FRR) will be calculated, as well as the time needed to recover the funds spent on the investment, in order to examine the economic viability of the project.
- For the calculation of these economic indicators, we accept an annual fuel price increase of 3.5%.

After a thorough market investigation, the following were considered, according to the Capital Expenditures and the maintenance and operational costs:

- A package proposal of selling the new optimized propeller with trading-in the existing original propeller to minimize CAPEX, was taken place.
- Propeller cost, including purchase, CFD study and installation ➔ 1,100,000 ($ USD)
- EPL cost, including class study, engine maker EPL study, engine maker S/E attendance, governor maker S/E attendance, class surveyor attendance ➔ 50,000 ($ USD)
- Maintenance costs remain the same as before.
- Fuel price was considered 1000 USD/ton although it is higher at the moment. However, the aim is a conservative approach to this specific investment.

Table 16: Economic feasibility study for the EPL implementation and propeller retrofit.

Ship 2, EEXI compliance		DR:	6%							
Calculation of Return of Investment		Year	0	1	2	3	4	5	6	7
			EPL implementation and propeller retrofit cost	**Operation**						
CAPEX ($ USD)		1150000	1150000							
OPEX Benefits ($ USD)		9255161	-	1189700	1231340	1274436	1319042	1365208	1412990	1462445
FNPV		6171967	1150000	1189700	1231340	1274436	1319042	1365208	1412990	1462445
Discounted Cash Flows		-	1150000	1122358	1095888	1070041	1044805	1020163	996103	972610
FRR		106.12%								
Oil Growing Price:	3.5%									

Table 17: Net Present Value for the whole range of the discount rate.

Discount Rate (%)	4	6	8	10
FNPV	6743023	6171967	5661357	5203356

As it is shown on the above two tables, FNPV>0 and FRR>0. To be more specific, these values are much greater than zero, thus the project is considered to be not only environmentally and economically viable but also very profitable in the long term. FNPV is a very large number for all the alternative cases of discount rate. The operational benefits that have to do only with the fuel, are estimated at 9,255,161 ($ USD) with a fairly conservative approach to fuel costs.

It is therefore clear from the above tables that compulsory compliance with EEXI can lead to profitable studies for shipping companies. With proper investigations and propeller replacement/redesign or use of ESDs (when requirements are less), it can be led to quite viable and cost-effective projects that may never have been thought of before EEXI was imposed.

6.0 Discussion

6.1 Conclusions

The Engine Power Limitation is simply a way of reducing an engine's maximum power output by changing the engine governor settings in order to obtain a better GHG emission Rating. The EPL includes a new set of governor settings calculated on the basis of sea trial result and shop trial data of the main engine. Its range is typically in 90-75% of SMCR. The IMO EIAPP NOx technical file and the engine's performance is NOT changed.

It is clear that when a significant reduction of EEXI is necessary in order to be compliant with the regulations, the application of EPL is the only way. It is considerably cheaper than the other alternatives such as ESDs or even the adoption of alternative fuels and specially vessels that have a relatively short lifespan left. The main problem that comes with the adoption of EPL is that the vessel does not become more efficient thus even if it is compliant at the moment with the EEXI regulation, it will be necessary in the future to invest in novel technologies.

Another aspect that should be taken into consideration from an environmental point of view, is that it is quite questionable whether or not the EEXI regulation will reduce the GHG emissions. It is generally accepted that over the last few years many shipowners decided to adopt a slow steaming profile due to the increased costs of fuel and this can also be confirmed from the AIS data of the two examined cases.

The case of the containership proved that the application of EPL with a propeller retrofit can provide significant fuel savings even from the first year of the operation. The initial propeller was designed to operate at a service speed that will be changed after the application of EPL therefore it will operate at a lower efficient point. Therefore, the redesign of the propeller with respect to the new operating point along with the application of EPL sounds like the optimal solution one can take, assuming that it is possible to cover the initial CAPEX which is high.

6.2 Further Research

The current diploma thesis was focused on two vessels that required a significant reduction of their EEXI in order to reach the required value. The EPL was the best choice however this is not always the case. A future investigation could be focused on a fleet with different requirements per vessels, for instance for a small reduction of EEXI, in the range of 3-5%, the application of ultra-low friction coating along with an energy saving device such as propeller cap fins or mewis duct can provide the necessary reduction.

Moreover, the application of the CII regulation will come into place soon therefore, it would be interesting in future research to assess the scenario of both the EEXI compliance along with the CII score that the investigated vessel will achieve, since as already mentioned the EEXI does not take into consideration the operational characteristics of the vessel.

