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ΤΟΜΕΑΣ ΜΕΛΕΤΗΣ ΠΛΟΙΟΥ ΚΑΙ ΘΑΛΑΣΣΙΩΝ ΜΕΤΑΦΟΡΩΝ

DIPLOMA THESIS

"Innovative Solutions for Compliance with EEXI Regulations: Evaluating the Effect of Energy Saving Devices and Engine Power Limitations on Vessel Performance."

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Athens, October 2022

ABSTRACT

This Thesis, entitled "The effect of Energy Saving Devices and the Engine Power limitation on both Energy Efficiency Existing Ship Index (EEXI) and the maximum allowed speed.", was developed within the field of undergraduate studies at the Naval Architecture and Marine Engineering department of the National Technical University of Athens, under the supervision of Associate Professor Dr. Nikolaos P. Ventikos.

The scope of this analysis is to mitigate the negative impacts, enhance the implementation of the index, and upgrade the entire world fleet. This is feasible with the assessment of the energy efficiency technologies on the operational profile of a vessel when combined with EPL.

The subject of this research is to incentivize development and deployment of further energy saving technologies and innovative ship designs. The revision of existing and setting of future design standards should be a matter of further analysis.

In the present thesis, a broad approach is carried out to the marine sector from an environmental point of view. This thesis refers to the Energy Efficiency Existing Index (EEXI) issues, undertaken by the International Maritime Organization (IMO) for limiting Greenhouse Gas Emissions (GHG).

At first, this paper identifies the Environmental challenges the shipping industry is facing, describes the initiatives undertaken until now, addresses the responsibility taken by the shipping industry, and presents the Initial IMO strategy with more gravity given to the short-term measures. Continuing the paper introduces the Regulatory framework concerning the short-term measures and in more detail the Energy Efficiency Existing Index (EEXI). This introduction includes the main parameters, the formula of the calculation, the implementation process, some specific vessel cases, and the main options to comply.

Proceeding the paper assesses the Post EEDI vessels on their compliance with the EEXI regulations. The analysis evaluated tankers, bulk carriers, and container ships from the IMO EEDI database for 2020. The results from the statistical analysis gave us some interesting conclusions about the fleet performance. One interesting discovery was that almost no vessel in all 3 categories reported the use of innovative electrical and/or mechanical energy-saving technologies and so there is considerable scope for further improvement.

ESDs can effectively help decrease the EEDI and EEXI because energy saving is simultaneously achieved without significantly changing ship dimensions or incurring additional costs. The relation between EPL and the usage of ESDs is investigated in order to assess the impact of their combination on older vessels that had ELP that limited their operational speeds.

In the last sector the study investigates with some case studies, the alternative options of a vessel to compliance. The difference on the operational profile after implementation and the relation between tha usage of ESDs and the feasible speeds this vessel can achieve in relation to just implementing EPL. The process is contacted with the use of a numerical computing environment named Ship Energy Compliance Software.

The platform operates as an interactive tool which, through appropriately configured boxes written in English, receives the necessary input data from the user and outputs the requested results according to the parameters set for each inquiry. The required input data relates to the basic characteristics of the ships, the specifications of their engines, the speed power curves for every loading condition and the

NOON reports in order to identify the Operational profile. The exported results provide the combination of ships EPL and ESDs net power saving (Category B and C), along with the estimated performance of the vessel in terms of speed feasibility.

All results are saved in the platform in order to be intelligible and their further processing to be feasible, while they are also presented in graphs and charts.

Abstract in Greek

Σήμερα, η ναυτιλιακή κοινότητα βρίσκεται σε άμεση ανάγκη εξεύρεσης αποδοτικών λύσεων, ικανών να συνεισφέρουν ενεργά στη μείωση των εκπομπών διοξειδίου του άνθρακα από τα πλοία.

Η παρούσα Διπλωματική Εργασία εκπονήθηκε στο πλαίσιο προπτυχιακών σπουδών στο τμήμα Ναυπηγικής και Ναυπηγικής του Εθνικού Μετσόβιου Πολυτεχνείου, υπό την επίβλεψη του Καθηγητή Δρ Νικόλαου Π. Βεντίκου.

Το αντικείμενο αυτής της ανάλυσης είναι η ενίσχυση της εφαρμογής του δείκτη, περιορισμος των αρνητικών επιπτώσεων απο την εφαρογη αυτη και η αναβάθμιση ολόκληρου του παγκόσμιου στόλου. Αυτό είναι εφικτό με την αξιολόγηση των τεχνολογιών ενεργειακής απόδοσης στο λειτουργικό προφίλ ενός πλοίου, όταν συνδυάζεται με την μείωσης ισχύος της κύριας μηχανής του πλοίου (EPL).

Αντικείμενο της παρούσας έρευνας είναι η παροχή κινήτρων για την ανάπτυξη και την εφαρμογή περαιτέρω τεχνολογιών εξοικονόμησης ενέργειας και καινοτόμων σχεδίων πλοίων. Η αναθεώρηση των υφιστάμενων και ο καθορισμός μελλοντικών προτύπων σχεδιασμού θα πρέπει να αποτελέσει αντικείμενο περαιτέρω ανάλυσης.

Η παρούσα εργασια αναφέρεται στα θέματα του δείκτη ενεργειακής απόδοσης (EEXI), που ανέλαβε ο Διεθνής Ναυτιλιακός Οργανισμός (IMO) για τον περιορισμό των εκπομπών αερίων του θερμοκηπίου (GHG).

Αρχικά, η παρούσα εργασία προσδιορίζει τις περιβαλλοντικές προκλήσεις που αντιμετωπίζει η ναυτιλιακή βιομηχανία, περιγράφει τις πρωτοβουλίες που έχουν αναληφθεί μέχρι σήμερα, εξετάζει την ευθύνη που έχει αναλάβει η ναυτιλιακή βιομηχανία και παρουσιάζει την αρχική στρατηγική του IMO με μεγαλύτερη βαρύτητα στα βραχυπρόθεσμα μέτρα (short term measures). Στη συνέχεια παρουσιάζεται το κανονιστικό πλαίσιο το οποίο περιβαλλει τα μέτρα αυτά και λεπτομερέστερα τον δείκτη ενεργειακής απόδοσης (EEXI). Η εισαγωγή αυτή περιλαμβάνει τις κύριες παραμέτρους, τον τύπο υπολογισμού, τη διαδικασία εφαρμογής, ορισμένες ειδικές περιπτώσεις πλοίων και τις κύριες τεχνικες λυσεις που υπαρχουν στην αγορα για ενα πλοιο.

Στη συνέχεια, η εργασία αξιολογεί τα πλοία τα οποια ναυπηγήθηκαν μετα το 2013 και ειναι μερος του κανονιστικου πλαισιου για τον δείκτη ενεργειακής απόδοσης (EEDI) ως προς τα ποσοστα συμμορφωσης με τους κανονισμούς EEXI. Η ανάλυση αξιολόγησε δεξαμενόπλοια, πλοία μεταφοράς χύδην φορτίου και πλοία μεταφοράς εμπορευματοκιβωτίων από τη βάση δεδομένων του IMO EEDI για το 2020. Τα αποτελέσματα της στατιστικής ανάλυσης μας έδωσαν ορισμένα ενδιαφέροντα συμπεράσματα σχετικά με τις επιδόσεις του στόλου. Μια ενδιαφέρουσα ανακάλυψη ήταν ότι σχεδόν κανένα πλοίο και στις 3 κατηγορίες δεν ανέφερε τη χρήση καινοτόμων ηλεκτρικών ή/και μηχανικών τεχνολογιών εξοικονόμησης ενέργειας και έτσι υπάρχουν σημαντικά περιθώρια περαιτέρω βελτίωσης.

Οι τεχνολογιες εξοικονόμησης ενέργειας μπορούν να συμβάλουν αποτελεσματικά στη μείωση του δεικτη EEDI και του EEXI, επειδή η εξοικονόμηση ενέργειας επιτυγχάνεται ταυτόχρονα χωρίς να αλλάζουν σημαντικά οι διαστάσεις του πλοίου ή να επιβαρύνονται με πρόσθετο κόστος. Η σχέση μεταξύ της μείωσης ισχύος της κύριας μηχανής του πλοίου (EPL) και της παραγωμενης ενεργειας απο τις τεχνολογιες αυτες διερευναται προκειμενου να εκτιμηθεί το αντίκτυπο του συνδυασμού τους σε παλαιότερα πλοία που μείωσης ισχύος της κύριας μηχανής του πλοίου περιόριζει τις λειτουργικές τους ταχύτητες.

Τελος η μελέτη διερευνά με ορισμένες μελέτες περιπτώσεων(case studies), τις εναλλακτικές επιλογές ενός πλοίου. Η διαφορά στο λειτουργικό προφίλ μετά την εφαρμογή της μείωσης ισχύος της κύριας μηχανής του πλοίου (EPL) και η σχέση μεταξύ της χρήσης των τεχνολογιών εξοικονόμησης ενέργειας και των εφικτών ταχυτήτων που μπορεί να επιτύχει το σκάφος αυτό σε σχέση με την εφαρμογή μονο της μειωσης ισχύος . Η διαδικασία προσεγγίζεται με τη χρήση ενός αριθμητικού υπολογιστικού περιβάλλοντος που ονομάζεται Ship Energy Compliance Software.

Η πλατφόρμα λειτουργεί ως διαδραστικό εργαλείο το οποίο, μέσω κατάλληλα διαμορφωμένων πλαισίων γραμμένων στην αγγλική γλώσσα, λαμβάνει τα απαραίτητα δεδομένα εισόδου από τον χρήστη και εξάγει τα ζητούμενα αποτελέσματα σύμφωνα με τις παραμέτρους που έχουν οριστεί για κάθε έρευνα. Τα απαιτούμενα δεδομένα εισόδου αφορούν τα βασικά χαρακτηριστικά των πλοίων, τις προδιαγραφές των μηχανών τους, τις καμπύλες ταχύτητας ισχύος για κάθε κατάσταση φόρτωσης και τις αναφορές ταχύτητας (NOON reports) προκειμένου να προσδιοριστεί το λειτουργικό προφίλ. Τα εξαγόμενα αποτελέσματα παρέχουν τον συνδυασμό μείωσης ισχύος της κύριας μηχανής του πλοίου (EPL) και της χρήσης των τεχνολογιών εξοικονόμησης ενέργειας (ESDs Κατηγορία Β και Γ), μαζί με την εκτιμώμενη απόδοση του πλοίου όσον αφορά τις εφικτες πλεον ταχύτητα.

Όλα τα αποτελέσματα αποθηκεύονται στην πλατφόρμα προκειμένου να είναι κατανοητά και να είναι εφικτή η περαιτέρω επεξεργασία τους, ενώ παρουσιάζονται επίσης σε γραφήματα και διαγράμματα.

Acknowledgment

The current thesis is the final chapter of my studies in the School of Naval Architecture and Marine Engineering of the National Technical University of Athens, and it is conducted under the supervisory of the Ship Design and Maritime Transport sector.

First and foremost, I would like to express my deep and honest gratitude to my thesis supervisor Prof. Nikolaos Ventikos, for his genuine support and invaluable guidance throughout the research and writing of my diploma thesis.

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Athens 2022,

Papaefthymiou Konstantinos

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Acronyms

EU: European Union

IMO: International Maritime Organization

MEPC: Marine Environmental Protection Committee

SEEMP: Ship Energy Efficiency Management Plan

ECAs: Emission Control Area

ISO: International Organization for Standardization

MEPC: Marine Environment Protection Committee

EMSA: European Maritime Safety Agency

EPA: Environmental Protection Agency

IACS: International Association of Classification Societies

EEXI: Energy Efficiency Existing Ship Index

GHG: Greenhouse gases

EEDI: Energy Efficiency Design Ship Index

EPL: Engine Power Limitation

SHaPoLI: Shaft Power Limitation

ESD: Energy Saving Device

EET: Energy Efficiency technology

P_{ME}: Power of main engines

MCR: Maximum continuous rating

SFOC: Specific fuel oil consumption

$P_{PTO(i)}$: Shaft generator

$P_{PTI(i)}$: Power of the Shaft motors

$P_{SM,max(i)}$: rated power consumption of each shaft motor.

n_{Gen} : weighted average efficiency of the generator(s)

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

P_{AEeff} : Innovative mechanical energy efficient technology for auxiliary engines

P_{AE} : Auxiliary engine power

V_{ref} : Reference speed on P_{ME}

k : the scale coefficient

DWT: Deadweight

1. Introduction

Air emissions from ships have been of concern to many researchers in the decades, as it appears to be a problem of growing concern. Research has shown that shipping activity is a major source of pollution. an important source of air pollution, particularly in coastal areas affecting air quality, global climate, the environment and human health.

(Papanastasiou and Melas, 2009; Chen et al., 2017; Chen et al. Tzannatos, 2009; Chatzinikolaou et al., 2015)

The purpose of this thesis is to analytically present the upcoming Energy Efficiency Existing Ship Index (EEXI),to analyze from a statistical point of view the impact of these regulation on Post EEDI vessels, then to meticulously investigate the effect of the Engine Power Limitation (EPL) in combination with ESDs on the INDEX in terms of compliance with the requirements, contribution to the reduction of the CO2 and finally to investigate the effect of this combination in the operational schedule of various vessels.

In the first part of the report, the Greenhouse effect is explained diving deep in the responsibility of the shipping industry in this environmental crisis. Under this scope, a brief analysis of the International Maritime Organization's (IMO) strategy about the reduction of the CO2 emissions from shipping is conducted. The report continuous with the EEXI, a part of the short-term measures, which is described from a theoretical point of view. The theoretical approach to the EEXI consists of an introduction to the INDEX, the corresponding formula and the included parameters, the calculation process followed with an example and at last the option in order to comply.

In the second part a statistical analysis is conducted, in which Post EEDI vessels from the IMO EEDI databased are testing on their compliance. In this part of the analysis the "weak" points of the fleet are detected. Then a detailed list of all the alternative options and more specific, different types of retrofits and modifications of any category is created. At last detailed case studies are conducted to provide valid deductions on the effect of these alternative options on the EPL and on the operational profile of these vessels.

This thesis, beyond presenting the EEXI requirements and applying the corresponding procedures, aims at revealing the importance of exploring different ways of compliance and showcases the disadvantages of Engine Power Limitation, as the only means of compliance both for commercial but also environmental reasons.

2. Environmental Problems and regulatory frameworks

2.1 Greenhouse effect and development of environmental responsibility in Shipping

The greenhouse effect is the process by which a planet's atmosphere retains heat and helps to raise its surface temperature. Light arriving from our Sun passes through Earth's atmosphere and warms its surface. The warmed surface then radiates heat, which is absorbed by greenhouse gases such as carbon dioxide. The result of the overall phenomenon is an increase in the average surface temperature, which makes the Earth habitable. Without the natural greenhouse effect, the earth's surface temperature would be -18 ° C on a global and annual basis, while in practice it is 14 ° C.

About 30% of the incoming solar radiation is reflected, at a rate of 6% by the atmosphere, 20% by the clouds and 4% by the Earth's surface. 70% of sunlight is absorbed, 16% by the atmosphere (including the stratospheric ozone layer), 3% by clouds and the largest percentage (51%) by the surface and oceans.

In recent years, the term is associated with an increase in the average temperature of the Earth's surface (global warming), while it is considered that the phenomenon has been significantly enhanced by anthropogenic activities

The problem is that recently, the greenhouse effect has become stronger. This is because humans have been burning large amounts of fossil fuels, which releases carbon dioxide. Since carbon dioxide is a greenhouse gas, it has caused the planet to warm over the past 150 years.

The greenhouse effect is natural, but it is enhanced by human activity, which helps to increase the concentration of greenhouse gases as well as the release of other trace elements, such as chlorofluorocarbons (CFC's). In recent years, there has been an increase in the concentration of several greenhouse gases, especially in the case of carbon dioxide, this increase was 31% in the period 1750 - 1998. Three-quarters of anthropogenic carbon dioxide production is due to the use of fossil fuels, while the rest comes from changes that take place in the soil, mainly through deforestation.

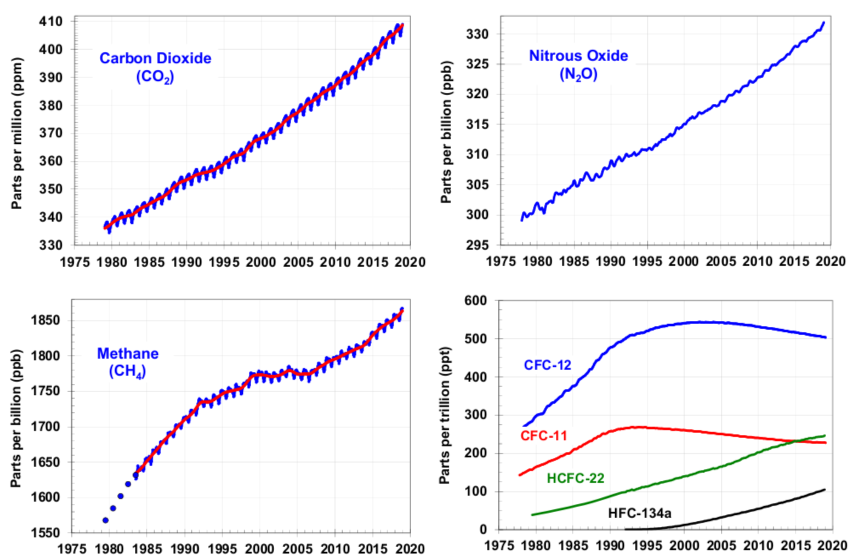


Figure 1:increase in the concentration of several greenhouse gases(source IMO)

(*Greenhouse Effect - Simple English Wikipedia, the Free Encyclopedia*, [s.d.])

The greenhouse effect occurs when certain gases in the Earth's atmosphere (the air around the Earth) trap infrared radiation. The most important greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide (CO2), and methane. When there is more greenhouse gas in the air, the air holds more` heat. This is why more greenhouse gases cause climate change and global warming.

The IPCC Sixth Assessment Report projects that global warming is very likely to reach 1.0 °C to 1.8 °C by the late 21st century under the very low GHG emissions scenario. In an intermediate scenario global warming would reach 2.1 °C to 3.5 °C, and 3.3 °C to 5.7 °C under the very high GHG emissions scenario. These projections are based on climate models in combination with observations. According to the IPCC, global warming can be kept below 1.5 °C with a two-thirds chance if emissions after 2018 do not exceed 420 or 570 gigatons of CO2. This corresponds to 10 to 13 years of current emissions.

Countries try to emit less greenhouse gases. The Kyoto Protocol was signed in 1997. It was meant to reduce the amount of greenhouse gases in the atmosphere to below their levels in 1990. However, carbon dioxide levels have continued to rise.

Energy conservation is used to burn less fossil fuel. People can also use energy sources that don't burn fossil fuel, like solar panels or electricity from nuclear power or wind power. Or they can prevent the carbon dioxide from getting out into the atmosphere, which is called carbon capture and storage (CCS). Geoengineering is also seen by some as one a way to slow or stop climate change.

The contribution of shipping is to global CO2 is marginal. Shipping produces 1billion CO2 per year and projections show that it can go up to 1,4b per year.

(Gupta, 2010)

2.2 International Initiatives for controlling the climate change

It fell to scientists to draw international attention to the threats posed by global warming. Evidence in the 1960s and '70s that concentrations of carbon dioxide (CO2) in the atmosphere were increasing first led climatologists and others to press for action. It took years before the international community responded.

In 1988, global warming and the depletion of the ozone layer became increasingly prominent in the international public debate and political agenda. UNEP organized an internal seminar in January to identify environmental sectors that might be sensitive to climate change. The Intergovernmental Panel on Climate Change (IPCC), a forum for the examination of greenhouse warming and global climate change, was established and met for the first time in November. The General Assembly identified climate change as a specific and urgent issue. In its resolution on the protection of global climate for present and future generations of mankind, it asked WMO and UNEP to initiate a comprehensive review and make recommendations on climate change, including possible response strategies to delay, limit or mitigate the impact of climate change. s a result, 1989 was a watershed year for climate change, as the first significant global efforts were taken. The Assembly, in resolution 44/207, endorsed the UNEP Governing Council's request to begin preparations with WMO for negotiations on a framework convention on climate change.

Efforts to raise awareness of the effects of climate changes were further advanced at the second World Climate Conference, held from 29 October to 7 November 1990. In its Ministerial Declaration, the

Conference stated that climate change was a global problem of unique character for which a global response was required. It called for negotiations to begin on a framework convention without further delay. As the urgency for a stronger international action on the environment, including climate change, gained momentum, the General Assembly decided to convene in 1992 in Rio de Janeiro, Brazil, the United Nations Conference on Environment and Development set a new framework for seeking international agreements to protect the integrity of the global environment. The most significant event during the Conference was the opening for signature of the United Nations Framework Convention on Climate Change (UNFCCC); by the end of 1992, 158 States had signed it. As the most important international action thus far on climate change, the Convention was to stabilize atmospheric concentrations of "greenhouse gases" at a level that would prevent dangerous anthropogenic interference with the climate system. It entered into force in 1994.

The cornerstone of the climate change action was, therefore, the adoption in Japan in December 1997 of the Kyoto Protocol to the UNFCCC, the most influential climate change action so far taken. It aimed to reduce the industrialized countries' overall emissions of carbon dioxide and other greenhouse gases by at least 5 per cent below the 1990 levels in the commitment period of 2008 to 2012. The Protocol, which opened for signature in March 1998, came into force on 16 February 2005, seven years after it was negotiated by over 160 nations.(Shishlov et al., 2016)

2.3 environmental responsibility in Shipping industry

In 2010, the global transport sector was responsible for almost a quarter of all anthropogenic CO2 emissions, resulting in the release of 8.8 billion metric tons (Gt) of CO2 into the atmosphere and consuming 47 million barrels per day of oil.

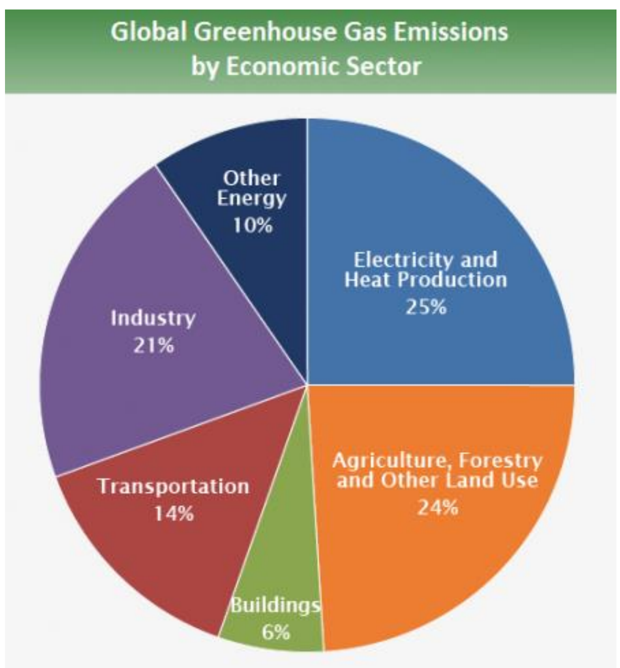


Figure 2 Source EPA, 2020

The contribution of shipping to global CO2 is marginal. Shipping produces 1billion CO2 per year.

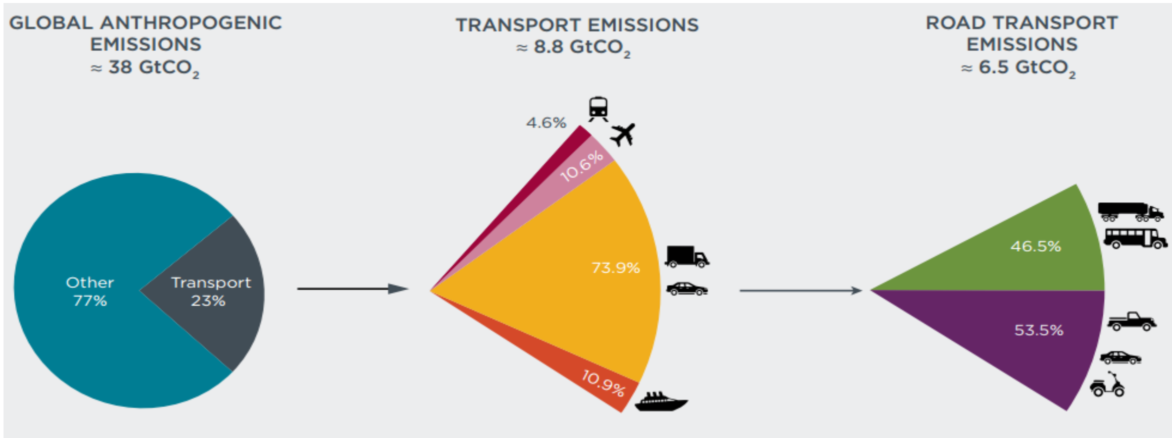


Figure 3 International Council on Clean Transportation

The most recent estimates included in the Fourth IMO GHG Study 2020 show that GHG emissions of

Total shipping has increased from 977 million tonnes in 2012 to 1,076 million tons in 2018 (9.6% increase) mostly due to a continuous increase of global maritime trade. The share of shipping emissions in global anthropogenic GHG emissions has increased from 2.76% in 2012 to 2.89% in 2018.

Year	Global anthropogenic CO_2 emissions	Total shipping CO^2	Total shipping as a percentage of global
2012	34,793	962	2.76%
2013	34,959	957	2.74%
2014	35,225	964	2.74%
2015	35,239	991	2.81%
2016	35,380	1,026	2.90%
2017	35,810	1,064	2.97%
2018	36,573	1,056	2.89%

Figure 4 Total shipping CO2 emissions 2012-2018 (million tonnes)

Based on various long-term economic and energy scenarios (not taking into account long-term effects of the COVID-19 pandemic), and without any additional measures, the Study describes that shipping emissions are projected to increase from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050.

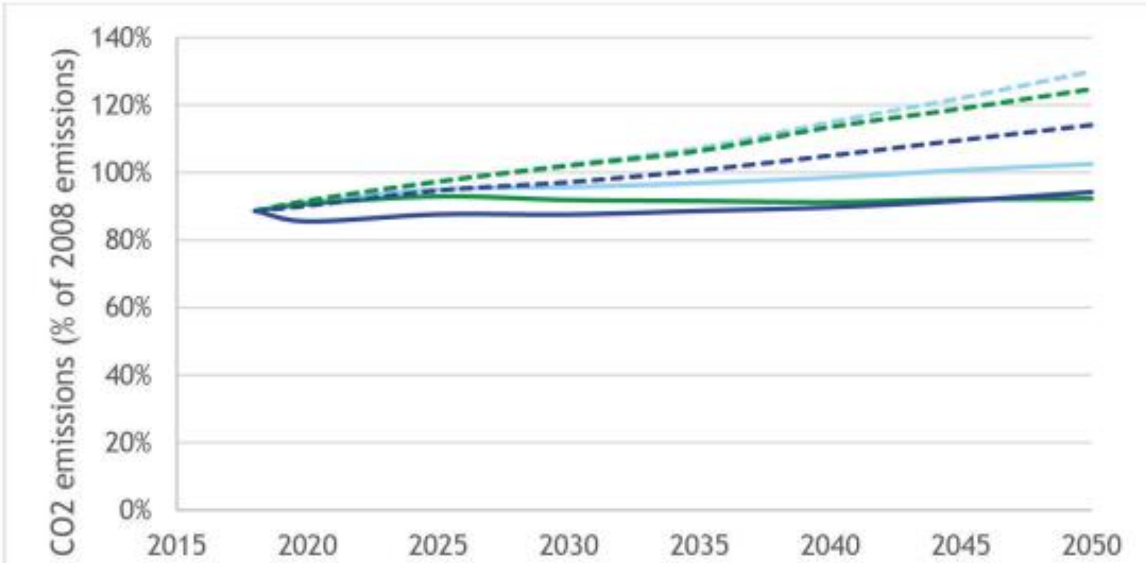


Figure 5 Projections of maritime ship emissions as a percentage of 2008 emissions for a range of long-term economic and energy scenarios (Source: 4th IMO GHG study)

2.4 IMO GHG strategy

In September 1997, an International Conference of Parties to the MARPOL Convention, which adopted the Protocol of 1997 to amend the MARPOL Convention (MARPOL Annex VI), also adopted resolution 8 on CO2 emissions from ships. This resolution invited the Marine Environment Protection Committee (MEPC) to consider what CO2 reduction strategies might be feasible in light of the relationship between CO2 and other atmospheric and marine pollutants. The resolution also invited IMO, in cooperation with the UNFCCC, to undertake a study of CO2 emissions from ships for the purpose of establishing the amount and relative percentage of CO2 emissions from ships as part of the global inventory of CO2 emissions

In 2000, the First IMO GHG Study on GHG emissions from ships was published, which estimated that ships engaged in international trade in 1996 contributed about 1.8 per cent of the world total anthropogenic CO2 emissions.

In December 2003, the IMO Assembly adopted resolution A.963(23) on IMO Policies and practices related to the reduction of greenhouse gas emissions from ships, which urged MEPC to identify and develop the mechanism(s) needed to achieve the limitation or reduction of GHG emissions from international shipping. In the ensuing years, MEPC has since been energetically pursuing measures to limit and reduce GHG emissions from international shipping.

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 NOx Technical Code 2008, which entered into force on 1 July 2010.

In July 2011, IMO adopted mandatory measures to improve the energy efficiency of international shipping through resolution MEPC.203(62), representing the first-ever mandatory global energy efficiency standard for an international industry sector, the first legally binding instrument to be adopted since the Kyoto Protocol that addresses GHG emissions and the first global mandatory GHG-reduction regime for an international industry sector.

The amendments adopted by resolution MEPC.203(62) added a new chapter 4 entitled "Regulations on energy efficiency for ships" to MARPOL Annex VI. This package of technical and operational requirements which apply to ships of 400 GT and above, are known as the Energy Efficiency Design Index (EEDI), applicable to new ships, which sets a minimum energy efficiency level for the work undertaken (e.g. CO2emissions per tonne-mile) for different ship types and sizes, and the Ship Energy Efficiency Management Plan (SEEMP), applicable to all ships. These mandatory requirements entered into force on 1 January 2013.

Since 2012, Marine Environment Protection Committee (MEPC) adopted/approved or amended important guidelines aimed at assisting the implementation of the mandatory regulations on Energy Efficiency for Ships in MARPOL Annex VI:

In 2018, IMO adopted an initial strategy on the reduction of GHG emissions from ships, setting out a vision which confirms IMO's commitment to reducing GHG emissions from international shipping and to phasing them out as soon as possible. The initial GHG strategy envisages, in particular, a reduction in carbon intensity of international shipping (to reduce CO2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008) and that total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to 2008.

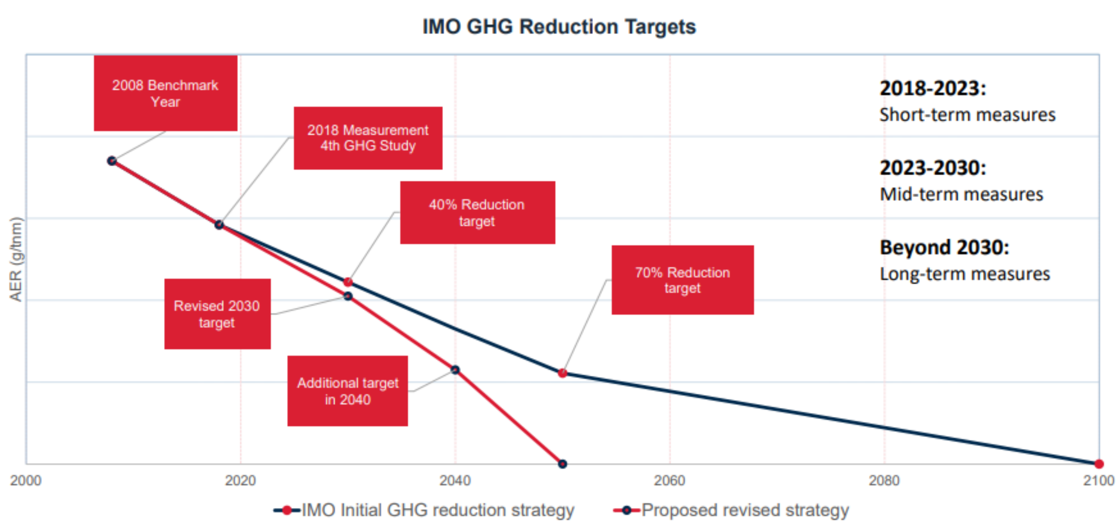


Figure 6 GHG emission gap between IMO GHG strategy and BAU emissions

The Initial Strategy identifies:

- possible candidate short-term measures, which could be agreed between 2018 and 2023, such as further improvement of the EEDI and the SEEMP, the development of operational indicators for both new and existing ships, the establishment of an Existing Fleet Improvement Programme, the use of speed optimization and speed reduction, the development and update of national action plans, the enhancement of technical cooperation activities managed by IMO, ports developments (e.g. onshore power supply from renewable sources), incentives for first movers to develop and take up new technologies, etc.

- possible candidate mid-term measures, which could be agreed between 2023 and 2030, such as the implementation programme for the effective uptake of alternative low-carbon and zero-carbon fuels or innovative emission reduction mechanisms to incentivize GHG emission reduction, including for example Market-based Measures.

- possible candidate long-term measures, which could be agreed beyond 2030, such as pursuing the development and provision of zero-carbon or fossil-free fuels or encouraging and facilitating the adoption of other innovative emission reduction mechanisms

2.5 Proposed short-term measures.

IMO's Marine Environment Protection Committee (MEPC 76), meeting in a remote session from 10 to 17 June 2021, adopted amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI that will require ships to reduce their greenhouse gas emissions. These amendments combine these technical and operational approaches to improve the energy efficiency of ships, also providing important building blocks for future GHG reduction measures.

The short-term measure is aimed at meeting the target set in the IMO Initial GHG Strategy – to reduce carbon intensity of all ships by 40% by 2030, compared to 2008. These are and some will be mandatory measures under MARPOL Annex VI. They will bring in:

(*IMO’s Work to Cut GHG Emissions from Ships*, [s.d.])

- EEDI and SEEMP
- EEXI and CII
- Methane emissions and volatile organic compounds
- Develop GHG Guidelines
- Initiate research and development for innovative technologies.
- Undertake additional GHG emission study

The EEDI, the predecessor of EEXI for new ships is the most important technical measure and aims at promoting the use of more energy efficient (less polluting) equipment and engines. The EEDI requires a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different ship type and size segments. Since 1 January 2013, following an initial two-year phase zero, new ship design needs to meet the reference level for their ship type. The level is to be tightened incrementally every five years, and so the EEDI is expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase.

The Ship Energy Efficiency Management Plan (SEEMP) is an operational measure that establishes a mechanism to improve the energy efficiency of a ship in a cost-effective manner. The SEEMP also provides an approach for shipping companies to manage ship and fleet efficiency performance over time using, for example, the Energy Efficiency Operational Indicator (EEOI) as a monitoring tool. The guidance on the development of the SEEMP for new and existing ships incorporates best practices for fuel efficient ship operation, as well as guidelines for voluntary use of the EEOI for new and existing ships (MEPC.1/Circ.684)

The CII determines the annual reduction factor needed to ensure continuous improvement of the ship's operational carbon intensity within a specific rating level. The actual annual operational CII achieved (attained annual operational CII) would be required to be documented and verified against the required annual operational CII. This would enable the operational carbon intensity rating to be determined. The rating would be given on a scale - operational carbon intensity rating A, B, C, D or E - indicating a major superior, minor superior, moderate, minor inferior, or inferior performance level. The performance level would be recorded in the ship's Ship Energy Efficiency Management Plan (SEEMP). A ship rated D for three consecutive years, or E, would have to submit a corrective action plan, to show how the required index (C or above) would be achieved. Administrations, port authorities and other stakeholders, as appropriate, are encouraged to provide incentives to ships rated as A or B.

(*Further Shipping GHG Emission Reduction Measures Adopted*, [s.d.])

The short-term measures are aimed at achieving the carbon intensity reduction aims of the IMO initial GHG Strategy. They do this by requiring all ships to calculate their Energy Efficiency Existing Ship Index (EEXI) and to establish their annual operational carbon intensity indicator (CII) and CII rating.

3. Energy Efficiency Existing Ships Index (EEXI)

3.1 Introduction to the EEXI

The Energy Efficiency existing ship Index (EEXI) is a short time measure introduced by IMO to reduce the greenhouse gas emissions of ships. The EEXI is a technical design related measure, an index that estimates grams of CO2 per transport work (g of CO2 per ton-mile), it can be expressed as the ratio of “environmental cost “divided by “benefit for society”. The philosophy behind EEXI is that its computation is simple and capable of broad application and promote efforts by all stakeholders to reduce CO2 emissions by reflecting a ship’s energy efficiency in actual use.

EEXI aims to improve the global fleet’s energy efficiency, there is a maximum threshold level that the index must fall below. The reference line forming the requirement level was implemented in 2013, with the requirement getting stricter. The baselines were created for every ship type separately using regression analysis of operation data. The Index also stimulates continued technical development of all the components influencing the fuel efficiency of a ship. It also separates the technical and design-based measures from the operational and commercial ones. EEXI does not require any measurement or reporting of true CO2 emissions while the ship is in operation.

EEXI regulation applies to ships of 400 gross tonnages and above, and whose ship type falls into one or more of the categories in regulation 2 of MARPOL Annex VI. Ships to which the regulation applies will be required to calculate the EEXI value of each individual ship (i.e. attained EEXI) and the value shall be equal to or less than the allowable maximum value (i.e. required EEXI). Furthermore, if attained EEXI cannot satisfy the required EEXI, the ship should implement any countermeasures, such as shaft/engine power limitation, retrofitting energy saving devices.

Attained EEXI ≤ Required EEXI

Ships must approve the attained EEXI value once in a life-time latest by the first periodical survey in 2023.

3.2 Formula explained, Attained EEXI, EEDI-EEXI relation.

The Energy Efficiency Design Index (EEDI) is a rate that estimates the energy efficiency of new vessels (gr-CO2/t*nm). According to the IMO, the main purpose of the EEDI it to provide a fair basis for comparison and to support the development of more innovative, energy efficient vessels. Furthermore, the regulation sets the minimum efficiency level of new vessels, based on ship type & size. In that direction, the reference lines for each ship type have been established. As stated by the (IMO, 2013), a reference line is a curve that represents an average index value fitted on a set of individual index values for a specific group of vessels. As explained by (Transport & Environment, 2017) the standard reference line, also known as baseline, is calculated from the average efficiency of the vessels that were built from 1999 to 2009.

At MEPC 62 (July 2011) adoption of amendments to MARPOL Annex VI (resolution MEPC.203(62)) made mandatory the Energy Efficiency Design Index (EEDI) was made mandatory for new ships. The EEDI for new ships aimed at promoting the use of more energy efficient (less polluting) equipment and engines. It requires a minimum energy efficiency level per capacity mile (e.g., tonne mile) for different ship types and size segments. EEDI provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO_2) per ship's capacity-mile (the smaller the EEDI the more energy efficient ship design) and is calculated by a formula based on the technical design parameters for a given ship.

Since 1 January 2013, following an initial two-year phase zero, new ship design needs to meet the reference level for their ship type. The level is tightened incrementally every five years, and the EEDI is expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase. The EEDI is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in a specific ship design to the industry.

Ship Type	Size	Phase 0 1 Jan 2013 – 31 Dec 2014	Phase 1 1 Jan 2015 – 31 Dec 2019	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Jan 2025 and onwards
Bulk carrier	20,000 DWT and above	0	10	20	30
	10,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Gas carrier	10,000 DWT and above	0	10	20	30
	2,000 – 10,000 DWT	n/a	0-10*	0-20*	0-30*
Tanker	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Container ship	15,000 DWT and above	0	10	20	30
	10,000 – 15,000 DWT	n/a	0-10*	0-20*	0-30*
General Cargo ships	15,000 DWT and above	0	10	15	30
	3,000 – 15,000 DWT	n/a	0-10*	0-15*	0-30*
Refrigerated cargo carrier	5,000 DWT and above	0	10	15	30
	3,000 – 5,000 DWT	n/a	0-10*	0-15*	0-30*
Combination carrier	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
LNG carrier***	10,000 DWT and above	n/a	10**	20	30
Ro-ro cargo ship (vehicle carrier)***	10,000 DWT and above	n/a	5**	15	30
Ro-ro cargo ship***	2,000 DWT and above	n/a	5**	20	30
	1,000 – 2,000 DWT	n/a	0-5*,**	0-20*	0-30*
Ro-ro passenger ship***	1000 DWT and above	n/a	5**	20	30
	250 – 1,000 DWT	n/a	0-5*,**	0-20*	0-30*
Cruise passenger ship*** having non-conventional propulsion	85,000 GT and above	n/a	5**	20	30
	25,000 – 85,000 GT	n/a	0-5*,**	0-20*	0-30*

Table 1: Reduction factors per phase of EEDI requirements

EEXI regulation applies to ships of 400 gross tonnages and above, and whose ship type falls into one or more of the categories in regulation 2 of MARPOL Annex VI. Ships to which the regulation applies will be required to calculate EEXI value of each individual ship (i.e. attained EEXI)

The final calculation formula is the same with the one of the EEDI and was finalized with MEPC 66/21 Annex 5 and is presented below:

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

Equation 1: EEXI formula

expressly provided otherwise. In referring to the aforementioned guidelines, the terminology "EEDI" should be read as "EEXI".

