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DIPLOMA THESIS

The effect of Engine Power Limitation on the Energy Efficiency Existing Ship Index (EEXI)

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Abstract

Nowadays, the shipping industry is in urgent need of efficient solutions able to contribute to the reduction of the CO_2 emissions from ships. Due to that fact, the International Maritime Organization established the Energy Efficiency Existing Ship Index (EEXI) and suggested a package of technical and operational means of complying with the requirements. Based on that, the current thesis aims to examine the effect of Engine Power Limitation, as a promising measure, on the upcoming EEXI. In order to achieve that, the study focuses on the subject from both a theoretical and a practical point of view. More specifically, from the theoretical perspective, the requirements of the EEXI in terms of applicability, calculation and safety are specified. Additionally, a list of proposed technical solutions is presented, with special emphasis given to the Engine Power Limitation. Regarding the calculation process, an extended case study is conducted for two different vessels, a 180,000 DWT Bulk Carrier and a 75,000 DWT Product Carrier. The study focuses on the determination of the required minimum propulsion power for safe navigation and the application of Engine Power Limitation, in order to verify its effect on the EEXI. Finally, based on the operational data provided by the noon reports, a comprehensive comparison between the theoretical and the corresponding real-time results is performed, in order to estimate the effect of EPL and EEXI on the actual CO_2 emissions of the examined vessels.

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. Λόγω αυτού, ο Διεθνής Ναυτιλιακός Οργανισμός (IMO) θέσπισε το Δείκτη Ενεργειακής Αποδοτικότητας για τα υπάρχοντα πλοία (EEXI). Ο συγκεκριμένος δείκτης είναι σχεδιαστικός και ακολουθεί τη φιλοσοφία του Δείκτη Ενεργειακής Αποδοτικότητας για τα νεότευκτα πλοία (EEDI). Στόχος του EEXI είναι ο προσδιορισμός αυστηρών απαιτήσεων όμοιες με εκείνες που ισχύουν για τον EEDI σε ότι αφορά τις εκπομπές διοξειδίου του άνθρακα. Για τη συμμόρφωση με το κανονιστικό πλαίσιο ο IMO προτείνει ένα πακέτο τεχνικών και λειτουργικών μέτρων. Με βάση τα παραπάνω, η παρούσα Διπλωματική εργασία καταπιάνεται με την επίδραση της μείωσης ισχύος της κύριας μηχανής του πλοίου (EPL), μέτρο το οποίο κρίνεται ως πολλά υποσχόμενο, στον επερχόμενο δείκτη ενεργειακής αποδοτικότητας (EEXI). Προς αυτή την κατεύθυνση, η εργασία εστιάζει στο ζήτημα τόσο από θεωρητικής, όσο και από υπολογιστικής σκοπιάς.

Ειδικότερα, το θεωρητικό μέρος προσδιορίζει τις απαιτήσεις του EEXI σχετικά με τα ζητήματα της εφαρμογής του κανονισμού, του αναλυτικού υπολογισμού και της ασφάλειας. Όσον αφορά το ζήτημα της εφαρμογής, ορίζεται με σαφήνεια το χρονοδιάγραμμα του EEXI, τα απαραίτητα περιεχόμενα που οφείλει να καλύπτει η απαιτούμενη τεχνική έκθεση, καθώς και η διαδικασία για τη βεβαίωση συμμόρφωσης με τις απαιτήσεις από τον νηογνώμονα. Σχετικά με τον αναλυτικό υπολογισμό, δίνεται έμφαση στην εξίσωση που προτείνεται από τον IMO για τον προσδιορισμό του EEXI, ενώ ταυτόχρονα ορίζονται οι σχετικοί παράμετροι και περιγράφεται η διαδικασία υπολογισμού τους με βάση τις οδηγίες του IMO. Ιδιαίτερη μνεία γίνεται στον προσδιορισμό της ταχύτητας αναφοράς για τα πλοία τα οποία υπάγονται στον EEXI, καθώς προτείνεται ένα σύνολο διαφορετικών μεθόδων για την προσέγγισή της. Όσον αφορά το ζήτημα της ασφάλειας, δίνεται έμφαση στον προσδιορισμό της ελάχιστης απαιτούμενης ισχύος για ασφαλή ναυσιπλοΐα, σύμφωνα με τις δύο μεθόδους που προτείνονται από τον IMO. Τέλος, στο θεωρητικό μέρος της εργασίας παρουσιάζεται ένα πλήθος προτεινόμενων καινοτόμων τεχνικών λύσεων που δύνανται να εφαρμοστούν τόσο στη γάστρα και την έλικα του πλοίου, όσο και στην κύρια μηχανή του. Ιδιαίτερη έμφαση δίνεται στη μείωση ισχύος της κύριας μηχανής (EPL), ως ένα οικονομικό, εύκολα εφαρμόσιμο και με μεγάλες προοπτικές συμμόρφωσης με τις απαιτήσεις του EEXI τεχνικό μέσο.