Finally, there are cases that it was necessary to reduce the MCR to the 40-50% of the initial value. Engines are designed both in terms of efficiency and in terms of endurance to operate close to their NCR. For the cases of large containerships, that require a reduction of 50% with respect to the reference EEDI curve, it is expected that the adoption of slow steaming that looks as the only viable alternative to reach the EEXI goal, will come along with significant future costs that are related to the excess strain of the engine. The results of the excess adoption of slow steaming cannot be seen today but it is clear that in the future it will be an another problem that the shipowners and the operators be faced with.

7.0 Appendix 1

7.1 Ship 1 calculations

The calculation of the attained EEXI for Ship 1 is presented below, the calculations are based on the guidelines presented on MEPC.308(73) and MEPC.333(76).

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

Beginning with the first parameter of the numerator of the equation, the correction factor for Ship specific design elements f_j, the investigated vessel is not ice-classed, or shuttle tanker, or roro-cargo ship or general cargo ship therefore:

$$f_j = 1$$

For the second term, concerned with the CO_2 emissions of the main engine, the P_{ME} is calculated at **75%** of the MCR, thus it is equal to **7470** kW. Also, from the shop tests the fuel used is MDO thus the C_F is equal to **3.206** t·CO_2/t·Fuel whereas the SFC_{ME} is equal to the ISO SFOC measurement at the 75% of the MCR, equal to **177.5** gr/k·Wh.

$$P_{ME} = 7470 \text{ kW}$$

$$CF_{ME} = 3.206 \text{ t}\cdot CO_2/\text{t}\cdot\text{Fuel}$$

$$SFC_{ME} = 177.5 \text{ gr/kW}\cdot\text{h}$$

The third term of the numerator, concerning the CO_2 emissions from the auxiliary engines is calculated according to the section 2.2.5.6 of MEPC.308(73), where for ships which total propulsion power is 10000 kW or less, P_{AE} can be calculated from:

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

The investigated vessel has neither shaft motors, nor shaft generators therefore $P_{PTI} = P_{PTO} = 0$, therefore:

$$P_{AE} = 0.05 \cdot P_{ME} = 498kW$$

The emission factor CF_{AE} is equal to CF_{ME} because in the auxiliary engines shop test, the fuel used is also MDO. The specific fuel consumption for the auxiliary engines is equal to the 50% ISO measurement of the auxiliary engine's MCR and is calculated as the weighted average of all the auxiliary engines according to section 2.2.7.1 of MEPC.308(73). For the investigated vessel SFC_{AE} is equal to **216.27** gr/kW·h.

$$P_{AE} = 498 \text{ kW}$$

$$CF_{AE} = 3.206 \text{ t}\cdot CO_2/\text{t}\cdot\text{Fuel}$$

$$SFC_{AE} = 216.27 \text{ gr/kW}\cdot\text{h}$$

Concerning the innovative mechanical energy efficient technology terms for either the main or the auxiliary engines, the investigated vessel is not equipped with any kind therefore P_{eff} = P_{AEeff} = 0.

Proceeding with the terms of the denominator and specifically the capacity term, it is equal to the deadweight of the vessel - since the ship type is tanker - according to the section 2.2.3 of MEPC.308(73). Thus:

$$Capacity = DWT_{summer} = 49992.19 \text{ t}$$

For tankers/bulk carriers EEXI is calculated for the summer draft, thus the scantling draft. To calculate the ship speed V_{ref}, Speed Trials/Model Tests are necessary for the condition of scantling draft. For the investigated vessel, model tests on the scantling draft were provided where the curve was interpolated with a third-degree polynomial in order to have a power-speed relationship.

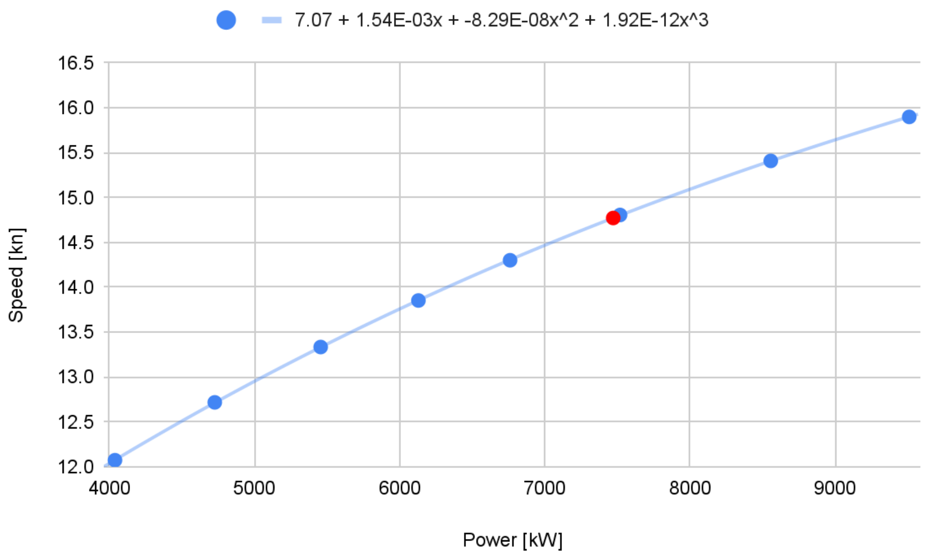

Figure 42: Speed – Power curve for Ship 1 before EPL

Having the power-speed relationship and the P_{ME} power the V_{ref} speed was calculated equal to:

$$V_{ref} = 14.77 \text{ kn}$$

The last step for the calculation of the EEXI is the estimation of the correction terms. Beginning with the correction term f_w called factor for speed reduction at sea, for the investigated ship this term is equal to 1.0.

$$f_w = 1.0$$

The next correction term f_c is related to the capacity of the vessel. The current vessel is a product carrier/chemical tanker with a tank capacity of 51960 m^3. f_c for chemical tankers can be calculated with the following formulas:

$$f_c = R^{-0.7} - 0.014, where\ R\ is\ less\ than\ 0.98$$

$$R = \frac{DWT_{summer}[t]}{Cargo\ tanks\ cubic\ capacity\ [m^3]}$$

Thus the cubic capacity correction factor for chemical tankers is equal to:

$$f_c = 1.0134$$

The factor f_l is applicable for general cargo ships equipped with cranes and cargo-related gear. Since the investigated vessel is a product carrier, this parameter is equal to 1.0.

$$f_l = 1.0$$

The next term f_i is related to the capacity correction due to any technical/regulatory limitation. The investigated vessel is not ice-classed but is built according to CSR therefore f_i is equal to f_{iCSR}.

$$f_{iCSR} = 1 + (0.08 \cdot \frac{LWT_{CSR}}{DWT_{summer}})$$

$$f_{iCSR} = 1.0175$$

The last term that must be calculated, is the factor for ice-classed ships (specifically IA and IA Super). As mentioned, the investigated vessel is not ice-classed, therefore:

$$f_m = 1.0$$

Having calculated all these terms, the attained EEXI value can be calculated:

$$attained\ EEXI = \frac{f_j \cdot (P_{ME} \cdot SFC_{ME} \cdot CF_{ME} + P_{AE} \cdot SFC_{AE} \cdot CF_{AE})}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \cdot f_m}$$

$$= \frac{1.0 \cdot (7470 \cdot 177.5 \cdot 3.206 + 498 \cdot 216.27 \cdot 3.206)}{1.0175 \cdot 1.0134 \cdot 1.0 \cdot 49992.19 \cdot 14.77 \cdot 1.0} = 6.04\ gCO_2/t \cdot nm$$

The required EEXI of this vessel is calculated based on the following formula:

$$required\ EEXI = a \cdot b^{-c} \cdot (1\text{-Y})/100$$

For the ship type tanker according MARPOL Annex VI, Ch.4 Reg. 21, the parameters of the above equation are equal to:

Table 18: Required EEXI formula parameters

a	1218.80
b	DWT_{summer} = 49992.19 [t]
c	0.488

The reduction factor Y for a tanker for DWT > 20000 t is equal to 20. Therefore, the required EEXI is equal to:

$$required\ EEXI = a \cdot b^{-c} \cdot \frac{1-Y}{100} = 1218.80 \cdot 49992.19^{-0.488} \cdot (1-20)/100 = 4.97\ gCO_2/t \cdot nm$$

In order to reach the required EEXI, the MCR must be limited to 6080 kW, a decrease of 39%. In that order the new P_{ME} will be the lowest between the 75% of the original MCR and the 83% of the limited one. The P_{ME} will be equal to:

$$P_{ME} = \min(0.83 \cdot MCR_{Lim}, 0.75 \cdot MCR) = 5046.4\ kW$$

For this value of P_{ME}, the SFOC and the V_{ref} will be calculated by interpolating a third-degree polynomial based on the data collected from the ME's shop test along with the model test.