- C_f Conversion factor between fuel consumption and CO2 emission:

CF is a non-dimensional conversion factor between fuel consumption measured in g and CO2 emission also measured in g based on carbon content. The subscripts $ME_{(i)}$ and AE_i refer to the main and auxiliary engine(s) respectively. C_f corresponds to the fuel used when determining SFC listed in the applicable test report included in a Technical File of the NOX Technical Code. The value of CF is as follows:

Type of fuel	Reference	Carbon content	C_F (t-CO_2/t-Fuel)
1 Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
2 Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
3 Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
4 Liquefied Petroleum Gas (LPG)	Propane	0.8182	3.000
	Butane	0.8264	3.030
5 Liquefied Natural Gas (LNG)		0.7500	2.750
6 Methanol		0.3750	1.375
7 Ethanol		0.5217	1.913

Table 2 Values Of CF (source MEPC 73/19/Add.1 2.2.1)

For those engines which do not have a test report included in the NOX Technical File and which do not have the SFC specified by the manufacturer, the CF corresponding to SFC_{app} should be defined as follows: C_f = 3.114 [$(t * C_{O2})/(t * Fuel)$] for diesel ships (incl. HFO use in practice)

- Capacity

  - For bulk carriers, tankers, gas carriers, LNG carriers, ro-ro cargo ships (vehicle carriers), ro-ro cargo ships, ro-ro passenger ships, general cargo ships, refrigerated cargo carrier and combination carriers, deadweight should be used as capacity.

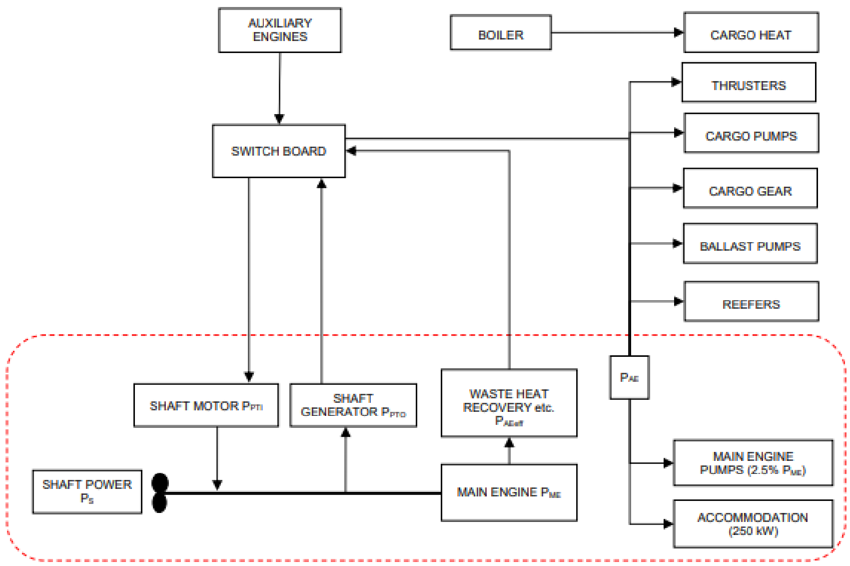
  - For passenger ships and cruise passenger ships, gross tonnage in accordance with the International Convention of Tonnage Measurement of Ships 1969, annex I, regulation 3, should be used as capacity.

  - For containerships, 70% of the deadweight (DWT) should be used as capacity.

  - Deadweight means the difference in tonnes between the displacement of a ship in water of relative density of 1,025 kg/m3 at the summer load draught and the lightweight of the ship. The summer load draught should be taken as the maximum summer draught as certified in the stability booklet approved by the Administration or an organization recognized by it.

- P, Power of main engines and auxiliary engines:
  P is the power of the main and auxiliary engines, measured in kW. The subscripts ME_i and AE_i refer to the main and auxiliary engine(s), respectively. The summation on (i) is for all engines with the number of engines (n_{ME})

A GENERIC AND SIMPLIFIED MARINE POWER PLANT



Note 1: Mechanical recovered waste energy directly coupled to shafts need not be measured, since the effect of the technology is directly reflected in the V_{ref} .

Note 2: In case of combined PTI/PTO, the normal operational mode at sea will determine which of these to be used in the calculation.

Figure 7:A GENERIC AND SIMPLIFIED MARINE POWER PLANT (SOURCE: MEPC.308(73))

- $P_{ME(i)}$ Power of main engines

$P_{ME(i)}$ is 75% of the rated installed power (MCR) for each main engine (i)

For LNG carriers having diesel electric propulsion system, $P_{ME(i)}$ should be calculated by the following formula:

$$P_{ME(i)} = 0.83 * \frac{MPP_{Motor(i)}}{n_i}$$

Where: $MPP_{Motor(i)}$ is the rated output of motor specified in the certified document.

n_i is to be taken as the product of electrical efficiency of generator, transformer, converter and motor, taking into consideration the weighted average as necessary.

In cases where overridable Shaft / Engine Power Limitation is installed in accordance with the Guidelines on the shaft / engine power limit to comply with the EEXI requirements and use of a power reserve (resolution MEPC.328(76)), $P_{ME(i)}$ is 83% of the limited installed power (MCR_{LIM}) or 75% of the original installed power (MCR), whichever is lower, for each main engine (i).

In cases where the overridable Shaft / Engine Power Limitation and shaft generator(s) are installed, of the EEDI Calculation Guidelines, "MCR_{ME}" should be read as " MCR_{LIM}".

(*MEPC.333(76) (1)*, [s.d.])

- $P_{PTO(i)}$ Shaft generator

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

For calculation of the effect of shaft generators two options are available:

Option 1:

The maximum allowable deduction for the calculation of $\Sigma P_{ME(i)}$ is to be no more than P_{AE} (see 2.3.6). For this case, $\Sigma P_{ME(i)}$ is calculated as:

$$\sum_{i=1}^{nME} P_{ME(i)} = 0.75 * \left(\sum_{i=1}^{n} MCR_{ME(i)} - \sum_{i=1}^{nPTO} 0.75 * MCR_{PTO(i)} \right)$$

where: $\sum_{i=1}^{nPTO} 0.75 * MCR_{PTO(i)} \leq P_{AE}/0.75$

Option 2:

Where an engine is installed with a higher rated power output than that which the propulsion system is limited to by verified technical means, then the value of $\Sigma P_{ME(i)}$ is 75% of that limited power for determining the reference speed, V_{ref} and for EEXI calculation. The following figure gives guidance for determination of $\Sigma P_{ME(i)}$:

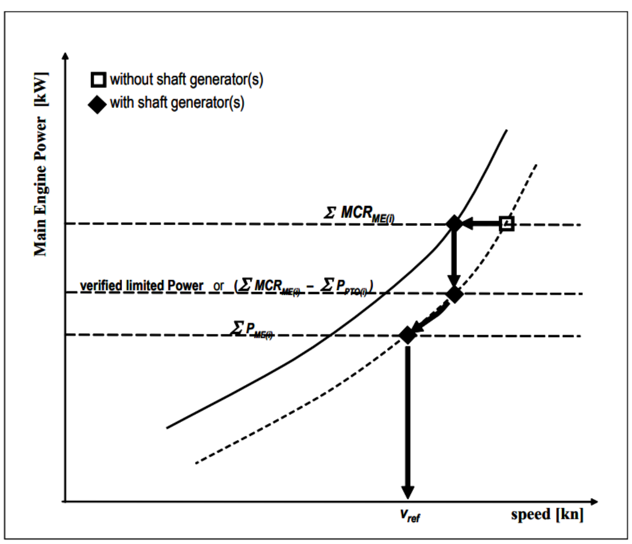


Figure 8: Reference speed in case of shaft gens

➢ $P_{PTI(i)}$ Power of the Shaft motors

In case where shaft motor(s) are installed, $P_{PTI(i)}$ is 75% of the rated power consumption of each shaft motor divided by the weighted average efficiency of the generator(s), as follows:

$$\sum P_{PTI(i)} = \frac{\sum(0.75 * P_{SM,max(i)})}{n_{Gen}}$$

Where:

$P_{SM,max(i)}$ is the rated power consumption of each shaft motor.

n_{Gen} is the weighted average efficiency of the generator(s)

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

$P_{eff(i)}$ is the output of the innovative mechanical energy efficient technology for propulsion at 75% main engine power

Mechanical recovered waste energy directly coupled to shafts need not be measured, since the effect of the technology is directly reflected in the Speed (Category A)

In case of a ship equipped with several engines, the CF and SFC should be the power weighted average of all the main engines.

➢ P_{AEeff} Innovative mechanical energy efficient technology for auxiliary engine

P_{AEeff} (i) is the auxiliary power reduction due to innovative electrical energy efficient technology measured at $P_{ME(i)}$.

➢ P_{AE} Auxiliary engine power

P_{AE} is the required auxiliary engine power to supply normal maximum sea load including necessary power for propulsion machinery/systems and accommodation, e.g. main engine pumps, navigational systems and equipment and living on board, but excluding the power not for propulsion machinery/systems, e.g. thrusters, cargo pumps, cargo gear, ballast pumps, maintaining cargo, e.g. reefers and cargo hold fans, in the condition where the ship engaged in voyage at the speed (V_{ref}) under the condition as mentioned in the regulations.

For ships which total propulsion power ($\sum MCR_{me(i)} + \frac{\sum P_{PTI(i)}}{0.75}$) is 10,000 kW or above, PAE is defined as:

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

For ships which total propulsion power ($\sum MCR_{me(i)} + \frac{\sum P_{PTI(i)}}{0.75}$) is below 10,000 kW, PAE is defined as:

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

For LNG carriers with a reliquefication system or compressor(s), designed to be used in normal operation and essential to maintain the LNG cargo tank pressure below the maximum allowable relief valve setting of a cargo tank in normal operation, the above formulas must change in accordance of MEPC 66/21 Annex 5, page 11.

For ships where power of auxiliary engines (PAE) value calculated with the above methods is significantly different from the total power used at normal seagoing, e.g. in cases of passenger ships, the PAE value should be estimated by the consumed electric power (excluding propulsion) in conditions when the ship is engaged in a voyage at reference speed (V_{ref}) as given in the electric power table, divided by the average efficiency of the generator(s) weighted by power (see appendix 2 of the EEDI Calculation Guidelines).

in cases where the electric power table is not available, the PAE value may be approximated either by:

- annual average figure of P_{AE} at sea from onboard monitoring obtained prior to the EEXI certification.
- for cruise passenger ships, approximated value of power of auxiliary engines (P_{AEapp}), as defined below:

$$P_{AE,app} = 0.1193 * GT = 1814.4 \ [kW]$$

- for ro-ro passenger ships, approximated value of power of auxiliary engines (P_{AEapp}), as defined below:

$$P_{AEapp} = 0.866 * GT^{0.732} \ [kW]$$

(*MEPC.333(76) (1)*, [s.d.])

➢ V_{ref} Ship speed

V_{ref} is the ship speed, (in knots), at the propulsion power P_{ME} on deep water and assuming the weather is calm with no wind and no waves in the condition corresponding to:

• the summer load line draft for all ships except containerships

• 70% of the DWT for containership

V_{ref}, Capacity and P should be consistent with each other. As for LNG carries having diesel electric or steam turbine propulsion systems, V_{ref} is the relevant speed at 83% of MPP_{Motor} or $MCR_{SteamTubine}$ respectively.

- For ships falling into the scope of the EEDI requirement, the ship speed Vref should be obtained from an approved speed-power curve as defined in the 2014 Guidelines on survey and certification of the energy efficiency design index (EEDI), as amended (resolution MEPC.254(67)

- For ships not falling into the scope of the EEDI requirement, the ship speed Vref should be obtained from an estimated speed-power curve as defined in the Guidelines on survey and certification of the attained EEXI (RESOLUTION MEPC.334(76))

- For ships not falling into the scope of the EEDI requirement but whose sea trial results, which may have been calibrated by the tank test, under the EEDI draught and the sea condition as specified in paragraph 2.2.2 of the EEDI Calculation Guidelines are included in the sea trial report, the ship speed Vref may be obtained from the sea trial report:

$$V_{ref} = V_{S,EEDI} * \left[\frac{P_{ME}}{P_{S,EEDI}}\right]^{\frac{1}{3}} \ [knot]$$

  Where:
  $V_{S,EEDI}$, is the sea trial service speed under the EEDI draught and
  $P_{S,EEDI}$ is power of the main engine corresponding to $V_{S,EEDI}$.

- For containerships, bulk carriers or tankers not falling into the scope of the EEDI requirement but whose sea trial results, which may have been calibrated by the tank test, under the design load draught and sea condition as specified in the EEDI Calculation Guidelines are included in the sea trial report, the ship speed Vref may be obtained from the sea trial report:

$$V_{ref} = k^{\frac{1}{3}} * \left(\frac{DWT_{S,service}}{Capacity}\right)^{\frac{2}{9}} * V_{S,service} * \left[\frac{P_{ME}}{P_{S,service}}\right]^{\frac{1}{3}} \ (knot$$

  $V_{S,service}$ is the sea trial service speed under the design draught
  $P_{S,service}$ is power of the main engine corresponding to $V_{S,service}$
  $DWT_{S,service}$ is the deadweight under the design draught
  k is the scale coefficient

  In this context, it is clarified that for the above type of ships it is possible to use the results from a sea trial report in conditions other than the design draft (typically at the ballast draft), provided that results from tank (model) tests are available both in the sea trial condition and the design condition, and the speed obtained at sea trials is calibrated by the tank (model) test to the speed at design draft according to the method given in ITTC procedure 7.5-04-01-01.2 Appendix E and shown in Figure 1. The referenced speed at EEDI (scantling, summer load line) draft Vref, may than be calculated from sea trial service speed at design draught according to the above formula.

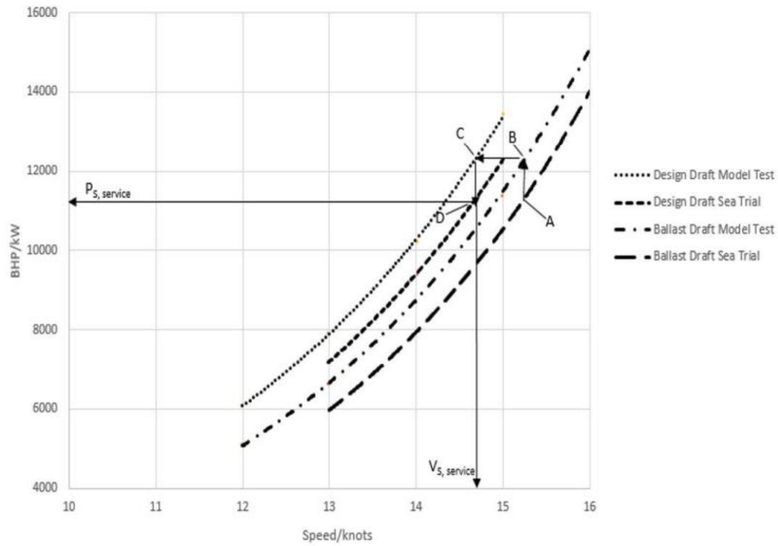


Figure 9 calibration of the speed obtained at sea trials at ballast draft to the speed at design draft,

- 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 speed V_{ref} can be approximated by $V_{ref,app}$ to be obtained from statistical mean of distribution of ship speed and engine power, as defined below:

$$V_{ref,app} = \left(V_{ref,avg} - m_V\right) \times \left[\frac{\sum P_{ME}}{0.75 * MCR_{avg}}\right]^{\frac{1}{3}} \quad \text{[knot]}$$

Only for LNGs

$$V_{ref,app} = \left(V_{ref,avg} - m_V\right) \times \left[\frac{\sum MPP_{Motor}}{MPP_{avg}}\right]^{\frac{1}{3}} \quad \text{[knot]}$$

Where:

$V_{ref,avg}$ is a statistical mean of distribution of ship speed in given ship type and ship size, to be calculated as follows:

$V_{ref,avg} = A * B^C$ where A, B and C are the parameters given in the table bellow. (*MEPC.333(76) (1)*, [s.d.])

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

Table 3:Parameters to calculate Vref,avg

m_V is a performance margin of a ship, which should be 5% of $V_{ref,avg}$ or 1 knot, whichever is lower.

MCR_{avg} is a statistical mean of distribution of MCRs for main engines and is to be calculated as follows:
$MCR_{avg} = D * E^F$ D, E and F are the parameters given in the table below.

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

Table 4:Parameters to calculate MCRavg or MPPavg

Is important to say that the different ways to calculate the Vref leads to different results of the attained EEXI. Something that we will showcase later. Ships that cannot provide the proper documentation (sea trials, model test , CFD , etc.) for the calculation of the speed will have to choose the approximation method which is most of the times lower and so EEXI tends to be higher.

- SFC Certified specific fuel consumption.

For engines certified to the E2 or E3 test cycles of the NOX Technical Code 2008, the engine Specific Fuel Consumption SFC_{ME} is that recorded in the test report included in a NOX technical file for the engine(s) at 75% of MCR power of its torque rating.

For engines certified to the D2 or C1 test cycles of the NOX Technical Code 2008, the engine Specific Fuel Consumption SFC_{AE} is that recorded on the test report included in a NOX technical file at the engine(s) 50% of MCR power or torque rating.

For those engines which do not have a test report included in the NOX Technical File, the SFC specified by the manufacturer with the approval of the verifier should be used.

For those engines which do not have a test report included in the NOX Technical File and which do not have the SFC specified by the manufacturer, the SFC can be approximated by SFC_{app} defined as follows

$$SFC_{ME,app} = 190\ [g/kWh]\ , \qquad SFC_{AE,app} = 215\ [g/kWh]$$

(*MEPC.333(76) (1)*, [s.d.])

- Correction factors

Include:

- Correction factor for ro-ro cargo and ro-ro passenger ships (f_{jRoRo})
- Correction factor for general cargo ships
- f_w Factor for speed reduction at sea
- f_i Capacity factor for technical/regulatory limitation on capacity
- Capacity correction factor for ice-classed ships
- f_{iCSR} Ships under the Common Structural Rules (CSR)
- f_c Cubic capacity correction factor for chemical tankers, gas carriers, ro-ro passenger ships, bulk carriers
- f_l Factor for general cargo ships equipped with cranes and cargo-related gear

(*ANNEX 5 RESOLUTION MEPC.308(73) (Adopted on 26 October 2018) 2018 GUIDELINES ON THE METHOD OF CALCULATION OF THE ATTAINED ENERGY EFFICIENCY DESIGN INDEX (EEDI) FOR NEW SHIPS*, [s.d.])

- Cubic capacity correction factor for ro-ro cargo ships (vehicle carrier) ($f_{cVEHICLE}$)
- Correction factor for ro-ro cargo and ro-ro passenger ships (f_{jRoRo})

(*MEPC.333(76) (1)*, [s.d.]) Annex 7

If not in any of those categories, the corrections F should be taken as 1.0

3.4 Required EEXI (reference lines and reduction factors)

The required Index that our attained EEXI must be lower is composed by 2 factors. First from the reference line values which are the same used on the EEDI index and then from the reduction factor (Y).

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

The reference lines are established for each ship type to which regulation 24 (Required EEDI) of MARPOL Annex VI is applicable. The purpose of the EEDI is to provide a fair basis for comparison, to stimulate the development of more efficient ships in general and to establish the minimum efficiency of new ships depending on ship type and size. Hence, the reference lines for each ship type is calculated in a transparent and robust manner.

A reference line is defined as a curve representing an average index value fitted on a set of individual index values for a defined group of ships. One reference line will be developed for each ship type, ensuring that only data from comparable ships are included in the calculation of each reference line.

The EEDI reference line values shall be calculated in accordance with regulations 24.3 and 24.4 RESOLUTION MEPC.328(76) Annex 1 and they shall be calculated as follows:

$$Reference\ line\ value = a * b^{-c}$$

where a, b and c are the parameters given in the table bellow:

Ship type defined in regulation 2	a	b	c
2.2.5 Bulk carrier	961.79	DWT of the ship where DWT≤279,000 279,000 where DWT > 279,000	0.477
2.2.7 Combination carrier	1,219.00	DWT of the ship	0.488
2.2.9 Containership	174.22	DWT of the ship	0.201
2.2.11 Cruise passenger ship having non-conventional propulsion	170.84	GT of the ship	0.214
2.2.14 Gas carrier	1,120.00	DWT of the ship	0.456
2.2.15 General cargo ship	107.48	DWT of the ship	0.216
2.2.16 LNG carrier	2,253.7	DWT of the ship	0.474
2.2.22 Refrigerated cargo carrier	227.01	DWT of the ship	0.244
2.2.26 Ro-ro cargo ship	1405.15	DWT of the ship	0.498
	1686.17*	DWT of the ship where DWT≤17,000* 17,000 where DWT > 17,000*	
2.2.27 Ro-ro cargo ship (vehicle carrier)	$(DWT/GT)^{-0.7}$ · 780.36 where DWT/GT < 0.3 1,812.63 where DWT/GT ≥ 0.3	DWT of the ship	0.471
2.2.28 Ro-ro passenger ship	752.16	DWT of the ship	0.381
	902.59*	DWT of the ship where DWT≤10,000* 10,000 where DWT > 10,000*	
2.2.29 Tanker	1,218.80	DWT of the ship	0.488

Table 5: Parameters to calculate ref lines

(*ANNEX 1 RESOLUTION MEPC.328(76) AMENDMENTS TO THE ANNEX OF THE PROTOCOL OF 1997 TO AMEND THE INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS, 1973, AS MODIFIED BY THE PROTOCOL OF 1978 RELATING THERETO 2021 Revised MARPOL Annex VI*, [s.d.]-a)

The second factor in the calculation of the Required EEXI of a specific vessel is the reduction factor.

The reduction factor (Y) is specified in the Table below for the required EEXI compared 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

Table 6:Reduction factors

Ship type	Size	Reduction factor
	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*

Table 7: Reduction factors

(*ANNEX 1 RESOLUTION MEPC.328(76) AMENDMENTS TO THE ANNEX OF THE PROTOCOL OF 1997 TO AMEND THE INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS, 1973, AS MODIFIED BY THE PROTOCOL OF 1978 RELATING THERETO 2021 Revised MARPOL Annex VI*, [s.d.]-a)

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

EEXI Survey and Certification

For verification of the attained EEXI, an application for a survey and an EEXI Technical File containing the necessary information for the verification and other relevant background documents should be submitted to a verifier, unless the attained EEDI of the ship satisfies the required EEXI

The EEXI Technical File should be written at least in English. The EEXI Technical File should include

1) Data (general information, principal particulars)
2) Power curves (for the calculation of the V_{ref})
3) Overview of the propulsion system and electric power supply system
4) Estimation process of speed power curve
5) Description of the energy saving equipment
6) Final detailed calculation of the attained EEXI

A sample of a Technical file can be found on the appendix of ANNEX 8 RESOLUTION MEPC.334(76)

3.5 Calculated value of attained EEXI

We can see bellow an example of the calculation of the attained EEXI of a vessel. On table 2 we can see the characteristics of the vessel, on table 3 we see the main Engine characteristics and on table 3 Auxiliary engine characteristics.

Vessel name	-
Vessel type	Bulk Carrier
IMO number	-
Length BP	168.01 [m]
Breadth	28.20 [m]
Depth main deck	14.20 [m]
summer load Draught	10.20 [m]
Deadweight (scantling)	32859.6 [ton]
Gross tonnage	19943.0 [ton]
Lightship weight	8253.8 [ton]
Tank/Hold capacity	42211.7 [m3]

Table 8 vessel characteristics

- Main engine

Manufacturer	MAN B&W
Type	6S42MC MK7
MCR_ME	6480.00 [kW]
Rotational Speed at MCR	136.0 [RPM]
SFC at 75%	172.84 [g/kWh]
CO2 Conversion Factor	3.206 [t/t]
Number of Sets	1

Table 9 Main Engine Characteristics

- Auxiliary engine

Manufacturer	YANMAR
Type	6EY18ALW
MCR_AE	550.00 [kW]
Rotational Speed at MCR	900.0 [RPM]
SFC at 50 %	212.00 [g/kWh]
CO2 Conversion Factor	3.206 [t/t]
Number of Sets	3

Table 10 Auxiliary Engine Characteristics

1) Auxiliary Engine Power Calculations

For ships for which the total propulsion power is below 10000.0 kW, Auxiliary Engine Power P(AE) is defined as:

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

therefore, P(AE) = 324.00 kW

2) Main Engine Power Calculations

$$\sum_{i=1}^{nME} P_{ME(i)} = 0.75 * \left(\sum_{i=1}^{n} MCR_{ME(i)} - \sum_{i=1}^{nPTO} 0.75 * MCR_{PTO(i)}\right)$$

Here,

0.75 x ΣP(PTO) = 0.75 x 0.00 kW = 0.00 kW.

P(AE) = 324.00 kW.

Therefore, final ΣP(PTO) = 0.00 kW.

Finally, ΣP(ME) = 4860.00 kW.

3) fj Ship specific design elements

Here, fj = 1.000.

4) Reference Ship Speed

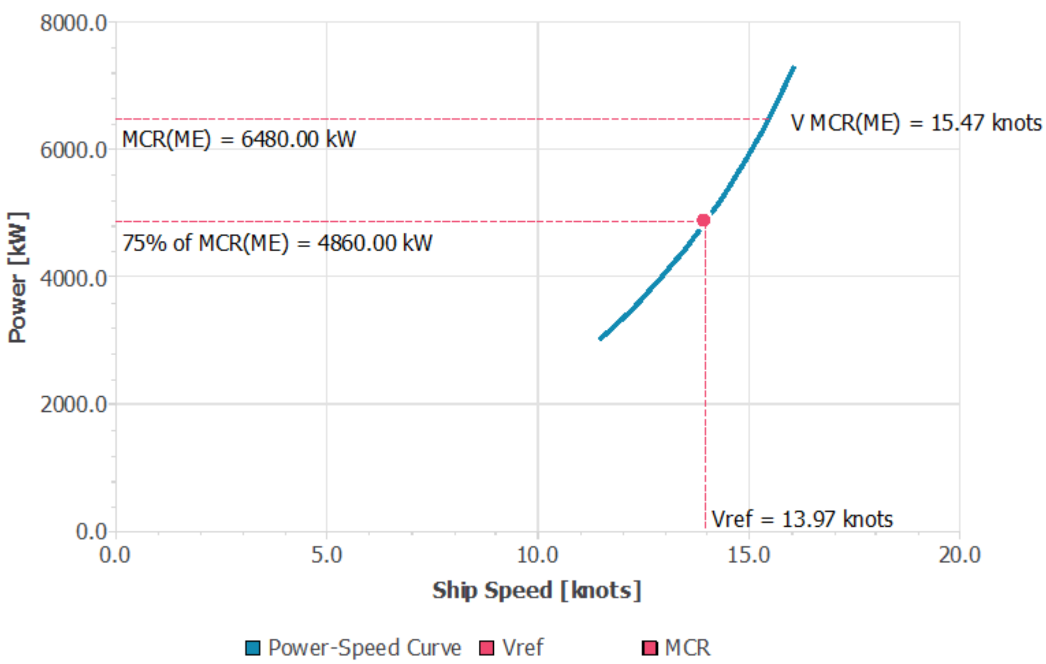


Figure 10: Speed-Power curve of example

Here V_{ref} is calculated 13.97 knots.

And so the final calculation :

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

$$= \frac{1 \times (4860.00 \times 3.206 \times 172.84) + (324.00 \times 3.206 \times 212.00) + 0 - 0}{1.006 \times 1 \times 1 \times 32859.6 \times 1 \times 13.97 \times 1}$$

= 6.308 g-CO2/ton.mile.

Equation 2: Detailed calculation

3.6 Sensitivity of the Index on the main parameters

- SFC

For those engines which do not have a test report included in the NOX Technical File and which do not have the SFC specified by the manufacturer, the SFC can be approximated by SFC_{app} defined as follows

$SFC_{ME,app} = 190\ [g/kWh]$, $SFC_{AE,app} = 215\ [g/kWh]$

It’s easy to understand looking at the formula that because the part of the auxiliary engines on the nominal of the fraction is significantly smaller than the part of the main , the relation between SFC_{ME} and the EEXI is almost liner.

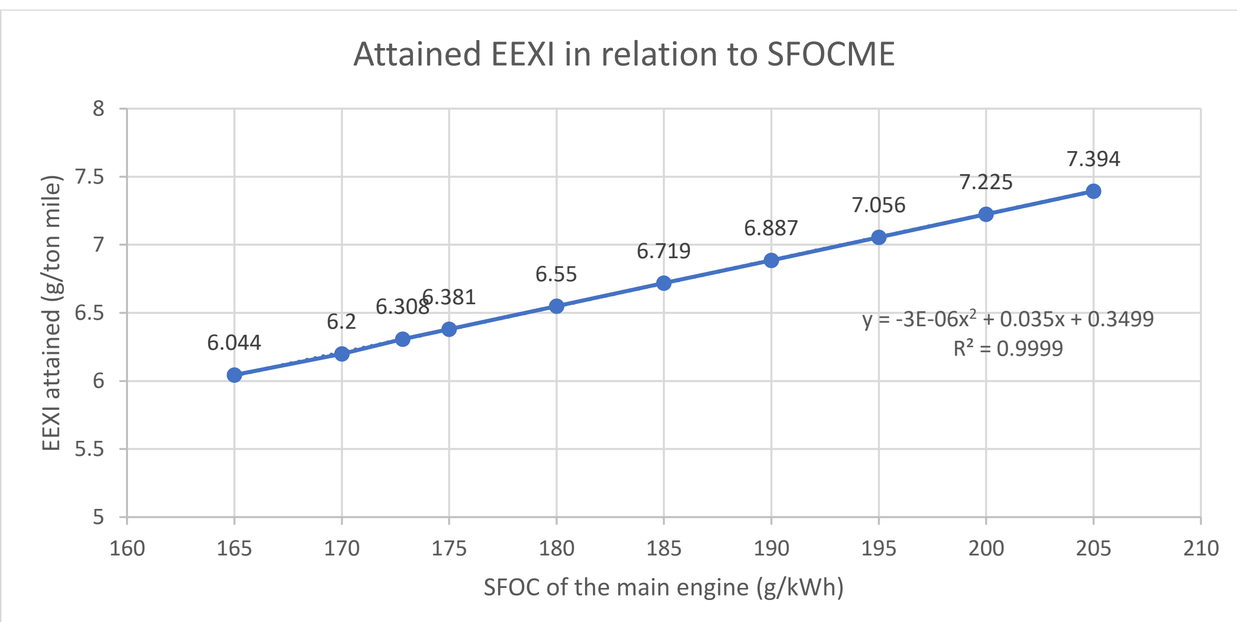


Figure 11:Relation between EEXI and SFOC

The specific analysis was contacted for a bulk carrier with DWT of 35.000 tones. The actual SFC that the manufactured provided was 172.84 (g/kWh) and the attained EEXI was 6.308 (g/ton*mile). In the case of absent data, we would use the approximation SFC per regulations which is 190 (g/kWh) and in this case the attained EEXI is 6.887 (g/ton*mile). The result shows that for a change in SFC of 9.93% from 190 to 172.84 we have a change in EEXI of 9.18%.

These numbers differ from vessel to vessel but with this example we can showcase the importance of the Specific fuel oil consumption of the main engines on the Index.

Clarkson's' database (as per Bibliographical data: Jasper Faber, Maarten 't Hoen, Marnix Koopman, Dagmar Nelissen, Saliha Ahdour Estimated Index Values of New Ships Analysis of EIVs of Ships That Have Entered The Fleet Since 2009 Delft, CE Delft, March 2015) further contains the specific fuel consumption of the main engine for 7,992 vessels (87% of the 9,179 ships built between 2009 and 2014 that were analyzed). The average specific fuel consumption for these ships is close to 175 g/kWh, which is much lower than the constant value of 190 g/kWh set by MEPC.333(76) (MEPC, 2021) for calculating the EEXI.

- V_{ref} , P_{ME}

Ships without acceptable documented proof of their speed ~ power curve from sea trials or model tests may have their reference speed (VREF in the EEXI equation) determined by a statistical method which imposes a penalty of 5% of speed or 1 knot, whichever is greater. In some cases, this may result in more stringent requirements than the EEDI framework for new ships.

Module 6 dives deep into the relation of the EEXI, EPL and $V_{ref} - P_{ME}$

3.7 Options to comply.

Multiple options to improve energy efficiency of existing ships. Any of these options should be allowed under the goal-based approach if such options are verifiable. If a ship prefers saving capital cost, it can choose the shaft/engine power limit to the optimum level. If a ship prefers higher speed, it can choose technical improvement. It should be up to each ship to decide which option to take.

EEDI and therefore EEXI are artificial indexes. Emissions of CO2 (nominator) transport work as the climate change impact divided by the transport work of the ship (denominator) or the benefit to the society. If we attempt to introduce some basic marine engineering in the EEXI INDEX, we can see the great influence of the ship speed in this index. EEXI (as EEDI) is strongly dependent on the ship's speed. Technical solutions which limit the ME power (and therefore speed) have the highest impact on EEXI.

$$EEXI = \frac{Emissions\ of\ CO_2}{Transport\ work} = \frac{Power\ X\ SFC\ X\ C_F}{Capacity\ X\ Speed}$$

Technical measures options	EEXI impact
Engine Power Limitation	High
Shaft Power Limitation	High
Fuel change (e.g. LNG)	Moderate
Main engine energy efficiency (e.g Rotors)	Moderate
Aux power installations (e.g. shaft gen, WHR)	Low
DWT increase	Low
Energy saving devices (e.g. ducts)	Low
.....	.....

Table 11: Technical measures and their Impact on EEXI

As the International Maritime Organization works to reduce greenhouse gas emissions from international shipping, technical measures to limit engine power are among the ideas being considered to reduce carbon dioxide (CO2) from the existing fleet. Engine power limitation (EPL) and Shaft power limitation are a semi-permanent, overridable limit on a ship's maximum power that could reduce fuel use and CO2 emissions if it reduces the operational speeds of affected vessels.

Both SHaPoLi and EPL systems are non-permanent, tamper-proof, and approved, verified methods of power limitation. The former applies a limit to the maximum shaft power and the latter to the engine power. A power reserve sits above the maximum power limitation and is only to be used in the interests of safety or saving life at sea. It can only be overridden by the Master or officer in charge of the navigational watch from the bridge without the need for entry into a machinery space (if possible). The use of the power reserve must provide an alert and be properly recorded in the vessel's Onboard Management Manual (OMM). The vessel's Flag State (or recognised organisation acting on Flag State's behalf) and the competent authority of the relevant port of destination are to be notified without delay.

- ENGINE POWER LIMITATION

Engine power means the mechanical power transmitted from the engine to the propeller shaft. In the case of multiple engines, the engine power means the sum of the power transmitted from the engines to the propeller shafts.

Overridable Engine Power Limitation (EPL) system means a verified and approved system for the limitation of the maximum engine power by technical means that can only be overridden by the ship's master or OICNW for the purpose of securing the safety of a ship or saving life at sea.

As the International Maritime Organization works to reduce greenhouse gas emissions from international shipping, technical measures to limit engine power are among the ideas being considered to reduce carbon dioxide (CO_2) from the existing fleet. Engine power limitation (EPL) is a semi-permanent, overridable limit on a ship's maximum power that could reduce fuel use and CO_2 emissions if it reduces the operational speeds of affected vessels.

EPL is the modification which applies load limitation to the engine. The factors that influence the evaluation of GHG ratings are engine output and fuel consumption. With EPL, it is possible to improve the rating by reducing the max limit of engine output. Engine performance is unchanged with the new load limit, and it can be operated the same as before below the new load limit. However, Ship's speed will also be limited, as the load above the limit cannot be output

The **requirements** for the mechanically controlled engines are a sealing device which can physically lock the fuel index by using a mechanical stop screw sealed by wire or an equivalent device with governor limit setting so that the ship's crew cannot release the EPL without permission from the ship's master and for the electronically controlled engine, fuel index limiter which can electronically lock the fuel index or direct limitation of the power in the engine's control system so that the ship's crew cannot release the EPL without permission from the ship's master.

(*MEPC.335(76)*, [s.d.])

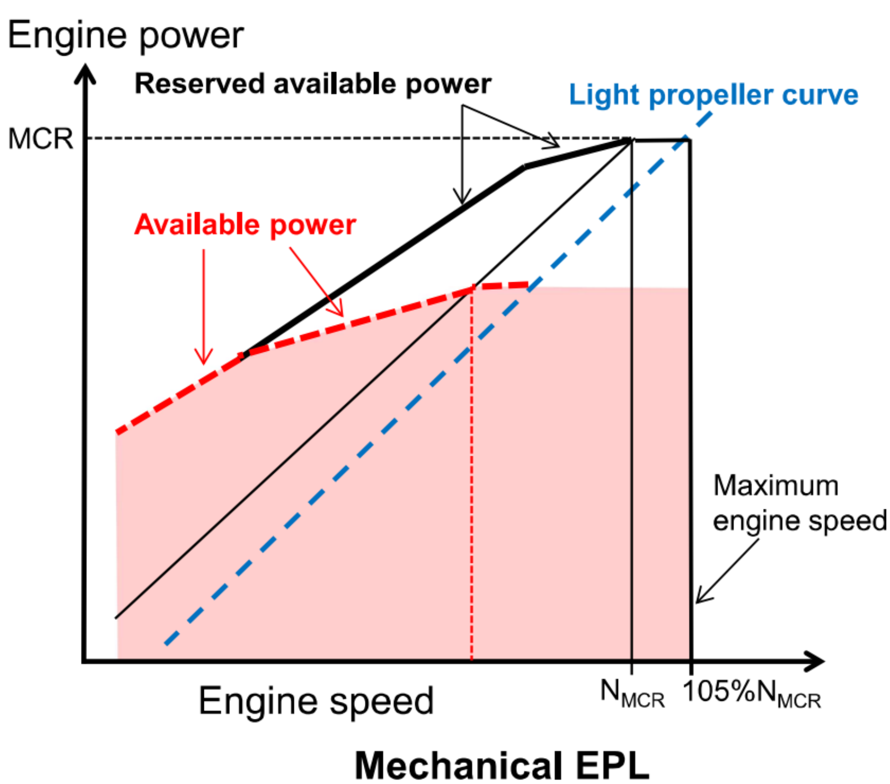


Figure 12: Engine load diagram on Engine power limitation

(*MEPC.335(76)*, [s.d.])

- Shaft power limitation

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.

Overridable Shaft Power Limitation (SHaPoLi) system means 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 Limitation (ShaPoLi) was developed to enable vessels to limit their fuel consumption and associated greenhouse gas (GHG) emissions by limiting the output power of Controllable Pitch Propeller (CPP) shafts. Installing ShaPoLi is a proven method for projects where vessels have an excess of installed propulsion power following the re-design of a propeller aimed at new operational requirements, and particularly for ships with more than one engine per propeller shaft. ShaPoLi enables an optimization of a ship’s propulsion and blade design to the fullest and brings additional fuel savings and a reduction in CO2 emissions.

The **requirements** of the main system consists a 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, a data recording and processing device for tracking and calculation of the data and a control unit for calculation and limitation of the power transmitted by the shaft to the propeller.

As a result of a expensive system requirements per regulations many of the vessels that want to comply fast and cost effective tent to choose EPL for compliance. Even if a ship could not afford to bear such a substantial cost for fuel change or retrofitting, still, it is possible to improve the ship's energy efficiency in an easy and costless way. By installing a simple mechanical fuel index sealing system limiting the maximum engine power to the optimum level, the ship cannot be operated above the optimum level of power except for emergency situations, so that operational speed optimization can be achieved from technical approach. Unlike the operational speed, the engine power is easy to be monitored, controlled, and verified, and controlling the engine power is enforceable under survey and certification within MARPOL Annex VI.