Όσον αφορά το υπολογιστικό μέρος, πραγματοποιείται αναλυτική μελέτη για δύο πλοία διαφορετικού τύπου, ενός πλοίου μεταφοράς φορτίου χύδην (Bulk Carrier), χωρητικότητας 180,000 τόνων, και ενός δεξαμενοπλοίου (Product Carrier), χωρητικότητας 75,000 τόνων. Η συγκεκριμένη επιλογή των πλοίων γίνεται λόγω του ότι αποτελούν δύο από τους πιο διαδεδομένους τύπους, στους οποίους πρόκειται κατά κύριο λόγο να εφαρμοστεί η μείωση ισχύος στην κύρια μηχανή ως μέσο συμμόρφωσης με τον EEXI.

Αρχικά, η διαδικασία καταπιάνεται με τον προσδιορισμό της ελάχιστης απαιτούμενης ισχύος για ασφαλή ναυσιπλοΐα. Πιο συγκεκριμένα, η απαιτούμενή ισχύς υπολογίζεται με βάση δύο διαφορετικές προσεγγίσεις, τη ‘Level 1’ και τη ‘Level 2’, όπως περιγράφονται από τον IMO. Η πρώτη μέθοδος βασίζεται σε στατιστικά δεδομένα και προσδιορίζει την ελάχιστη απαιτούμενη ισχύ με βάση τον τύπο και τη χωρητικότητα του πλοίου. Όσον αφορά τη δεύτερη μέθοδο, βασίζεται κατά κύριο λόγο τόσο στα χαρακτηριστικά του πλοίου, όσο και στην κατάσταση θάλασσας που περιγράφεται από κατάλληλο φάσμα. Ειδικότερα, η μέθοδος αυτή έχει ως στόχο να προσδιορίσει την απαιτούμενη ισχύ ενός πλοίου, ώστε αυτό να είναι σε θέση να αναπτύξει την αναγκαία ταχύτητα προχώρησης που απαιτείται για λόγους ασφαλείας σε κακές καιρικές

συνθήκες. Ο προσδιορισμός την ισχύος προϋποθέτει τον υπολογισμό της αντίστασης που το πλοίο καλείται να υπερνικήσει. Με βάση την αντίσταση και την ώση που απαιτείται γίνεται χρήση των διαγραμμάτων έλικας σε ελεύθερη ροή, προκειμένου να υπολογιστούν οι σχετικοί συντελεστές, και εν τέλει η απαιτούμενή ισχύς της έλικας. Έτσι, λαμβάνοντας υπόψιν τον βαθμό απόδοσης του άξονα της μηχανής, προσδιορίζεται η ζητούμενη ισχύς της. Παράλληλα, η δεύτερη μέθοδος δεν προσδιορίζει μονάχα την απαιτούμενη ισχύ αλλά και τις αντίστοιχες στροφές, θέτοντας έτσι τον περιορισμό ότι το συγκεκριμένο σημείο λειτουργίας οφείλει να βρίσκεται κάτω από το όριο ροπής/ταχύτητας της κύριας μηχανής για να είναι αποδεκτό. Τα αποτελέσματα των δύο μεθόδων υποδεικνύουν ότι η πρώτη μέθοδος έχει ιδιαίτερα υψηλότερες απαιτήσεις ισχύος συγκριτικά με τη δεύτερη, και για τα δύο πλοία.