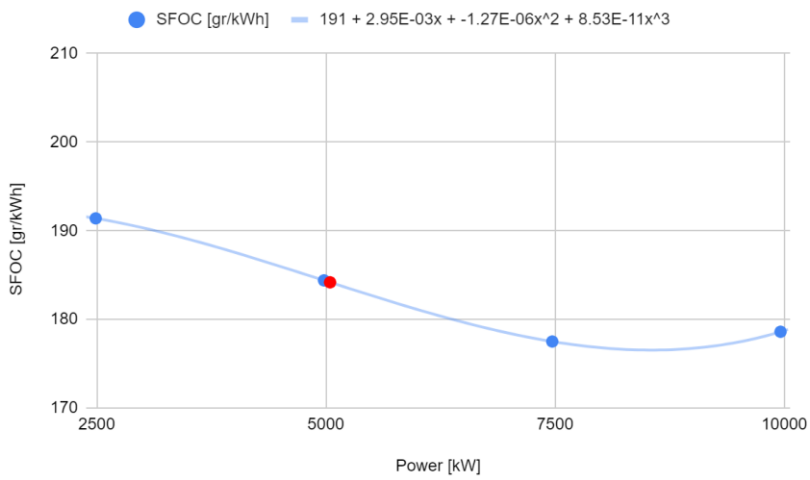

Figure 43: SFOC – Power curve for Ship 1

$$SFC_{ME} = 184.2 \text{ gr/kW·h}$$

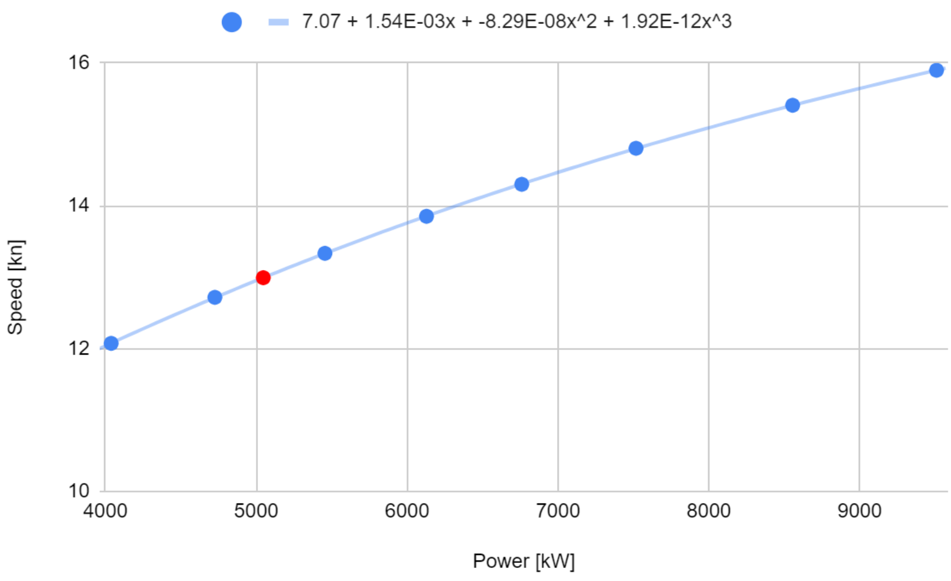

Figure 44:Speed – Power curve for Ship 1 after EPL

$$V_{ref} = 12.99 \text{ kn}$$

Having calculated these three parameters, the rest remain unchanged, the attained EEXI after the application of EPL can be calculated.

$$attained\ EEXI = \frac{f_j \cdot (P_{ME} \cdot SFC_{ME} \cdot CF_{ME} + P_{AE} \cdot SFC_{AE} \cdot CF_{AE})}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \cdot f_m}$$

$$= \frac{1.0 \cdot (5046.4 \cdot 184.2 \cdot 3.206 + 498 \cdot 216.27 \cdot 3.206)}{1.0175 \cdot 1.0134 \cdot 1.0 \cdot 49992.19 \cdot 12.99 \cdot 1.0}$$

$$= 4.96\ gCO_2/t \cdot nm$$

7.2 Ship 2 calculations

The calculation of the attained EEXI for Ship 2 is presented below, the calculations are based on the guidelines presented on MEPC.308(73) and MEPC.333(76).

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

Beginning with the first parameter of the numerator of the equation, the correction factor for Ship specific design elements f_j, the investigated vessel is not ice-classed, or shuttle tanker, or roro-cargo ship or general cargo ship therefore:

$$f_j = 1$$

For the second term, concerned with the CO_2 emissions of the main engine, the P_{ME} is calculated at **75%** of the MCR, thus it is equal to **42806** kW. Also, from the shop tests the fuel used is MDO thus the C_F is equal to **3.206** t·CO_2/t·Fuel whereas the SFC_{ME} is equal to the ISO SFOC measurement at the 75% of the MCR, equal to **172.24** gr/k·Wh.

$$P_{ME} = 42806 \text{ kW}$$

$$CF_{ME} = 3.206 \text{ t}\cdot CO_2/\text{t}\cdot\text{Fuel}$$

$$SFC_{ME} = 172.24 \text{ gr/kW}\cdot\text{h}$$

The third term of the numerator, concerning the CO_2 emissions from the auxiliary engines is calculated according to the section 2.2.5.6 of MEPC.308(73), where for ships which total propulsion power is above 10000 kW, P_{AE} can be calculated from:

$$P_{AE_{\sum MCR_{ME(i)} \geq 10{,}000kW}} = \left(0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right)\right) + 250$$