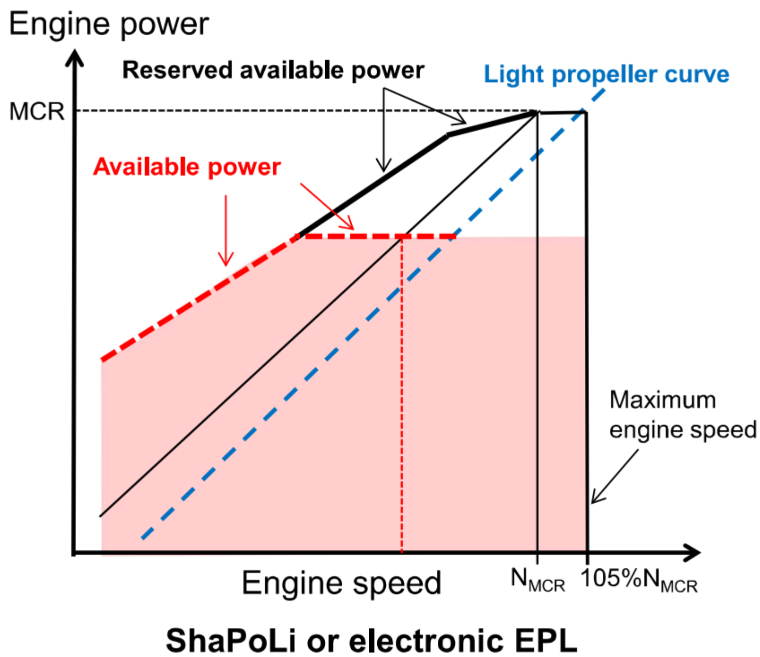


Figure 13 Engine load diagram on SHaPoLi

Overridable power limitation (OPL) – including both engine power limitation (EPL) and shaft power limitation (ShaPoLi) – offers an immediate compliance option for EEXI. It is relatively non-invasive, has a low capital cost, and is applicable to most ship types. At the same time, however, its ability to impact subsequent CII ratings will be limited due to existing operational speeds and average main engine loads.

Put simply, while OPL may offer a ticket to the decarbonization game, it is unlikely to be enough to keep you in it for long. Therefore, should adaptions or changes to vessel operations be required to meet the incoming EEXI requirement, it may make commercial sense to also consider steps to address operational carbon intensity reduction simultaneously. That way the vessel can avoid making further adaptions in the relatively near future.

(*MEPC.335(76)*, [s.d.])

- Fuel Change

While future fuels have a critical role to play in helping the maritime industry to achieve the IMO's target to reduce the carbon intensity of international shipping by 40% by 2030, the path ahead is littered with uncertainties.

LNG is both an established reality in the newbuild market and an excellent option for retrofits; it instantly and drastically reduces CO_2, NO_x, SO_x and particulate emissions. It is well established as a maritime fuel around the world in virtually every vessel segment, with mature legislation frameworks and robust bunkering infrastructure.

Methanol is currently attracting a great deal of attention as an alternative fuel for newbuilds and retrofits. Methanol's physical properties make it an attractive option, and the use of hydrogen from renewable electricity and recaptured carbon to make green methanol would make it carbon neutral.

In the longer term, ammonia and ultimately hydrogen represent the 100% carbon-free fuels of the future. Interest in these fuels is increasing,

All these future fuels can have a significant positive impact on a vessel's EEXI and CII rating. Nevertheless, their implementation requires significant investment in both bunkering infrastructure and onboard fuel storage and handling systems.

- Innovative Energy Efficiency Technologies

EETs have a direct impact on vessel propulsion efficiency by reducing hull resistance and improving propeller thrust. Installing a replacement propeller that is optimised for the vessel's current operational profile also offers significant potential benefits. Depending on the vessel type, energy savings in the region of 5–10% can be achieved by combining EETs and an optimized propeller. The problem is that many younger vessels already have EETs installed, so the room for improvement is limited. For this reason we may see alternative EETs such as air lubrication systems and wind rotors.

Innovative energy efficiency technologies are allocated to category (A), (B) and (C), depending on their characteristics and effects to the EEXI formula. Furthermore, innovative energy efficiency technologies of category (B) and (C) are categorized to two sub-categories (category (B-1) and (B-2), and (C-1) and (C-2), respectively).

Category (A): Technologies that shift the power curve, which results in the change of combination of P_P and V_{ref} : e.g. when V_{ref} is kept constant, P_P will be reduced and when P_P is kept constant, V_{ref} will be increased

Category (B): Technologies that reduce the propulsion power, P_P, at V_{ref} , but not generate electricity. The saved energy is counted as P_{eff}

- **Category (B-1):** Technologies which can be used at any time during the operation and thus the availability factor (f_{eff}) should be treated as 1.00.
- **Category (B-2):** Technologies which can be used at their full output only under limited condition. The setting of availability factor (f_{eff}) should be less than 1.00.

Category (C): Technologies that generate electricity. The saved energy is counted as P_{AEeff}

- **Category (C-1):** Technologies which can be used at any time during the operation and thus the availability factor (f_{eff}) should be treated as 1.00.

- **Category (C-2):** Technologies which can be used at their full output only under limited condition. The setting of availability factor (f_{eff}) should be less than 1.00

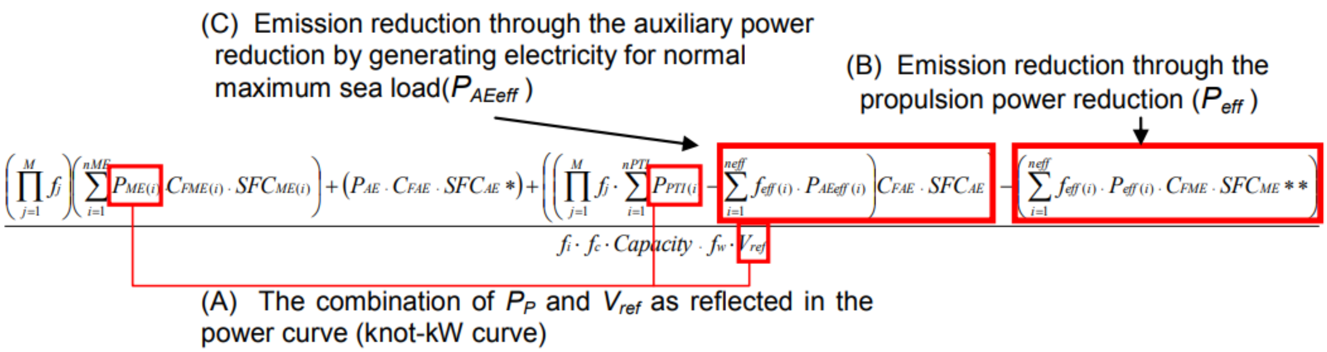


Figure 14: EEXI formula Source: MEPC.1/Circ.815 17 June 2013

(14_Circ-896, n.d.) 2021 GUIDANCE ON TREATMENT OF INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES FOR CALCULATION AND VERIFICATION OF THE ATTAINED EEDI AND EEXI

Innovative Energy Efficiency Technologies				
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 overall performance of the vessel	Can be treated separately from the overall performance of the vessel		Effective at all time	Depending on ambient environment
	$f_{eff}=1$	$f_{eff}<1$	$f_{eff}=1$	$f_{eff}<1$
– low friction coating – bare optimization – rudder resistance – propeller design	– hull air lubrication system (air cavity via air injection to reduce ship resistance) (can be switched off)	– wind assistance (sails, Flettner-Rotors, kites)	– waste heat recovery system (exhaust gas heat recovery and conversion to electric power)	– photovoltaic cells

Figure 15:Categorizing of Innovative Energy Efficiency Technologies

The analysis will examine further the EETs in module 5 for the purpose of their use in module 5.

4. Post EEDI vessels Statistical analysis

4.1Overview of EEDI frameworks and regulations

This module will assess the Post EEDI vessels on their compliance with the EEXI regulations.

As mentioned before, Since 1 January 2013, following an initial two-year phase zero, new ship design needs to meet the reference level for their ship type. The level is tightened incrementally every five years, and the EEDI is expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase. The EEDI is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in a specific ship design to the industry.

In simple words in this part of the thesis we will examine the compliance of the Post EEDI vessels in all phases that are included in the EEDI database.

The analysis will consider tankers, bulk carriers and container ships, IMO data for 2019 shows that the bigger ships in the global fleet emitted more than 600m tonnes of CO_2. Containers, bulkers and tankers made up the vast majority of both global emissions and voyages

THE global shipping fleet emitted 614m tonnes of carbon dioxide in 2019, according to the first emissions-collection database compiled by the International Maritime Organization.

A report on the IMO Data Collection System, as it is officially known, seen by Lloyd's List, shows containerships, tankers and bulkers accounted for 78.6% of the total CO_2 emitted by international shipping. Another 10 ship types accounted for the remainder.

The data system covers only vessels of 5,000 gross tonnes and above and is based on emissions reporting from shipping companies.

While the three conventional ship types accounted for the majority of emissions, they also accounted for almost 92% of global deadweight tonnes-nautical miles. Bulkers alone took up over 41% of this share.

(Joung et al., 2020)

(*Shipping's 'Big Three' Account for Almost 80% of CO2 Emissions :: Lloyd's List*, [s.d.])

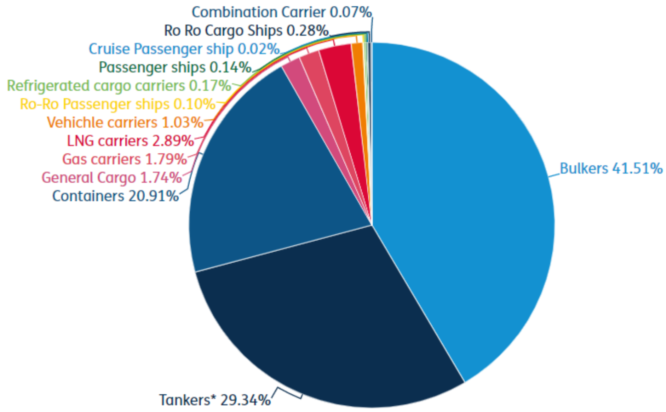


Figure 16 :Share of DWT-nautical miles (source DCS report)

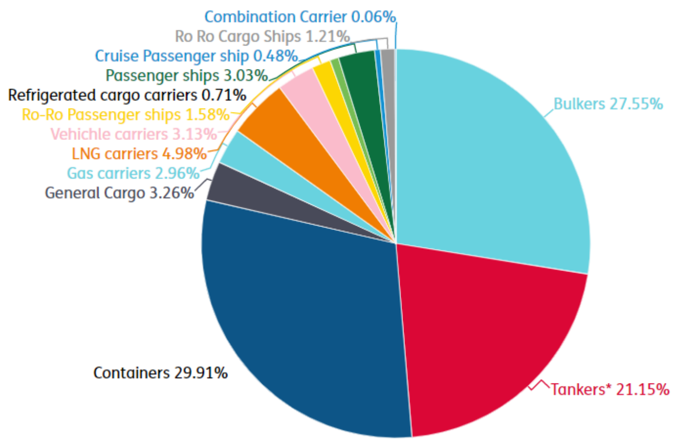


Figure 17: Share of total CO3 emissions (source DCS report)

4.2 Data Source

4.2.1 IMO EEDI Database

The IMO EEDI database was established to assist with the review of the reduction phases and time periods as required in regulation 21.6 of MARPOL Annex VI:

In accordance with regulation 21.6 of MARPOL Annex VI, at the beginning of phase 1 (1 January 2015 to 31 December 2019) and at the midpoint of phase 2 (1 January 2020 to 31 December 2024), the Organization shall review the status of technological developments and, if proven necessary, amend the time periods, the EEDI reference line parameters for relevant ship types and the reduction rates set out in regulation 21.

In this regard, MEPC 66 agreed to establish an EEDI database to provide data and related information to support the reviews.

It was originally agreed at MEPC 66 in April 2014 to establish the database with ad hoc submissions of the following particulars:

- Type of ship
- Capacity of ship (GT/DWT as appropriate)
- Year of delivery
- Applicable phase
- Required EEDI
- Attained EEDI
- Use of innovative energy efficiency technologies (tick-box indication of whether the fourth and fifth terms of the numerator of the EEDI equation are employed)

By this stage Phase 0 was already in force. MEPC 67 INF.4 (October 2014) reported that 158 ships had been submitted including a number of ships where EEDI was applied on a voluntary basis. This increased to 454 ships in MEPC 68 INF.13, 1000 ships in MEPC 69 INF.16 and 1917 ships in MEPC 70 INF.14. In the same period, the number of IACS members submitting ships increased from 4 to 8.

MEPC 70 agreed that additional parameters should be provided from 1st April 2017:

- Dimensional parameters – length between perpendiculars, breadth and draught
- Ship speed V_{ref} and power of main engines P_{ME}
- Name, outline and means/ways of performance of innovative technologies

The template for reporting was provided in Annex 14 of MEPC 71/17Add.1.

The database increased in size with later MEPCs

- MEPC 71 2443 ships
- MEPC 72 2769 ships – this being the first report after the expanded set of parameters were agreed
- MEPC 73 3622 ships

MEPC 73/5/5 proposed mandatory reporting of EEDI values to address the problem of there being ships that had been delivered, but not reported to the database, since reporting was voluntary. This was followed by MEPC 74/5/11 with a proposal for a draft amendment. MEPC 74 agreed draft amendments to MARPOL Annex VI Regulation 20 making submissions to the IMO EEDI database mandatory. MEPC 75 would have adopted these amendments with a provisional entry into force date of 1 September 2021

MEPC 74/5/11 further increases the number of parameters to be reported as follows:

- Commercial size in TEU for container ships, CEU for vehicle carriers and cubic meter for gas carriers and LNG carriers
- Type of fuel or primary fuel
- f_{DFgas} for ships equipped with dual fuel engines
- Ice class
- Short statement describing principal design elements or changes employed to achieve the attained EED

At the time of MEPC 74 there were 4505 ships in the database.

Submissions to the IMO contain an IMO number and the precise data used to calculate EEDI, however the IMO number is removed, and all the data is rounded up as a means to preserve anonymity.

The version of the IMO EEDI database used for this report is dated 18 Feb 2022 (21 Apr 2022 revised with a minor change) and contains the following ships.

Number of ships in each ship type						
Applicable Phase	**Non-mandatory**	**0**	**1**	**2**	**3**	**Total**
Bulk carrier	161	1,742	1,289	44	-	**3,236**
Gas carrier	30	243	173	6	-	**452**
Tanker	210	876	1,244	35	-	**2,365**
Containership	141	373	511	2	-	**1,027**
General cargo ship	25	83	217	21	-	**346**
Refrigerated cargo carrier	-	9	17	6	-	**32**
Combination carrier	-	-	5	-	-	**5**
LNG carrier[1]	2	2	98	-	-	**102**
Ro-ro cargo ship (vehicle carrier)	6	49	31	-	-	**86**
Ro-ro cargo ship	6	11	28	-	-	**45**
Ro-ro passenger ship	-	4	20	-	-	**24**
Cruise passenger ship having non-conventional propulsion[2]	1	-	36	4	-	**41**
Total	**582**	**3,392**	**3,669**	**118**	**-**	**7,761**

Table 12 :IMO EEDI Database Summary

4.2.2 Shortcomings of the IMO EEDI Database

(As per Technical Study on the future of the Ship Energy Efficiency Design Index, Written by Arcsilea LTD American Bureau of Shipping Vessel Performance Solutions APS November 2021)

From various reports and papers that examined for different reasons the IMO EEDI database we know that several shortcomings exist, which may be divided into two categories:

- Reporting or recording errors
- Omission of key information

As far as our analysis is concerned, we are to examine the first category for the simple reason that we only calculate the Required EEXI using the type of the vessel and its DWT from the data base and we compare it with the Attained EEDI. (See paragraph 4.3 method of calculation)

In the first category, we have:

- widespread confusion between installed power and PME with some smaller ship sectors having incorrect data for up to 50% of the ships.
- Data entry or calculation errors - required EEDI, year of delivery, draught etc. These are mostly inconsequential however it does highlight a more general issue with a lack of quality control in the database.
- Within the containership sector, some reported deadweight capacity where 70% deadweight is used instead of 100%, even though the EEDI database clearly states that 100% deadweight is to be used. This error causes larger ships with better EEDI scores to be represented in a smaller size segment and makes these sectors seem capable of better efficiency than is in fact possible.

With the current state of the IMO EEDI database, the errors mean that statistical analysis of the database to inform about the compliance percentages of post EEDI vessels should be done with great care and an understanding of the limitations and specificities of the underlying data.

There are also a number of other underlying issues with the data in the database.

Ships with EEDI calculated voluntarily (denoted non-mandatory in the database) are known to have not been assessed as strictly to the guidelines as ships for which EEDI was mandatory. IACS PR 38 did not apply until 1 July 2013, after the start of Phase 0, however as we have seen, most Phase 0 ships did not start being delivered until 2015. Additionally, the speed trial procedures in ISO 15016:2002 that were applied to these ships were not aligned with the EEDI requirements, and it was not until revision in April 2015 (ISO 15016:2015) that this was changed.

This means that attained EEDI of ships delivered before 2015 may have data quality issues and should be treated with caution.

4.3 Method of calculation

4.3.1 Data used.

As we mentioned before the data used from the IMO EEDI data base where the ones needed in order to calculate the Required EEXI as per RESOLUTION MEPC.328(76), Regulation 24-25, in order to compare it with the Attained EEDI which is one of the parameters of the database.

For the categorization of the results the applicable phase of the vessels was used as well as the year of built.

As we mentioned in paragraph 4.4.2 certain mistakes on the data entry on the IMO EEDI database were found and so in order to have better results, we excluded some of these entries.

Also, vessels with DWT smaller than the one on the reduction factors table were not included as well, because even if these vessels need to have an EEXI technical file they are always compliant with the regulations.

After excluding these categories of entries, we finalize the bellow pool of vessels for the analysis.

Ship Type analysis 2011-2022	Bulk Carriers	Container Ships	Tankers	Total
Number of ships in mandatory phase	2865	879	2082	5951
Number of ships in non-mandatory phase	161	137	203	501
Total number of ships in all phases	3026	1016	2285	6322

Table 13: Pool of Vessels for the analysis

More specifically, from the Data base the following data were used in order to complete the analysis.

- Applicable phase
- Capacity (DWT)
- Year of delivery
- Attained EEDI (non-mandatory)
- Attained EEDI (mandatory)
- EEDI 5th term (innovative electrical technology) only for containers
-

Specifically for the container ships the Energy efficiency technologies were used in order to compare the results between vessels that use them and those that do not.

Last, we need to state that these data have been rounded.

- DWT has been rounded up to the nearest 500 by the secretariat
- Lpp(m) has been rounded up to the nearest 10 by the secretariat
- Bs(m) has been rounded up to the nearest 1 by the secretariat
- Draught has been rounded up to the nearest 1 by the secretariat
- Vref has been rounded up to the nearest 0.5 by the secretariat
- $P_{ME}(KW)$ has been rounded up to the nearest 100 by the secretariat

From these parameters we only use the DWT.

4.3.2 Calculation Process

For every one of the 3 categories that we examined in our analysis almost the same calculation process was contacted. First, we copied the excel file of the IMO EEDI Database per category (Tankers, Bulk carriers, Container ships) on a new excel file.

For every category we created a new sheet named "help" in which we inputted the Reference line values, the reduction factor and in some cases the linear interpolation numbers in order to find the reduction factor. (As per RESOLUTION MEPC.328(76), Regulation 24-25). Bulk carriers with DWT between 10.000 – 20.000 tonnes, have a reduction factor 0-20, Tankers with DWT 4.000-20.000 tonnes need a reduction factor 0-20 and Container ships with DWT of 10.000-15.000 tonnes have a reduction factor 0-20 which is to be found with the previously named method. For the purposes of linear interpolation, we used the function of excel FORECAST.

After we have our HELP sheet, we start by adding calculation columns to the table of the copied database as seen below.

Applicable	SHIP NO	Capacity (DWT)	Year of delivery	Required EEDI	Attained EEDI	Attained EEDI before 2014	Vref (knot)	P_{ME} (kW)	Attained EEDI reduction rate relative to referenc	Reduction Factor (Y)	RefLines	Req EEXI	Diference
Applicable Phase	Ship no.	Capacity (DWT)	Year of delivery		Attained EEDI		Vref (knot)	P_{ME} (kW)	Attained EEDI reduction rate relative to reference line value				
Applicable		Capacity (DWT)	Year of delivery	Non-mandatory*	Mandatory	Non-mandatory	Vref (knot)	P_{ME} (kW)					
Non-mandatory	1	34,500	2012	6.6		6.386	-	-	3.6%	20.0	6.58476907	5.267815259	-1.1182
Non-mandatory	2	34,500	2012	6.6		6.259	-	-	5.5%	20.0	6.58476907	5.267815259	-0.9908
Non-mandatory	3	34,500	2012	6.6		6.242	-	-	5.8%	20.0	6.58476907	5.267815259	-0.9740
Non-mandatory	4	36,500	2015	6.4		5.265	-	-	18.3%	20.0	6.41012592	5.128100737	-0.1369
Non-mandatory	5	36,500	2014	6.4		5.351	-	-	17.0%	20.0	6.41012592	5.128100737	-0.2229
Non-mandatory	6	36,500	2014	6.4		5.351	14.5	6,400	17.0%	20.0	6.41012592	5.128100737	-0.2229
Non-mandatory	7	36,500	2013	6.4		5.431	-	-	15.8%	20.0	6.41012592	5.128100737	-0.3029
Non-mandatory	8	36,500	2014	6.4		5.438	-	-	15.7%	20.0	6.41012592	5.128100737	-0.3099
Non-mandatory	9	36,500	2014	6.4		5.431	-	-	15.8%	20.0	6.41012592	5.128100737	-0.3029
Non-mandatory	10	36,500	2013	6.4		5.431	-	-	15.8%	20.0	6.41012592	5.128100737	-0.3029
Non-mandatory	11	36,500	2014	6.4		5.431	-	-	15.8%	20.0	6.41012592	5.128100737	-0.3029
Non-mandatory	12	37,500	2012	6.4		5.663	14.5	7,000	11.1%	20.0	6.32801271	5.062410166	-0.6006
Non-mandatory	13	37,500	2012	6.4		5.663	-	-	11.1%	20.0	6.32801271	5.062410166	-0.6006
Non-mandatory	14	37,500	2013	6.4		5.501	15.5	7,400	13.5%	20.0	6.32801271	5.062410166	-0.4386
Non-mandatory	15	37,500	2013	6.4		5.501	-	-	13.5%	20.0	6.32801271	5.062410166	-0.4386

Table 14: Excel sheet with IMO data base

The first column we add is the Reduction factor, in which we use the function IF to distinguish the different Reduction factors Per DWT. If the dwt is in the spectrum of the liner interpolation, then the Reduction factor comes from the Sheet help. For example a bulkers DWT is in cell C4 then the calculation is as follows: =IF(C4<20000, help!U7,IF(C4<200000,20,IF(C4>=200000,15)))

After we calculate the Reference lines of the vessels in the same way. Example calculation for the same bulker is as follows: =IF(C4<279000,961.79*C4^ (-0.477),961.79*279000^(-0.477))

The third column is the REQUIRED EEXI which is just the reference lines multiplied by the reduction factor. The example for the same bulker is as follows: =(1-S4/100) *T4

After we have these new parameters ready for every vessel of the database, we just extract from the Required EEXI the attained EEDI and so, we understand that if their difference is positive then the vessel has Required EEXI bigger than the attained and so its compliant. If the difference is negative, then the vessels are not compliant with the EEXI regulations. By copying and pasting the differences of the vessels on a new sheet we can calculate the percentages of the positive and negative values using the function COUNTIF for the whole column. An example of the usage of this function on column A is as follows: =COUNTIF (A2:A3222,"<0"). On this example the function counts the negative values and so the non-compliant vessels.

Lastly by filtering the first sheet table we can just extract the "difference" column for vessels built on specific years, specific phases and on specific DWT spectrums so we can analyze the data pool in more detail.

4.4 General Findings

4.4.1 Bulk Carriers

Bulk carriers produced an estimated approximate 160m tons of CO_2 last year, roughly 0.5% of total global emissions. However, while bulkers account for around 20% of the shipping industry's CO_2 emissions, the bulker fleet moved around 50% of global seaborne trade in tonne-miles last year, and emitted 6m less CO_2 than the containership fleet, while moving over three times as much cargo in tonnes.

A total of 3026 bulk carriers built between 2011 and 2022 falling from non-mandatory to phase 2 of the EEDI were analyzed. In general, from the 3026 vessels investigated 1693 (56%) comply already with the EEXI regulations and 1333 (44%) need corrective actions in order to comply.

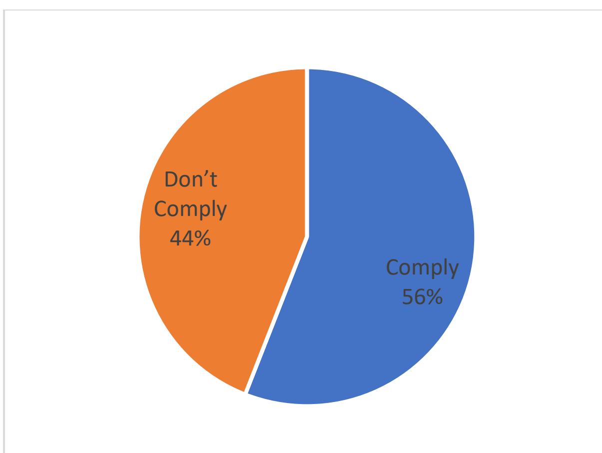


Figure 18: overall compliance of bulk carriers

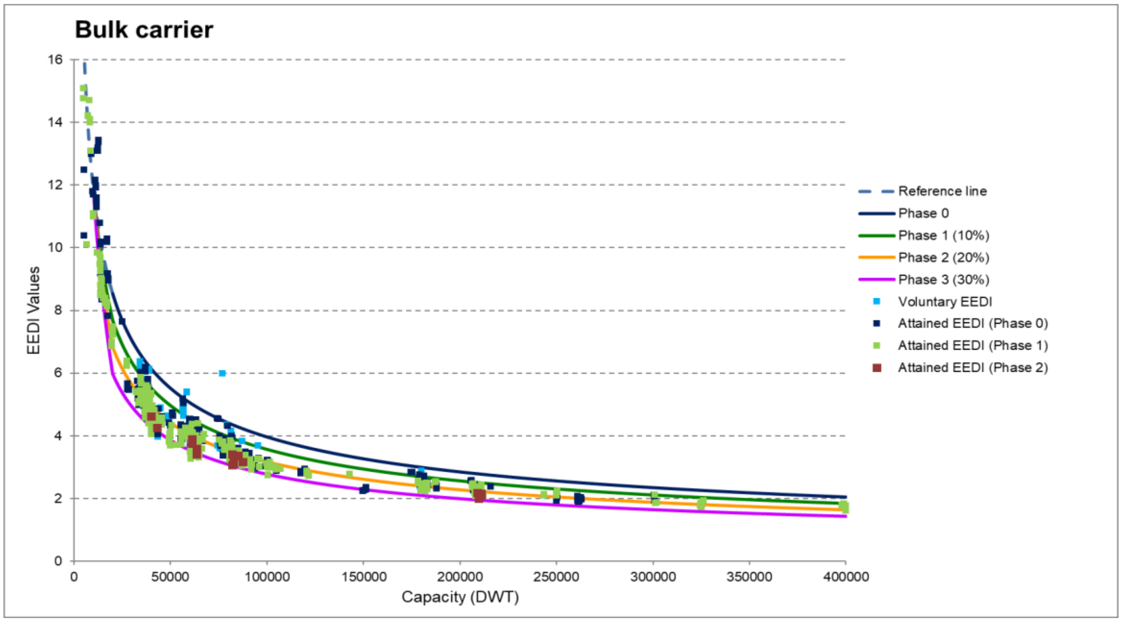


Figure 19: EEDI database for bulk carriers

From the three categories investigated Bulk carriers showcase the worst compliance with the EEXI regulations

(*Seven out of 10 Bulk Carriers Not Ready for EEXI - Splash247*, [s.d.])

No ship in this category reported using innovative mechanical or electrical technologies to achieve current efficiencies. This suggests that there is scope for further improvements if available energy saving technologies are used.

It's only logical that newer vessels score better for the EEXI, that's proven also by our analysis. Below we present on figure 12 the percentages of compliance for the Bulk carriers depending on the year of built.

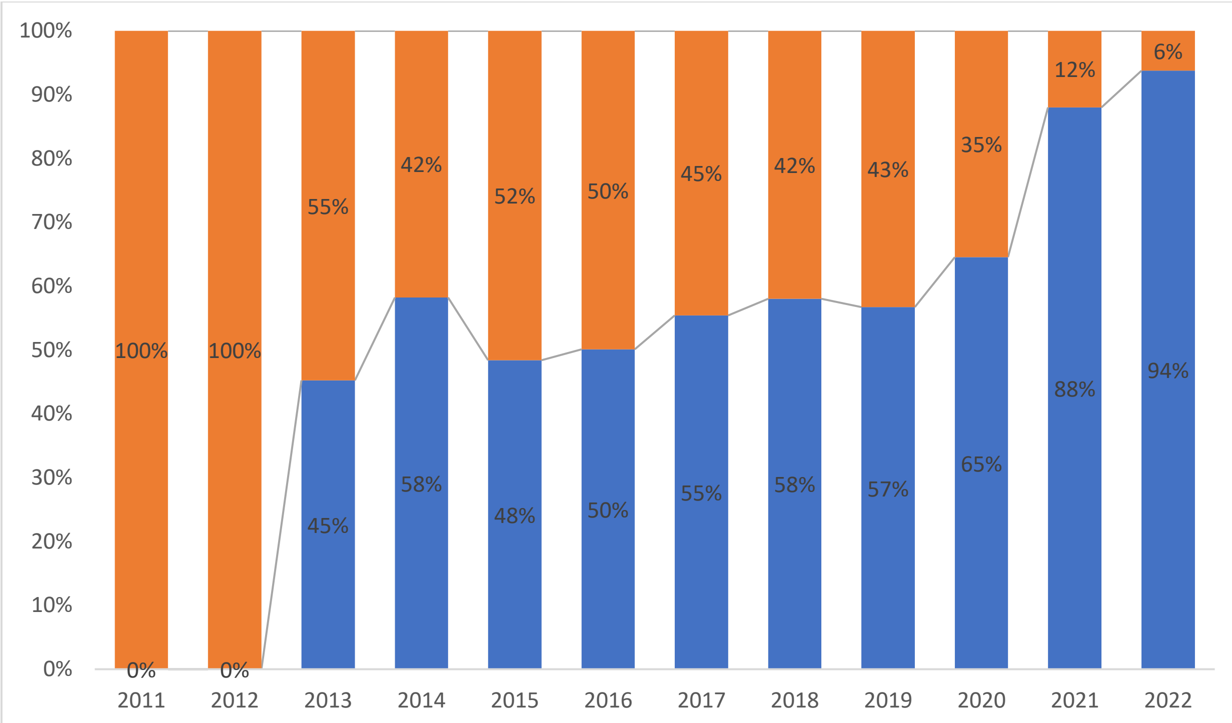


Figure 20: Compliance percentages of post EEDI Bulk Carriers per Year of built.

Its easy to identify that ships built before 2013 have a non-mandatory EEDI measurement and even though the sample is very small (35 vessels) we can see that they have 0% of compliance. After 2013 until 2015 we have vessels that fall into Phase 0 requirements and the results change drastically. We can see that in the year 2014 bulk carriers tend to showcase better results than the years around it.

"Examination of EEDI database shows that EEDI improvements follow a trend of steep improvement in the early years of implementation followed by a plateau. In fact, the best attained EEDI scores tend to be around 2015, likely before the change to ISO 15016 in 2015 which generally reduced Vref for the same sea trial." (Commission, 2021)

(as per Decarbonization of Shipping Technical Study on the future of the Ship Energy Efficiency Design Index Final Report by EUROPEAN COMMISSION November 2021)

The results of the Final report of the European commission perfectly match our results.

Ships built between 2015-2020 fall into phase 1 requirements and show as the paper suggests we have better results but not dramatically increasing.

For ships built between 2021 -2022 and fall into phase 2 it's easy to recognize that their percentages go way higher.

In the following table we can see the results in detail.

Year Of built	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Comply	0%	0%	45%	58%	48%	50%	55%	58%	57%	65%	88%	94%
Don't comply	100%	100%	55%	42%	52%	50%	45%	42%	43%	35%	12%	6%
Total number	4	31	84	194	506	571	395	262	386	423	142	16

Table 15: Number of vessels and percentage of compliance per year built.

Following the previous analysis there is interest in categorizing the previous vessels only per phase. The results can be seen in the following table.

Phase Of EEDI	Non mandatory	Phase 0	Phase 1	Phase 2
Comply	35%	52%	63%	100%
Don't comply	65%	48%	37%	0%
Total number of ships	161	1736	1085	44

Table 16: Number of vessels and percentage of compliance per Phase of EEDI built.

For better understanding of the results, we use the following figure.

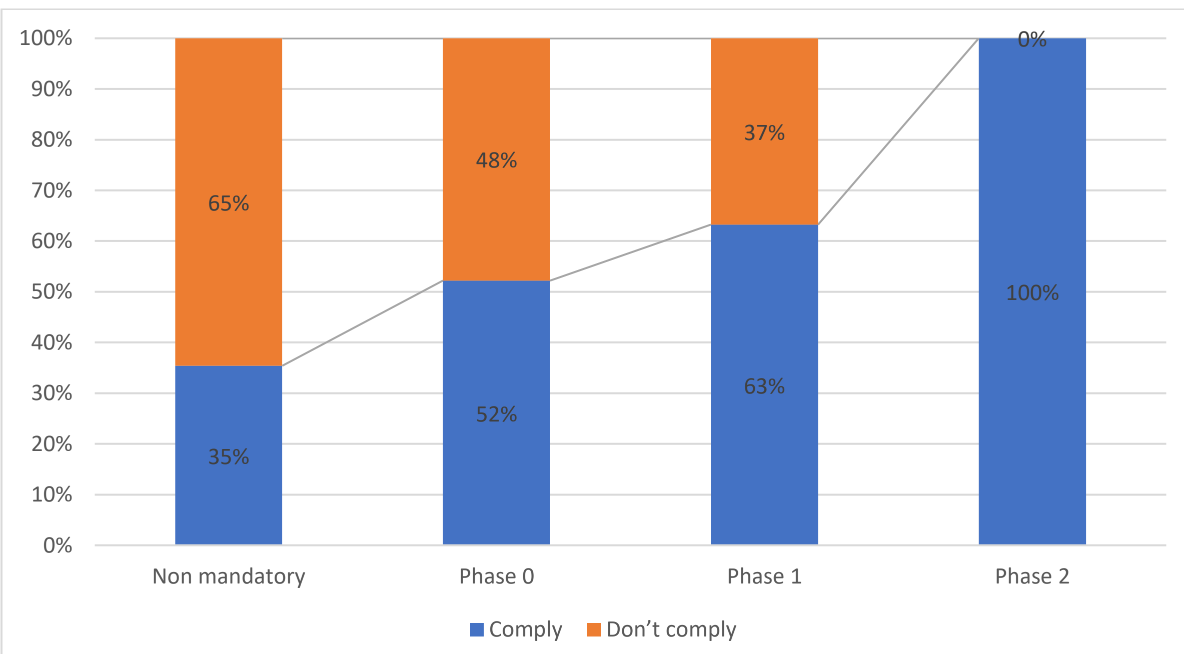


Figure 21: percentage of compliance per Phase built of the vessel.

In order to have a more detailed look of the fleet and to identify potential problems that it may face, we categorized the vessels as per DWT. The categorization is based on the ICCT categorization for similar analysis. The results can be seen in the table below. (Rutherford, Mao, Osipova, et al., 2020)

DWT Spectrum (tons)	10.000-34.999	35.000-49.999	50.000-59.999	60.000-79.999	80.000-99.999	100.000-199.999	200.000+
Comply	40%	53%	40%	75%	35%	28%	88%
Don't comply	60%	47%	60%	25%	65%	72%	12%
Total number of ships	170	570	121	952	675	248	290

Table 17: percentage of compliance depending on the DWT of the vessel.

The numbers presented above are presented on the following figure for better understanding.

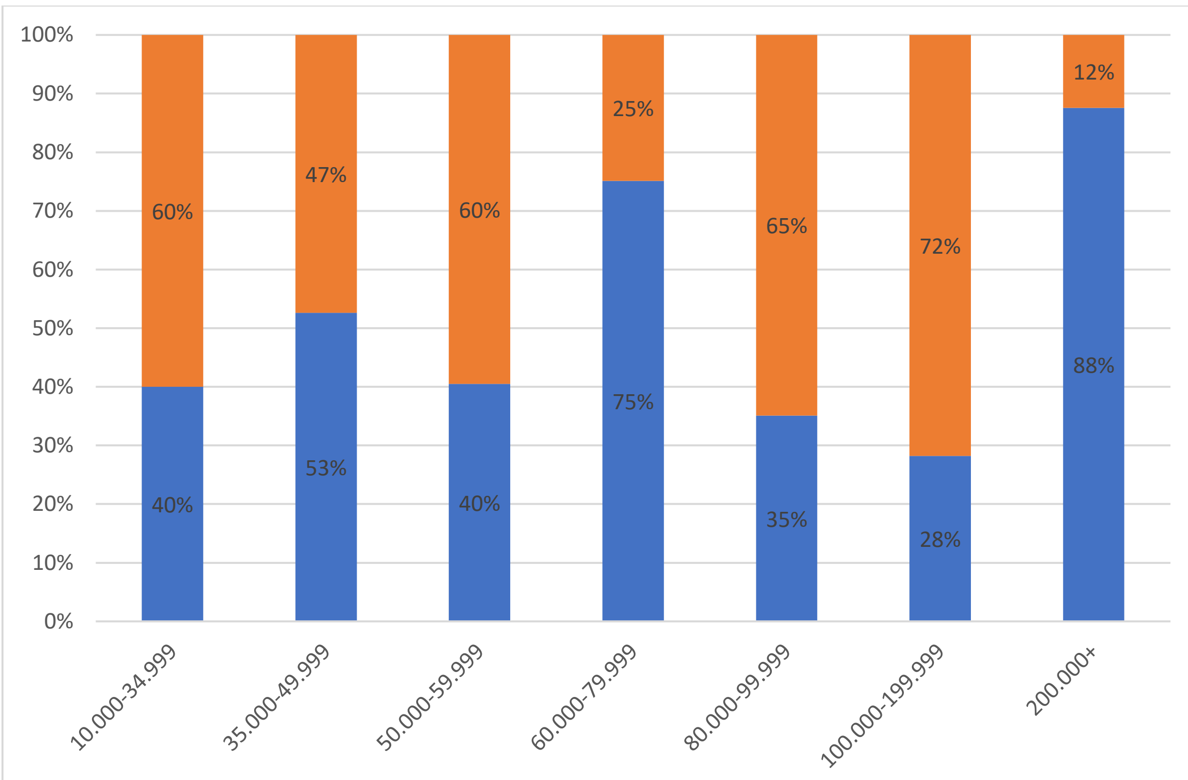


Figure 22: percentage of compliance depending on the DWT of the vessel.

In Figure 15 we can identify that the vessels with the biggest percentages of compliance with the regulations are the ships with DWT between 60.000-79.999 tons which for the most part are the panamax and account for the biggest portion of the fleet with 952 in total.

Interesting to comment on is that the compliance of bulk carriers changes dramatically when the reduction factor drops from 20 to 15 after 200.000 tons, from 28% compliance to 88%.

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*

Table 18: Reduction factors for bulk carriers as per MEPC 76

(*ANNEX 1 RESOLUTION MEPC.328(76) AMENDMENTS TO THE ANNEX OF THE PROTOCOL OF 1997 TO AMEND THE INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS, 1973, AS MODIFIED BY THE PROTOCOL OF 1978 RELATING THERETO 2021 Revised MARPOL Annex VI*, [s.d.]-b)

More comments on the results we occur on the last module.

4.4.2 Tankers

According to Statista, the capacity of the world's oil tanker fleet increased significantly from 1980 to 2020 by more than 77%. Despite the growing contribution of renewables to global energy consumption, the global market remains highly dependent on oil. In 2020, the world's oil tanker fleet had a deadweight of approximately 601 million tons.

(*Choices and Challenges: The EEXI and the Tanker Sector - Splash247*, [s.d.]-a)

A total of 2280 tankers built between 2011 and 2022 and falling from non-mandatory to phase 2 of the EEDI were analyzed. In general, of the 2280 vessels investigated 1824 or (80%) complied with EEXI regulations and 456 or (20%) need corrective action in order to comply.