Παράλληλα, το υπολογιστικό κομμάτι ασχολείται με την εφαρμογή της μείωσης ισχύος (EPL) προκειμένου να εξετασθεί η συμμόρφωση με τις απαιτήσεις του EEXI. Η μείωση ισχύος εφαρμόζεται για έξι διάφορες περιπτώσεις ανά πλοίο, οι οποίες λαμβάνονται υπόψιν για την πληρέστερη κατανόηση των σχετικών αναγκών. Ειδικότερα, στην πρώτη εξεταζόμενη περίπτωση για το δείκτη EEXI, θεωρείται ότι η μείωση ισχύος είναι μηδενική. Στις επόμενες δύο περιπτώσεις, η ισχύς της μηχανής μειώνεται στα επίπεδα που ορίζονται από την ελάχιστη απαιτούμενη ισχύ με βάση τις δύο σχετικές μεθόδους υπολογισμού, 'Level 1' και 'Level 2'. Οι εν λόγω περιπτώσεις, εξασφαλίζουν ότι το πλοίο θα έχει πάντοτε επαρκή ισχύ σε περίπτωση κακών καιρικών φαινομένων, σύμφωνα με τις απαιτήσεις του IMO, ενώ ταυτόχρονα διερευνάται και ταυτόχρονη πιθανή συμμόρφωση με τον EEXI. Έπειτα, στις περιπτώσεις τέσσερα και πέντε η μείωση ισχύος έχει ως στόχο τη συμμόρφωση με τις απαιτήσεις του EEXI, όπως αυτές διαμορφώνονται ανάλογα με το χρονικό σημείο στο οποίο εφαρμόζονται. Ειδικότερα, γνωρίζοντας τις σχετικές απαιτήσεις, εξετάζεται το ελάχιστο ποσοστό EPL που απαιτείται για τη συμμόρφωση του πλοίου με τις διατάξεις του IMO. Ακόμη, μελετάται μία επιπλέον περίπτωση κατά την οποία η ισχύς μειώνεται σε τέτοιο βαθμό, ώστε η αντίστοιχη ταχύτητα αναφοράς να ισούται με τη μέση πραγματική ταχύτητα του πλοίου.

Στο επόμενο στάδιο της υπολογιστικής διαδικασίας, με βάση τα πραγματικά δεδομένα των δύο πλοίων, τα οποία αντλούνται από τις ημερήσιες αναφορές, πραγματοποιείται σύγκριση μεταξύ των θεωρητικών και των αντίστοιχων πραγματικών αποτελεσμάτων. Η σύγκριση γίνεται με τη βοήθεια ιστογραμμάτων που κατανέμουν τα πραγματικά δεδομένα σε κατάλληλα διαστήματα και βοηθούν στη συσχέτιση με τις θεωρητικές τιμές. Η εν λόγω διαδικασία στοχεύει στη μελέτη των πραγματικών ταχυτήτων των δύο πλοίων, ενώ ταυτόχρονα επιδιώκει να διερευνήσει εκτενώς την επίδραση της μείωσης ισχύος (EPL) και του EEXI στις πραγματικές εκπομπές διοξειδίου του άνθρακα.

Τέλος, εξάγονται αναλυτικά συμπεράσματα που αφορούν τόσο τη συμμόρφωση με τις απαιτήσεις του EEXI, όσο και τη συνεισφορά του EPL στη μείωση των αερίων ρύπων. Πιο συγκεκριμένα, και για τα δύο πλοία που μελετώνται προκύπτει ότι η συμμόρφωση με τις απαιτήσεις του EEXI προϋποθέτει ένα ιδιαίτερα υψηλό EPL. Παράλληλα, αντίστοιχη απαίτηση για υψηλή μείωση ισχύος υπάρχει και σε ότι αφορά τη μείωση των πραγματικών εκπομπών διοξειδίου του άνθρακα.

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Table of Contents

1 Introduction 1
1.1 Overview of Greenhouse Gases 1
1.2 Reducing greenhouse gas emissions from shipping 5
1.3 Objectives and Structure 9
2 Energy Efficiency Existing Ship Index (EEXI) 11
2.1 Introduction to the Energy Efficiency Design Index (EEDI) 11
2.2 Introduction to the EEXI 11
2.3 EEXI implementation 12
2.3.1 Timeline 12
2.3.2 Technical File 14
2.3.3 Operational approach 16
2.3.4 Required EEXI 17
2.4 EEXI Calculation 20
2.4.1 EEXI Calculation formula 20
2.4.2 Parameters' specifications 21
2.4.3 Reference speed 24
2.4.4 Minimum propulsion power determination 28
2.4.5 Calculated value of attained EEXI 35
3 Means of complying with the EEXI 37
3.1 Hull and Propeller Retrofits 37
3.2 Modification of the Main Engine 40
4 Engine Power Limitation 43
4.1 IMO Guidelines on EPL 43
4.2 RightShip's EPL acceptance criteria 44
4.3 Hyundai's recommendations on EPL 47
4.4 The disadvantage of Engine Power Limitation 49
5 Case study: The effect of EPL on the EEXI and CO_2 emissions 50
5.1 180,000 DWT Bulk Carrier 51
5.1.1 Data 51
5.1.2 Minimum Propulsion Power Calculation 52
5.1.3 Power / Speed Curve 61
5.1.4 EEXI Calculation 65
5.1.5 EEXI Requirements 67