The investigated vessel has neither shaft motors, nor shaft generators therefore $P_{PTI} = P_{PTO} = 0$, therefore:

$$P_{AE} = 0.025 \cdot \sum_{i=1}^{nME} MCR_{ME(i)} + 250 = 1677kW$$

The emission factor CF_{AE} is equal to CF_{ME} because in the auxiliary engines shop test, the fuel used is also MDO, most of the time. The specific fuel consumption for the auxiliary engines is equal to the 50% ISO measurement of the auxiliary engine's MCR and is calculated as the weighted average of all the auxiliary engines according to section 2.2.7.1 of MEPC.308(73). For the specific investigated vessel SFC_{AE} is equal to **216.27** gr/kW·h.

$$P_{AE} = 498 \text{ kW}$$

$$CF_{AE} = 3.206 \text{ t·}CO_2\text{/t·Fuel}$$

$$SFC_{AE} = 199.775 \text{ gr/kW·h}$$

Concerning the innovative mechanical energy efficient technology terms for either the main or the auxiliary engines, the investigated vessel is not equipped with any kind therefore P_{eff} = P_{AEeff} = 0.

Proceeding with the terms of the denominator and specifically the capacity term, it is equal to the 70% of deadweight summer of the vessel - since the ship type is containership - according to the section 2.2.3 of MEPC.308(73). Thus:

$$Capacity = DWT_{summer} = 60117.19 \text{ t}$$

To calculate the ship speed V_{ref}, for the case of containership, a different approach will be followed. According to MEPC.308(73), the admiralty equation will be used to transfer the power-speed curve calculated at the design draft, at the draft corresponding to the 70% of DWT_{summer}. However, according to the 78th session of MEPC, this adjustment of the power-speed curve might not be necessary based on the conditions of the following table.

Table 19: Admiralty equation applicability

Ship size applicability	**Derivation of *Vref***
where *($DWT_{s,service}$ / Capacity) < 1.0* or where *DWT ≤ 120,000 tonnes* and *($DWT_{s,service}$ / Capacity) > 1.08* or where *DWT* > 120,000 tonnes and *($DWT_{s,service}$ / Capacity) > 1.12*	In case the curve at service draft is available, the speed V_d is derived at the P_{ME}. Subsequently, the V_{ref} at EEXI draft is calculated based on the formula below: $V_{ref} = k^{\frac{1}{3}} * \left(\frac{DWT_{s,service}}{Capacity}\right)^{\frac{2}{9}} * V_d$ In case the curve at service draft is not available and only one service point is available ($P_{s,service}$, $V_{s,service}$), then the V_{ref} at EEXI draft is calculated based on the formula below: $V_{ref} = k^{\frac{1}{3}} * \left(\frac{DWT_{s,service}}{Capacity}\right)^{\frac{2}{9}} * V_{s,service} * \left(\frac{P_{ME}}{P_{s,service}}\right)^{\frac{1}{3}}$
where *DWT* > *120,000 tonnes* and *1.0 < (DWTs,service / Capacity) ≤ 1.12*	*Vref* to be derived from the available curve at P_{ME}.
where *DWT ≤ 120000 tonnes* and *1.0 < (DWTs,service / Capacity) ≤ 1.08*	*Vref* to be derived from the available curve at P_{ME}.

For the investigated vessel, the DWT of the above table is equal to the DWT_{summer} whereas the $DWT_{s,service}$ is equal to the DWT_{Design} and the capacity is equal to the 70% of the DWT_{summer}. Thus:

$$DWT_{summer} = 85881.7 \text{ t} < 120000 \text{ t}$$

$$DWT_{s,service} = DWT_{Design} = 61073.2 \text{ t}$$

$$\text{Capacity} = 70\% \cdot DWT_{summer} = 60117.19 \text{ t}$$

$$DWT_{s,service}/\text{Capacity} = 61073.2/60117.19 = 1.016 < 1.08$$

Based on the above results, it is clear that the V_{ref} will be derived from the available curve, which is the model test curve at the design draft, without being corrected by the admiralty equation.