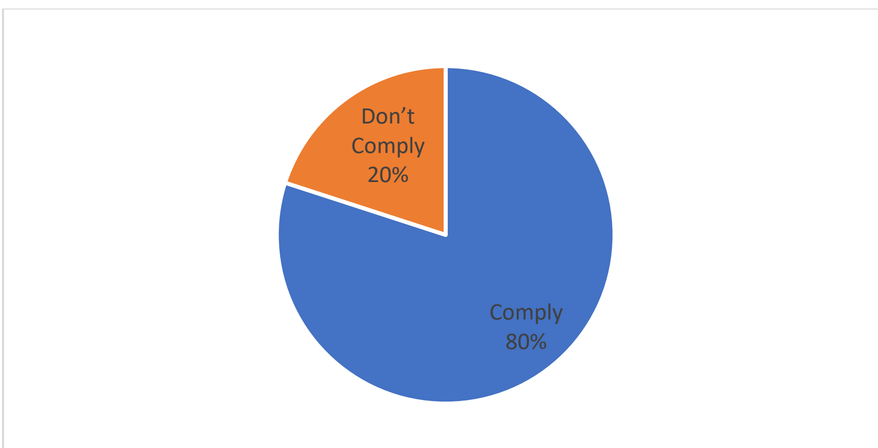


Figure 23 whole fleet of post EEDI tankers compliance with EEXI

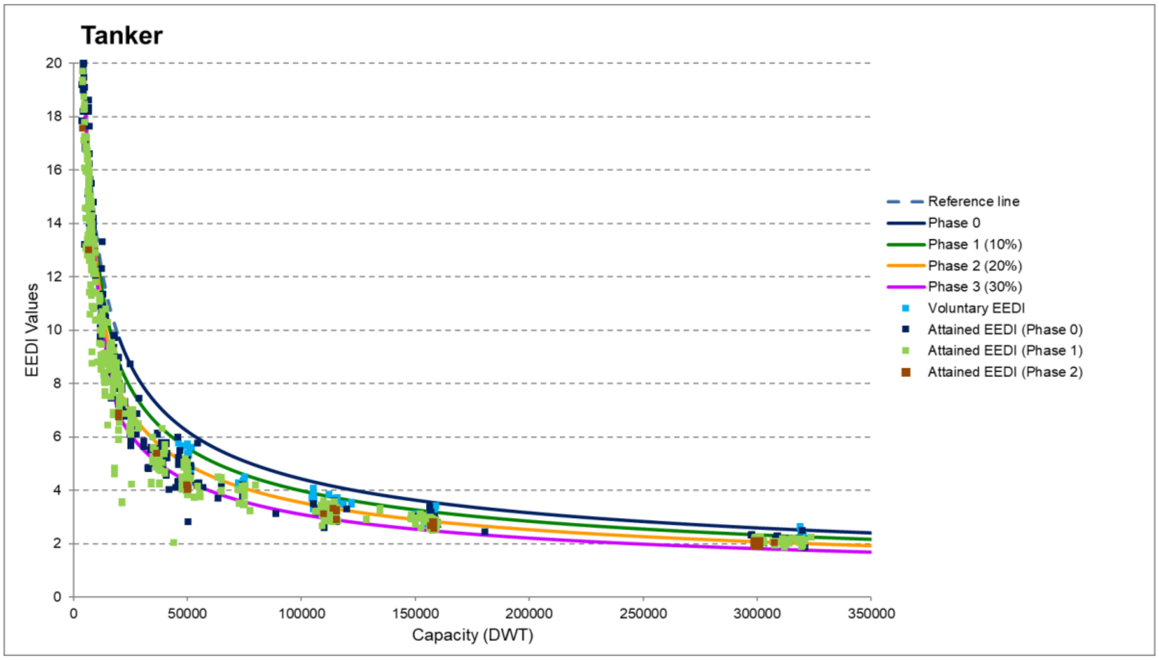


Figure 24: EEDI database for tankers

From the three categories investigated Tankers showcase the best compliance percentages with the EEXI regulations. Although that's not an indication that the world fleet will not have a problem complying and that's because 70% of current global tanker fleet was contracted prior to January 2013 and delivered prior to July 2015, these ships do not have an EEDI value, so their EEXI will have to be estimated using the guidelines developed by IMO. Analysis by ABS suggests that almost 7,000 tankers are likely to have to explore alternative compliance options to meet their target EEXI values.

Almost no ship in this category reported using innovative mechanical or electrical technologies to achieve current efficiencies. This suggests that there is scope for further improvements if available energy saving technologies are used.

In the table below we present the percentages of compliance for the tanker fleet based on the year of delivery. For easier understanding of the results, we use figure 17.

Year of built	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Comply	4%	11%	40%	74%	86%	85%	81%	83%	84%	86%	92%	92%
Don't comply	96%	89%	60%	26%	14%	15%	19%	17%	16%	14%	8%	8%
Total number of ships	28	56	72	129	222	339	352	311	322	214	222	13

Table 19: Compliance percentages of post EEDI Tankers per Year of built.

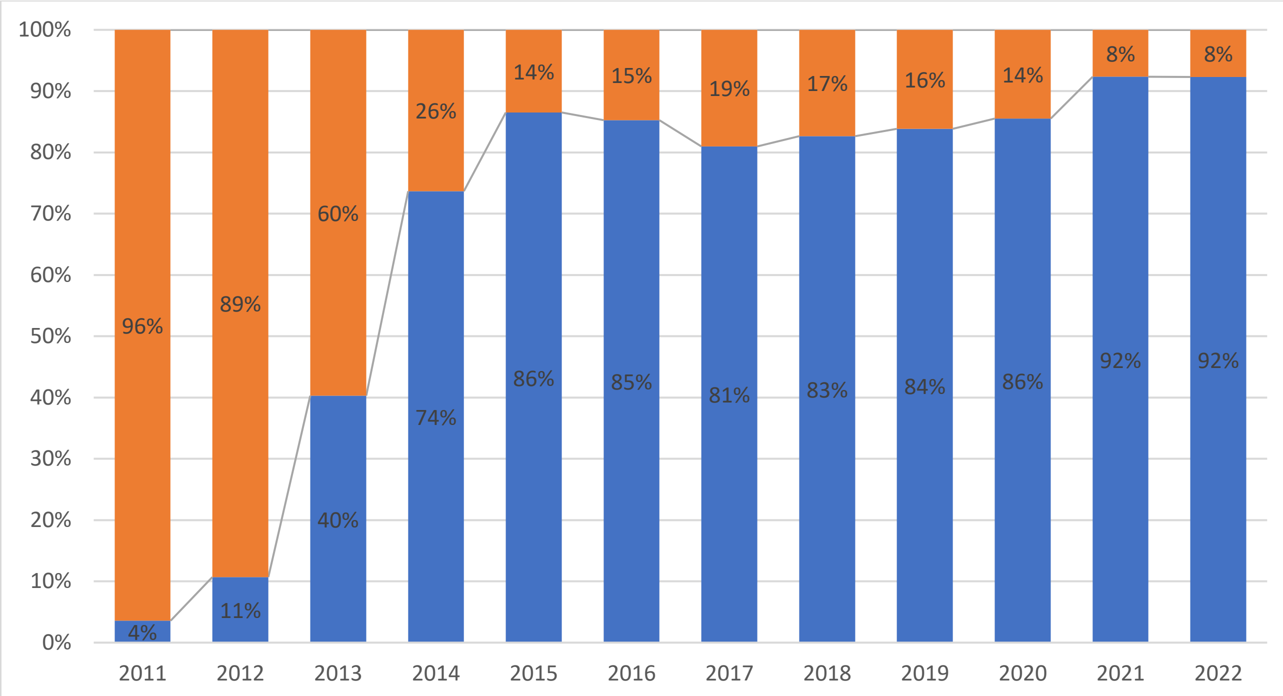


Figure 25: Compliance percentages of post EEDI Tankers per Year of built.

It's easy to identify that ships built before 2013 have a non-mandatory EEDI measurement and even though the sample is very small (84 vessels) we can see that they have a very small compliance. From 2013 until 2015 we have vessels that fall into Phase 0 requirements and the results change drastically over year. After 2015 and the change in the ISO 15016 the percentages are relative the same only to change again after 2021 and phase 2.

The changes over the phase built can be seen in table 11 and figure 18.

Phase	Non mandatory	Phase 0	Phase 1	Phase 2
Comply	39%	83%	85%	100%
Don't Comply	61%	17%	15%	0%
Total number	203	841	1203	33

Table 20: Number of vessels and percentage of compliance per Phase of EEDI built

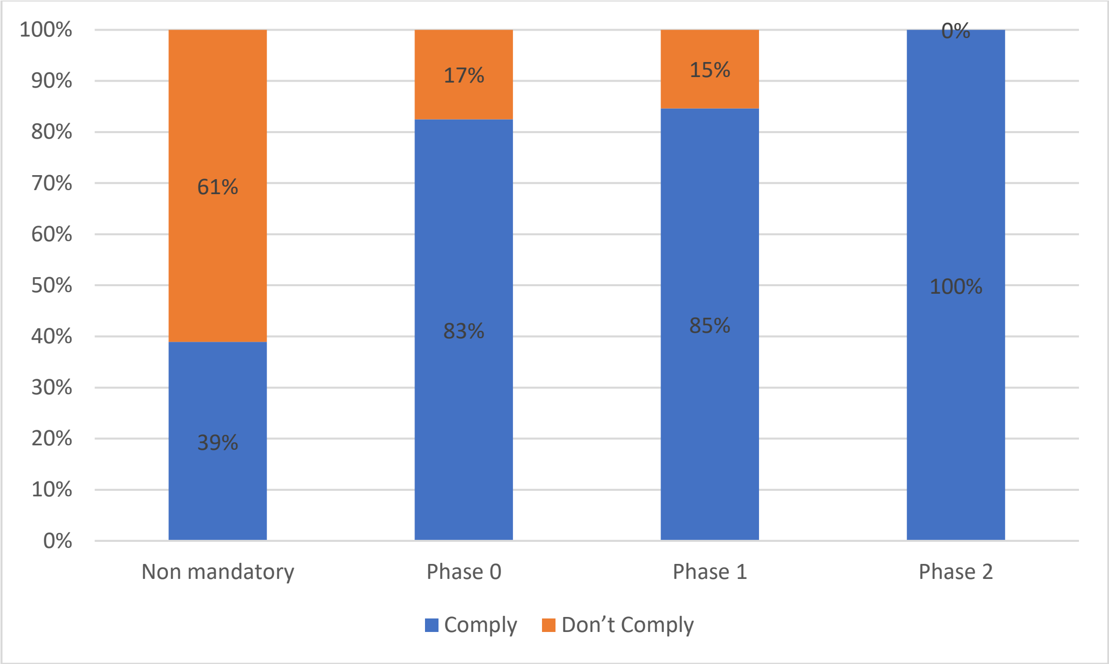


Figure 26: percentage of compliance per Phase built of the vessel.

Continuing in the same format for a more detailed look of the fleet and to identify potential problems that it may face, we categorized the vessels as per DWT. The categorization became based on the ICCT categorization for similar analysis. The results can be seen on the table below.

DWT Spectrum (tons)	4.000-9.999	10.000-34.999	35.000-49.999	50.000-59.999	60.000-79.999	80.000-119.999	120.000-199.999	200.000+
Comply	74%	80%	82%	93%	66%	86%	57%	74%
Don’t Comply	26%	20%	18%	7%	34%	14%	43%	26%
Total number	222	353	205	558	85	335	226	280

Table 21: percentage of compliance depending on the DWT of the vessel.

The numbers presented above are presented on the following figure for better understanding.

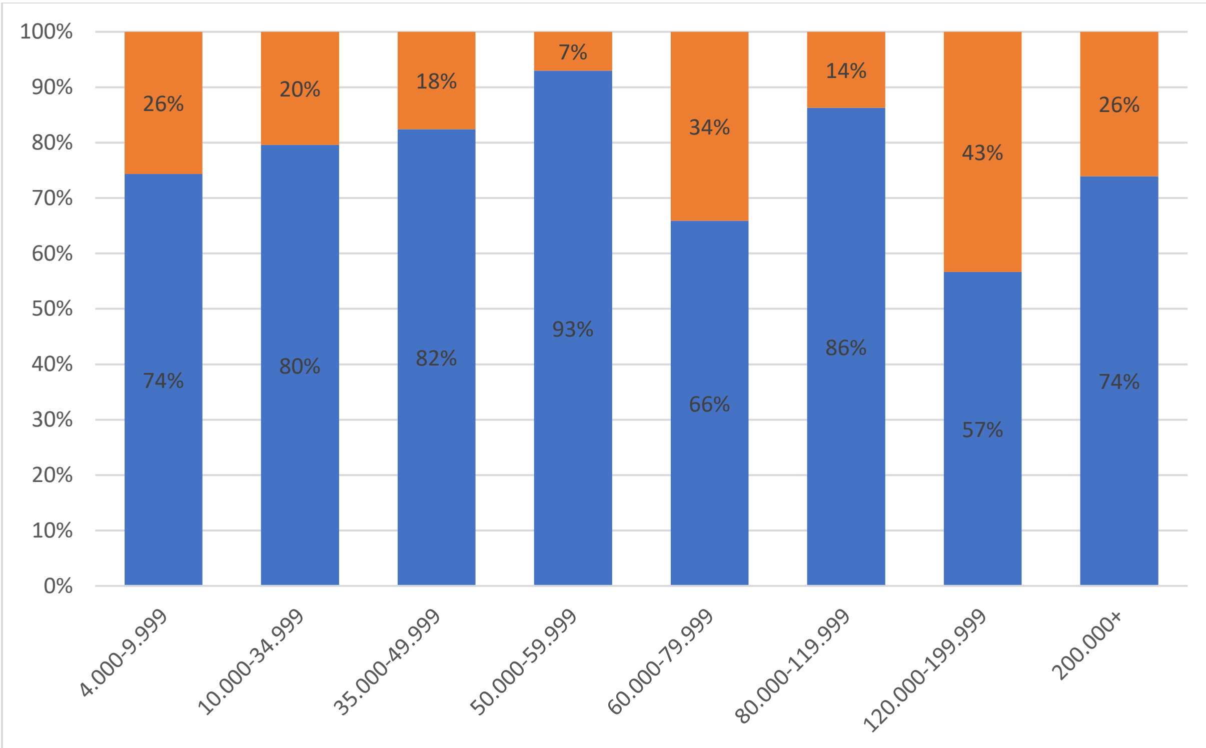


Figure 27: percentage of compliance depending on the DWT of the vessel.

As we can see from the graph Vessels up to 50.000- 60.000 tons DWT we have an easier way into the implementation. (as per Decarbonization of Shipping Technical Study on the future of the Ship Energy Efficiency Design Index Final Report by EUROPEAN COMMISSION November 2021) "Tankers up to around 50,000 deadweight appear able to meet Phase 3, however many of these are aided by the chemical tanker correction factor – ships that are not able to use this correction factor may have problems meeting Phase 3, however this may prompt shipowners to choose to build to the IBC code in order to qualify for this correction factor, with no real CO_2 saving. Ships larger than 50,000 dwt generally will be challenged to meet Phase 3 with the VLCCs facing the greatest difficulty."

Although Vessels with DWT greater than 200.000 tons are the least efficient the reduced reduction factor from 20 to 15 assists in easy implementation of many.

More comments on the results occur on the last module, where we will present the results for all types of vessels together.

4.4.3Container ships

A report on the IMO Data Collection System, as it is officially known, seen by Lloyd's List, shows containerships, tankers and bulkers accounted for 78.6% of the total CO_2 emitted by international shipping.

Container ships account for the 29.91% of the total CO_2 emissions, while their share of DWT-nautical miles is 20.91% (as per DCS report)

A total of 1016 container ships built between 2011 and 2022 falling from non-mandatory to phase 2 of the EEDI were analyzed. In general, from the 1016 vessels investigated 781 (77%) comply already with the EEXI regulations and 235 (23%) need corrective actions in order to comply.

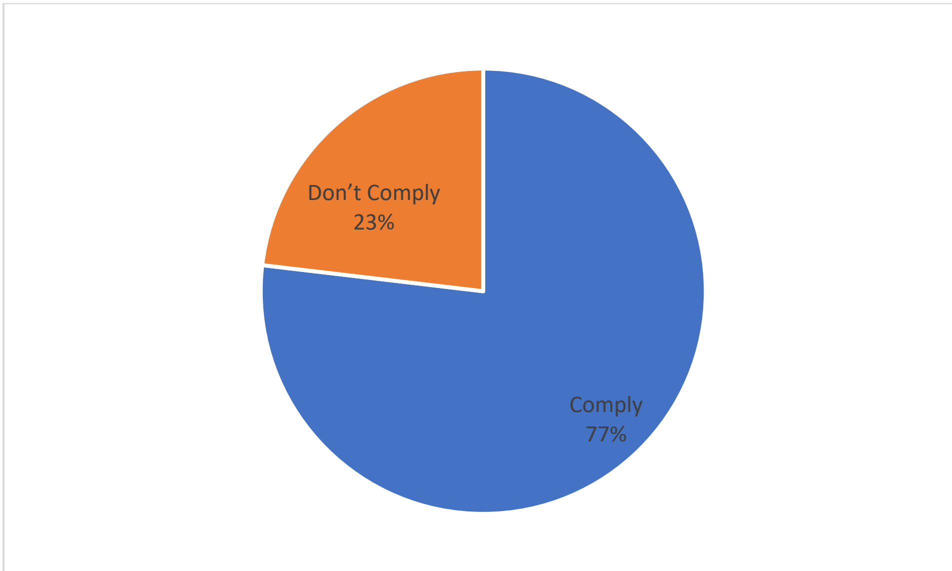


Figure 28: Overall compliance of Containerships

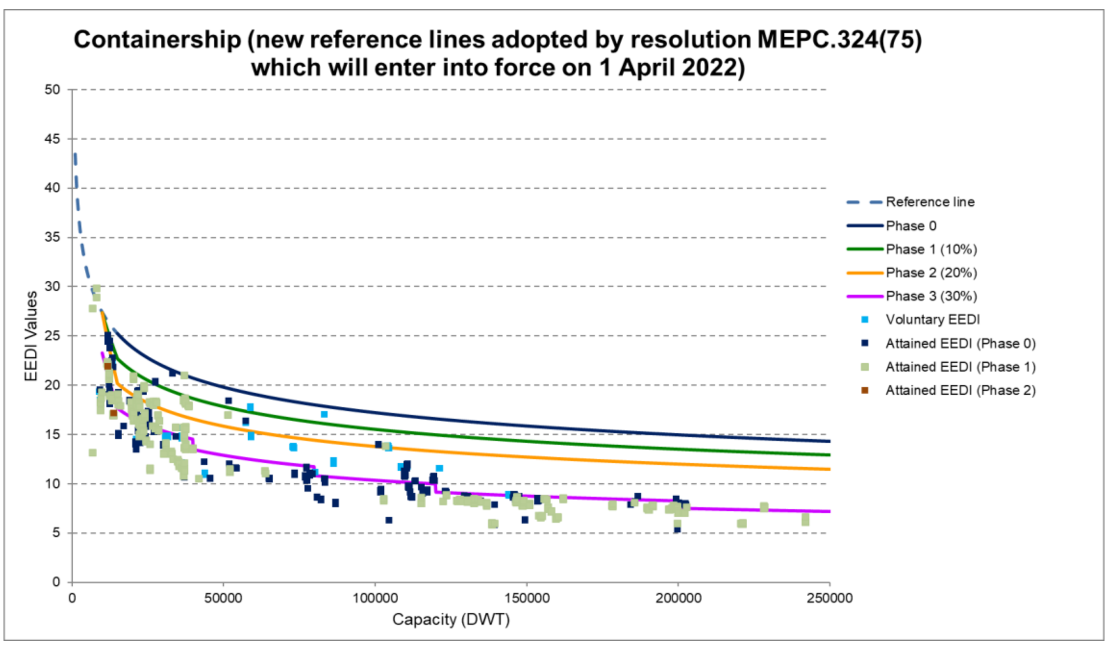


Figure 29: EEDI database for containerships

From the three categories investigated container ships showcase close to the tankers the best compliance with the EEXI regulations

Only 28 ships in this category reported using innovative mechanical or electrical technologies to achieve current efficiencies. This suggests that there is scope for further improvements if available energy saving technologies are used.

In the table below we present the percentages of compliance for the containers fleet based on the year of delivery. For easier understanding of the results, we use figure 30.

Containers	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Comply	0%	0%	54%	67%	79%	73%	81%	83%	82%	88%	89%	100%
Don't comply	100%	100%	46%	33%	21%	27%	19%	17%	18%	12%	11%	0%
Total number of ships	6	17	71	84	150	113	111	127	110	102	118	5

Table 22:Compliance percentages of post EEDI Container ships per Year of built

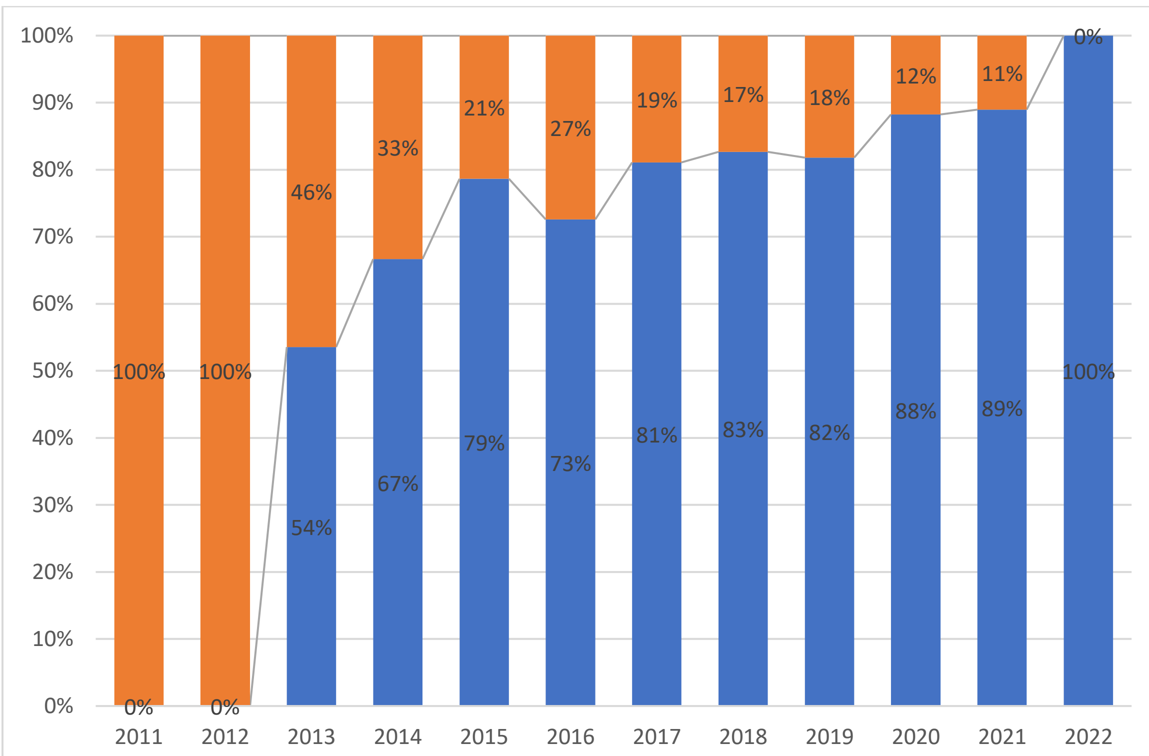


Figure 30: : Compliance percentages of post EEDI Container ships per Year of built

It's easy to identify that ships built before 2013 have a non-mandatory EEDI measurement and even though the sample is very small (23 vessels) we can see that they have 0% compliance. After 2013 until 2015 we have vessels that fall into Phase 0 requirements and the results change drastically. We can see that in the year 2015 vessels tend to showcase better results than the years around it. This is happening due to the change to ISO 15016 which generally reduced the Vref for the same sea trial. From 2016 until 2020 we can see a steady improvement until 2021 and 2022, even though for the year 2022 we only have 5 vessels they all comply.

Following the previous analysis there is interest on categorizing the previous vessels only per phase. The results can be seen in the following table.

Phase of the EEDI	Non mandatory	Phase 0	Phase 1	Phase 2
Comply	39%	79%	86%	100%
Don't comply	61%	21%	14%	0%
Total number of ships	137	372	505	2

Table 23:Number of vessels and percentage of compliance per Phase of EEDI built.

For better understanding of the results, we use the following figure.

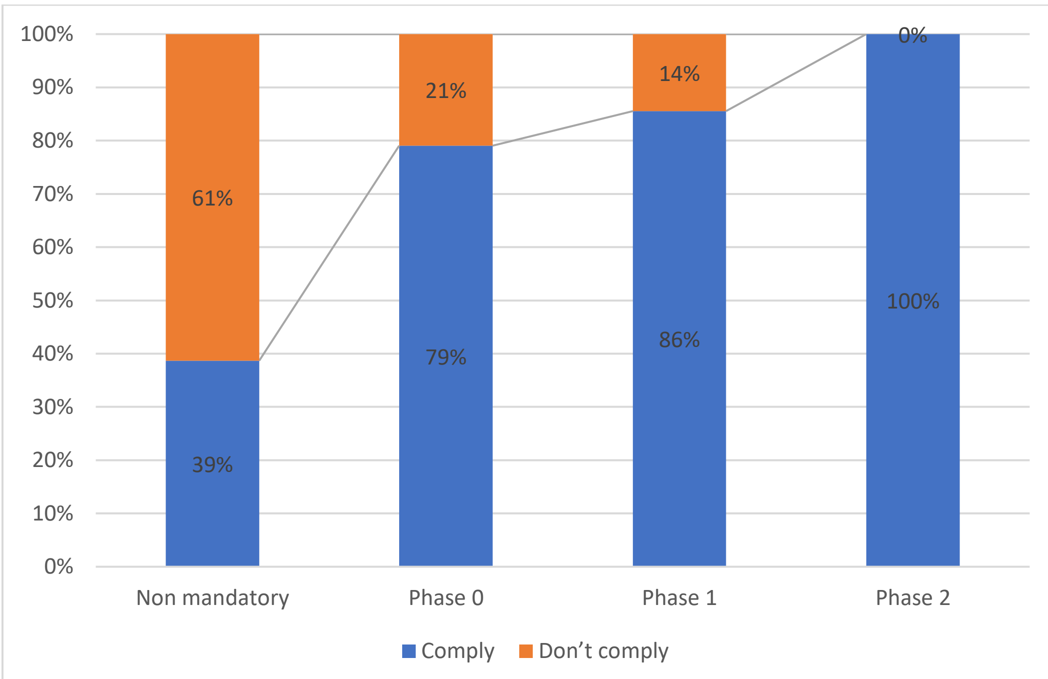


Figure 31: percentage of compliance per Phase built of the vessel.

In order to have a more detailed look at the fleet and to identify potential problems that it may face, we categorized the vessels as per DWT. The categorization became based on the ICCT categorization for similar analysis. The results can be seen in the table below.

DWT	10.000-19.999	20.000-29.999	30.000-49.999	50.000-79.999	80.000-119.999	120.000-149.999	150.000-199.999	200.000+
Comply	89%	77%	84%	56%	65%	84%	93%	48%
Don't Comply	11%	23%	16%	44%	35%	16%	7%	52%
Total number	101	206	167	79	147	151	107	61

Table 24: Percentages of compliance depending on DWT for containerships.

The numbers presented above are presented on the following figure for better understanding.

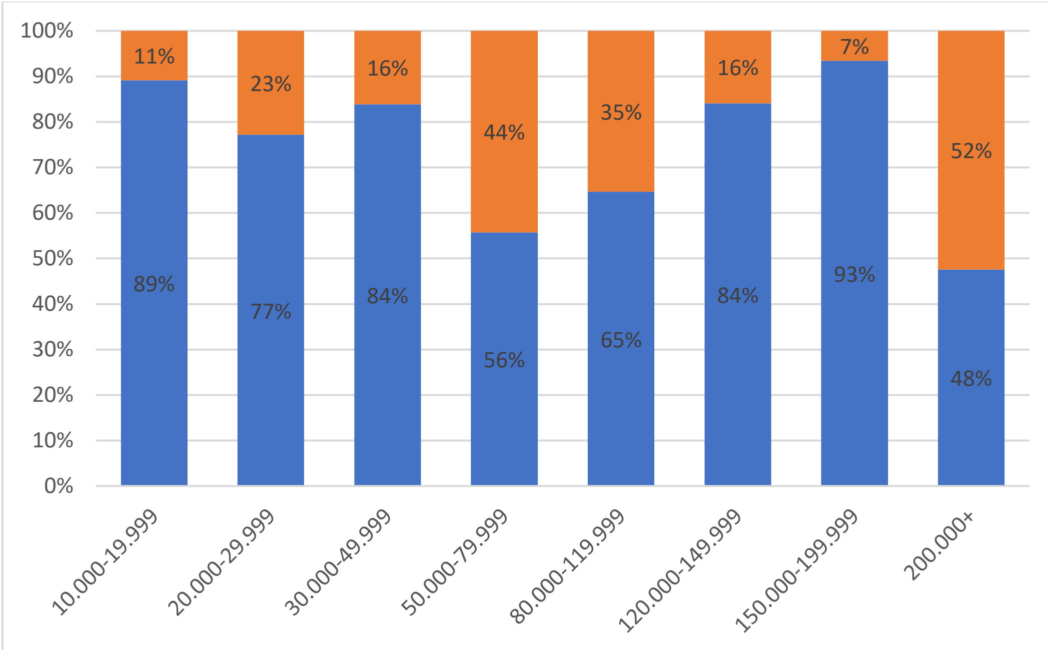


Figure 32:: Percentages of compliance depending on DWT for containerships.

As we can see from the graph smaller vessels up to 50.000 tons of DWT have an easier way of going into the EEXI regulations. The numbers show a regression of compliance for vessels 50.000-80.000 and 80.000-120.000 tons. Bigger vessels seem way more efficient (120.000-200.00) tons but as we identify container ships bigger than 200.000 tons have the worst results.

"The regression of the reference line for container ships was relatively poor with a R2 of 0.6191 and wide scatter with some phase 3 compliance already evident from the original population of container ships between 1999-2009. Equally there are ships which are around 25-30% worse than the reference line The 1st generation post panamax ships between around 50-100k deadweight which were very high powered and fast also further skewed the shape of the regression line and makes the very largest ships seem more efficient than they are. This is made worse by the fact that the very largest containerships that we have today were not represented at all in the regression line. "

"Also Ships above 120,000 dwt seem to achieve 45% or more better than the reference line, however the range is between 45% to over 60% with the main cluster being between 45-50%."

(as per Decarbonization of Shipping Technical Study on the future of the Ship Energy Efficiency Design Index Final Report by EUROPEAN COMMISSION November 2021)

That study led the IMO to take some drastic measures only for the container sector and especially for the bigger vessels.

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*

Table 25: Reduction factors for containerships (source MEPC 76)

As we can see the Reduction factors decided for the container ship sector are the stricter in the whole sector and the only ones that increase as the DWT of the vessels increases. That happened for the simple fact that the bigger vessels needed to be stricter regulated because the reference lines did not actually represent them, for the simple reason that during 2008 that the reference lines where measured and calculated the Container ships fleet consisted of smaller vessels.

Although the reduction factors are so strict, bigger vessels, with the exception of vessels bigger than 200.000 tons which present the worst compliance percentages because they have a reduction factor of 50%, have still very good results.

More comments on the results will occur in the last module, where we will present the results for all types of vessels together.

4.5 Overall results and discussion

In this paragraph the overall results will be presented for easier comparison between them.

We first present the Total number, the compliance percentages per phase, and the average distance of the attained EEXI values relative to the Required of the fleet, summarized by ship type. Second, we summarize the number of vessels examined, the compliance percentages and again the average distance between Attained EEXI and Required EEXI, by ship type and year of built. Following that we pressend

	Bulk Carriers	Tankers	Container
Total number	3026	2280	1016
Total number in mandatory phase	2865	879	2207
Compliance Percentages	55.9%	80.0%	76.9%
Compliance Percentages only mandatory	57.1%	84.0%	82.8%
Non-mandatory phase compliance	35.4%	38.9%	38.7%
Phase 0 compliance	52.2%	82.5%	79.0%
Phase 1 compliance	63.2%	84.6%	85.5%
Phase 2 compliance	100%	100%	100%
Average distance to EEXI lines	+1%	+7%	+9%

Table 26: summarized results of the fleet

Individual compliance percentages and distance on average from the EEXI required lines, for each ship type depending on the year of built were calculated using the methods highlighted above. The summarized results are shown in Table 26.

Ship type	Parameter	Built year											
		2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Bulk Carrier	Number of vessels examined	4	31	84	194	506	571	395	262	386	423	142	16
	Compliance percentages	0%	0%	45.2%	58.2%	48.4	50.1%	55.4%	58.0%	56.7%	64.5%	88.0%	93.8%
	Average distance to Required EEXI	-14%	-17	-3.9%	-1.5%	-0.2%	-0.3%	0.9%	2.3%	2.0%	3.3%	6.8%	5.8%
Tanker	Number of vessels examined	28	56	72	129	222	339	352	311	322	214	222	13
	Compliance percentages	3.60%	10.70%	40.3%	73.6%	86.50%	85.3%	81.0%	82.60%	83.90%	85.50%	92.30%	92.30%
	Average distance to Required EEXI	-10%	-9%	-2%	7%	9%	7%	6%	7%	8%	8%	11%	8%
Container	Number of vessels examined	6	17	71	84	150	113	11	127	110	102	118	5
	Compliance percentages	0%	0%	53.50%	66.70%	78.70%	72.60%	81.10%	82.70%	81.80%	88.20%	89.00%	100%
	Average distance to Required EEXI	-19%	-15%	2%	11%	9%	9%	8%	9%	9%	13%	13%	18%

Table 27: summarized results for fleet based on year built

As shown in Table 27, Compliance percentages and Average distance to Required EEXI are sensitive to build year and ship type. Newer ships subject to the first phases of the EEDI are closest to complying with the EEXI requirements.

As we mentioned before for the non-mandatory vessels the percentages of compliance for all 3 categories are almost 0 % even though the number of vessels is very small in order to take the results into account. We can also see that the Average distance of the attained EEDI for these vessels to Required EEXI for those 2 years (2011-2012) is not only negative, which means that on average these vessels have a higher attained index than the required but is bigger than 14 % for all 3 categories. Going forward to the years 2013-2014 In which a lot more vessels are on the phase 1 category we can see that the percentages of compliance increase dramatically with the worst result to appear on bulk carriers with half of them still need corrective actions in order to comply. For Tankers and containers, we can see that on average the fleet built those 2 years starts to have positive average distance to required EEXI which means that on average vessels tend to comply. For bulk carriers the scattering is bigger. That means that although more than half of bulk carriers comply, the ones that don't have a big distance between their attained index and the required one.

For the years 2015- 2020 the percentages increase steadily. For Bulk carriers' compliance is more than 50 % almost all these years and we have the first positive distances after 2018. For tankers compliance is 84% and we can see that the average distance is around 8%. Remarkably the best year is 2015 and that's, as we mention above, cause of the change on ISO2015 which made reference speed (V_{ref}) lower for the same sea trials. Containers appear the same steadily increase pattern as well for their compliance, although the average distance is kept steady until 2019. The result on the change of ISO 2015 is easily seen here as well with 2015 compliance to be around 79%.

2021 onwards bulk carriers demonstrate a huge leap in compliance and average distance is almost doubled. Tankers similarly have better numbers in both percentages and averages going into phase 2. The difference between years 2020 and 2021 is not big for containers but for 2022 although we have extended increases, we only have 5 vessels to examine.

Except the year of built, vessels showcased extensive differences based on their size. In the table below we can see which are the challenging size areas, in order to comply with the regulations.

Ship Type	Capacity (DWT)	Parameters			
		Average DWT	Total number	Compliance percentages	Average distance to Required EEXI
Bulk Carrier	10.000-34.999	24.094	170	40%	-4%
	35.000 - 49.999	38.679	570	53%	0%
	50.000 - 59.999	56.591	121	40%	-3%
	60.000 - 79.999	63.598	952	75%	3%
	80.000 - 99.999	82.925	675	35%	0%
	100.000 - 199.999	143.175	248	28%	-3%
	200.000 +	248.822	290	88%	8%
Tanker	4.000-9.999	6.775	222	74%	6%
	10.000-34.999	19.99	353	80%	8%
	35.000-49.999	41.702	205	82%	9%
	50.000-59.999	50.103	558	93%	12%
	60.000-79.999	73.593	85	66%	3%
	80.000-119.999	111.973	335	86%	6%
	120.000-199.999	155.555	226	57%	0%
	200.000+	309.153	280	74%	2%
Container	10.000-19.999	13.332	101	89%	3%
	20.000-29.999	23.561	206	77%	8%
	30.000-49.999	36.667	167	84%	17%
	50.000-79.999	67.994	79	56%	3%
	80.000-119.999	105.058	147	65%	5%
	120.000-149.999	137.964	151	84%	8%
	150.000-199.999	177.64	107	93%	9%
	200.000+	213.893	61	48%	5%

Table 28: Summarized results based on DWT.

As shown in table 28 Compliance percentages and Average distance to Required EEXI are sensitive to ship type and ship size.
As shown in Table 28, Compliance percentages varied from 28% for the bigger bulk carriers (100.000 – 199.999 ton DWT) to 93% for mid-sized oil tankers and containers. this corresponds to Average distance to required EEXI ranging from -3% for the same category of bulks up to +12% for medium range tankers. For bulk carriers very good performances are spotted for the new panamax (60.000-80.000 tons of dwt) and for very large vessels after 200.000 tons and the drop of the reduction factor from 20 to 15. The worst performances are easily by those before the change of the reduction factor ranging up to 200.000 and lower.

Tankers up to 60.000 dwt tend to have better results. “Many ships smaller than and around 50,000 dwt benefit from the chemical tanker correction factor and this is a major factor in the seemingly good performance in this size segment, with many ships meeting Phase 3.”
As per (Decarbonization of Shipping Technical Study on the future of the Ship Energy Efficiency Design Index Final Report by EUROPEAN COMMISSION November 2021). Vessels around 60.000 – 80.000 tons, around aframax size have relative low numbers. The same pattern we saw on bulk carriers is exhibited here as well. Vessels from 120k – 200k tons showcase the worst results but after the reduction factor change for vessels bigger than 200k we have easier compliance.

New smaller Container ships up to 50.000 tons tend to benefit from small correction factors and demonstrates better results. The huge leap in the reduction factor from 20 to 30 for vessels bigger than 40.000 tones is easily spotted. Compliance displays a drop from 84% to 56 in this area. We can also see that the average distance from the required EEXI here is 17%, the biggest demonstrated in every size and type. At last compliance takes a huge hit again for vessels bigger than 200.000 tons for those vessels, reduction factor is 50%.

Analysis of the IMO EEDI database reveals that with the exception of bulk carriers a large share of ships in almost all class categories already comply with the EEXI regulations. However, we need to remember that we examine new post EEDI vessels, and we can easily spot that various sizes categories and older vessels in particular already have problems facing the new regulations. Given that almost no vessel in all 3 categories has reported the use of innovative electrical and/or mechanical energy saving technologies, there is considerable scope for further improvement. This applies to all major ship types, of which only 9% of containerships have reported the use of innovative technologies. Therefore, in order to incentivize development and deployment of further energy saving technologies and innovative ship designs, the revision of existing and setting of future design standards should be a matter of further analysis.

In the next Chapter we give insight on the categories, use, and implementation of Energy efficiency technologies. Finally with the assistance of software we perform some case studies trying to assess the impact they will have on already existing vessels, and their operational profile.

(Understanding New IMO Decarbonization Measures: EEXI and CII BV Solutions M&O – Focus on EEXI and CII| Bvsolutions, [s.d.]) https://www.bvsolutions-m-o.com/magazine/understanding-new-imo-decarbonization-measures-eexi-and-cii

5 Innovative Energy Efficiency Devices, ESDs (CATEGORIZING OF INNOVATIVE ENERGY EFFICIENCY TECHNOLOGIES)

5.1 Alternative options to comply with the EEXI regulations.

It is believed that most ship owners will seek to comply with EEXI by adopting either engine power limitation (EPL) or shaft power limitation (ShaPoLi), with the latter potentially being the preferred choice for multi-engine setups. Regardless of the route chosen, the result will be a reduction in the amount of power delivered to the propeller and therefore a potential long-term impact on a vessel's economic performance.

While speed reduction might be a valid option for vessels with high installed power and high design speed, for vessels such as tankers and bulkers, which are designed to sail at much lower speeds, EPL and ShaPoLi solutions may offer limited benefits in terms of commercial flexibility and attractiveness to charterers.

Wärtsilä has recently been working with customers to examine the operational profiles of one of its bulkers over the last 12 months. In this case, while a speed reduction of 5% enabled by EPL was acceptable when considering the average vessel speed, it would have impacted around 15% of the vessel's sailing days over the 12-month period when the vessel needed to sail at higher speeds. Another limiting effect of EPL and ShaPoLi is that they do not result in any real impact on a vessel's carbon footprint and therefore have no benefit in terms of the vessel's CII rating.