5.1.6 Comparison with operational data from the noon reports 69
5.2 75,000 DWT Product Carrier 79
5.2.1 Data 79
5.2.2 Minimum Propulsion Power Calculation 80
5.2.3 Power/Speed Curve 81
5.2.4 EEXI Calculation 82
5.2.5 EEXI Requirements 83
5.2.6 Comparison with operational data from the noon reports 84
6 Conclusion 95
7 References 97

1 Introduction

Nowadays, air pollution is a major issue global community needs to face. Human activities have led to huge demand of energy, especially within the last couple of decades. In order to produce that energy, industries exploit fossil fuels. Thus, great amounts of gases and chemicals are released in the atmosphere. These pollutants, inevitably, affect both the environment and the human health.

Gases that trap heat in the atmosphere are called Greenhouse Gases (GHG). The majority of direct emissions comes from the consumption of fossil fuel in order to produce energy. Emissions are also caused due to chemical reactions and leakages from industrial processes. The main aspect of those gases is that they absorb radiation emitted from the surface of the earth, contributing to the greenhouse effect.

1.1 Overview of Greenhouse Gases

According to the (EPA, 2021), the most important GHGs are Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O) and Fluorinated Gases. A brief overview of those gases is presented below:

- **Carbon Dioxide (CO_2):** Carbon Dioxide enters the atmosphere mostly through burning fossil fuels such as coal and natural gas. It is also emitted as a result of chemical reactions, such the manufacture process of cement. CO_2 is sequestered from the atmosphere when it is absorbed by plants as part of the biological carbon cycle.
- **Methane (CH_4):** Methane is emitted during the production and transportation of coal, natural gas and oil. Its emissions also result from agricultural practices and by the disintegration of organic waste in municipal solid waste landfills.
- **Nitrous Oxide (N_2O):** Nitrous Oxide is emitted during agricultural and industrial activities, combustion of fossil fuels and solid waste, as well as during treatment of wastewater.
- **Fluorinated gases**: Synthetic, powerful GHGs, that are emitted through a variety of industrial processes. Fluorinated gases are sometimes used as substitutes for stratospheric ozone-depleting substances. These gases are typically emitted in smaller quantities, but because they are potent greenhouse gases, they are sometimes referred to as high global warming potential gases.

As explained by the (EPA, 2021), in order to clarify the contribution of each gas on the climate change, three major issues need to be clarified:

1. **How much there is in the atmosphere**
   Concentration is the amount of a particular gas in the air. It is measured in parts per million, billion, or even trillion. One part per million corresponds to one drop of water diluted into about 13 gallons of liquid. Larger emissions of GHG lead to higher concentration in the atmosphere.

2. **How long do they stay**
   Each one of the aforementioned gases remains in the atmosphere for an uncertain period of time that ranges from a few to thousands of years, but certainly long enough to become well mixed. Thus, the amount that is measured in the atmosphere is approximately the same all over the world, regardless of the source of the emissions.

3. **How severe is their impact**
   Some gases are more effective compared to others in terms of making the planet warmer. Consequently, for each GHG a Global Warming Potential (GWP) rate is calculated to estimate how long it remains in the atmosphere and its energy absorption level.