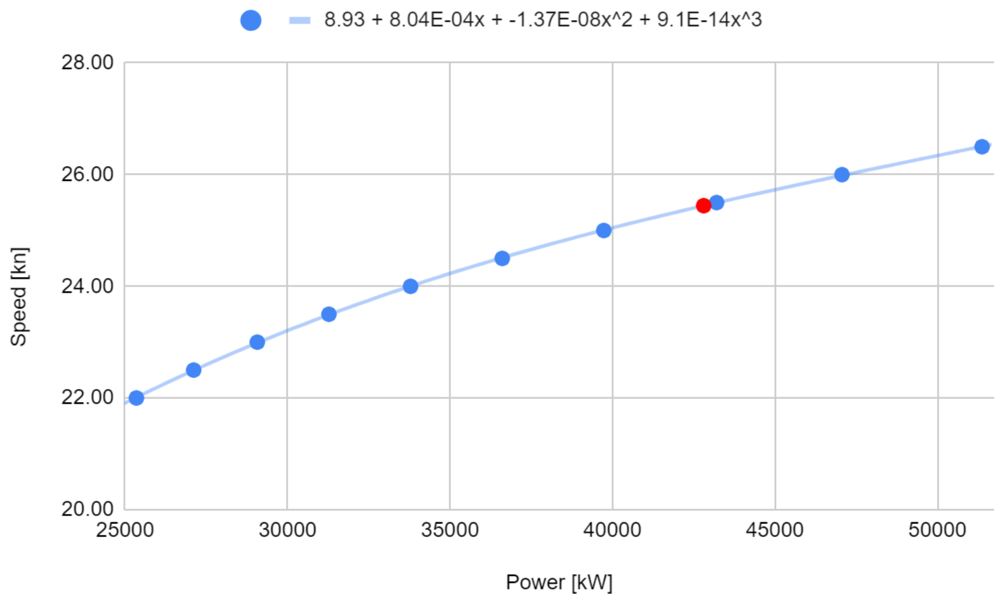

Figure 45: Speed – Power curve for Ship 2 before EPL

Having the power-speed relationship and the P_{ME} power the V_{ref} speed was calculated equal to:

$$V_{ref} = 25.44 \text{ kn}$$

The last step for the calculation of the EEXI is the estimation of the correction terms. Beginning with the correction term f_w called factor for speed reduction at sea, for the investigated ship this term is equal to 1.0.

$$f_w = 1.0$$

As for cubic capacity correction factor f_c which is related to the capacity of the vessel, should be assumed to be one, as no necessity of the factor is granted.

$$f_c = 1$$

The next term f_i is related to the capacity correction due to any technical/regulatory limitation. The investigated vessel is not ice-classed or CSR, so:

$$f_i = 1$$

The last term that must be calculated, is the factor for ice-classed ships (specifically IA and IA Super). As mentioned, the investigated vessel is not ice-classed, therefore:

$$f_m = 1.0$$

Having calculated all these terms, the attained EEXI value can be calculated:

$$\begin{aligned} attained\ EEXI &= \frac{f_j \cdot (P_{ME} \cdot SFC_{ME} \cdot CF_{ME} + P_{AE} \cdot SFC_{AE} \cdot CF_{AE})}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \cdot f_m} \\ &= \frac{1.0 \cdot (42806 \cdot 172.24 \cdot 3.206 + 1677 \cdot 199.775 \cdot 3.206)}{1.0 \cdot 1.0 \cdot 1.0 \cdot 60117.19 \cdot 1.0 \cdot 25.44 \cdot 1.0} \\ &= 16.15\ gCO_2/t \cdot nm \end{aligned}$$

The required EEXI of this vessel is calculated based on the following formula:

$$required\ EEXI = a \cdot b^{-c} \cdot (1\text{-}Y)/100$$

For the ship type containership according to MARPOL Annex VI, Ch.4 Reg. 21, the parameters of the above equation are equal to:

Table 20: Required EEXI formula parameters

a	174.22
b	DWT_{summer} = 85881.7 [t]
c	0.201

The reduction factor Y for a containership for 80000 > DWT > 120000 t is equal to 35. Therefore, the required EEXI is equal to:

$$required\ EEXI = a \cdot b^{-c} \cdot \frac{100-Y}{100} = 174.22 \cdot 85881.7^{-0.201} \cdot \frac{100-35}{100} = 11.54\ gCO_2/t \cdot nm$$

In order to comply with the permitted EEXI for this vessel, an EPL must be applied first. Subsequently, a propeller change will also be considered, where the power-speed curve for the new propeller has been calculated from numerical simulations (CFD). The new speed-power curve after application of EPL is displayed below [Figure k].