ESDs have a direct impact on vessel propulsion efficiency by reducing hull resistance and improving propeller thrust. Installing a replacement propeller that is optimized for the vessel's current operational profile also offers significant potential benefits. Depending on the vessel type, energy savings in the region of 5–10% can be achieved by combining ESDs and an optimized propeller. The problem is that many younger vessels already have ESDs installed, so the room for improvement is limited. For this reason, we may see alternative ESDs such as air lubrication systems and wind rotors.

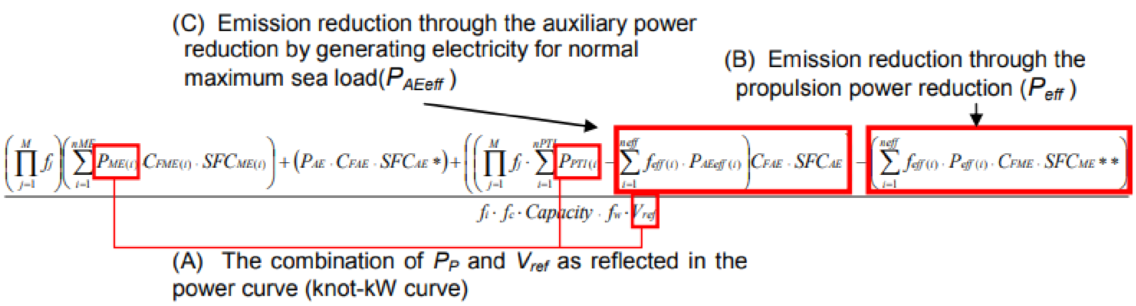
Typically, larger improvements in the EEXI can be expected when the retrofitting of energy efficiency technologies is performed in combination with a derating of the main engine

5.2 Categorization of the Energy efficiency devices

Innovative energy efficiency technologies are allocated to category (A), (B) and (C), depending on their characteristics and effects to the EEDI formula. Furthermore, innovative energy efficiency technologies of category (B) and (C) are categorized to two sub-categories (category (B-1) and (B-2), and (C-1) and (C-2), respectively).

Innovative Energy Efficiency Technologies				
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 overall performance of the vessel	Can be treated separately from the overall performance of the vessel		Effective at all time	Depending on ambient environment
	$f_{eff} = 1$	$f_{eff} < 1$	$f_{eff} = 1$	$f_{eff} < 1$
– low friction coating – bare optimization – rudder resistance – propeller design	– hull air lubrication system (air cavity via air injection to reduce ship resistance) (can be switched off)	– wind assistance (sails, Flettner-Rotors, kites)	– waste heat recovery system (exhaust gas heat recovery and conversion to electric power)	– photovoltaic cells

Table 29: Categorizing ESDs based on IMO.



Equation 3: Impact of ESDs on the formula

5.3 Category (A)

Technologies that shift the power curve, which results in the change of combination of P_P and V_{ref} : e.g., when V_{ref} is kept constant, $P_P$will be reduced and when $P_P$is kept constant, V_{ref} will be increased.

Innovative energy efficiency technologies in category (A) affect P_P and/or V_{ref} and their effects cannot be measured in isolation. Therefore, these effects should not be calculated nor certified in isolation in this guidance but should be treated as a part of vessel in EEDI Calculation Guidelines and EEDI Survey Guidelines. That means that they are inseparable from the overall performance of the vessel.

Category A ESDs are relatively inexpensive, simple to install and have a short engineering period compared to other categories. But its difficult to expect a dramatic improvement in the EEXI rating, because the effects are reflected in the V_{ref} and the speed is in proportion of the cubic root of the power saving ratio.

$$V_{ref} \sim \sqrt[3]{P_{ME}}$$

Hull form optimization retrofits

These ESDs address issues related to the basic hull form design including selecting proper proportions, reducing resistance by optimizing the hull form and appendage design, and assessing the impact on resistance of waves and wind.

Some of hull optimization ESDs on the market are:

- Bulbous bow retrofit (reduces wave-making resistance)

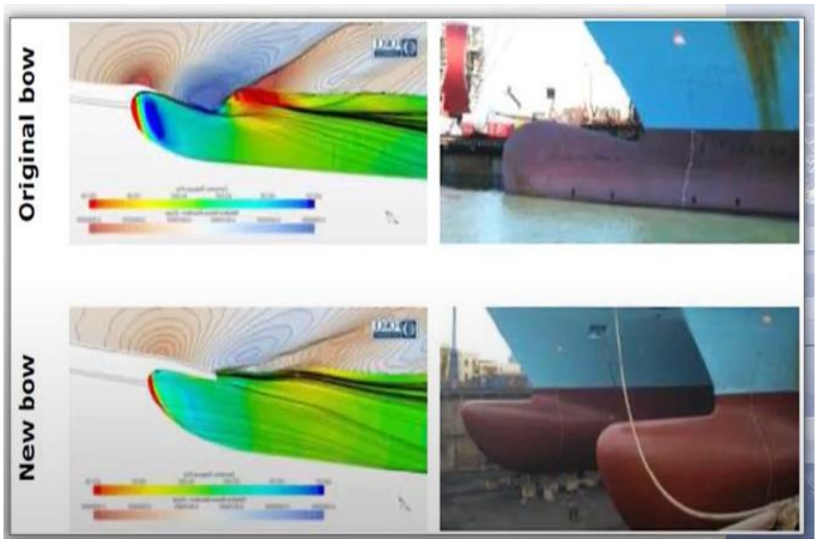


Figure 33: Bulbous bow retrofit

- Vortex flow control fins (reduce friction resistance)

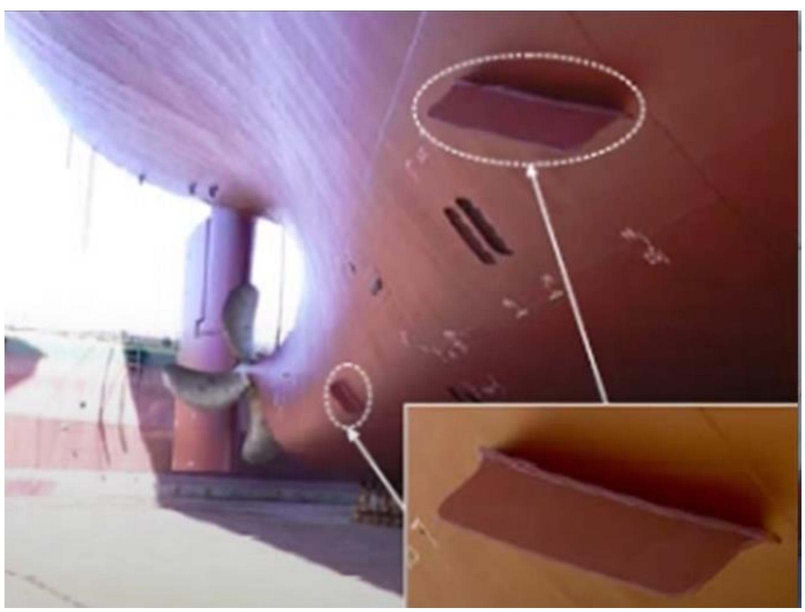


Figure 34: fins

- Hull coating techniques (reduce friction resistance)

Figure 35: hull coating techniques

Propulsion improving devices (PID)

These devices are designed to be installed near the propellers or near the rudder in order to increase propulsion power. Some devices prevent propulsion loss due to rotational flow occurring behind the propeller, others prevent the generation of a hub vortex behind the propeller and some convert force to thrust and increase power performance.

Some propeller optimizations ESDs or Propulsion improving devices (PID) on the market are:

Prevent Rotational flow:

- Swirl recovery vanes
- Pre-swirl stator (duct,fin)
- Contra-rotating propellers (CRP)

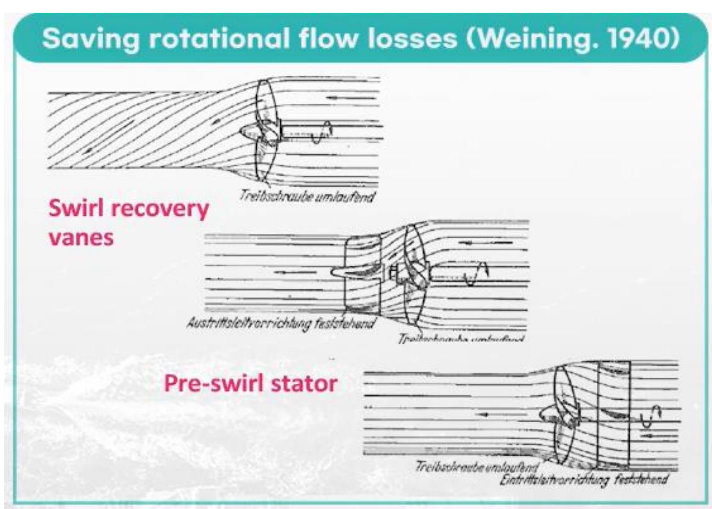


Figure 36: Rotational flow losses

Prevention of Hub vortex

- Rudder bulb
- Propeller boss cap fin (PBCF)
- Pre swirl fins
- Efficiency rudders

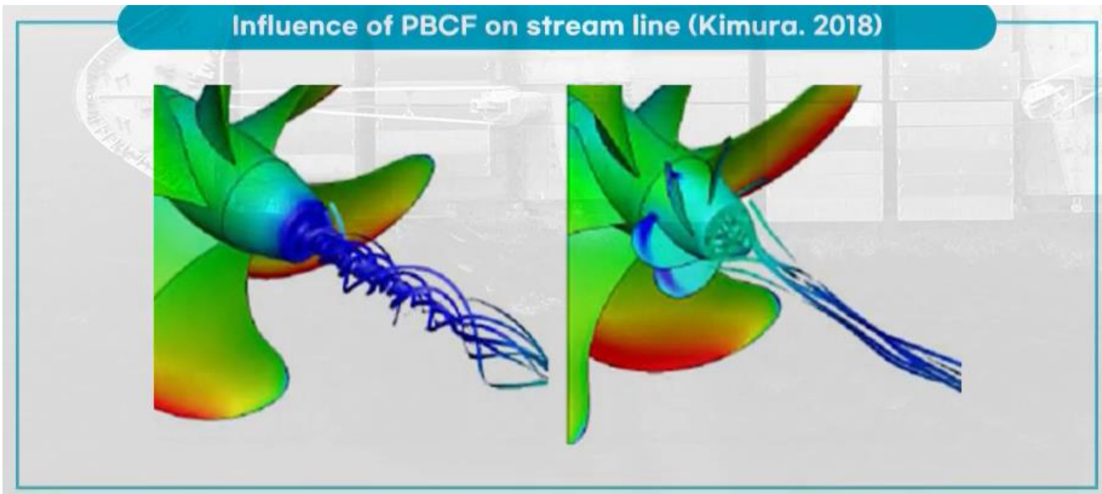


Figure 37: Influence of PBCF on stream line

Additional thrust

- Rudder fins

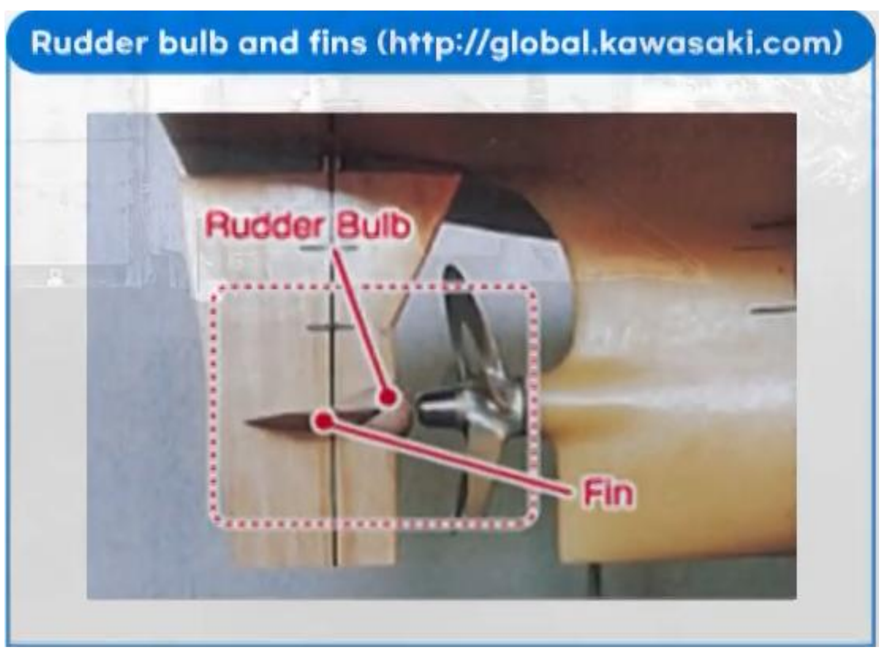


Figure 38:Rudder bulb and fins

5.4 Category B

Technologies that reduce the propulsion power, PP, at Vref, but not generate electricity. The saved energy is counted as Peff

- Category (B-1): Technologies which can be used at any time during the operation and thus the availability factor (feff) should be treated as 1.00.

- Category (B-2): Technologies which can be used at their full output only under limited condition. The setting of availability factor (feff) should be less than 1.00.

ESDs in Category B are technologies that can reduce the propulsion power and can be treated separately from the overall performance of the ship, that means that the devices can be turned on and off. Unlike category A it is possible to reduce the EEXI almost proportional to the power saving rate, because ESDs category B power reduction terms are directly reflected in the numerator of EEXI formula. In the drawbacks these devices are rather expensive and require long engineering time.

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

Equation 4: Impact of CAT B on the EEXI formula

As we can see from the formula in order to calculate the effect of the ESDs category B we need to calculate the $P_{eff(i)}$ and $f_{eff(i)}$ with $f_{eff(i)}$ being 1 for category B1

Examples of ESDs category B on the market

5.4.1 Category B-1 Hull Air lubrication system

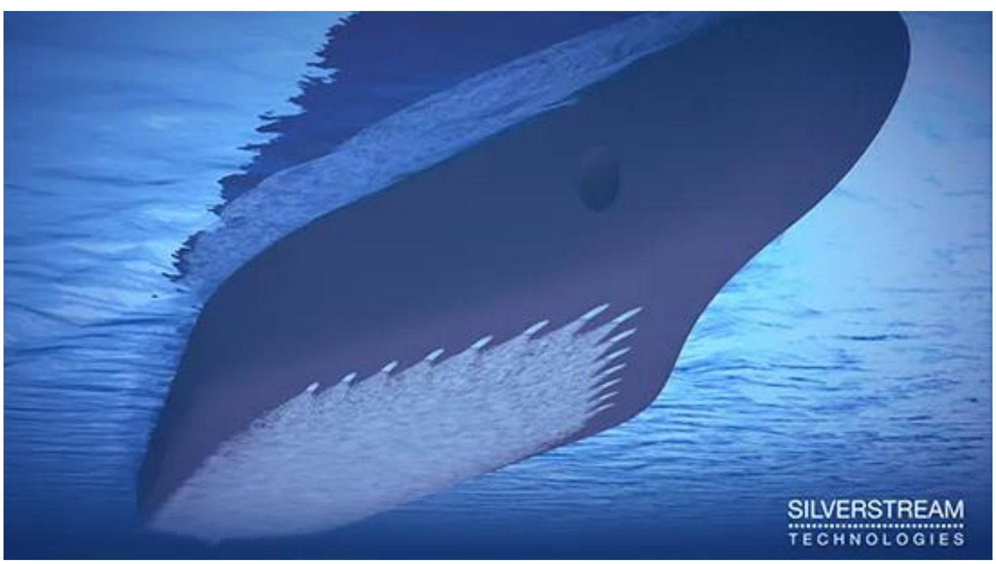


Figure 39: Hull air lubrication system

An air lubrication system is one of the innovative energy efficiency technologies. Ship frictional resistance can be reduced by covering the ship surface with air bubbles, which is injected from the fore part of the ship bottom by using blowers, etc.

This technology is applicable only to ships with a flat bottom and small draught, because its effective only when the bubble sheet is continuously maintained on the bottom of the hull.

Three distinct approaches are identified: the injection of bubbles, air films, and air cavity ships. The first technique, bubble Injection, is a direct means to reduce the friction of the ship by positive interaction with the boundary layer. When the bubbles are within 300 viscous wall units -defined as $I = \frac{v}{U_0}$ and U_0 the friction velocity of the fully wetted flow $U_0 = \sqrt{\frac{\tau}{\rho}}$ the effect of air lubrication can be measured in laboratory tests, indicating a strong dependence on the boundary layer (Sanders et al., 2006). When the bubbles are farther away from the wall, no effect Is measured. The use of air films is self-explanatory; the air film separates the water from the hull thus reducing friction. Air cavity ships are vessels that have a series of openings In the bottom where a free surface Is formed. The downside of all three techniques Is that It is surprisingly easy to increase, rather than to decrease, the resistance and that many aspects of the behavior of air In water are poorly understood. For example, the full-scale demonstrator vessel Seiun Maru showed a 2% decrease at only a limited speed range with an increase in required power over most over Its speed range, notwithstanding huge resistance decreases tested at model scale.

(Foeth, [s.d.])

Method of Calculation

Power reduction factor P_{eff} due to an air lubrication system as an innovative energy efficiency technology is calculated by the following formula. The first and second terms of the right-hand side represent the reduction of propulsion power by the air lubrication system and the additional power necessary for running the system, respectively. For this system, f_{eff} is 1.0 in EEDI formula.

$$P_{eff} = P_{PeffAL} - P_{AEeffAL} * \frac{C_{FAE}}{C_{FME}} * \frac{SFC_{AE}}{SFC_{ME}}$$

- P_{eff} is the effective power reduction in kW due to the air lubrication system at the 75 per cent of the rated installed power (MCR). In case that shaft generators are installed, P_{eff} should be calculated at the 75 per cent MCR having after deducted any installed shaft generators in accordance with paragraph 2.5 of EEXI Calculation Guidelines. P_{eff} should be calculated both in the fully loaded and the sea trial conditions.

- P_{PeffAL} is the reduction of propulsion power due to the air lubrication system in kW. P_{PeffAL} should be calculated both in the condition corresponding to the Capacity as defined in EEDI Calculation Guidelines (hereinafter referred to as "fully loaded condition") and the sea trial condition, taking the following items into account.

- Area of ships surface covered with air
- Thickness of air layer
- Reduction rate of frictional resistance due to the coverage of air layer
- change of propulsion efficiency due to the interaction with air bubbles (self-propulsion factors and propeller open water characteristics
- change of resistance due to additional device if equipped.

- $P_{AEeffAL}$ is additional auxiliary power in kW necessary for running the air lubrication system in the fully loaded condition. $P_{AEeffAL}$ should be calculated as 75 per cent of the rated output of blowers based on the manufacturer's test report. For a system where the calculated value above is significantly different from the output used at normal operation in the fully loaded condition, the $P_{AEeffAL}$ value may be estimated by an alternative method. In this case, the calculation process should be submitted to a verifier.

5.4.2 Category B-2 wind assistance

Wind propulsion systems belong to innovative mechanical energy efficient technologies which reduce the CO2 emissions of ships. There are different types of wind propulsion technologies (sails, wings, kites, etc.) which generate forces dependent on wind conditions. This technical guidance defines the available effective power of wind propulsion systems as the product of the reference speed and the sum of the wind propulsion system force and the global wind probability distribution.

These can increase propulsion by using wind thus are Dependent on the weather, so this effect is concluded on the EEXI formula with f_{eff} being less than 1.

The available effective power of wind propulsion systems as innovative energy efficient technology is calculated by the following formula:

$$(f_{eff} * P_{eff}) = (\frac{0.5144 * V_{ref}}{n_T} * \sum_{i=1}^{m}\sum_{j=1}^{n} F(V_{ref})_{i,j} * W_{i,j}) - (\sum_{i=1}^{m}\sum_{j=1}^{n} P(V_{ref})_{i,j} * W_{i,j})$$

In our analysis we are trying to assess the impact these devises will have on the operational profile of various vessels and so we are not going into detail calculation of the available effective power. On the next module we will assume the $f_{eff} * P_{eff}$ trying to investigate the impact of our assumptions on the EEXI and thus the maximum speed the ship will be able to achieve after the engine power limitation with and without the ESD.

Wind has been used to propel ships for millennia, but the vast practical benefits of modern propulsion systems have meant the progressive decline and disappearance of sails from all merchant vessels. The feasibility of returning to sails needs to be integrated with the complexity of operation imposed by this type of propulsion. However, the large fuel-saving benefits that wind power can provide should not be underestimated. Wind power seems to be reasonably easy to achieve in an effective way. Unfortunately, the technology commercially available at present is not advanced enough to achieve this aim. However, significant progress has been made during the last few years and it is reasonable to expect further improvements in the short term. In the following, the most promising technologies under development are discussed.

- **Towing kites**

The principle behind towing kites is relatively simple, although the technology necessary to deploy, control and recover the kite is rather complex. In practice, extra power is provided to propel the ship by flying a kite tethered to the vessel's bow. The kite speed through the air increases its efficiency compared to standard sails but the setup requires a computer to control the kite.

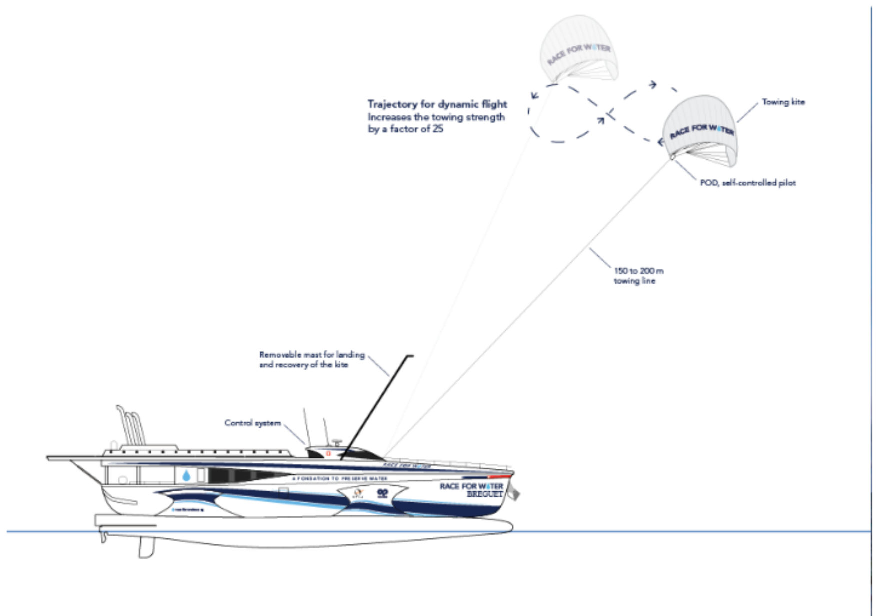


Figure 40: Towing kites

TU Delft and MARIN estimate that large fuel savings are possible using these systems for slower ships (typically bulk carriers and tankers), however the envelope of operability of kites is limited to a relatively narrow range of wind conditions (essentially quartering winds), which further limits the usefulness of these systems. In order to evaluate the actual cost-benefit of kites, it is therefore necessary to estimate their potential when deployed on specific routes where wind patterns can be predicted.

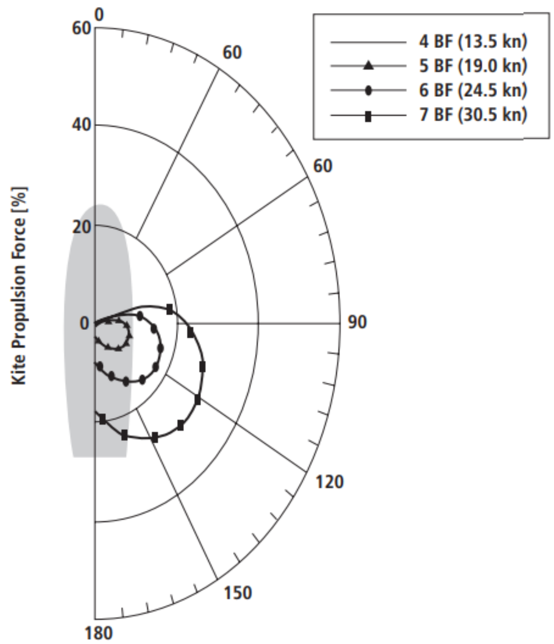


Figure 41: Relative Kite Propulsion Polar Plot (source: Ship Energy Efficiency Measures ABS study)

- Rotor Sails, Flettner Rotors and Windmills

  Flettner rotors are vertical, cylindrical sails spinning around their axis. A propulsive force is generated in the direction perpendicular to that of the wind hitting the rotor as a result of the Magnus effect.

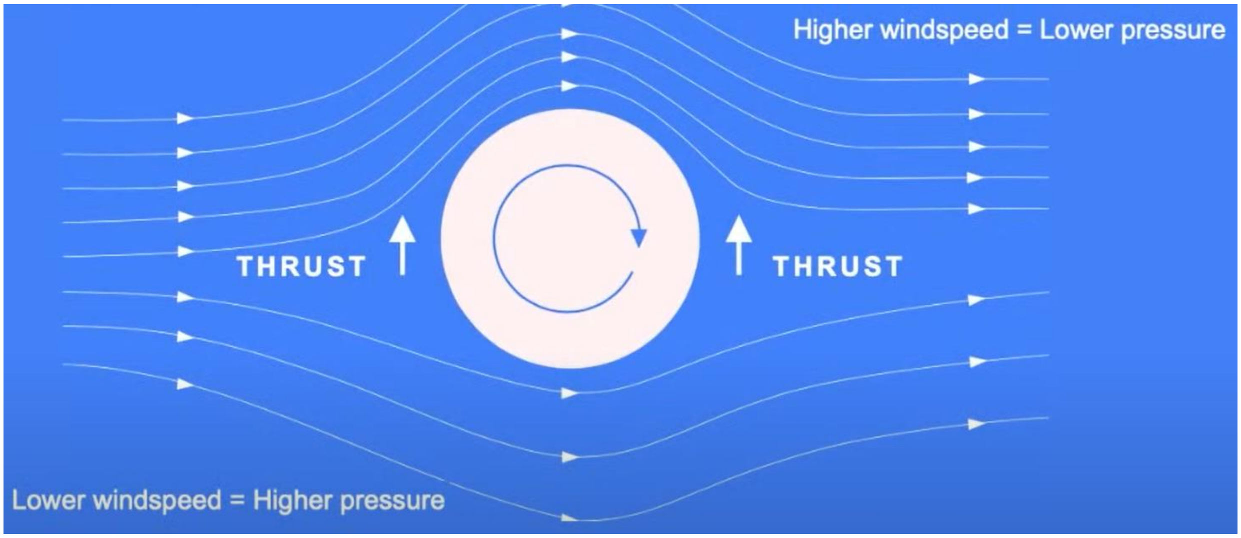


Figure 42: Magnus effect

For this reason, rotor sails offer maximum efficiency near apparent beam wind conditions, a characteristic that could make them interesting as a complement to towing kites.

Figure 43: Rotor sails

However, rotors are normally powered by a diesel engine driven motor to achieve the necessary RPM. Also, unless they are made to telescopically collapse onto the deck to minimize aerodynamic drag when they are not in use, they might increase fuel consumption for a large range of wind directions. For these reasons, it is unclear if the overall efficiency of these systems can offer them a realistic chance of commercial success.

5.5 Category (C)

Technologies that generate electricity. The saved energy is counted as P_{AEeff}

- Category (C-1): Technologies which can be used at any time during the operation and thus the availability factor (f_{eff}) should be treated as 1.00. Category

- (C-2): Technologies which can be used at their full output only under limited condition. The setting of availability factor (f_{eff}) should be less than 1.00.

ESDs in Category C are technologies that can generate additional electricity. They can reduce the EEXI almost proportionally to the power saving rate. On the downside these devices are rather expensive and require long engineering time, also few of the have a proven track record.

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

Equation 5: Impact Of CAT C on EEXI formula

As we can see from the formula in order to calculate the effect of the ESDs category C we need to calculate the $P_{AEeff(i)}$ and $f_{eff(i)}$ with $f_{eff(i)}$ being 1 for category C1

Examples of ESDs category C on the market

5.5.1 Category C-1 Waste heat recovery system.

A significant amount of heat is generated by the machinery plant on a ship. While modern diesel engines are very efficient, with greater than 50 percent of the energy generated by the combustion of fuel oil being converted to mechanical energy, they still generate a large amount of waste heat when running at full load. The heat is removed from the engine in many forms. About 5 percent of the engine's total energy production goes to the engine cooling water system and about 25 percent is contained in the exhaust gas. In both these forms the heat is useful as a heat source for other systems.

Waste heat energy technologies increase the efficiency utilization of the energy generated from fuel combustion in the engine through recovery of the thermal energy of exhaust gas, cooling water, etc., thereby generating electricity.

There are the following two methods of generating electricity by the waste heat energy technologies (electric generation type)

- Method to recover thermal energy by a heat exchanger and to drive the thermal engine which drives an electric generator.

- Method to drive directly an electric generator using power turbine, etc.

Furthermore, there is a waste heat recovery system which combines both of the above methods.

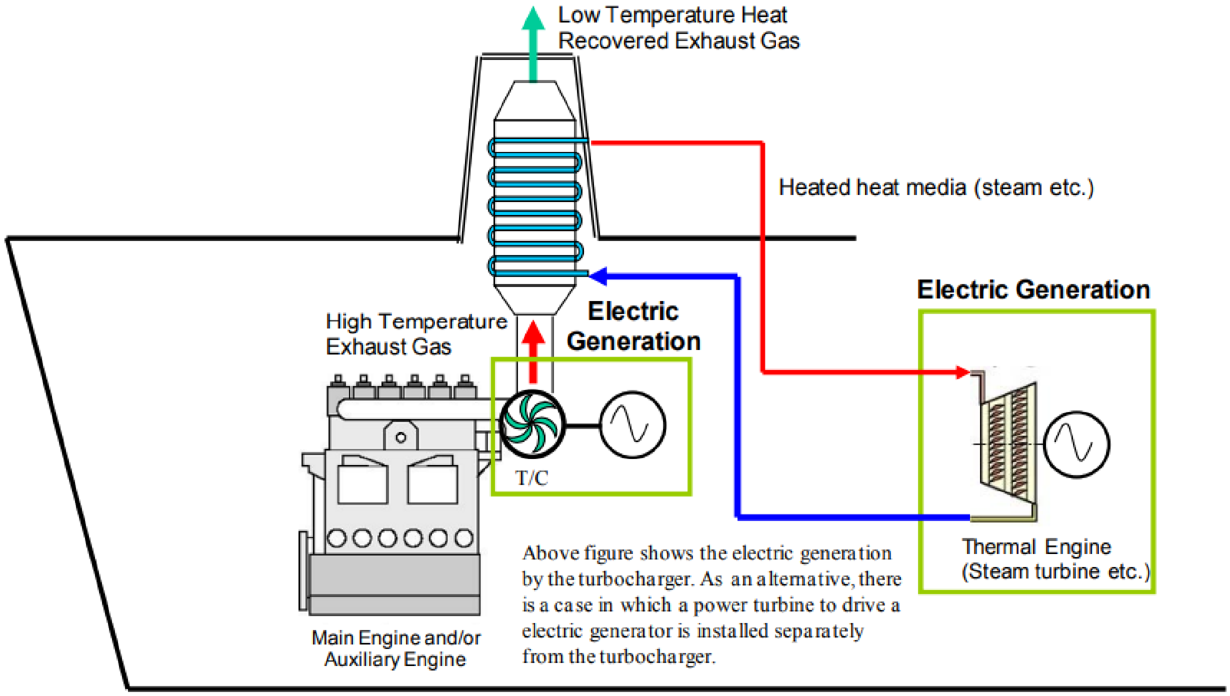


Figure 44: Schematic illustration of Exhaust Heat Recovery

Method of calculation

The reduction of power by the waste heat recovery system is calculated by the following equation. For this system, f_{eff} is 1.00 in EEXI formula.

$$P_{AEeff} = P'_{AEeff} - P_{AEeffloss}$$

In the above equation, P'_{AEeff} is power produced by the waste heat recovery system. $P_{AEeffloss}$ is the necessary power to drive the waste heat recovery system.

- P_{AEeff} is the reduction of the ship's total auxiliary power (kW) by the waste heat recovery system under the ship performance condition applied for EEXI calculation. The power generated by the system under this condition and fed into the main switch board is to be taken into account, regardless of its application on board the vessel.

- P'_{AEeff} is defined by the following equation.

$$P'_{AEeff} = \frac{W_e}{n_g}$$

Where:
W_e: Calculated production of electricity by the waste heat recovery system
n_g: Weighted average generator efficiency.

- P_{AEeff} is determined by the following factors:

    - temperature and mass flow of exhaust gas of the engines
    - constitution of the waste heat recovery system
    - efficiency and performance of the components of the waste heat recovery system.

- $P_{AEeffloss}$ is the power (kW) for the pump, etc., necessary to drive the waste heat recovery system.

As we mentioned before in our analysis, we are trying to assess the impact these devices will have on the operational profile of various vessels and so we are not going into detail calculation of the available effective power. On the next module we will assume the $f_{eff} * P_{AEeff}$ trying to investigate the impact of our assumptions on the EEXI and thus the maximum speed the ship will be able to achieve after the engine power limitation with and without the ESD.

5.5.2 Category C-2 photovoltaic cells

Photovoltaic (PV) power generation system set on a ship will provide part of the electric power either for propelling the ship or for use inboard. PV power generation system consists of PV modules and other electric equipment. Figure 1 shows a schematic diagram of PV power generation system. The PV module consists of combining solar cells and there are some types of solar cell such as "Crystalline silicon terrestrial photovoltaic" and "Thin-film terrestrial photovoltaic".

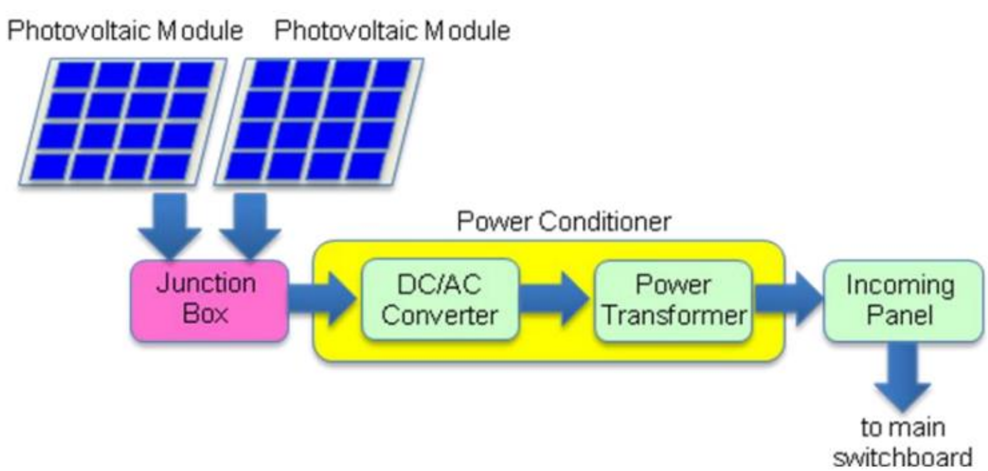


Figure 45: Photovoltaic power generation system

There have been attempts to use PV panels to power small craft, such as the 30-m long catamaran Planet Solar, designed to circumnavigate the world on a 500 m2 array. However, because of the low electrical output per unit surface, PV solar panels are better suited as an additional source of auxiliary power. In this role they have already been utilized on commercial vessels such as the NYK car carrier Auriga Leader, equipped with 328 solar panels.

Method of calculation

The auxiliary power reduction due to the PV power generation system can be calculated as follows:

$$(f_{eff} \ * P_{AEeff}) = (f_{rad} * \left(1 + \frac{L_{temp}}{100}\right) * (P_{max} * \left(1 - \frac{L_{others}}{100}\right) * \frac{N}{n_{GEN}})$$

$(f_{eff} \ * P_{AEeff}$ is the total net electric power (kW) generated by the PV power generation system. In the next module instead of trying to calculate it we assume it in order to assess the impact on the EEXI.

Effective coefficient f_{eff} is the ratio of average PV power generation in main global shipping routes to the nominal PV power generation specified by the manufacturer. Effective coefficient can be calculated by the following formula using the solar irradiance and air temperature of main global shipping routes:

$$f_{eff} = f_{rad} * (1 + \frac{L_{temp}}{100})$$

f_{rad} is the ratio of the average solar irradiance on the main global shipping route to the nominal solar irradiance specified by the manufacturer. Nominal maximum generating power P_{max} is measured under the Standard Test Condition (STC) of IEC standard. STC specified by manufacturer is that: Air Mass (AM) 1.5, the module's temperature is 25°C, and the solar irradiance is 1000 $\frac{W}{m^2}$. The average solar irradiance on main global shipping route is 200 $\frac{W}{m^2}$. Therefore, frad is calculated by the following formula:

$$f_{rad} = \frac{200\frac{W}{m^2}}{1000 * \ W/m^2} = 0.2$$

L_{temp} is the correction factor, which is usually in minus, and derived from the temperature of PV modules, and the value is expressed in percentage.

$L_{temp} = f_{temp} *$ (40°C -25°C)

P_{AEeff} is the generated PV power divided by the weighted average efficiency of the generator(s) under the condition specified by the manufacturer and expressed as follows:

$$P_{AEeff} = P_{max} * \left(1 - \frac{L_{others}}{100}\right) * \frac{N}{n_{GEN}}$$

Where n_{GEN} is the weighted average efficiency of the generator(s)

P_{max} is the nominal maximum generated PV power generation of a module expressed in kilowatt, specified based on IEC Standards.

N is the number of modules used in a PV power generation system.

L_{others} is the summation of other losses expressed by percent and includes the losses in a power conditioner, at contact, by electrical resistance, etc. Based on experiences, it is estimated that L_{others} is 10 per cent (the loss in the power conditioner: 5 per cent and the sum of other losses: 5%). However, for the loss in the power conditioner, it is practical to apply the value specified based on IEC Standards

As we mentioned before in our analysis, we are trying to assess the impact these devices will have on the operational profile of various vessels and so we are not going into detail calculation of the available effective power. On the next module we will assume the $f_{eff} * P_{AEeff}$ trying to investigate the impact of our assumptions on the EEXI and thus the maximum speed the ship will be able to achieve after the engine power limitation with and without the ESD.

6 Cases studies for the evaluation of the effect of ESDs on both EPL and Speed.

6.1 Description of software.

The name of the software is Ship-EEXI/CII. IMO Energy Efficiency Existing Ship Index (EEXI) and CII (Carbon Intensity) automated calculation and reporting software with enhanced SEEMP planning and implementation modules.

This metaverse platform is integrated with the ships lifecycle energy efficiency software offering automated studies/forecasting for IMO's Ship Energy Efficiency (EEXI) and Carbon Intensity (CII) standards and class reporting as required for all large commercial ships from January 2023.

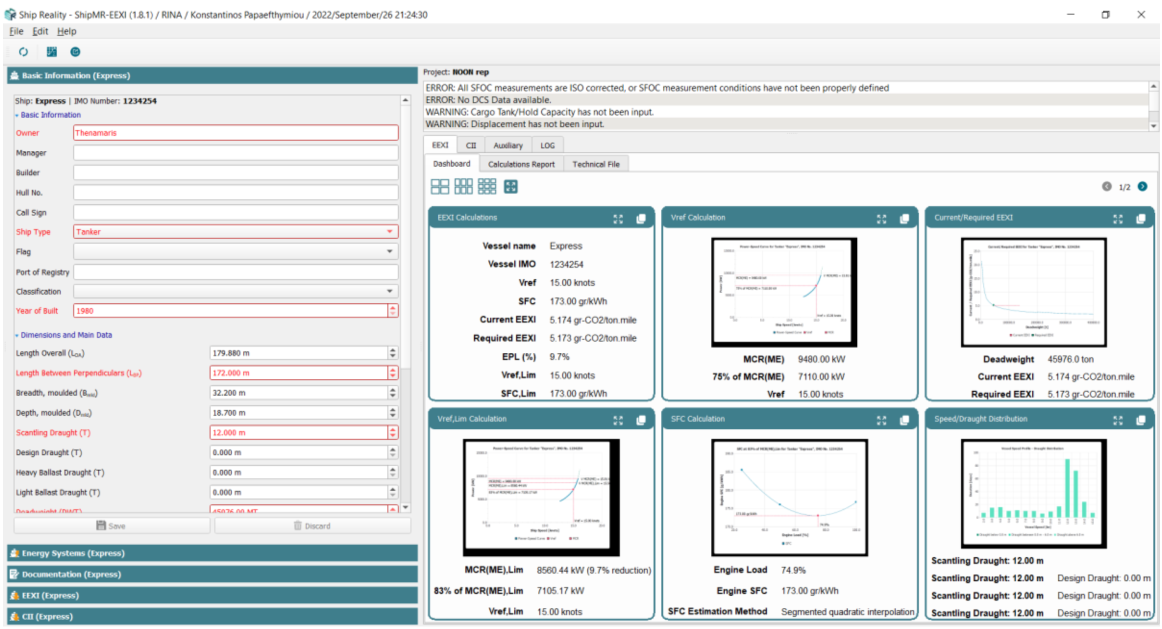


Figure 46: interface of software.