An extensive overview of the U.S. Greenhouse Gas emissions in 2019 is presented in the following figure:

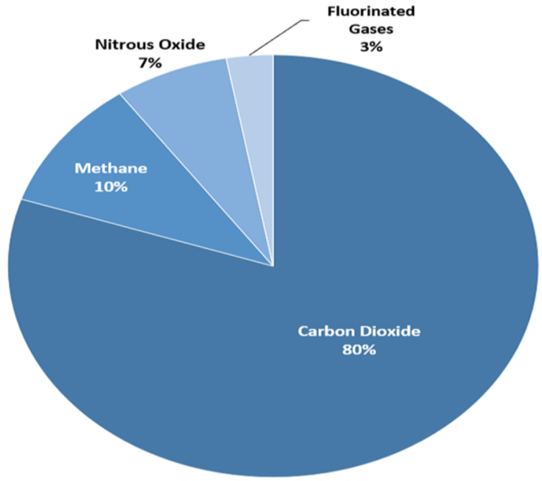

Figure 1. Total U.S. Emissions in 2019 = 6,558 million Metric Tons of CO_2 equivalent (EPA, 2021)

In order for a more comprehensive analysis of the heating effect caused by each GHG to be given, the Climate Forcing Indicator is introduced. As defined by the (EPA & NOAA, 2021), this indicator estimates the "Radiative Forcing" caused by Greenhouse Gases in the atmosphere and is presented in the following figure:

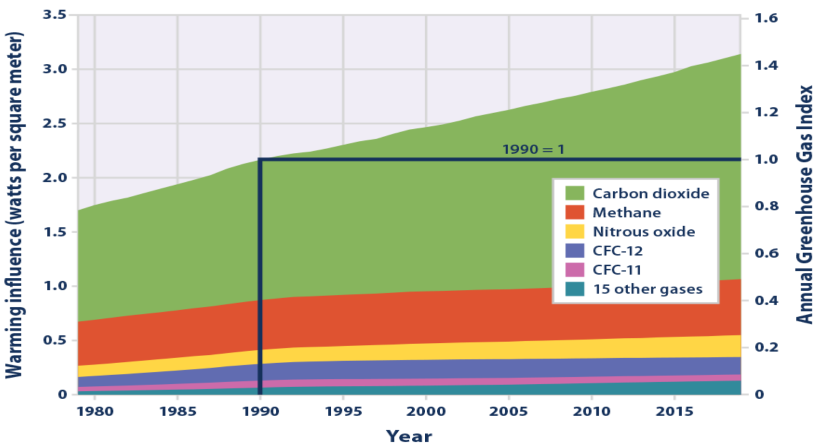

Figure 2. Radiative Forcing Caused by Major Long-Lived GHGs, 1979-2019 (EPA & NOAA, 2021)

As mentioned by the (EPA & NOAA, 2021), this figure estimates the amount of radiative forcing caused by GHGs, based on the change in concentration of these gases in the atmosphere of the earth since 1750. It represents the size of the energy imbalance in the atmosphere. On the right side of the figure, radiative forcing has been converted to the Annual Greenhouse Gas Index that is set to a value of 1.0 for 1990.

Sources of GHG emissions

Human activities are responsible for the escalated increase of greenhouses gases in the atmosphere within the last 150 years. The greatest amount of GHG emissions comes from the fossil fuel burning procedure for transportation, electricity, heat and other human needs. As reported by the (EPA, 2021), the main sources of greenhouse gas emissions in the United States are presented as follows:

- **Transportation:** The transportation sector generates the largest share of GHG emissions that primarily come from burning fossil fuel for cars, trucks, ships, trains and planes. Over 90% of fuel used in this sector is petroleum based, which mostly includes gasoline and diesel.

- **Electricity production:** Electricity production generates the second largest share of GHG emissions. Approximately, 63% of the produced electricity comes from burning fossil fuels, mostly coal and natural gas.

- **Industry:** The GHG emissions from the industry come from burning fossil fuels for energy, as well as from chemical reactions in order to produce goods from raw materials.

- **Commercial & Residential:** Emissions primarily arise from fossil fuels burnt for heat, the use of various products that contain GHGs and the handling of waste.

- **Agriculture:** They mostly come from livestock such as cows, agricultural soils and rice production.

- **Land Use & Forestry:** Land areas can act as a sink, absorbing CO_2 from the atmosphere, or a source of GHG emissions. In the US, since 1990, managed forests and other lands are a net sink, having absorbed more CO_2 from the atmosphere than they emit.