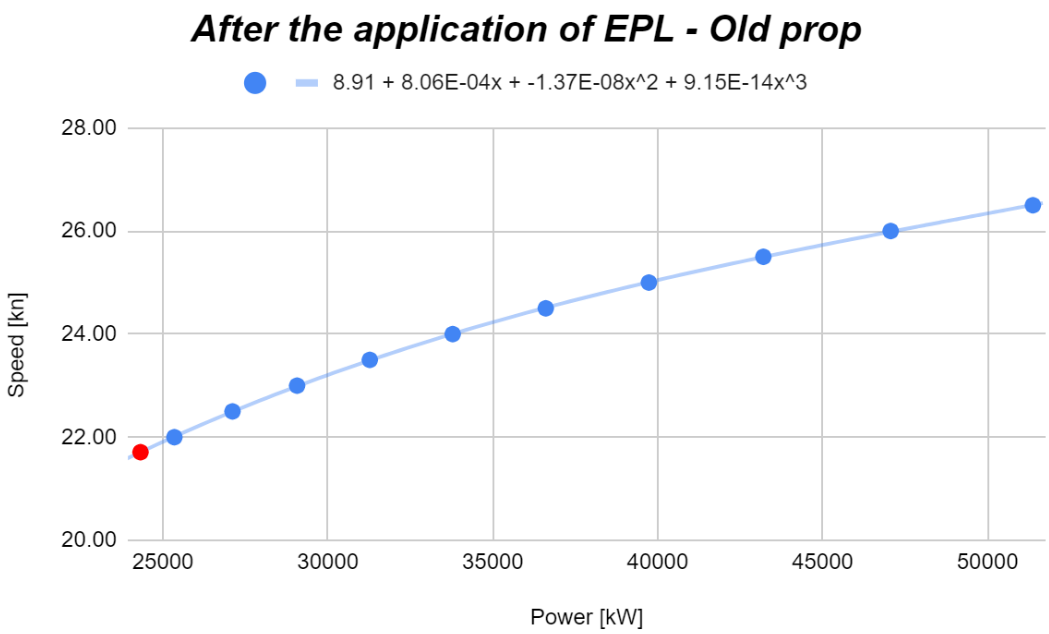

Figure 46: Speed – Power curve for Ship 2 after EPL – old propeller

By implementing a trial-and-error procedure we concluded a new MCR of about 29300 kW. This MCR results after EPL application, keeping the old propeller. The new attained EEXI is calculated based on these three updated parameters. SFOC: **179.37** gr/kW·h, P_{ME} : **24319** kW, V_{ref} = **21.71** kW. The non-dimensional factors remained unchanged.

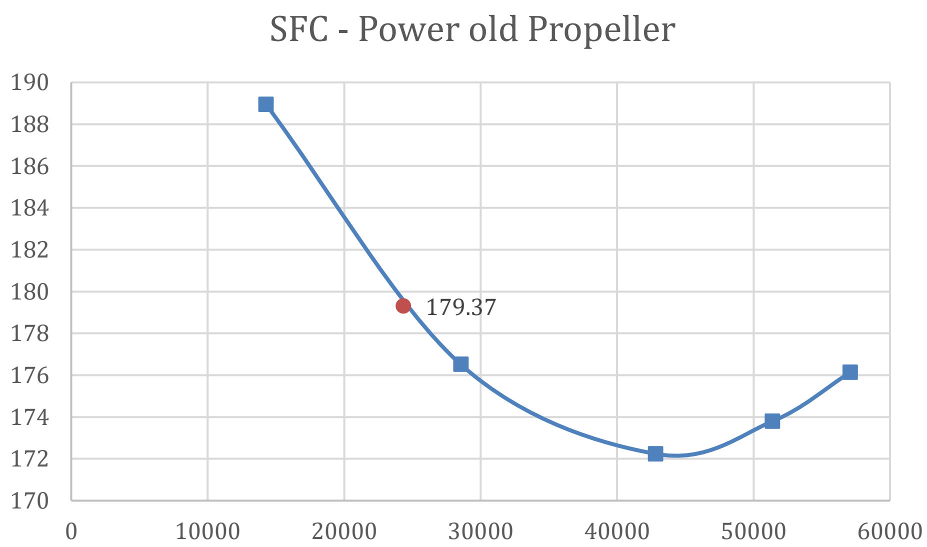

Figure 47:SFC - Power for the old propeller

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

$$\begin{aligned} attained\ EEXI &= \frac{f_j \cdot (P_{ME} \cdot SFC_{ME} \cdot CF_{ME} + P_{AE} \cdot SFC_{AE} \cdot CF_{AE})}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \cdot f_m} \\ &= \frac{1.0 \cdot (24319 \cdot 179.4 \cdot 3.206 + 1677 \cdot 199.775 \cdot 3.206)}{1.0 \cdot 1.0 \cdot 1.0 \cdot 60117.19 \cdot 21.71 \cdot 1.0} \\ &= 11.53\ gCO_2/t \cdot nm \end{aligned}$$

Continuing, the diagram below shows the new speed-power curve after the application of EPL and propeller change for better performance at the specific power and operating speed where the ship must operate in order to be compliant with the EEXI requirements. The new attained EEXI is calculated based on these three updated parameters. SFOC: **178.44** gr/kW·h, P_{ME} : **25606** kW, V_{ref} = **22.67** kW. The non-dimensional factors remained unchanged.