6.2 Data used and data entry.

For each vessel the parameters that are introduced in section 3.3 (main parameters) will be used with some additions for our analysis to be feasible.

The first data we need to input for each vessel are the main characteristics in the section bar, "basic information". These parameters include, but are not limited to, the basic dimensions (Length Between Perpendiculars, Breadth, Depth, main deck, Summer Load Draught, Deadweight at Summer (Scantling) Draught, Gross Tonnage, volume of displacement, light ship, cargo (tank/hold) capacity, and some ship notations such as CSR ship or iced class vessels.

This data is to be taken from the Capacity plan or Trim and stability booklet.

After the main dimensions are inputted, we proceed to the next section bar "energy systems". There we input the main engine characteristics first. It's vital for the calculations to correctly input the engine type, Power at MCR but also the fuel data. For the fuel of the ME, we need its type cause with this we find the conversion factor C_{O2} but also the SFOC at 25%, 50%, 75% and 100% for our interpolation to be correct. For this data we look on the NOx technical files of the ME and we are looking for the shop tests.

Next, we input the same data for the auxiliary engines with the exact same way from the AE NOx technical files.

One of the most important data we need to input for our analysis is the Speed-Power curves of the vessel. The sea trials or model tests for design and/or ballast conditions are vital in order to proceed. The input of the curves is possible with an external image digitizer application. The procedure starts with the images of the Speed power curves from the sea trials or model test files and by calibrating the axis we marked the points on top of the image. The application then outputs the points (speed,Power). Continuing the process the points are copied onto an excel file only to be inputted in the software as points.

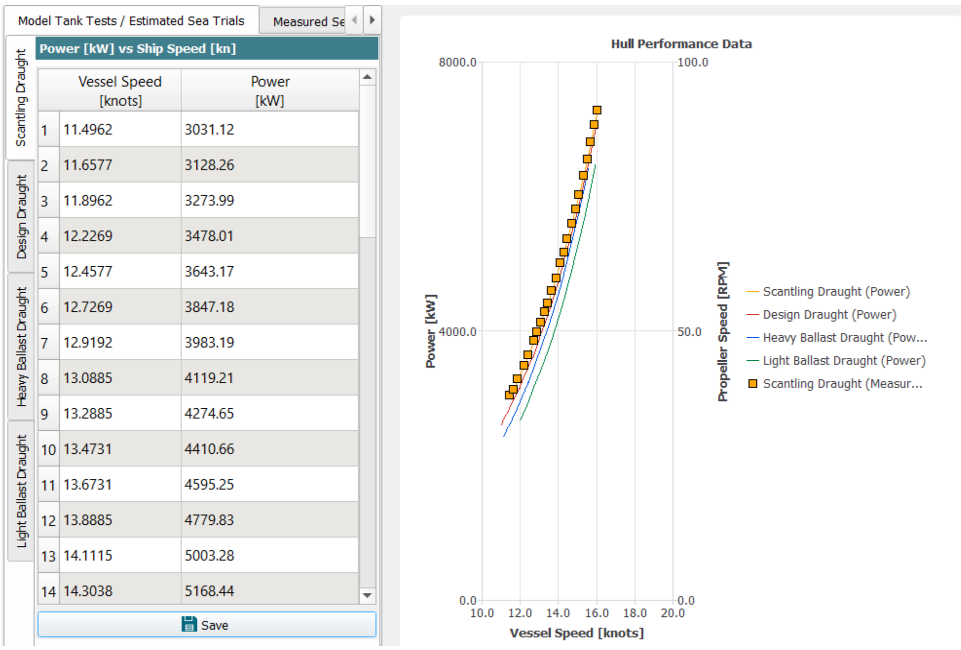
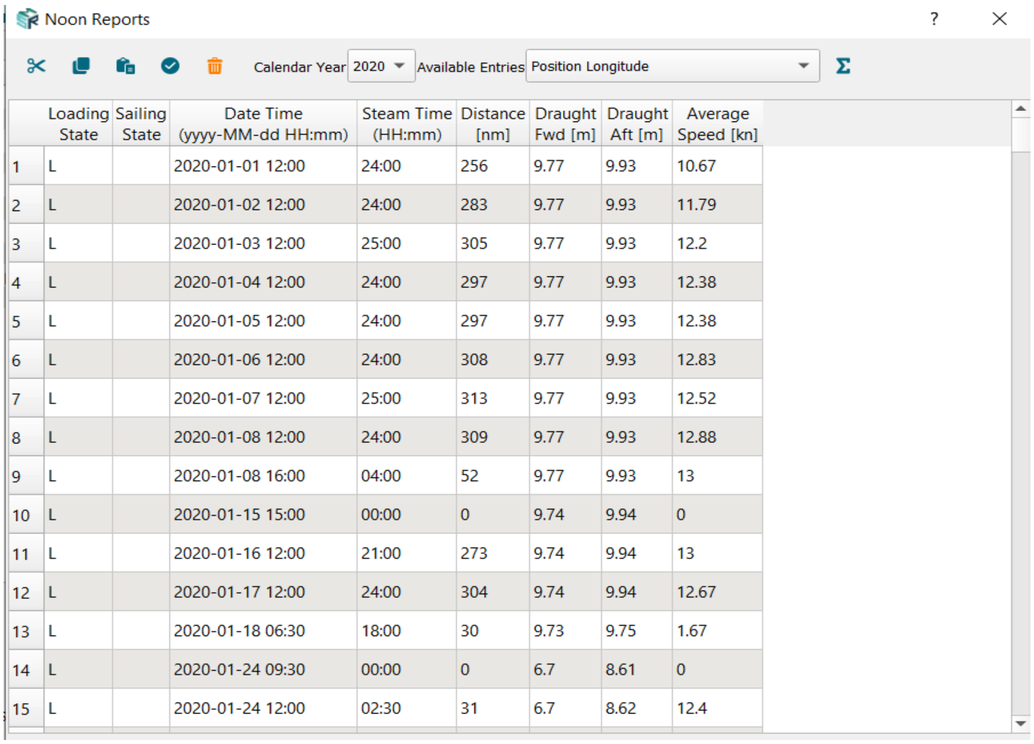


Figure 47: How to insert a Speed-Power curve.

The last data entry we are obligated to input in order to continue are the NOON Reports. As previously mentioned for every vessel examined, we have created an Excel file. For the input from the NOON report sheet, we need the loading state in order to identify the speed power curve we are comparing, the date time, the steam time, the distance traveled, the draught and the average speed.



	Loading State	Sailing State	Date Time (yyyy-MM-dd HH:mm)	Steam Time (HH:mm)	Distance [nm]	Draught Fwd [m]	Draught Aft [m]	Average Speed [kn]
1	L		2020-01-01 12:00	24:00	256	9.77	9.93	10.67
2	L		2020-01-02 12:00	24:00	283	9.77	9.93	11.79
3	L		2020-01-03 12:00	25:00	305	9.77	9.93	12.2
4	L		2020-01-04 12:00	24:00	297	9.77	9.93	12.38
5	L		2020-01-05 12:00	24:00	297	9.77	9.93	12.38
6	L		2020-01-06 12:00	24:00	308	9.77	9.93	12.83
7	L		2020-01-07 12:00	25:00	313	9.77	9.93	12.52
8	L		2020-01-08 12:00	24:00	309	9.77	9.93	12.88
9	L		2020-01-08 16:00	04:00	52	9.77	9.93	13
10	L		2020-01-15 15:00	00:00	0	9.74	9.94	0
11	L		2020-01-16 12:00	21:00	273	9.74	9.94	13
12	L		2020-01-17 12:00	24:00	304	9.74	9.94	12.67
13	L		2020-01-18 06:30	18:00	30	9.73	9.75	1.67
14	L		2020-01-24 09:30	00:00	0	6.7	8.61	0
15	L		2020-01-24 12:00	02:30	31	6.7	8.62	12.4

Figure 48: Insert NOON reports on the software.

For the draughts we use the trim and stability booklet and specifically the hydrostatic tables to interpolate the draught from the given DWT.

6.3 Introduction on the calculations for the following case studies

For these various case studies, we are going to follow the same procedure of calculations but the results for each ship may differ.

Vessel case study	Type	Year of built	DWT	MCR
case study 1	Bulk carrier	2006	32859.6 [ton]	6480.00 [kW]
case study 2	Bulk carrier	2008	82612.0 [ton]	9800.00 [kW]
case study 3	Tanker	2007	53714.0 [ton]	10620.60 [kW]
case study 4	Tanker	2009	45976.0 [ton]	9480.0 [kW]
case study 5	Bulk carrier	2019	82031.1 [ton]	9801.00 [kW]

Table 30: Vessels used for the case studies.

The scope is stated above and it's the assessment of the energy efficiency technologies on the operational profile of a vessel when combined with EPL.

First for each vessel we are presenting the basic data for the calculations of not only the EEXI but also for the EPL.

The software runs an iterative procedure to the formula of EEXI with 3 parameters connected to each other until the result of EEXI is equal or lower to this of the required value. These parameters are Pme, Vref and SFOCme. The software identifies the solution to the problem based on an initial guess of Pme, then from the speed power curves on EEDI conditions we have the Vref for this specific Pme. Using now quadratic interpolation with the Pme guessed before we can find the SFOCme. (the quadratic interpolation is based on a curve of SFOCs with 4 points on 25% , 50% ,75% and 100% of engine load). An example can be seen in the following figure.

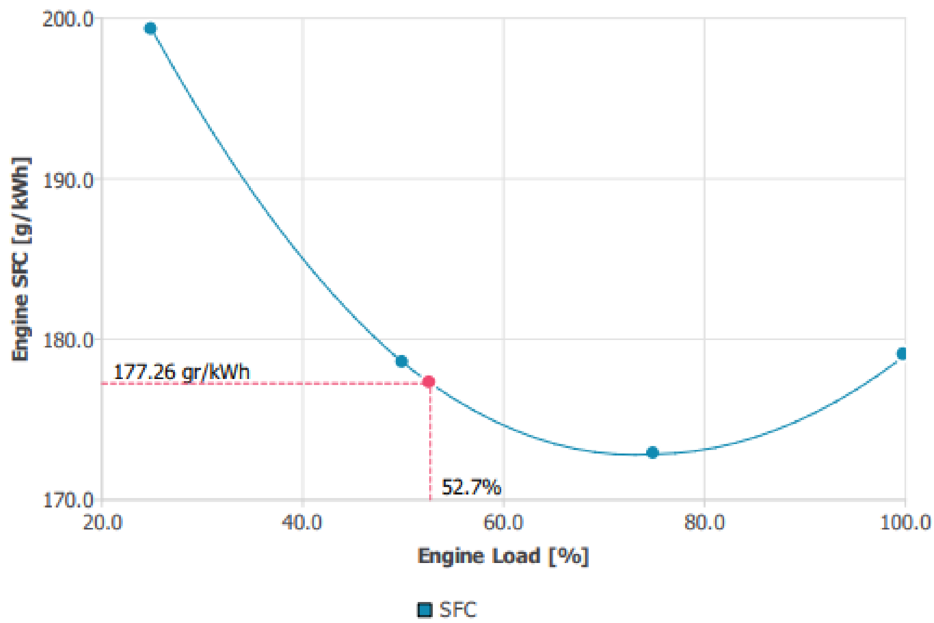


Figure 49: SFC at 83%of MCR(ME),Lim for Bulk carrier : Ship 1

With the help of NOON reports and the speed power curves of the vessel for every loading condition we can find if the ship after EPL can reach the speeds operated before the regulations and the derating of the engine.

The software simply finds the maximum speed on every speed-power curve based on the maximum power of the derated engine. having the loading state of every NOON report and so the appropriate speed-power curve we just compare the 2 speeds (the maximum on this loading state and the one on the NOON report), if the one on the NOON report is bigger than this particular sailing state is now unreachable.

Extending we explore the hypothetical cases of these vessels having ESDs combined with a lower EPL and examine again the impact (of the EPL) on the operational profile. The procedure is the same as before with the only difference that now having smaller EPL we achieve higher speeds for every loading state and thus fewer sailing states are unreachable if any.

First, we showcase some balance points between the EPL and Power savings from ESDs category B or C. After we display the relation between EPL and EDS category B and C on graphs and tables, then for one of those points we investigate in depth the various speeds in relation with their draught and at last, we demonstrate all of these balance points (EPL-ESDs) on tables with their percentages of achievable now speeds.

For these purposes after we calculate the Engine power limitation needed in order to have an Attained EEXI equal or lower than the Required we lower it every time approximate by 14.2% (1/7 that means we have 7 points of calculations) all the way to 0% of EPL. From the formula of the EEXI we can calculate the KW of category B or C ESD needed for these points (so the formula has a result of EEXI equal or lower that of the Required). With this we can find the relation between kW of EDSs and the change on the maximum speed of the vessel.

For the last step the software having already the Speed-power curves of the vessel on EEDI conditions calculates the new maximum speed for the new EPL. Then we examine once again the speed profile of the vessel.

The software gives us some very interesting graphs about the feasibility of different speeds after the combination of various EPL and ESDs.

Following we have 4 case studies.

The sample size is limited, but the selection aimed at investigating specific aspects.

6.4 Bulk carriers

6.4.1 Case study 1

Vessel Characteristics

Vessel Type	Bulk Carrier
Year of built	2006
Length Between Perpendiculars	168.01 [m]
Breadth	28.20 [m]
Depth, main deck	14.20 [m]
Summer Load Draught	10.20 [m]
Deadweight at Summer (Scantling) Draught	32859.6 [ton]
Gross Tonnage	19943
Lightship Weight	8253.8 [ton]
Tank/Hold Capacity	42211.7 [m3]

Main Engine Characteristics

Maximum Continuous Rating	6480.00 [kW]
Rotational Speed at MCR	136.0 [RPM]
Specific Fuel Consumption at 75% (SFC)	172.84 [g/kWh]
CO2 Conversion Factor	3.206 [t/t]
Number of Sets	1

Auxiliary Engine Characteristics

Maximum Continuous Rating	550.00 [kW]
Rotational Speed at MCR	900.0 [RPM]
Specific Fuel Consumption at 50% (SFC)	212.00 [g/kWh]

CO2 Conversion Factor	3.206 [t/t]
Number of Sets	3

Calculation of Current EEXI

ΣP(ME) at 75% MCR	4860.00 [kW]
Capacity	32859.6 [ton]
fj	1
fi	1.006
fc	1
fl	1
fw	1
fm	1
Vref	13.97 [knots]
Attained EEXI	6.308 g-CO2/ton.mile

Required EEXI

Ship Type	Bulk Carrier
a	961.79
b	32859.6
c	0.477
EEDI Reference line value	6.740 (g-CO2/ton.mile)
Deadweight	32859.6
Reduction Factor	20
Required EEXI	5.392 g-CO2/ton.mile.

Vessel 1 does not meet the requirements of the EEXI Regulations.

A reduction to EEXI of 6.308 - 5.392 = 0.916 g-CO2/ton.mile is further required.

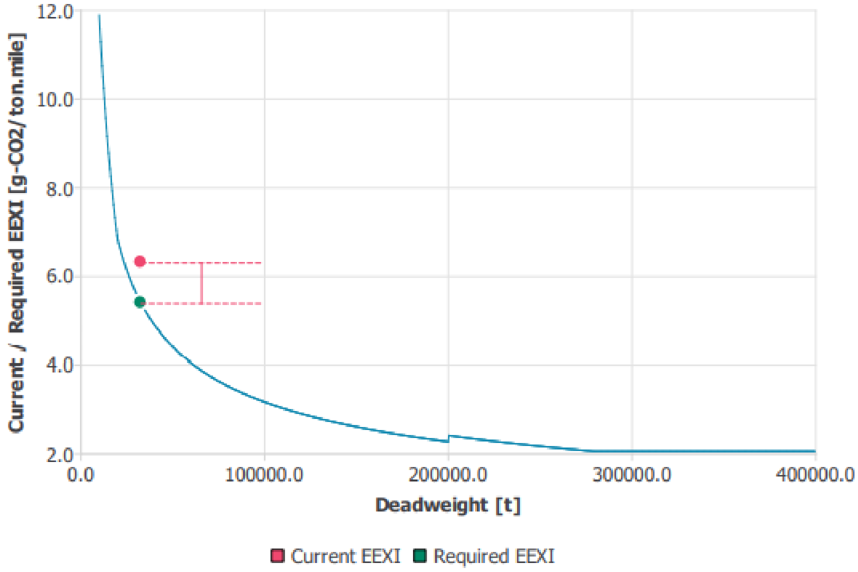


Figure 50: distance of Attained EEXI relative to the Req curve.

Engine Power Limitation Calculations

MCR(ME)	6480 [kW]
MCR(ME),Lim	4114.80 [kW]
ΣP(ME)	3415.28 [kW]
SFC(ME)	177.26 [g/kWh]
Power Reduction	36.5 [%]
Actual attained EEXI	5.39 [g-CO2/ton*mile]

As we can see the vessel need a 36.5% power reduction in order to achieve the required by the regulations index.

Speed Reduction.

Speed Vref	13.97 [knots]
Speed Vref,Lim	12.13 [knots]
Speed Reduction	13.20 [%]
Actual attained EEXI	5.39 [g-CO2/ton.mile]

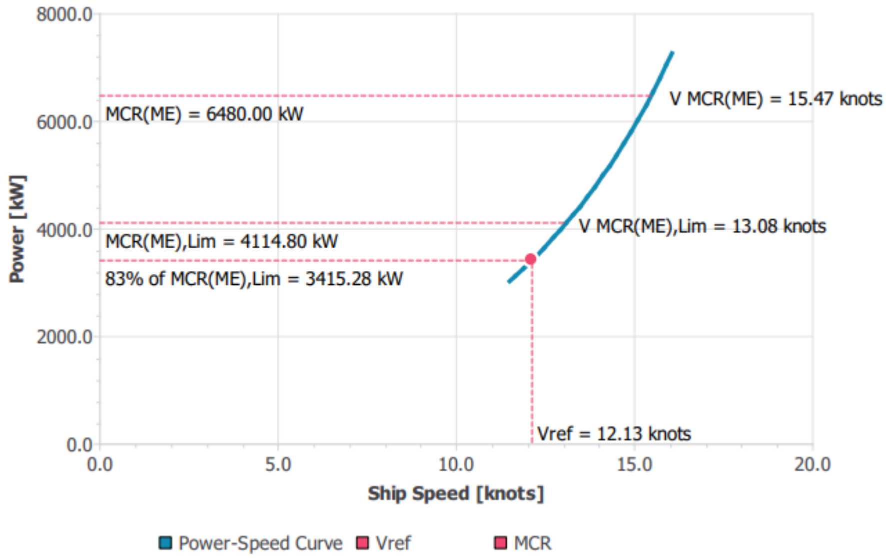


Figure 51: Power-Speed curve of vessel 1 at scantling draught

And we have a 13.2% speed reduction.

Having the noon reports of the vessel we can examine its operational profile.

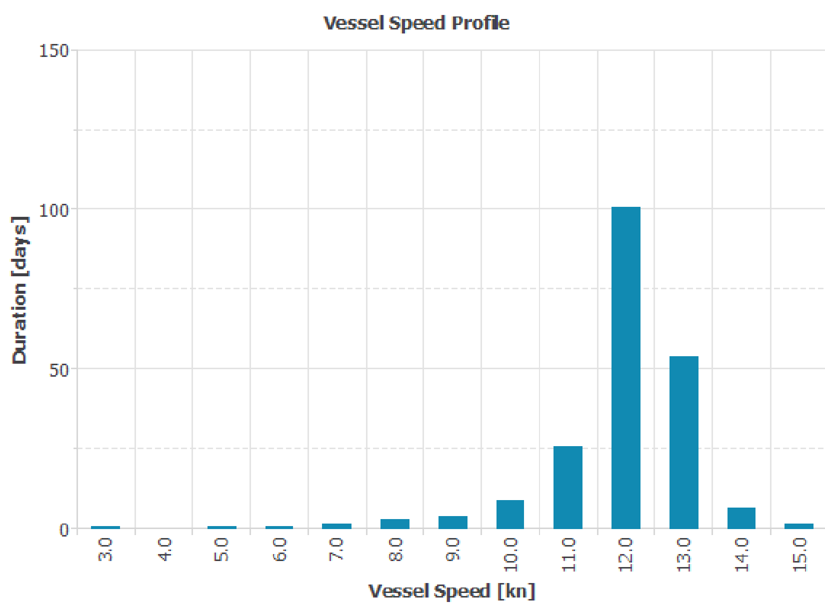


Figure 52: Speed profile of Vessel 1

Although we can see that after the EPL some of these speeds are not feasible any more.

On the graph below we see various speeds and their duration as per NOON reports. With red we see the speeds that are not feasible at all with yellow the speeds that are feasible, but the power margin is between 0-5%, with green speeds are feasible with power margin of 5-15% and with blue the power margin is more than 15%.

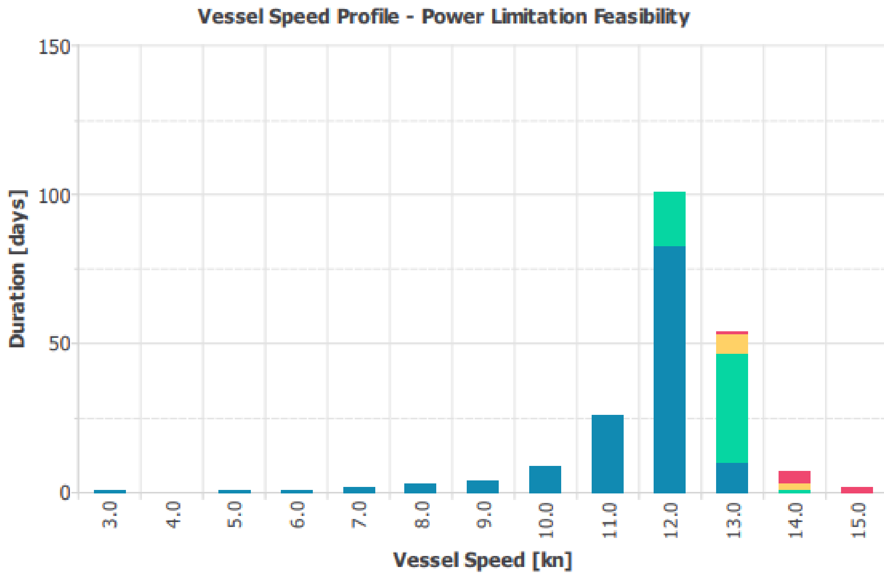


Figure 53:Speed profile of Vessel 1 after Mechanical EPL.

Its easy to see that for some specific draughts some speeds are no longer feasible after the de rating of the engine based on the speed power curves, we have on the various loading conditions.

Examining now only the high speeds per draught we can see on the next table with red the speed that are not feasible at all, with yellow the speeds that are feasible but the power margin is between 0-5% , with green speeds are feasible with power margin of 5-15% and with blue the power margin is more than 15%.

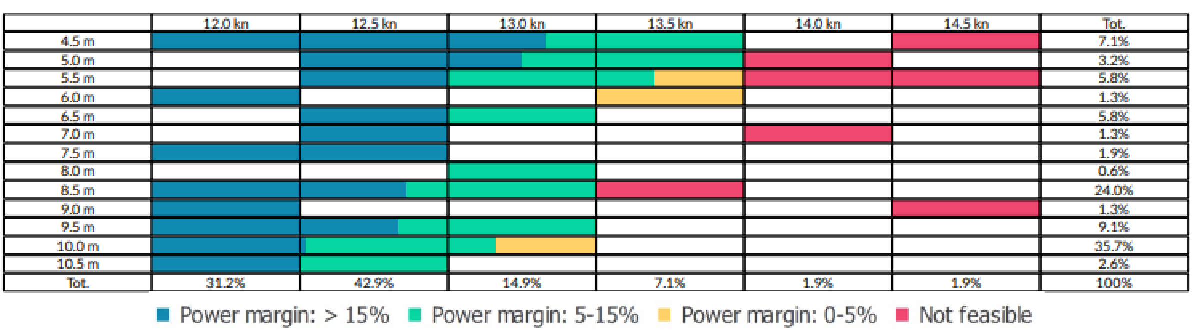


Figure 54: Vessel Performance (after EPL) per Draught at high vessel Speeds

Specifically We can see on the table below which speeds are not acceptable and their percentages on the overall operational profile of the vessel.

report data.

Speed [knots]	Not Feasible	0-5%	5-15%	>15%	Summary
3.0	-	-	-	0.5%	0.5% (1)
4.0	-	-	-	-	0.0% (0)
5.0	-	-	-	0.5%	0.5% (1)
6.0	-	-	-	0.5%	0.5% (1)
7.0	-	-	-	0.9%	0.9% (2)
8.0	-	-	-	1.4%	1.4% (3)
9.0	-	-	-	1.9%	1.9% (4)
10.0	-	-	-	4.3%	4.3% (9)
11.0	-	-	-	12.3%	12.3% (26)
12.0	-	-	8.5%	39.3%	47.9% (101)
13.0	0.5%	2.8%	17.5%	4.7%	25.6% (54)
14.0	1.9%	0.9%	0.5%	-	3.3% (7)
15.0	0.9%	-	-	-	0.9% (2)
Summary	3.3% (7)	3.8% (8)	26.5% (56)	66.4% (140)	100.0% (211)

Table 31:Vessel performance estimation (after Mechanical EPL installation) based on existing noon report.

Statistics Summary

On the Table we can see that from a total number of valid records (211) from the NOON reports

The Total number of Not Feasible Records: 7 (3.3%)

Total number of Records with Power Margin in the range 0-5%: 8 (3.8%)

Total number of Records with Power Margin in the range 5-15%: 56 (26.5%)

Total number of Records with Power Margin above 15%: 140 (66.4%)

Recapping we can see that after the engine power limitation of the engine the ship cannot longer proceed with the same operational profile.

As we mentioned before, in our analysis, we are trying to assess the impact energy efficiency devises will have on the operational profile of various vessels and so we are not going into detail calculation of the available effective power. Now we will assume the $f_{eff} * P_{eff}$ trying to investigate the impact of our assumptions on the EEXI and thus the maximum speed the ship will be able to achieve after the engine power limitation with an ESD for the categories B and C .

For these calculations as we mentioned before we go backwards. This is easy for categories B and C because their impact is calculated in the EEXI formula.

For the specific ship we can see the relation of EPL and the power savings ($f_{eff} * P_{eff}$) of a category B ESD in kW.

For Category B EET, the table below provides the net propulsion power savings $(f_{eff} * P_{eff})$ combined with appropriate Mechanical EPL, in order to satisfy the EEXI requirement. Every row in this table is a point of balance in which the Attained EEXI is lower than the Required. For instance in this particular vessel, we can have an EPL of 31.1% if we add to it an ESD category B that the $f_{eff} * P_{eff}$ is

122.98 kW. For B-1 category that f_{eff} Is 1 that means that P_{eff} is 122.98 kW, for category B -2 that $f_{eff} <$ 1 that means that P_{eff} must be higher than 122.98.

Net propulsion power savings (Cat. B) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Propulsion Power Savings
[%]	[kW]
0.0	763.21
9.7	759.71
15.1	579.36
20.4	410.45
25.8	259.40
31.1	122.98
36.5	0.00

Table 32:Effect of Category B ESD adoption on required Mechanical Engine Power Limitation.

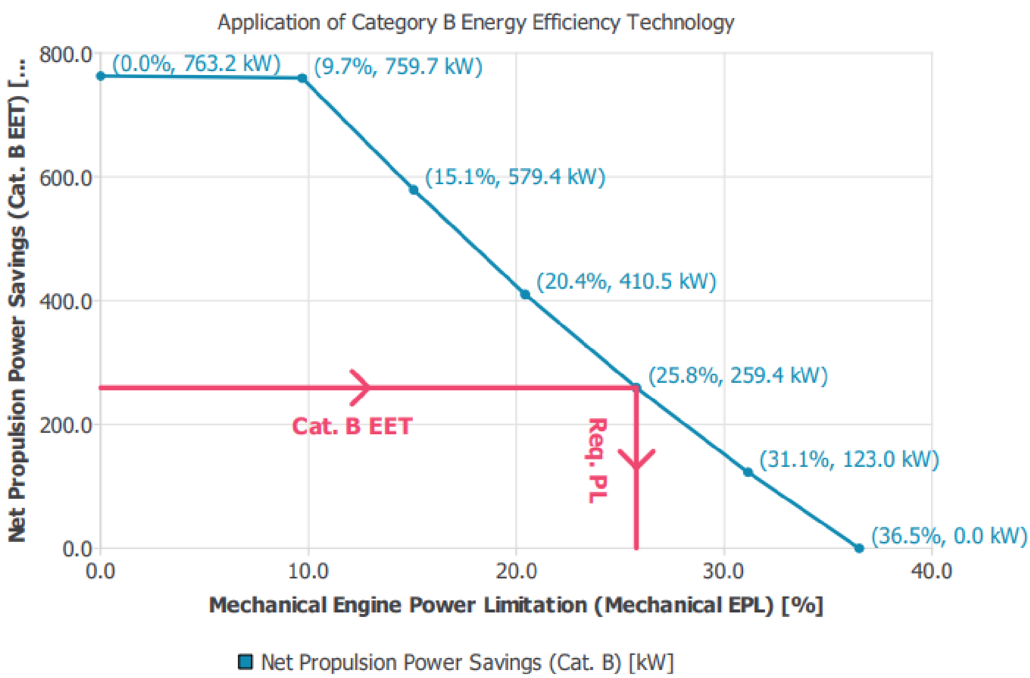


Figure 55:Effect of Category B ESD adoption on required Mechanical Engine Power Limitation.

For example, if no EET is installed, the required Mechanical Engine Power Limitation to meet the EEXI regulation will be 36.5%, and the maximum speed of the vessel at scantling draught conditions will be 13.08 knots. On the other hand, if Category B EET is installed, offering propulsion power savings of 259.40 kW, the required Mechanical Engine Power Limitation will be 25.8%

For Category C EET, the table below provides the net auxiliary power savings ($f_{eff} * P_{AEeff}$), combined with appropriate Mechanical EPL, in order to satisfy the EEXI requirement.

Net auxilliary power savings (Cat. C) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Aux. Power Savings
[%]	[kW]
0.0	622.24
9.7	619.37
15.1	472.42
20.4	335.58
25.8	213.16
31.1	101.82
36.5	0.00

Table 33:Effect of Category C ESD adoption on required Mechanical Engine Power Limitation.

Every row in this table is a point of balance in which the Attained EEXI is lower than the Required. For instance, in this particular vessel, we can have an EPL of 31.1% if we add to it an ESD category C that the $f_{eff} * P_{eff}$ is 101.82 kW. For C-1 category that f_{eff} Is 1 that means that P_{eff} is 101.82 kW, for category C -2 that $f_{eff} < 1$ that means that P_{eff} must be higher than 101.82.

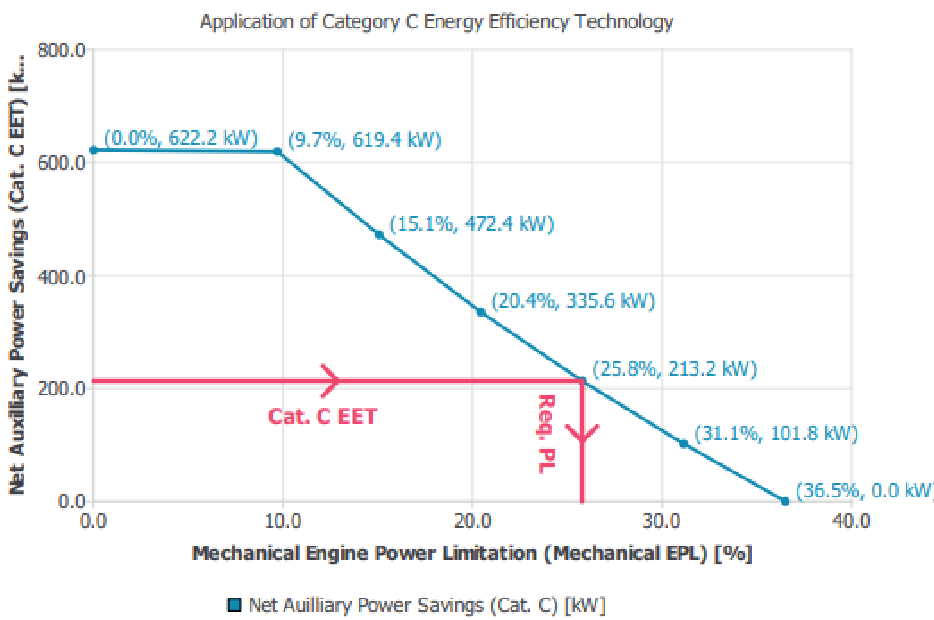


Figure 56: Effect of Category C ESDs adoption on required Mechanical Engine Power Limitation.

For example, if no EET is installed, the required Mechanical Engine Power Limitation to meet the EEXI regulation will be 36.5%. On the other hand, if Category C EET is installed, offering propulsion power savings of 213.16 kW, the required Mechanical EPL of the Main Engine(s) will be 25.8%.

Scenario: Feasibility study for speed schedule with 25.8% EPL in combination with ESD

In order to achieve the same EPL of 25.8 % with the category B we needed propulsion power savings of 259.40 kW and with category C propulsion power savings of 213.16 kW. The main reason for this is that the power savings ($f_{eff} * P_{eff}$) are multiplied with the conversion factor and the specific oil consumption and the latter is always higher on the auxiliary engines.

Now for the same operational profile with Category B or C EET installed in combination with an EPL of 25.8%. We can see that now 96.7% of the total number of records from the NOON reports are now feasible.

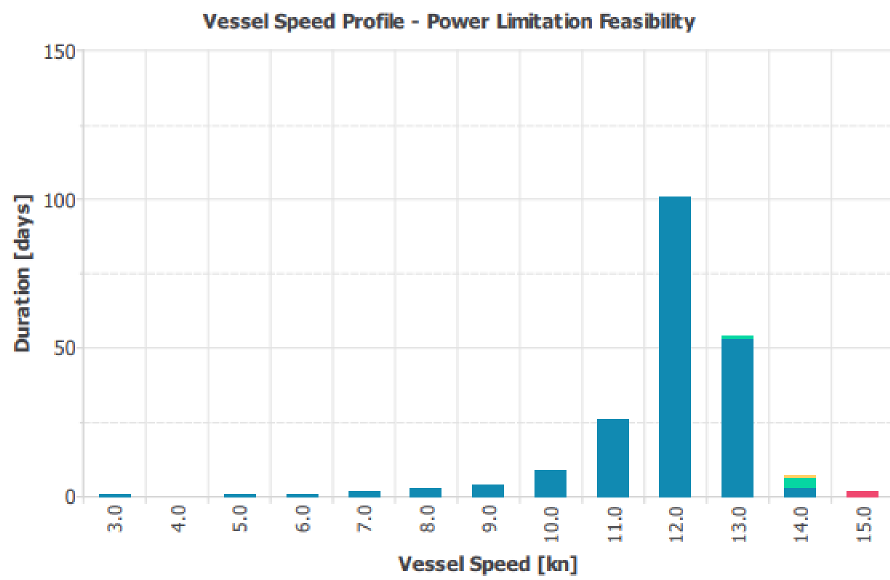


Figure 57:Speed profile of Vessel 1 after Mechanical EPL in combination with ESDs (SCENARIO)

	12.0 kn	12.5 kn	13.0 kn	13.5 kn	14.0 kn	14.5 kn	Tot.
4.5 m							7.1%
5.0 m							3.2%
5.5 m							5.8%
6.0 m							1.3%
6.5 m							5.8%
7.0 m							1.3%
7.5 m							1.9%
8.0 m							0.6%
8.5 m							24.0%
9.0 m							1.3%
9.5 m							9.1%
10.0 m							35.7%
10.5 m							2.6%
Tot.	31.2%	42.9%	14.9%	7.1%	1.9%	1.9%	100%

Table 34:Vessel Performance (SCENARIO) per Draught at high vessel Speeds

Speed [knots]	Not Feasible	0-5%	5-15%	>15%	Summary
3.0	-	-	-	0.5%	0.5% (1)
4.0	-	-	-	-	0.0% (0)
5.0	-	-	-	0.5%	0.5% (1)
6.0	-	-	-	0.5%	0.5% (1)
7.0	-	-	-	0.9%	0.9% (2)
8.0	-	-	-	1.4%	1.4% (3)
9.0	-	-	-	1.9%	1.9% (4)
10.0	-	-	-	4.3%	4.3% (9)
11.0	-	-	-	12.3%	12.3% (26)
12.0	-	-	-	47.9%	47.9% (101)
13.0	-	-	0.5%	25.1%	25.6% (54)
14.0	-	0.5%	1.4%	1.4%	3.3% (7)
15.0	0.9%	-	-	-	0.9% (2)
Summary	0.9% (2)	0.5% (1)	1.9% (4)	96.7% (204)	100.0% (211)

Table 35:Vessel performance estimation (SCENARIO) based on existing noon report

Total number of Valid Records: 211

Total number of Not Feasible Records: 2 (0.9%)

Total number of Records with Power Margin in the range 0-5%: 1 (0.5%)

Total number of Records with Power Margin in the range 5-15%: 4 (1.9%)

Total number of Records with Power Margin above 15%: 204 (96.7%)

Summing up in the next table we can see which speeds are feasible for some different combinations of EPL and ESDs. We need to keep in mind that for every row in the table we use either ESD of category B or Category C and the EPL. For instance, in order to have EPL of 31.1 % we need to install a category B ESD of 122.98 kW or a category C of 101.82 kW and we will be able to achieve 87.7 % of the records from the NOON reports.

All scenarios presented

Combination of EET and EPL			Feasible Speeds			
EPL [%]	Cat B [kW]	Cat C [kW]	Not Feasible	Margin 0-5%	Margin 5-15%	Margin > 15%
0	763.21	622.24	0.0% (0)	0.0% (0)	0.0% (0)	100% (211)
9.7	759.71	619.37	0.0% (0)	0.0% (0)	0,5% (1)	99.5% (210)
15.1	579.36	472.42	0.0% (0)	0.5% (1)	0,5% (1)	99.1% (209)
20.4	410.45	335.58	0.5% (1)	0.5% (1)	1.4% (3)	97.6% (206)
25.8	259.4	213.16	0.9% (2)	0.5% (1)	1.9% (4)	96.7% (204)
31.1	122.98	101.82	1.9% (4)	0.5% (1)	10.0% (21)	87.7% (185)
36.5	0	0	3.3% (7)	3.8% (8)	26.5% (56)	66.4% (140)

Table 36: All scenarios of combinations (EPL & B or C cat of ESDs) and their performance

On the table above we have concluded combinations that are not achievable like the point with 0% EPL with 622.24 kW of Category C ESD, but we take as results that in the neighborhood of compliance very small power savings produce great results. In this instance going from almost 10% EPL we came to 0% with the addition of almost 4 kW of power from an ESD. This effect is more easily seen in table 37.

Combination of EPL and ESDs (B or C)			Vmax MCR(ME),Lim [kn]	
EPL [%]	Cat B [kW]	Cat C [kW]	Scantling Draught	Design Draught
0	763.21	622.24	15.47	15.57
9.7	759.71	619.37	14.94	15.05
15.1	579.36	472.42	14.61	14.74
20.4	410.45	335.58	14.28	14.4
25.8	259.4	213.16	13.92	14.07
31.1	122.98	101.82	13.52	13.7
36.5	0	0	13.08	13.3

Table 37:All scenarios of combinations (EPL & B or C cat of ESDs) and their maximum speed

6.4.2 Case study 2

Vessel Characteristics

Vessel Type	Bulk Carrier
Year of built	2008
Length Between Perpendiculars	222.00 [m]
Breadth	32.26 [m]
Depth, main deck	20.03 [m]
Summer Load Draught	14.4 [m]
Deadweight at Summer (Scantling) Draught	82612.0 [ton]
Gross Tonnage	43158
Lightship Weight	11168.0 [ton]
Tank/Hold Capacity	97186.1 [m3]

Main Engine Characteristics

Maximum Continuous Rating	9800.00 [kW]
Rotational Speed at MCR	113.0 [RPM]
Specific Fuel Consumption at 75% (SFC)	171.59 [g/kWh]
CO2 Conversion Factor	3.206 [t/t]
Number of Sets	1

Auxiliary Engine Characteristics

Maximum Continuous Rating	440.0 [kW]
Rotational Speed at MCR	900.0 [RPM]
Specific Fuel Consumption at 50% (SFC)	215.86 [g/kWh]
CO2 Conversion Factor	3.206 [t/t]
Number of Sets	3

Calculation of Current EEXI

ΣP(ME) at 75% MCR	7350.00 [kW]
Capacity	82612.0 [ton]
fj	1
fi	1
fc	1
fl	1
fw	1
fm	1
Vref	13.87 [knots]
Attained EEXI	3.83 g-CO2/ton.mile

Required EEXI

Ship Type	Bulk Carrier
a	961.79
b	82612
c	0.477
EEDI Reference line value	4.34 (g-CO2/ton.mile)
Deadweight	82612
Reduction Factor	20
Required EEXI	3.47 g-CO2/ton.mile.

Vessel 2 does not meet the requirements of EEXI Regulation.

A reduction to EEXI of 3.83 - 3.47 = 0.36 g-CO2/ton.mile is further required.

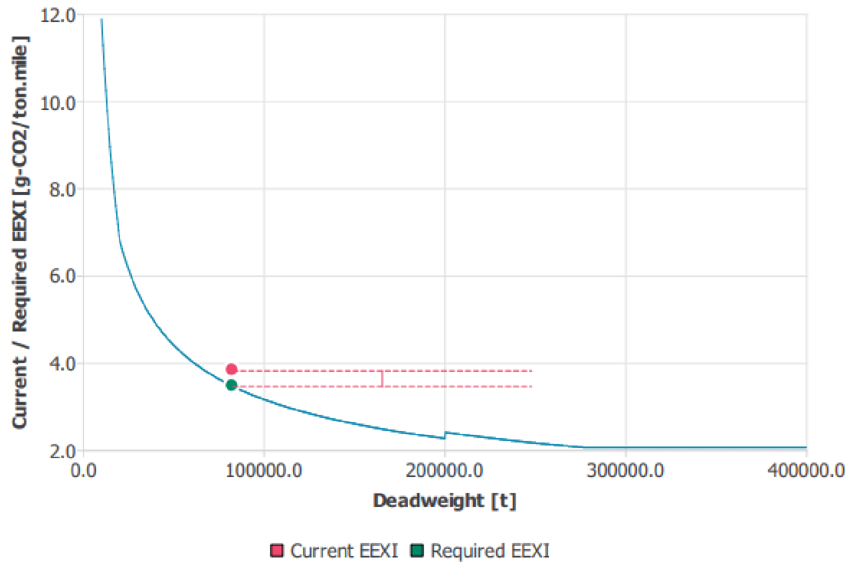


Figure 58:Current/Required EEXI for Vessel 2

Engine Power Limitation Calculations

MCR(ME)	9800.00 [kW]
MCR(ME),Lim	7526.40 [kW]
ΣP(ME)	6246.91 [kW]
SFC(ME)	172.35 [g/kWh]
Power Reduction	23.20 [%]
Actual attained EEXI	3.47 [g-CO2/ton.mile]

Speed Reduction.

Speed Vref	13.87 [knots]
Speed Vref,Lim	13.21 [knots]
Speed Reduction	4.73 [%]
Actual attained EEXI	3.47 [g-CO2/ton.mile]

As we can see the vessel need a 23.20 % power reduction in order to achieve the required by the regulations index.

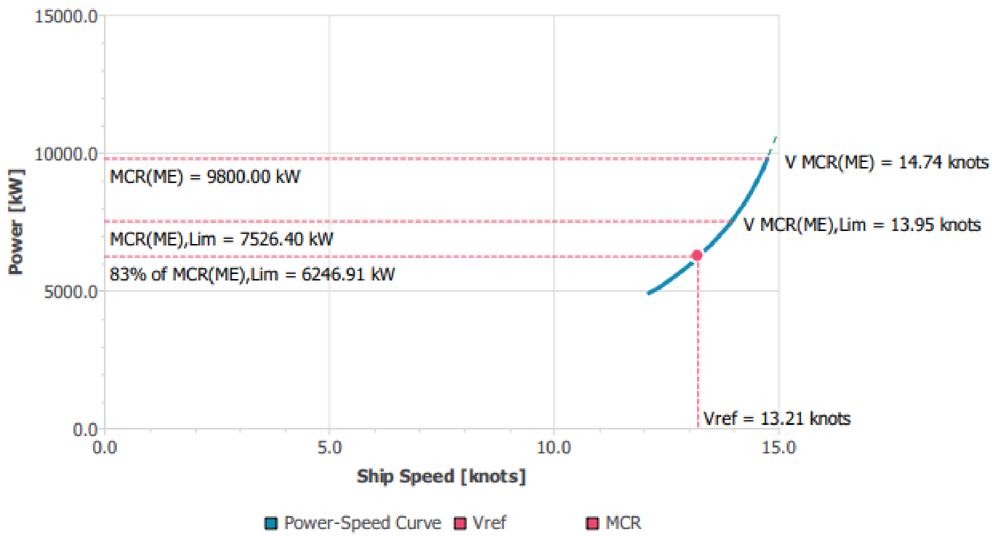


Figure 59:Power-Speed Curve of Vessel 2 at Scantling Draught.

And we have a 4.73% speed reduction.

The operational profile of vessel 2 from its noon reports:

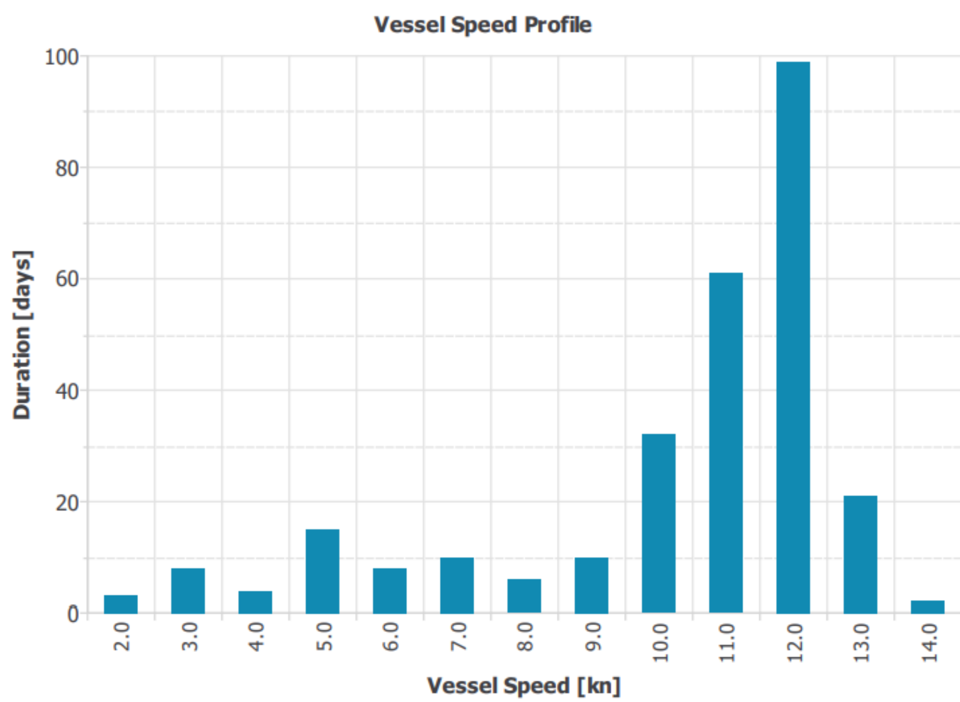


Figure 60:speed profile of vessel 2

After implementation of the EPL some of these speeds are no longer feasible.

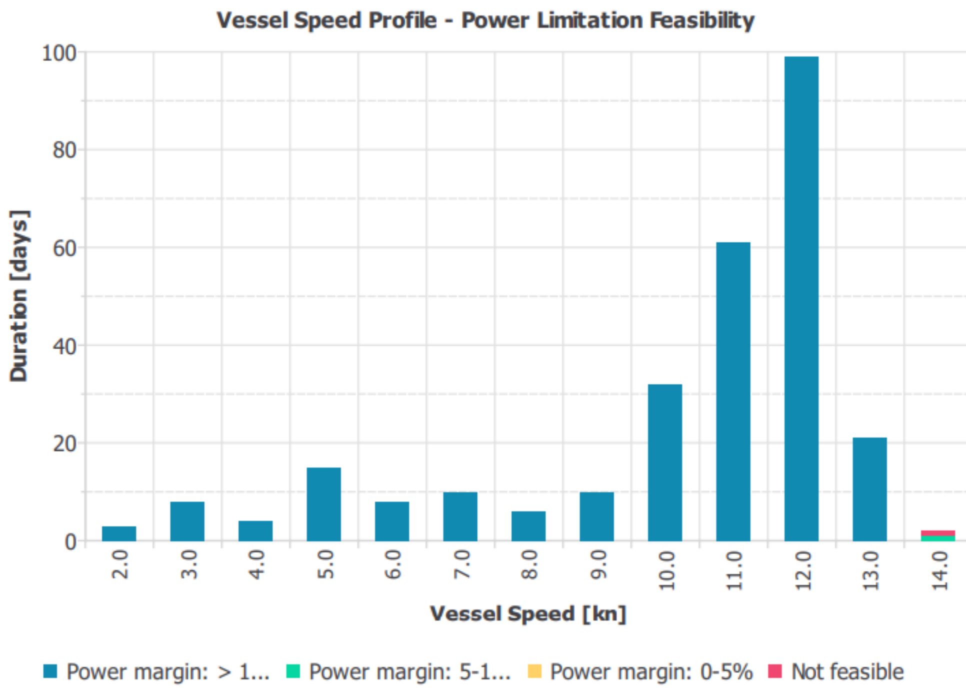


Figure 61: Speed of Vessel 2 after Mechanical EPL.

Examining now only the high speeds per draught we can see on the next table with red the speed that are not feasible at all, with yellow the speeds that are feasible but the power margin is between 0-5% , with green speeds are feasible with power margin of 5-15% and with blue the power margin is more than 15%.

	9.0 kn	9.5 kn	10.0 kn	10.5 kn	11.0 kn	11.5 kn	12.0 kn	12.5 kn	13.0 kn	13.5 kn	14.0 kn	Tot.
5.5 m												22.3%
6.0 m												2.7%
6.5 m												3.6%
7.0 m												1.3%
7.5 m												8.5%
8.0 m												0.0%
8.5 m												0.4%
9.0 m												1.3%
9.5 m												0.0%
10.0 m												0.0%
10.5 m												0.9%
11.0 m												0.0%
11.5 m												9.8%
12.0 m												21.0%
12.5 m												12.1%
13.0 m												12.1%
13.5 m												0.9%
14.0 m												3.1%
Tot.	2.2%	3.6%	5.8%	11.2%	13.8%	24.6%	23.2%	9.8%	4.5%	0.9%	0.4%	100%

■ Power margin: > 15% ■ Power margin: 5-15% ■ Power margin: 0-5% ■ Not feasible

Table 38:Vessel Performance (after EPL) per Draught at high vessel Speeds

On the table below its visible which speeds are not acceptable and their percentages on the overall operational profile of the vessel.

Speed [knots]	Not Feasible	0-5%	5-15%	>15%	Summary
2.0	-	-	-	1.1%	1.1% (3)
3.0	-	-	-	2.9%	2.9% (8)
4.0	-	-	-	1.4%	1.4% (4)
5.0	-	-	-	5.4%	5.4% (15)
6.0	-	-	-	2.9%	2.9% (8)
7.0	-	-	-	3.6%	3.6% (10)
8.0	-	-	-	2.2%	2.2% (6)
9.0	-	-	-	3.6%	3.6% (10)
10.0	-	-	-	11.5%	11.5% (32)
11.0	-	-	-	21.9%	21.9% (61)
12.0	-	-	-	35.5%	35.5% (99)
13.0	-	-	-	7.5%	7.5% (21)
14.0	0.4%	-	0.4%	-	0.7% (2)
Summary	0.4% (1)	0.0% (0)	0.4% (1)	99.3% (277)	100.0% (279)

Table 39: Vessel performance estimation (after Mechanical EPL installation) based on existing noon report

Statistics Summary

Total number of Valid Records: 279

Total number of Not Feasible Records: 1 (0.4%)

Total number of Records with Power Margin in the range 0-5%: 0 (0.0%)

Total number of Records with Power Margin in the range 5-15%: 1 (0.4%)

Total number of Records with Power Margin above 15%: 277 (99.3%)

Its easy to identify that the vessel doesn’t have a problem on its operational schedule. Vessel 2 already has installed and ESD Category A (Mewis Duct) and the Speed-power curves investigated are new after the installation.

Figure 62: Mewis Duct installed in Vessel 2

Now we will examine the effect of the ESDs on the vessel beginning with category B

For Category B EET, the table and the figure below provides the net propulsion power savings ($f_{eff} * P_{eff}$) combined with appropriate Mechanical EPL.

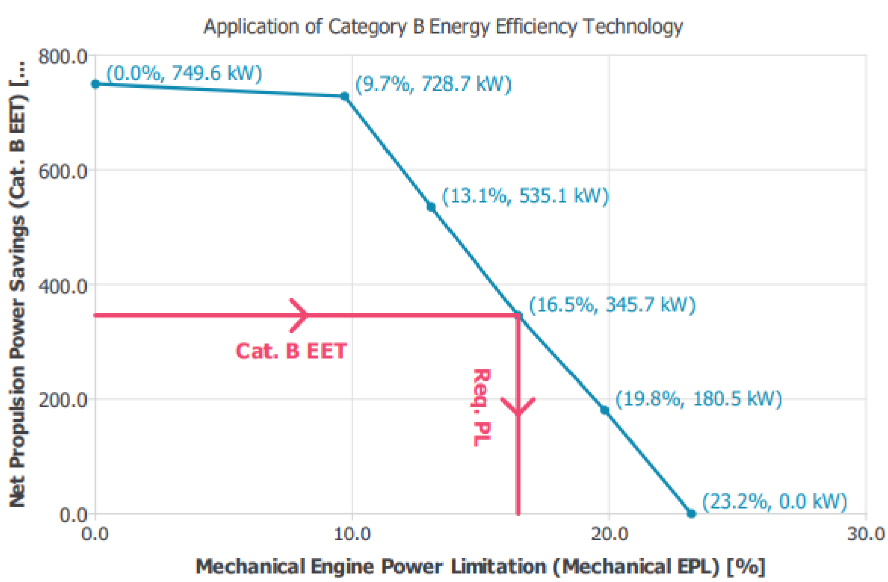


Figure 63:Effect of Category B ESDs adoption on required Mechanical Engine Power Limitation for vessel 2

Net propulsion power savings (Cat. B) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Propulsion Power Savings
[%]	[kW]
0.0	749.62
9.7	728.65
13.1	535.14
16.5	345.68
19.8	180.45
23.2	0.00

Table 40:Effect of Category B EET adoption on required Mechanical Engine Power Limitation

For Category C EET, the table and the figure below provides the net auxiliary power savings $(f_{eff} * P_{AEeff})$, combined with appropriate Mechanical EPL, in order to satisfy the EEXI requirement.

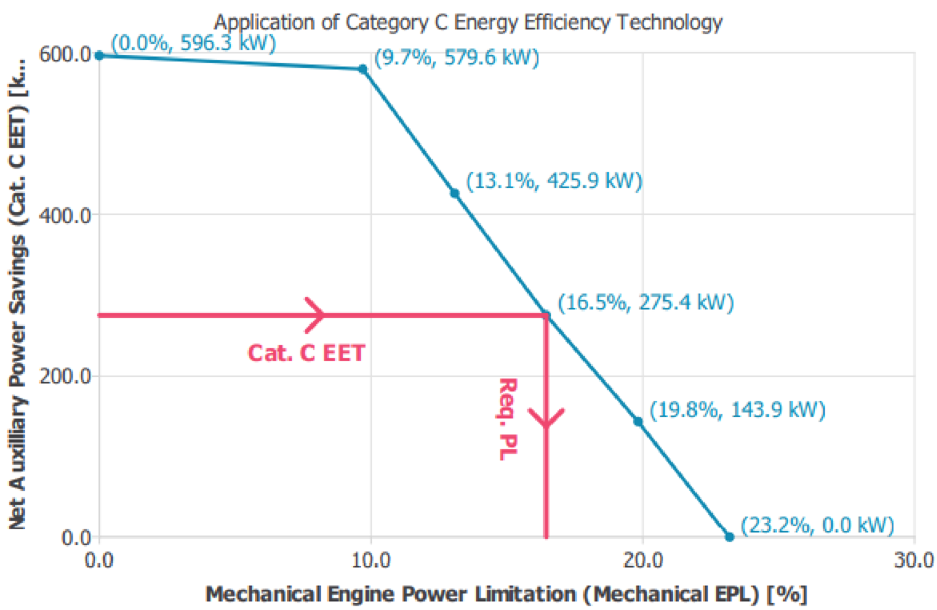


Figure 64:Effect of Category C ESDs adoption on required Mechanical Engine Power Limitation for vessel 2

Net auxilliary power savings (Cat. C) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Aux. Power Savings
[%]	[kW]
0.0	596.33
9.7	579.65
13.1	425.92
16.5	275.38
19.8	143.94
23.2	0.00

Table 41:Effect of Category C ESDs adoption on required Mechanical Engine Power Limitation

Scenario: Feasibility study for speed schedule with 16.5% EPL in combination with ESD

Examining now further the specific point with 16.5% EPL in combination with 345.68 kW of Category B ESD **OR** 275.38 kW of Category C we take some interesting information about the vessel

For this specific point examining again the new acceptable operational profile we can see the graphs bellow.

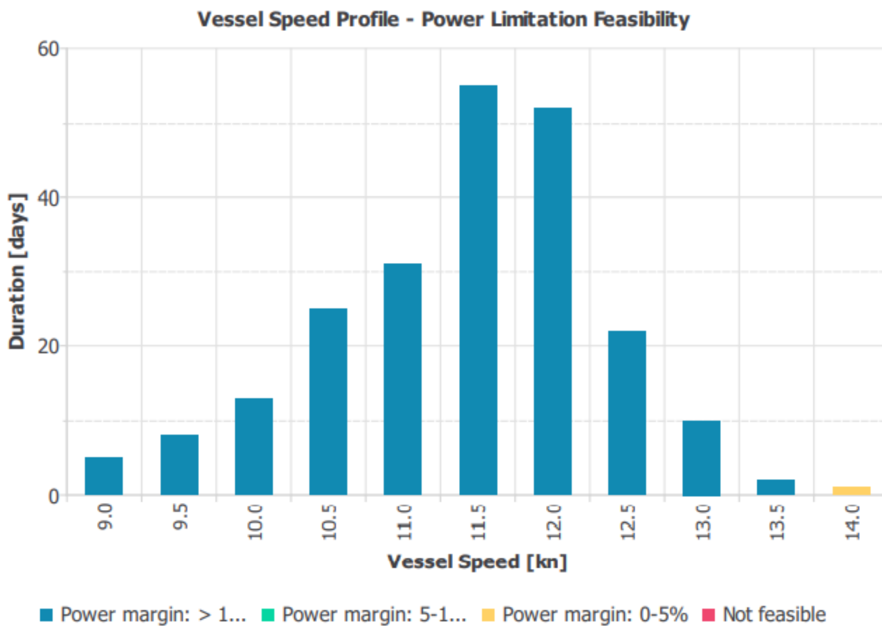


Figure 65:Speed profile of Vessel 1 after Mechanical EPL in combination with ESDs (SCENARIO)

	9.0 kn	9.5 kn	10.0 kn	10.5 kn	11.0 kn	11.5 kn	12.0 kn	12.5 kn	13.0 kn	13.5 kn	14.0 kn	Tot.
5.5 m												22.3%
6.0 m												2.7%
6.5 m												3.6%
7.0 m												1.3%
7.5 m												8.5%
8.0 m												0.0%
8.5 m												0.4%
9.0 m												1.3%
9.5 m												0.0%
10.0 m												0.0%
10.5 m												0.9%
11.0 m												0.0%
11.5 m												9.8%
12.0 m												21.0%
12.5 m												12.1%
13.0 m												12.1%
13.5 m												0.9%
14.0 m												3.1%
Tot.	2.2%	3.6%	5.8%	11.2%	13.8%	24.6%	23.2%	9.8%	4.5%	0.9%	0.4%	100%

■ Power margin: > 15% ■ Power margin: 5-15% ■ Power margin: 0-5% ■ Not feasible

Table 42: Vessel Performance (SCENARIO) per Draught at high vessel Speeds

Speed [knots]	Not Feasible	0-5%	5-15%	>15%	Summary
2.0	-	-	-	1.1%	1.1% (3)
3.0	-	-	-	2.9%	2.9% (8)
4.0	-	-	-	1.4%	1.4% (4)
5.0	-	-	-	5.4%	5.4% (15)
6.0	-	-	-	2.9%	2.9% (8)
7.0	-	-	-	3.6%	3.6% (10)
8.0	-	-	-	2.2%	2.2% (6)
9.0	-	-	-	3.6%	3.6% (10)
10.0	-	-	-	11.5%	11.5% (32)
11.0	-	-	-	21.9%	21.9% (61)
12.0	-	-	-	35.5%	35.5% (99)
13.0	-	-	-	7.5%	7.5% (21)
14.0	-	0.4%	-	0.4%	0.7% (2)
Summary	0.0% (0)	0.4% (1)	0.0% (0)	99.6% (278)	100.0% (279)

Table 43: Vessel performance estimation (SCENARIO) based on existing noon report

Statistics Summary

Total number of Valid Records: 279

Total number of Not Feasible Records: 0 (0.0%)

Total number of Records with Power Margin in the range 0-5%: 1 (0.4%)

Total number of Records with Power Margin in the range 5-15%: 0 (0.0%)

Total number of Records with Power Margin above 15%: 278 (99.6%)

Summing up in the next table we can see which speeds are feasible for some different combinations of EPL and ESDs. We need to keep in mind that for every row in the table we use either ESD of category B or Category C and the EPL.

All scenarios presented

Combination of EET and EPL			Feasible Speeds			
EPL [%]	Cat B [kW]	Cat C [kW]	Not Feasible	Margin 0-5%	Margin 5-15%	Margin > 15%
0	749.62	596.33	0.0% (0)	0.0% (0)	0.0% (0)	100% (279)
9.7	728.65	579.65	0.0% (0)	0.0% (0)	0.4% (1)	99.6% (278)
13.1	535.14	425.92	0.0% (0)	0.0% (0)	0.4% (1)	99.6% (278)
16.5	345.68	275.38	0.0% (0)	0.4% (1)	0.0% (0)	99.6% (278)
19.8	180.45	143.94	0.0% (0)	0.4% (1)	0.0% (0)	99.6% (278)
23.2	0	0	0.4% (1)	0.0% (0)	0.4% (1)	99.3% (277)

Table 44: All scenarios of combinations (EPL & B or C cat of ESDs) and their performance

On the next table we can see the maximum Speed on Summer drought (scantling) and design drought in relation to the kW produced from the ESDs in combination with the appropriate EPL for vessel 3.

Combination of EPL and ESDs (B or C)			Vmax MCR(ME),Lim [kn]	
EPL [%]	Cat B [kW]	Cat C [kW]	Scantling Draught [kn]	Design Draught [kn]
0	749.62	596.33	14.9	15.22
9.7	728.65	579.65	14.47	14.85
13.1	535.14	425.92	14.36	14.72
16.5	345.68	275.38	14.24	14.57
19.8	180.45	143.94	14.1	14.43
23.2	0	0	13.95	14.26

Table 45: All scenarios of combinations (EPL & B or C cat of ESDs) and their maximum speed

6.5 Tankers

6.5.1 Case study 3

Vessel characteristics

Vessel Type	Tanker
Year of built	2007
Length Between Perpendiculars	180.00 [m]
Breadth	32.20 [m]
Depth, main deck	19.70 [m]
Summer Load Draught	13.00 [m
Deadweight at Summer (Scantling) Draught	53714.0 [ton]
Gross Tonnage	31433

Main Engine Characteristics

Maximum Continuous Rating	10620.60 [kW]
Rotational Speed at MCR	100.0 [RPM]
Specific Fuel Consumption at 75% (SFC)	167.10 [g/kWh]
CO2 Conversion Factor	3.206
Number of Sets	1

Auxiliary Engine Characteristics

Maximum Continuous Rating	800.00 [kW]
Rotational Speed at MCR	900.0 [RPM]
Specific Fuel Consumption at 50% (SFC)	208.07 [g/kWh]
CO2 Conversion Factor	3.206 [t/t]
Number of Sets	3

Calculation of Current EEXI

ΣP(ME) at 75% MCR	7965.45 [kW]
Capacity	53714.0 [ton]
fj	1
fi	1
fc	1
fl	1
fw	1
fm	1
Vref	14.98 [knots]
Attained EEXI	5.732 g-CO2/ton.mile.

Required EEXI

Ship Type	Tanker
a	1218.8
b	53714
c	0.488
EEDI Reference line value	5.993 (g-CO2/ton.mile)
Deadweight	53714
Reduction Factor	20
Required EEXI	4.794 (g-CO2/ton.mile)

Vessel 3 does not meet the requirements of EEXI Regulation.

A reduction to EEXI of 5.732 - 4.794 = 0.938 g-CO2/ton.mile is further required.

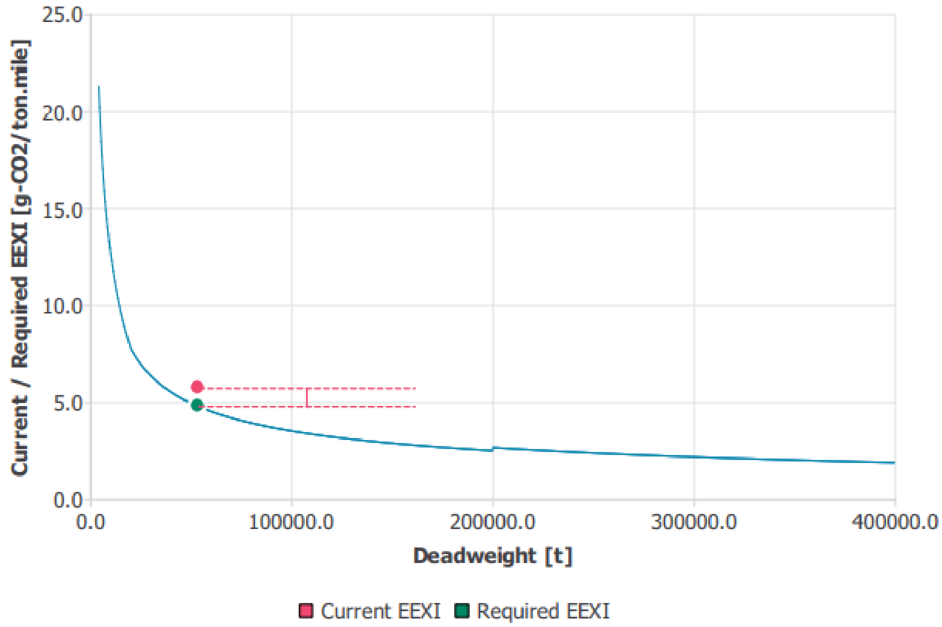


Figure 66 : Current/Required EEXI for ship 3

Engine Power Limitation Calculations

MCR(ME)	10620.60 [kW]
MCR(ME),Lim	6669.74 [kW]
ΣP(ME)	5535.88 [kW]
SFC(ME)	172.90 [g/kWh]
Power Reduction	37.20 [%]
Actual attained EEXI	4.792 g-CO2/ton.mile.

As we can see the vessel needs a 37.20 % power reduction in order to achieve the required by the regulations index.

Speed Reduction.

Speed Vref	14.98 [knots]
Speed Vref,Lim	13.26 [knots]
Speed Reduction	11.47 [%]
Actual attained EEXI	4.792 g-CO2/ton.mile.

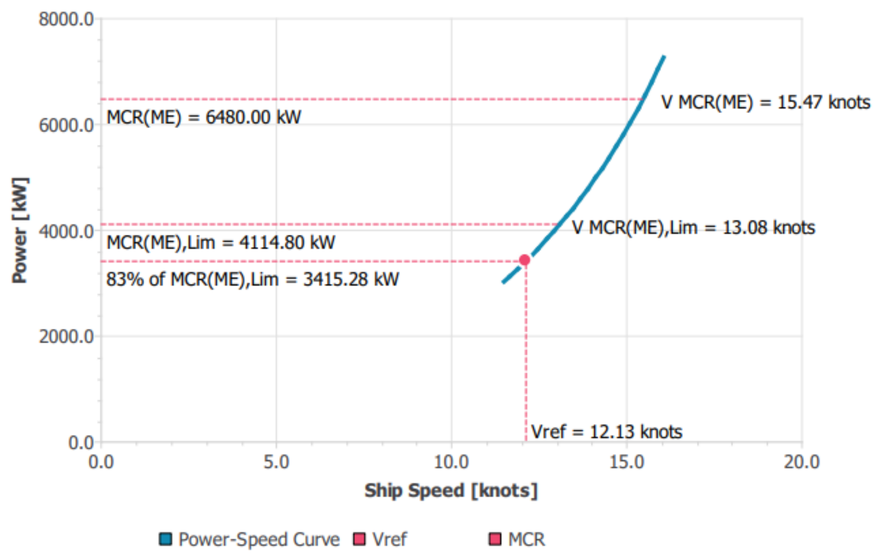


Figure 67: Power-Speed Curve of Vessel 3 at Scantling Draught for the Calculation of Vref.

We have a 11.47 speed reduction.

Following the same procedure as before we can examine the operational profile of vessel 2 with the help of its noon reports.

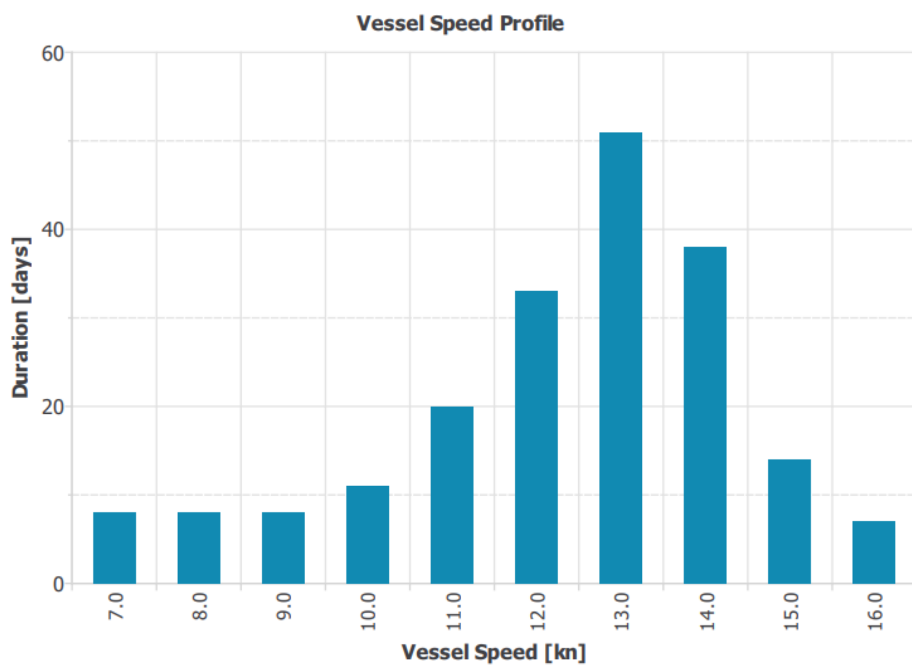


Figure 68: Speed profile of vessel 3

Proceeding in the same way as before after the implementation of the EPL some of these speeds are not feasible.

On the graph bellow we can see with red the speeds that are not feasible at all, with yellow the speeds that are feasible but the power margin is between 0-5% , with green speeds are feasible with power margin of 5-15% and with blue the power margin is more than 15%.

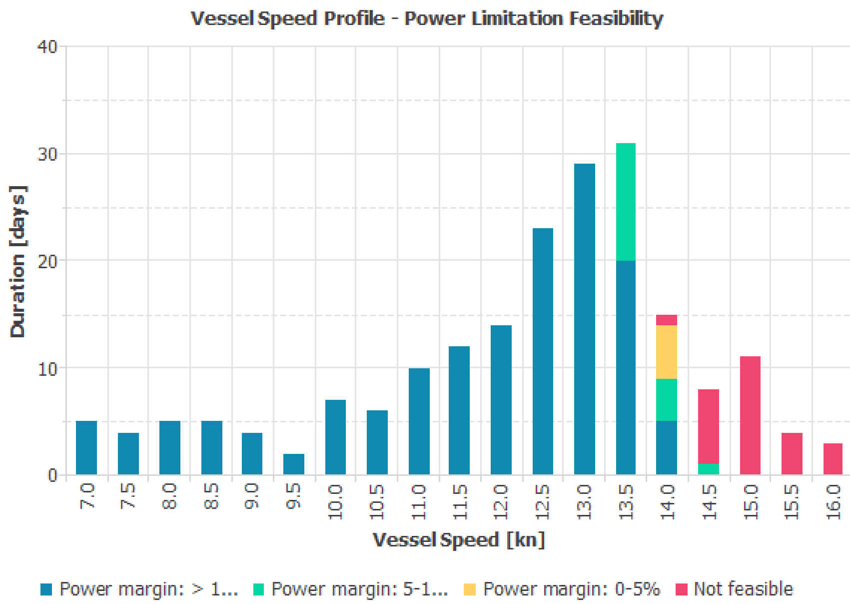


Figure 69:Speed profile of Vessel 3 after Mechanical EPL.

On the table below its visible which speeds are not acceptable and their percentages on the overall operational profile of the vessel.

Speed [knots]	Not Feasible	0-5%	5-15%	>15%	Summary
7.0	-	-	-	4.0%	4.0% (8)
8.0	-	-	-	4.0%	4.0% (8)
9.0	-	-	-	4.0%	4.0% (8)
10.0	-	-	-	5.6%	5.6% (11)
11.0	-	-	-	10.1%	10.1% (20)
12.0	-	-	-	16.7%	16.7% (33)
13.0	-	-	0.5%	25.3%	25.8% (51)
14.0	2.5%	2.5%	7.6%	6.6%	19.2% (38)
15.0	7.1%	-	-	-	7.1% (14)
16.0	3.5%	-	-	-	3.5% (7)
Summary	13.1% (26)	2.5% (5)	8.1% (16)	76.3% (151)	100.0% (198)

Table 46:Vessel performance estimation (after Mechanical EPL installation) based on existing noon

Statistics Summary

Total number of Valid Records: 198

Total number of Not Feasible Records: 26 (13.1%)

Total number of Records with Power Margin in the range 0-5%: 5 (2.5%)

Total number of Records with Power Margin in the range 5-15%: 16 (8.1%)

Total number of Records with Power Margin above 15%: 151 (76.3%)

For Category B EET, the table and the figure below provides the net propulsion power savings ($f_{eff} * P_{eff}$) combined with appropriate Mechanical EPL.

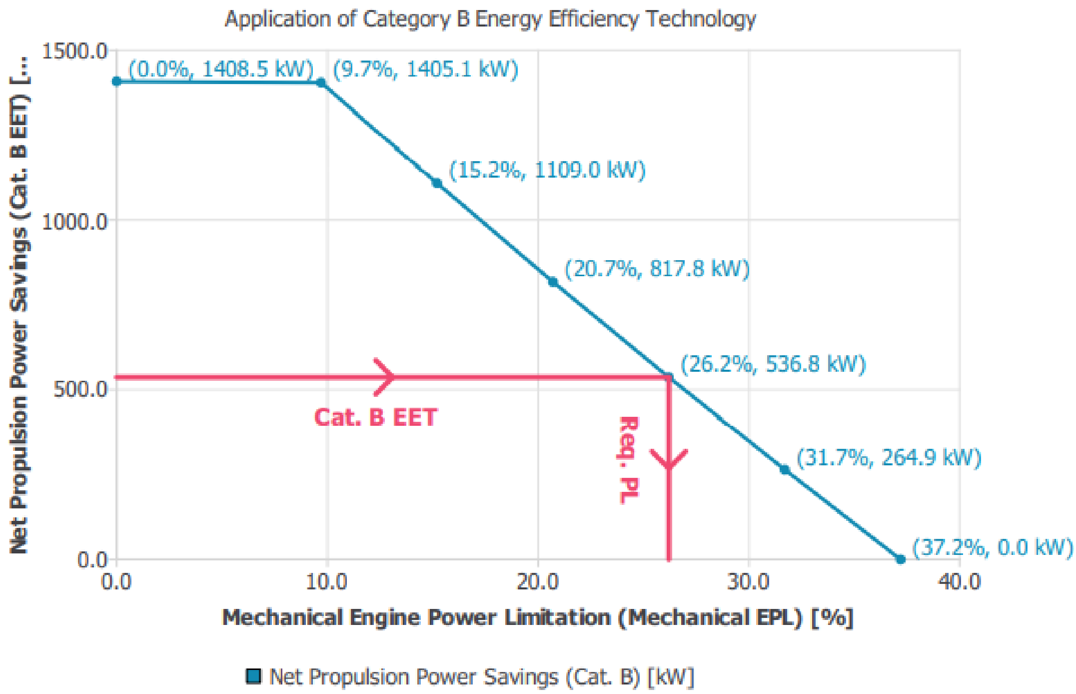


Figure 70: Effect of Category B ESDs adoption on required Mechanical Engine Power Limitation

Net propulsion power savings (Cat. B) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Propulsion Power Savings
[%]	[kW]
0.0	1408.49
9.7	1405.10
15.2	1109.02
20.7	817.79
26.2	536.78
31.7	264.87
37.2	0.00

Table 47:Effect of Category B ESDs adoption on required Mechanical Engine Power Limitation.

For Category C EET, the table and the figure below provides the net auxiliary power savings ($f_{eff} * P_{AEeff}$), combined with appropriate Mechanical EPL, in order to satisfy the EEXI requirement.

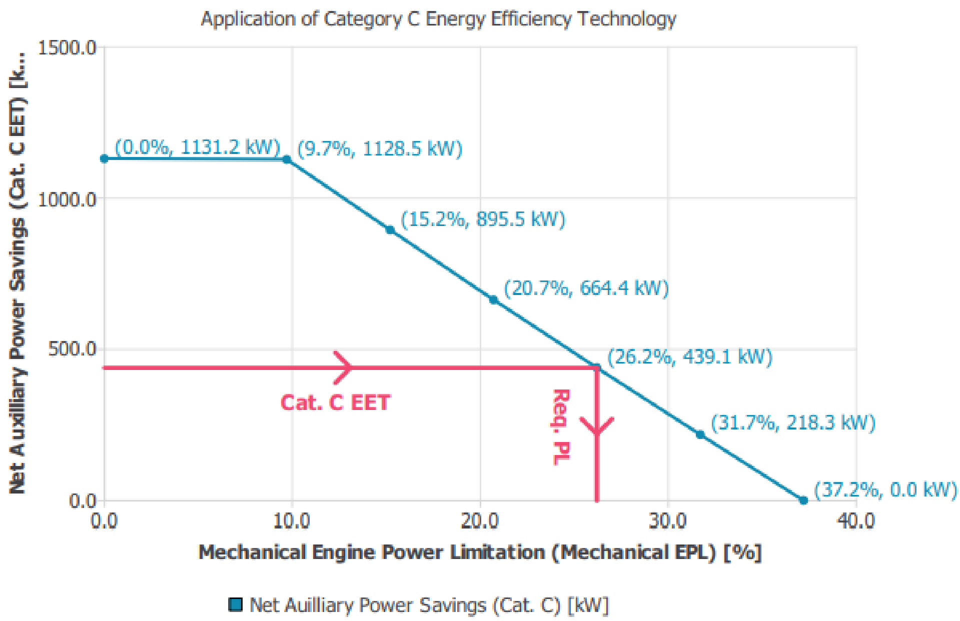


Figure 71: Effect of Category C ESD adoption on required Mechanical Engine Power Limitation.

Net auxilliary power savings (Cat. C) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Aux. Power Savings
[%]	[kW]
0.0	1131.15
9.7	1128.49
15.2	895.54
20.7	664.43
26.2	439.11
31.7	218.31
37.2	0.00

Table 48: Effect of Category C ESD adoption on required Mechanical Engine Power Limitation.

Scenario: Feasibility study for speed schedule with 26.5% EPL in combination with ESD

Examining now further the specific point with 26.2% EPL in combination with 526.78 kW of Category B ESD **OR** 439.11 kW of Category C we take some interesting information about the vessel. In contrast with the previous case study (vessel 1) we can see that in order to succeed the same reduction in EPL we need almost double the amount in kW from ESDs. This is happening since Vessel 2 is almost double in size and operates in higher speeds than Vessel 1.