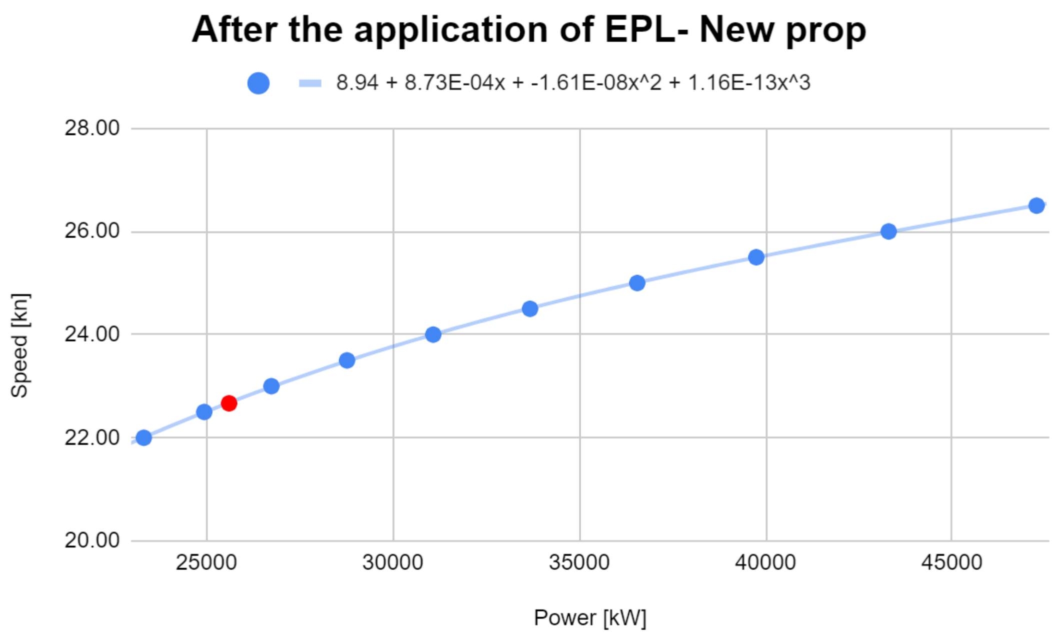

Figure 48: Speed – Power curve for Ship 2 after EPL – new propeller

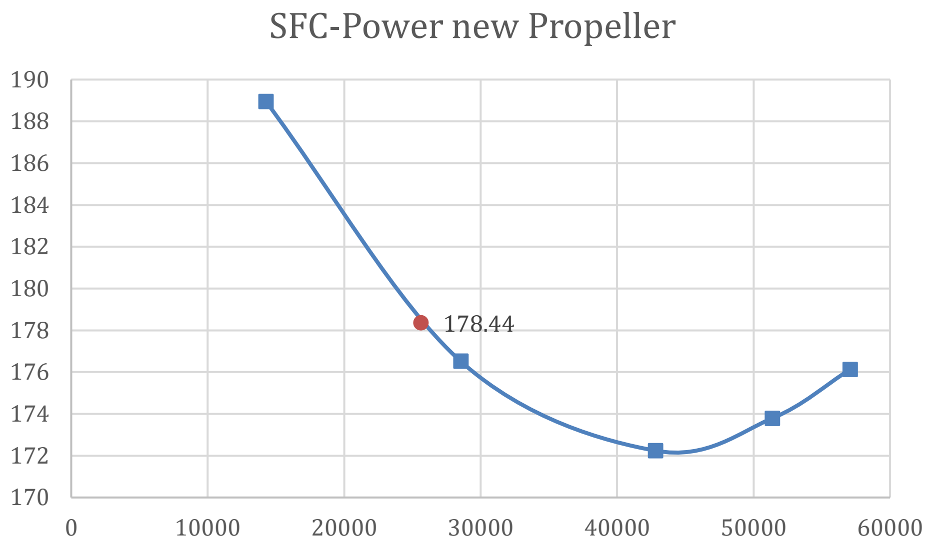

Figure 49:SFC - Power for the new propeller

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

$$attained\ EEXI = \frac{f_j \cdot (P_{ME} \cdot SFC_{ME} \cdot CF_{ME} + P_{AE} \cdot SFC_{AE} \cdot CF_{AE})}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \cdot f_m}$$

$$= \frac{1.0 \cdot (25606 \cdot 178.44 \cdot 3.206 + 1677 \cdot 199.775 \cdot 3.206)}{1.0 \cdot 1.0 \cdot 1.0 \cdot 60117.19 \cdot 22.67 \cdot 1.0}$$

$$= 11.53\ gCO_2/t \cdot nm$$

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