In order to achieve the same EPL of 26.2 % with the category B we needed propulsion power savings of 526.78 kW and with category C propulsion power savings of 439.11 kW.

For this specific point examining again the new acceptable operational profile we can see…

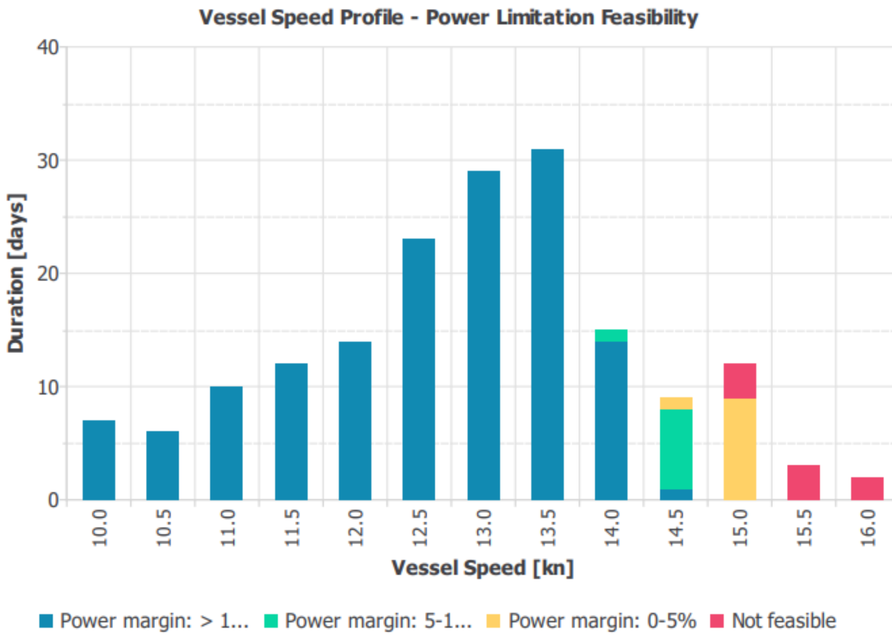


Figure 72: Speed profile of Vessel 1 after Mechanical EPL in combination with ESDs (SCENARIO)

Examining now only the high speeds per draught we can see on the next table with red the speed that are not feasible at all, with yellow the speeds that are feasible but the power margin is between 0-5% , with green speeds are feasible with power margin of 5-15% and with blue the power margin is more than 15%.

	10.0 kn	10.5 kn	11.0 kn	11.5 kn	12.0 kn	12.5 kn	13.0 kn	13.5 kn	14.0 kn	14.5 kn	15.0 kn	15.5 kn	16.0 kn	Tot.
6.0 m														9.2%
6.5 m														30.1%
7.0 m														1.7%
7.5 m														1.2%
8.0 m														0.0%
8.5 m														0.0%
9.0 m														1.7%
9.5 m														0.0%
10.0 m														1.7%
10.5 m														0.0%
11.0 m														13.3%
11.5 m														11.6%
12.0 m														9.2%
12.5 m														13.9%
13.0 m														6.4%
Tot.	4.0%	3.5%	5.8%	6.9%	8.1%	13.3%	16.8%	17.9%	8.7%	5.2%	6.9%	1.7%	1.2%	100%

■ Power margin: > 15% ■ Power margin: 5-15% ■ Power margin: 0-5% ■ Not feasible

Figure 73: Vessel Performance (SCENARIO) per Draught at high vessel Speeds

Speed [knots]	Not Feasible	0-5%	5-15%	>15%	Summary
7.0	-	-	-	4.0%	4.0% (8)
8.0	-	-	-	4.0%	4.0% (8)
9.0	-	-	-	4.0%	4.0% (8)
10.0	-	-	-	5.6%	5.6% (11)
11.0	-	-	-	10.1%	10.1% (20)
12.0	-	-	-	16.7%	16.7% (33)
13.0	-	-	-	25.8%	25.8% (51)
14.0	-	-	2.5%	16.7%	19.2% (38)
15.0	1.5%	5.1%	1.5%	-	8.1% (16)
16.0	2.5%	-	-	-	2.5% (5)
Summary	4.0% (8)	5.1% (10)	4.0% (8)	86.9% (172)	100.0% (198)

Table 49: Vessel performance estimation (SCENARIO) based on existing noon report

Statistics Summary

Total number of Valid Records: 198

Total number of Not Feasible Records: 8 (4.0%)

Total number of Records with Power Margin in the range 0-5%: 10 (5.1%)

Total number of Records with Power Margin in the range 5-15%: 8 (4.0%)

Total number of Records with Power Margin above 15%: 172 (86.9%)

In contrast with the previous vessel even thought we used almost double the amount in kW from ESDs in order to decrease the EPL from 37.2% to 26.2% we still have only 86.9% from the noon reports record feasible.

Summing up in the next table we can see which speeds are feasible for some different combinations of EPL and ESDs. We need to keep in mind that for every row in the table we use either ESD of category B or Category C and the EPL.

All scenarios presented

Combination of EET and EPL			Feasible Speeds			
EPL [%]	Cat B [kW]	Cat C [kW]	Not Feasible	Margin 0-5%	Margin 5-15%	Margin > 15%
0	1408.49	1131.15	0% (0)	0% (0)	0% (0)	100.0% (198)
9.7	1405.1	1128.49	0% (0)	0.5% (1)	1.0% (2)	98.5% (196)
15.2	1109.02	895.54	1.5% (3)	1.0% (2)	4.5% (9)	92.9% (184)
20.7	817.79	664.43	2.5% (5)	1.0% (2)	7.1% (14)	89.4% (177)
26.2	536.78	439.11	4.0% (8)	5.1% (10)	4.0% (8)	86.9% (172)
31.7	264.87	218.31	10.6% (21)	1.0% (2)	4.5% (9)	83.8% (166)
37.2	0	0	13.1% (26)	2.5% (5)	8.1% (16)	76.3% (151)

Table 50: All scenarios of combinations (EPL & B or C cat of ESDs) and their performance

On the next table we can see the maximum Speed on Summer drought (scantling) in relation to the kW produced from the ESDs in combination with the appropriate EPL.

Combination of EPL and ESDs (B or C)			Vmax MCR(ME),Lim [kn]	
EPL [%]	Cat B [kW]	Cat C [kW]	Scantling Draught	Design Draught
0	1408.49	1131.15	16.4	16.8
9.7	1405.1	1128.49	15.93	16.48
15.2	1109.02	895.54	15.6	16.24
20.7	817.79	664.43	15.25	16.05
26.2	536.78	439.11	14.9	15.82
31.7	264.87	218.31	14.5	15.53
37.2	0	0	14.1	15.22

Table 51: All scenarios of combinations (EPL & B or C cat of ESDs) and their maximum speed

6.5.2 Case study 4

Vessel Characteristics

Vessel Type	Tanker
Year of built	2009
Length Between Perpendiculars	172.00 [m]
Breadth	32.20 [m]
Depth, main deck	18.70 [m]
Summer Load Draught	12.00 [m
Deadweight at Summer (Scantling) Draught	45976.0 [ton]
Gross Tonnage	31433

Main Engine Characteristics

Maximum Continuous Rating	9480.0 [kW]
Rotational Speed at MCR	127.0 [RPM]
Specific Fuel Consumption at 75% (SFC)	173.00 [g/kWh]
CO2 Conversion Factor	3.206
Number of Sets	1

Auxiliary Engine Characteristics

Maximum Continuous Rating	800.00 [kW]
Rotational Speed at MCR	900.0 [RPM]
Specific Fuel Consumption at 50% (SFC)	195.50 [g/kWh]
CO2 Conversion Factor	3.206 [t/t]
Number of Sets	3

Calculation of Current EEXI

P(ME) at 75% MCR	7110.00 [kW]
Capacity	45976.0 [ton]
fj	1
fi	1
fc	1
fl	1
fw	1
fm	1
Vref	15.00 [knots]
Attained EEXI	6.04 g-CO2/ton.mile.

Required EEXI

Ship Type	Tanker
a	1218.8
b	45976
c	0.488
EEDI Reference line value	6.47 (g-CO2/ton.mile)
Deadweight	45976
Reduction Factor	20
Required EEXI	5.17 (g-CO2/ton.mile)

Vessel 4 does not meet the requirements of EEXI Regulation.

A reduction to EEXI of 6.04 - 5.17 = 0.87 g-CO2/ton.mile is further required.

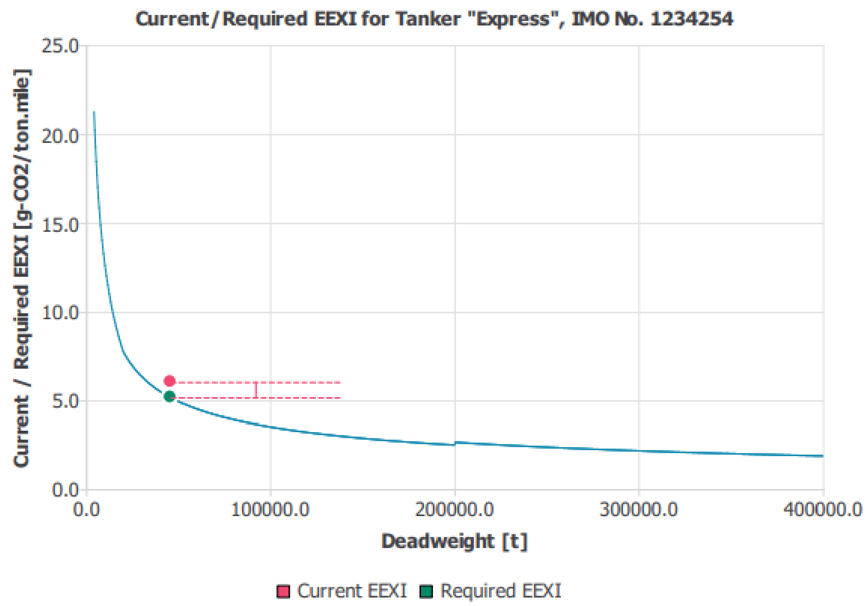


Figure 74: Current/Required EEXI for Vessel 4

Engine Power Limitation Calculations

MCR(ME)	9480.00 [kW]
MCR(ME),Lim	6550.68 [kW]
P(ME)	5437.06 [kW]
SFC(ME)	174.43 [g/kWh]
Power Reduction	30.90 [%]
Actual attained EEXI	5.17 g-CO2/ton.mile.

Speed Reduction.

Speed Vref	15.00 [knots]
Speed Vref,Lim	13.73 [knots]
Speed Reduction	8.47 [%]
Actual attained EEXI	5.17 g-CO2/ton.mile.

As we can see the vessel needs a 37.20 % power reduction in order to achieve the required by the regulations index.

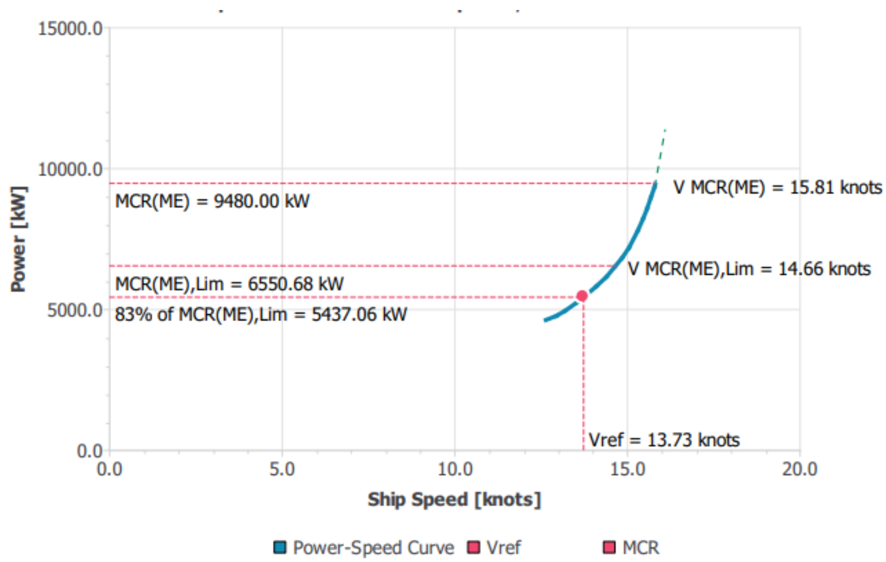


Figure 75:Power-Speed Curve of Vessel 4 at Scantling Draught

We have a 8.47% reduction of speed on scantling draught

The operational profile of vessel 3 from its noon reports:

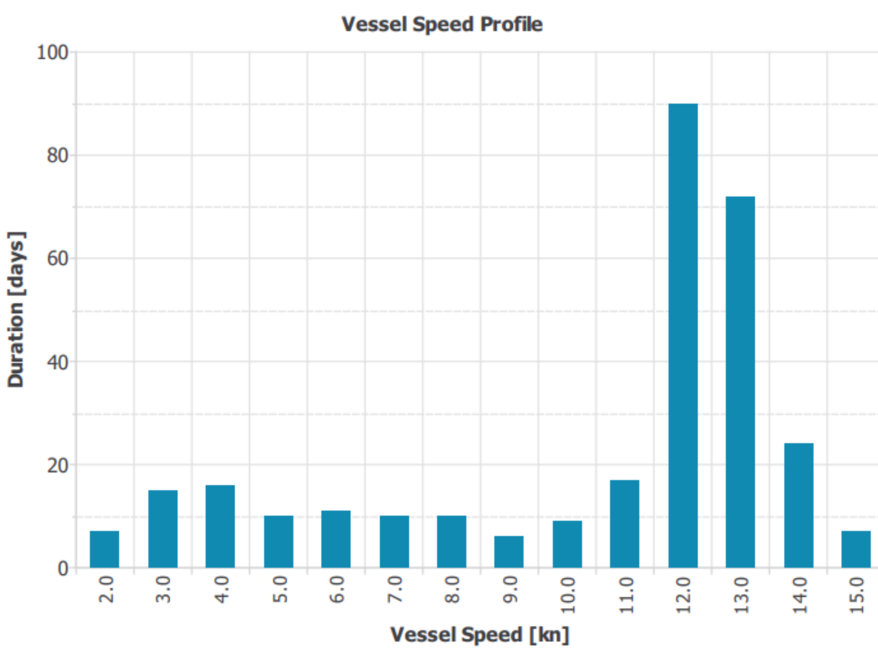


Figure 76: Speed profile of Vessel 4

After the implementation of the EPL some of these speeds are not feasible.

On the graph bellow we can see with red the speeds that are not feasible at all, with yellow the speeds that are feasible but the power margin is between 0-5% , with green speeds are feasible with power margin of 5-15% and with blue the power margin is more than 15%.

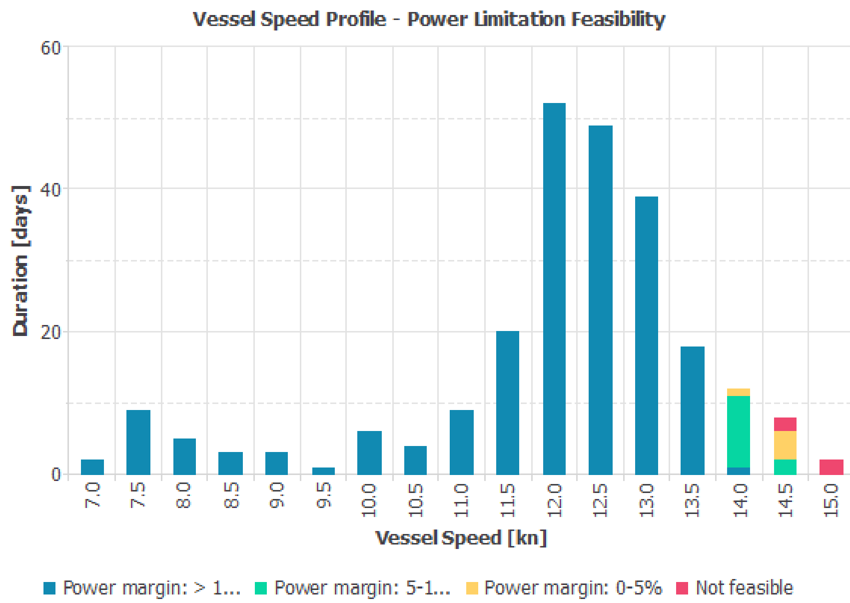


Figure 77:Speed profile of Vessel 3 at high vessel speeds after Mechanical EPL

Examining now only the high speeds per draught we can see on the next table with red the speed that are not feasible at all, with yellow the speeds that are feasible but the power margin is between 0-5% , with green speeds are feasible with power margin of 5-15% and with blue the power margin is more than 15%.

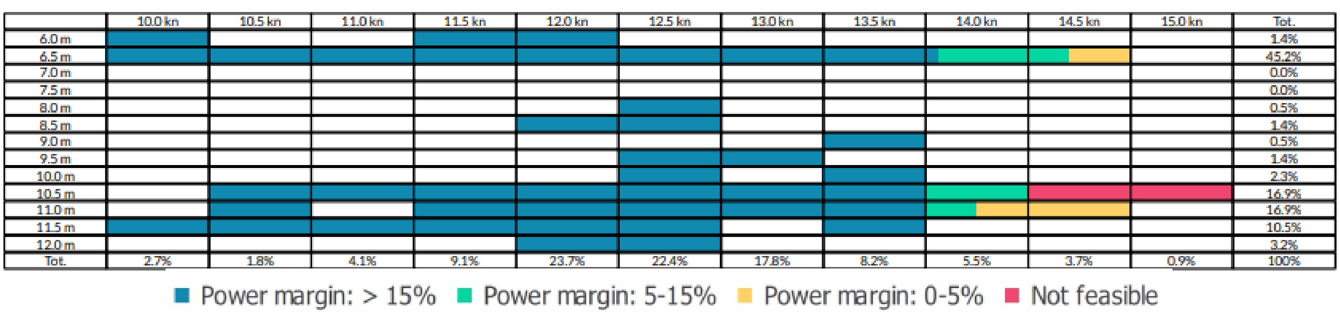


Figure 78:Vessel Performance (after EPL) per Draught at high vessel Speeds

On the table below its visible which speeds are not acceptable and their percentages on the overall operational profile of the vessel.

Speed [knots]	Not Feasible	0-5%	5-15%	>15%	Summary
2.0	-	-	-	2.3%	2.3% (7)
3.0	-	-	-	4.9%	4.9% (15)
4.0	-	-	-	5.3%	5.3% (16)
5.0	-	-	-	3.3%	3.3% (10)
6.0	-	-	-	3.6%	3.6% (11)
7.0	-	-	-	3.3%	3.3% (10)
8.0	-	-	-	3.3%	3.3% (10)
9.0	-	-	-	2.0%	2.0% (6)
10.0	-	-	-	3.0%	3.0% (9)
11.0	-	-	-	5.6%	5.6% (17)
12.0	-	-	-	29.6%	29.6% (90)
13.0	-	-	-	23.7%	23.7% (72)
14.0	-	0.7%	3.9%	3.3%	7.9% (24)
15.0	1.3%	1.0%	-	-	2.3% (7)
Summary	1.3% (4)	1.6% (5)	3.9% (12)	93.1% (283)	100.0% (304)

Table 52: Vessel performance estimation (after Mechanical EPL installation) based on existing noon report data

Statistics Summary

Total number of Valid Records: 304

Total number of Not Feasible Records: 4 (1.3%)

Total number of Records with Power Margin in the range 0-5%: 5 (1.6%)

Total number of Records with Power Margin in the range 5-15%: 12 (3.9%)

Total number of Records with Power Margin above 15%: 283 (93.1%)

We can see that this particular vessel doesn't showcase a big problem on achieving its operational profile even with 30.90% EPL on its power.

Now we will examine the effect of the ESDs on the vessel beginning with category B

For Category B EET, the table and the figure below provides the net propulsion power savings ($f_{eff} * P_{eff}$) combined with appropriate Mechanical EPL.

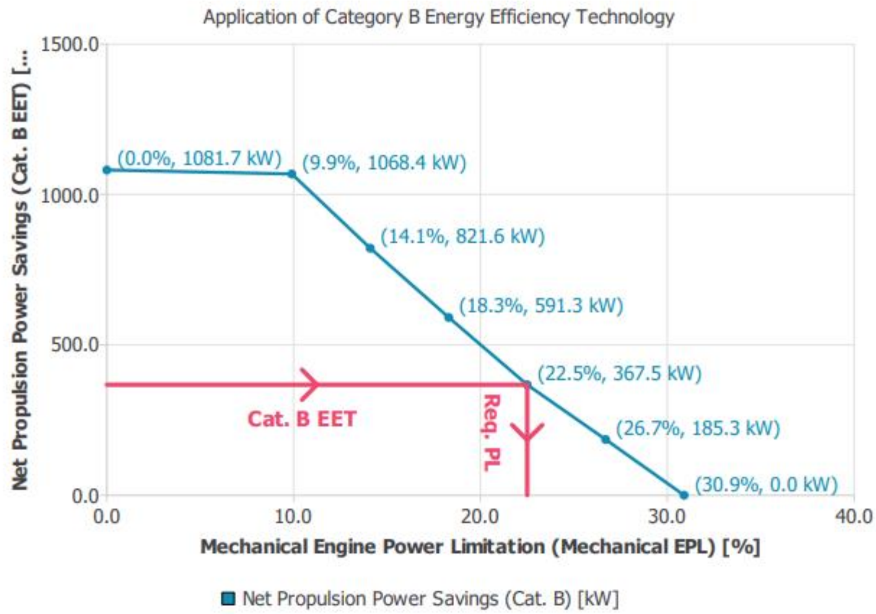


Figure 79: Effect of Category B ESDs adoption on required Mechanical Engine Power Limitation for vessel 4

Net propulsion power savings (Cat. B) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Propulsion Power Savings
[%]	[kW]
0.0	1081.66
9.9	1068.43
14.1	821.63
18.3	591.31
22.5	367.45
26.7	185.34
30.9	0.00

Table 53: Effect of Category B ESDs adoption on required Mechanical Engine Power Limitation

For Category C EET, the table and the figure below provides the net auxiliary power savings $(f_{eff} * P_{AEeff})$, combined with appropriate Mechanical EPL, in order to satisfy the EEXI requirement.

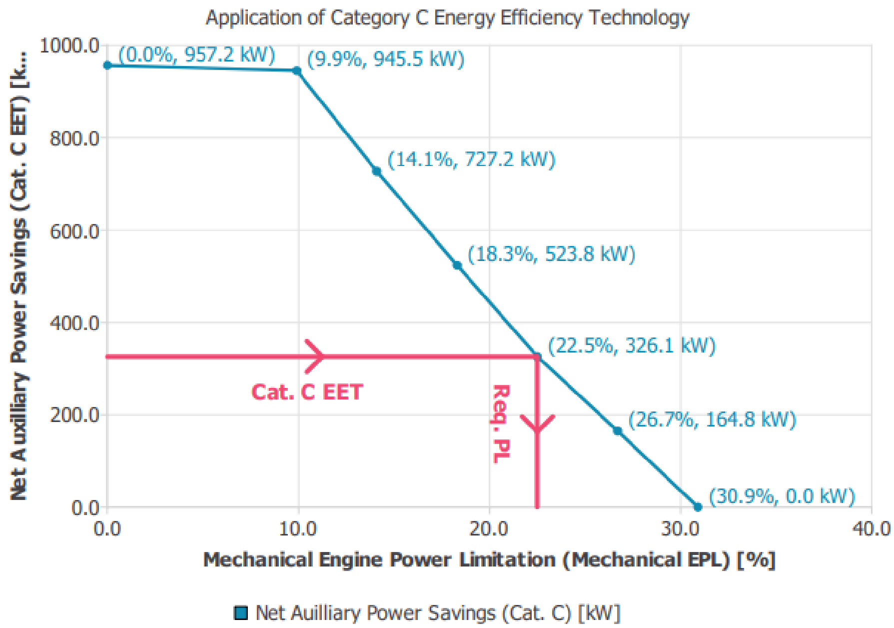


Figure 80: Effect of Category C ESDs on required Mechanical Engine Power Limitation.

Net auxilliary power savings (Cat. C) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Aux. Power Savings
[%]	[kW]
0.0	957.18
9.9	945.45
14.1	727.18
18.3	523.82
22.5	326.05
26.7	164.85
30.9	0.00

Table 54: Effect of Category C ESDs on required Mechanical Engine Power Limitation.

Scenario: Feasibility study for speed schedule with 22.5% EPL in combination with ESD

Examining now further the specific point with 22.5% EPL in combination with 367.45 kW of Category B ESD **OR** 326.05 kW of Category C, we take some interesting information about the vessel

For this specific point examining again the new acceptable operational profile we can see the graphs bellow.

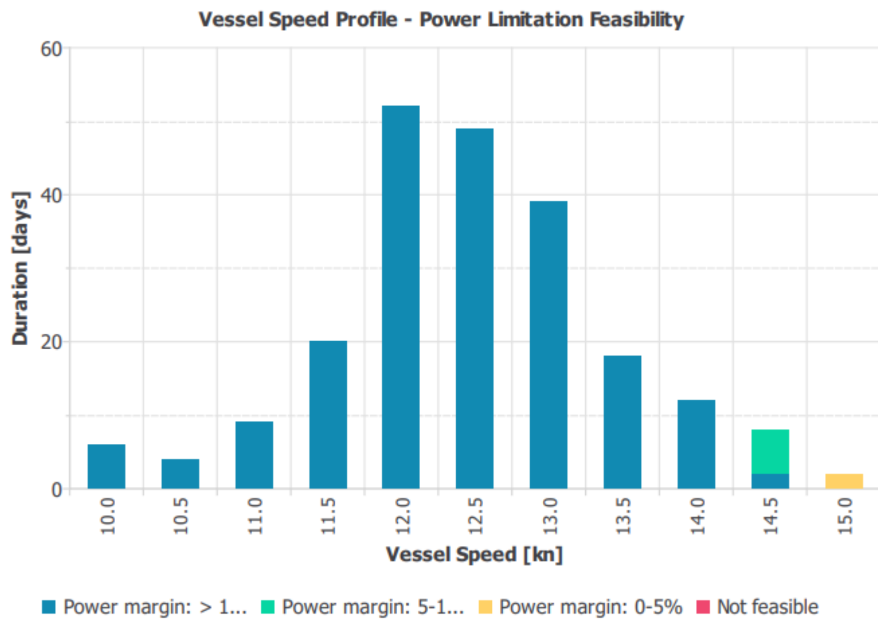


Figure 81: Speed profile of Vessel 1 after Mechanical EPL in combination with ESDs (SCENARIO)

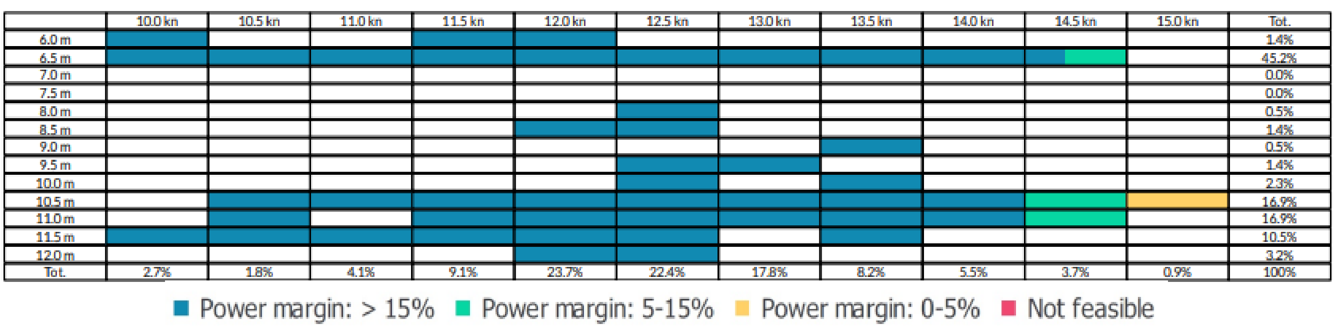


Figure 82: Vessel Performance (SCENARIO) per Draught at high vessel Speeds

Speed [knots]	Not Feasible	0-5%	5-15%	>15%	Summary
2.0	-	-	-	2.3%	2.3% (7)
3.0	-	-	-	4.9%	4.9% (15)
4.0	-	-	-	5.3%	5.3% (16)
5.0	-	-	-	3.3%	3.3% (10)
6.0	-	-	-	3.6%	3.6% (11)
7.0	-	-	-	3.3%	3.3% (10)
8.0	-	-	-	3.3%	3.3% (10)
9.0	-	-	-	2.0%	2.0% (6)
10.0	-	-	-	3.0%	3.0% (9)
11.0	-	-	-	5.6%	5.6% (17)
12.0	-	-	-	29.6%	29.6% (90)
13.0	-	-	-	23.7%	23.7% (72)
14.0	-	-	0.3%	7.6%	7.9% (24)
15.0	-	0.7%	1.6%	-	2.3% (7)
Summary	0.0% (0)	0.7% (2)	2.0% (6)	97.4% (296)	100.0% (304)

Table 55 : Vessel performance estimation (SCENARIO) based on existing noon report

Statistics Summary

Total number of Valid Records: 304

Total number of Not Feasible Records: 0 (0.0%)

Total number of Records with Power Margin in the range 0-5%: 2 (0.7%)

Total number of Records with Power Margin in the range 5-15%: 6 (2.0%)

Total number of Records with Power Margin above 15%: 296 (97.4%)

Summing up in the next table we can see which speeds are feasible for some different combinations of EPL and ESDs. We need to keep in mind that for every row in the table we use either ESD of category B or Category C and the EPL.

All scenarios presented

Combination of EET and EPL			Feasible Speeds			
EPL [%]	Cat B [kW]	Cat C [kW]	Not Feasible	Margin 0-5%	Margin 5-15%	Margin > 15%
0	1081.66	957.18	0% (0)	0% (0)	0% (0)	100% (304)
9.9	1068.43	945.45	0% (0)	0% (0)	0% (0)	100% (304)
14.1	821.63	727.18	0.0% (0)	0.0% (0)	0.7% (2)	99.3% (302)
18.3	591.31	523.82	0.0% (0)	0.0% (0)	1.3% (4)	98.7% (300)
22.5	367.45	326.05	0.0% (0)	0.7% (2)	2.0% (6)	97.4% (296)
26.7	185.34	164.85	0.7% (2)	0.7% (2)	3.6% (11)	95.1% (289)
30.9	0	0	1.3% (4)	1.6% (5)	3.9% (12)	93.1% (283)

Table 56: All scenarios of combinations (EPL & B or C cat of ESDs) and their performance

On the next table we can see the maximum Speed on Summer drought (scantling) and design drought in relation to the kW produced from the ESDs in combination with the appropriate EPL for vessel 3.

Combination of EPL and ESDs (B or C)			Vmax MCR(ME),Lim [kn]	
EPL [%]	Cat B [kW]	Cat C [kW]	Scantling Draught	Design Draught
0	1081.66	957.18	15.81	16.47
9.9	1068.43	945.45	15.56	16.17
14.1	821.63	727.18	15.42	16.02
18.3	591.31	523.82	15.28	15.87
22.5	367.45	326.05	15.11	15.69
26.7	185.34	164.85	14.8	15.49
30.9	0	0	14.6	15.23

Table 57: All scenarios of combinations (EPL & B or C cat of ESDs) and their maximum speed

6.6 Case study 5

Vessel Characteristics

Vessel Type	Bulk Carrier
Year of built	2019
Length Between Perpendiculars	225.30 [m]
Breadth	32.26 [m]
Depth, main deck	20.00 [m]
Summer Load Draught	14.45 [m]
Deadweight at Summer (Scantling) Draught	82031.1 [ton]
Gross Tonnage	44095

Main Engine Characteristics

Maximum Continuous Rating	9801.00 [kW]
Rotational Speed at MCR	90.3 [RPM]
Specific Fuel Consumption at 75% (SFC)	162.91 [g/kWh]
CO2 Conversion Factor	3.206
Number of Sets	1

Auxiliary Engine Characteristics

Maximum Continuous Rating	690.00 [kW]
Rotational Speed at MCR	900.0 [RPM]
Specific Fuel Consumption at 50% (SFC)	235.3 [g/kWh]
CO2 Conversion Factor	3.206 [t/t]
Number of Sets	3

Calculation of Current EEXI

ΣP(ME) at 75% MCR	7350.75 [kW]
Capacity	82031.1 [ton]
fj	1
fi	1.013
fc	1
fl	1
fw	1
fm	1
Vref	14.40 [knots]
Attained EEXI	3.52 g-CO2/ton.mile.

The present vessel is a Bulk Carrier built in accordance with the Common Structural Rules (CSR) of the classification societies and assigned the class notation CSR, therefore, according to MEPC. 308(73) Paragraph 2.2.11.3.

Here, f(CSR) is calculated as 1.013.

Required EEXI

Ship Type	Bulk Carrier
a	961.79
b	82031.1
c	0.477
EEDI Reference line value	4.36 (g-CO2/ton.mile)
Deadweight	82031.1
Reduction Factor	20
Required EEXI	3.48 (g-CO2/ton.mile)

Engine Power Limitation Calculations

MCR(ME)	9801.00 [kW]
MCR(ME),Lim	8722.89 [kW]
ΣP(ME)	7240.00 [kW]
SFC(ME)	162.99 [g/kWh]
Power Reduction	11.00 [%]
Actual attained EEXI	3.48 g-CO2/ton.mile.

Speed Reduction.

Speed Vref	14.40 [knots]
Speed Vref,Lim	14.34 [knots]
Speed Reduction	0.37 [%]
Actual attained EEXI	3.48 g-CO2/ton.mile.

Vessel 3 does not meet the requirements of EEXI Regulation.

A reduction to EEXI of 3.52 - 3.48 = 0.04 g-CO2/ton.mile is further required.

In this case study we can easily see that although we have a very small difference in Required and attained index (0.04 g-CO2/ton.mile) we need an EPL of 11.00%.

In this particular case with such a small EPL the vessel can proceed with de rating the engine without the problem of interfiaring with the operational profile. What is interesting to see is that with a very small amount of Power savings (either propulsion or Auxiliary) we can avoid completely the EPL.

Net propulsion power savings (Cat. B) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Propulsion Power Savings
[%]	[kW]
0.0	91.64
11.0	0.00

Figure 83: Effect of Category B EET adoption on required Mechanical Engine Power Limitation.

Net auxilliary power savings (Cat. C) and corresponding required Mechanical EPL	
Required Mechanical EPL	Net Aux. Power Savings
[%]	[kW]
0.0	63.44
11.0	0.00

Figure 84: Effect of Category C EET adoption on required Mechanical Engine Power Limitation.

In this case study its showcased that for new vessels which are more efficient there is the alternative of using an ESD instead of EPL. We can see that with only 63.44 kW of power savings from category C or 91.64 kW of power savings category B we have a complient vessel without the usage of engine power limitation.

In this context we can experiment with ESDs of category A. As shown before Technologies that shift the power curve, which results in the change of combination of P_P and V_{ref} : e.g., when V_{ref} is kept constant, P_P will be reduced and when P_P is kept constant, V_{ref} will be increased.

In the next table we see the Effect of category on the EPL .

Required Mechanical EPL	Propulsion Power Savings	Required Vref
[%]	[%]	[knots]
0.0	4.2	14.56
11.0	0.0	14.34

The propulsion power savings are calculated via the following process. In order to meet the EEXI regulation, the calculated Vref, for a given Mechanical EPL, of the vessel should be equal to the required Vref. The new power-speed curves are obtained by shifting the current power- speed curves to the right, so that for power equal to the 83% Overridable Limited Maximum Continuous Rating (MCR,Lim), Vref is equal to the required Vref. The propulsion power savings are, then, calculated as the power allowance, for Vref equal to the calculated Vref, between the two (2) power-speed curves.

In the table above its shown that with only 4.2% propulsion power savings the vessel wont need EPL in order to be compliant with the regulations.

A list of the most commonly adopted EET of Category A, combined with their propulsion power saving, is shown below(source MAN 2020)

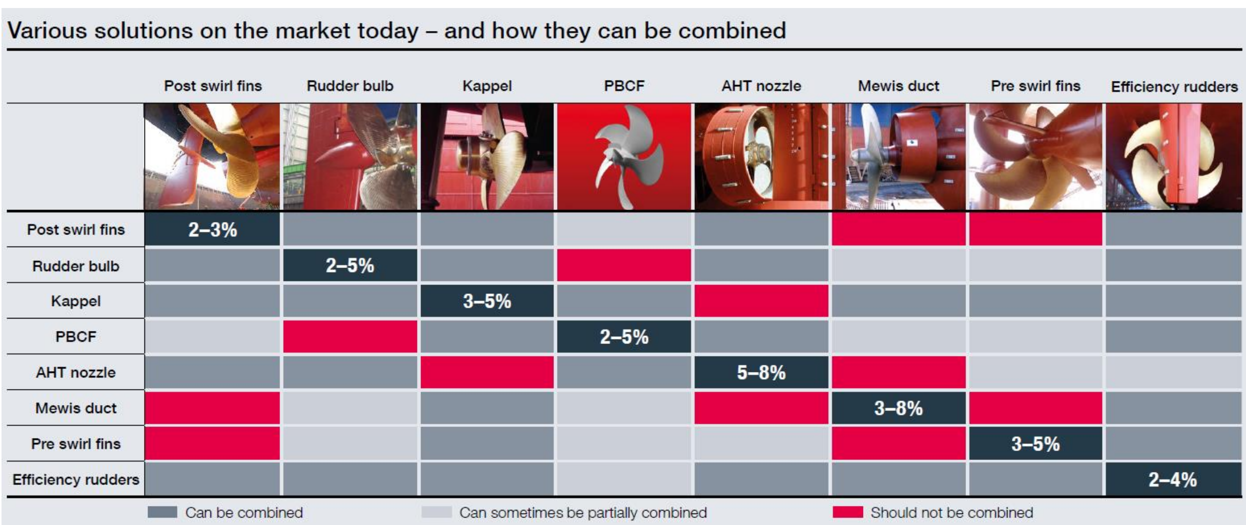


Table 58: MAN, list of adopted Cat A ESDs and how to combine

As a result, we can see that a 4.2% propulsion power savings is more than feasible. The vessel will be compliant with the regulations without an EPL.

7 Conclusions

This thesis aimed to extensively describe the upcoming EEXI regulation, as part of the IMO's strategy to reduce the CO2 emissions from existing vessels. It also aimed to provide a wide list of applicable technical solutions that are able to contribute to the compliance with the EEXI requirements. The most promising solution was considered by the industry, to be the limitation of the main engine. The effect of EPL limitation on EEXI compliance is by now known, the effect of ESDs thought is a matter of further consideration. Also, the analysis of the Post EEDI fleet gave us insights on both the actual implementation of the EEDI regulations on the EEXI ones but also the absence of ESDs highlighted again the importance of incentivize development and deployment further the energy saving technologies and innovative ship designs.

In that direction the main conclusions deriving from this report are the following:

- The majority of pre-EEDI vessels will need corrective actions in order to comply with the requirements. This comes from the fact that the non-mandatory vessels but also the phase 0 vessels showcased very low compliance.
- Newer ships subject to the first phases of the EEDI are closest on complying with the EEXI requirements. Analysis of the IMO EEDI database reveals that with the exception of bulk carriers, a large share of ships in almost all class categories already comply with the EEXI regulations.
- All phase 2 and onwards vessel comply without corrective actions.
- Some specific DWT categories of vessels will experience trouble complying and especially the ones close to the size that the reduction factor is changing. Perfect example of this are the bulk carries near 200.000 tones (reduction factor 20). The compliance skyrockets from 28% to 88% for the vessels bigger than 200.00 for the simple fact that they have 5% smaller reduction factor(15%). Same results were found for container ships on the size fraction 150.000-200.000 that with a reduction factor of 45 and a compliance of 93% we go for vessels bigger than 200.000 to a reduction factor of 50 and a compliance of 48%.
- Almost no vessel in all 3 categories has reported the use innovative electrical and/or mechanical energy saving technologies, there is considerable scope for further improvement.
- Some vessels will have to consider different options in order to comply to keep the same operational profile.
- Compliance with the technical EEXI favors pre-EEDI ships with oversized main engines.
- Most pre-EEDI ships might be able to achieve EEXI compliance without influencing the ships' operational schedules with only EPL.
- Some vessels will experience changes in their operational schedule for EEXI compliance through EPL. Investing in ESDs of all 3 categories may help on keeping the same operational schedule on some cases.
- Vessels that need significant EPL for compliance can't use ESDs alone. It is necessary to use them only in combination with a smaller EPL.
- As revealed from the last case study vessels with very small EPL (<10%) can easily be compliant with a retrofit without any de-rating.

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