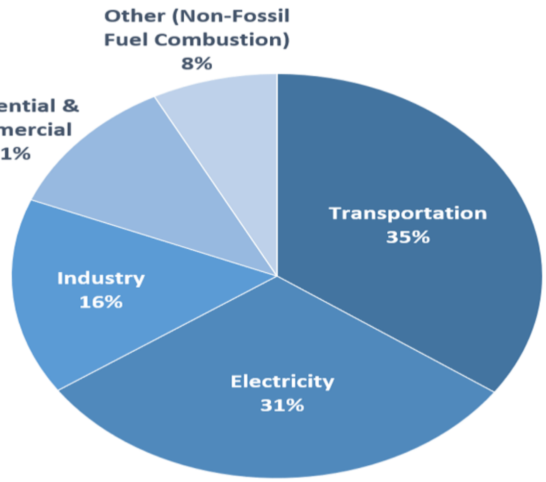

Figure 3. All emission estimates from the Inventory of U.S. GHG Emissions and Sinks: 1990-2019 (EPA, 2021)

Effects of greenhouse gases

The extensive GHG emissions heavily affect the planet. By burning fossil fuels huge amounts of gases are trapped in the atmosphere, having a huge impact on both the environment and the society.

As stated by (Cook, 2016), extreme weather phenomena such as heatwaves, flooding, droughts and wildfires have become more frequent during the latest decades. Heatwaves are getting hotter and lasting longer. More heat leads to more evaporation, and thus more moisture in the atmosphere which means more flooding events. The melting of glaciers and ice sheets causes the rise of the seal level and consequently threatens millions of people living near coastlines. Furthermore, the emitted carbon dioxide is absorbed into the ocean and acidifies the waters. In order for a clearer picture of the effect that the climate change has on the environment the following figure is provided:

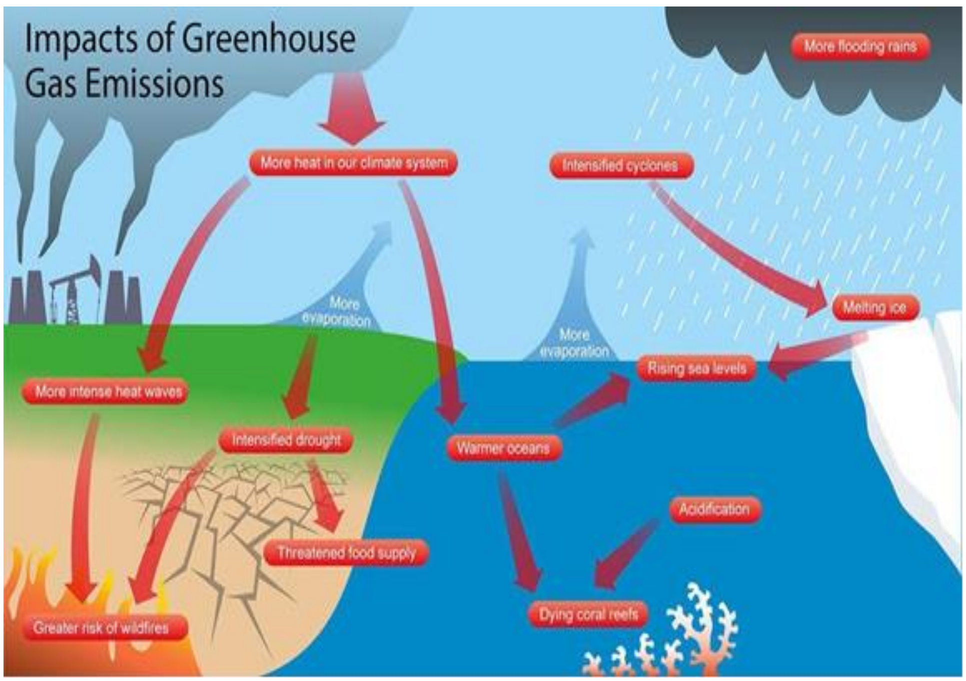

Figure 4. Impacts of GHG emissions (Cook, 2016)

As a result, global warming causes a wide range of impacts on the natural environment, that inevitably affects human society in many different ways.

According to the (WHO, 2021), climate change due to GHG emissions is one of the most severe health threats that humanity has to face. Despite the fact that no one is safe from its consequences, the people whose health is being affected the most are the ones who have contributed the least to the causes of the climate change; Children, ethnic minorities, poor communities, migrants, older population and those with underlying health conditions.

As specified by the (CDC, 2020), the impact of the climate change on human health, in accordance with the environmental effects, is presented in the following figure:

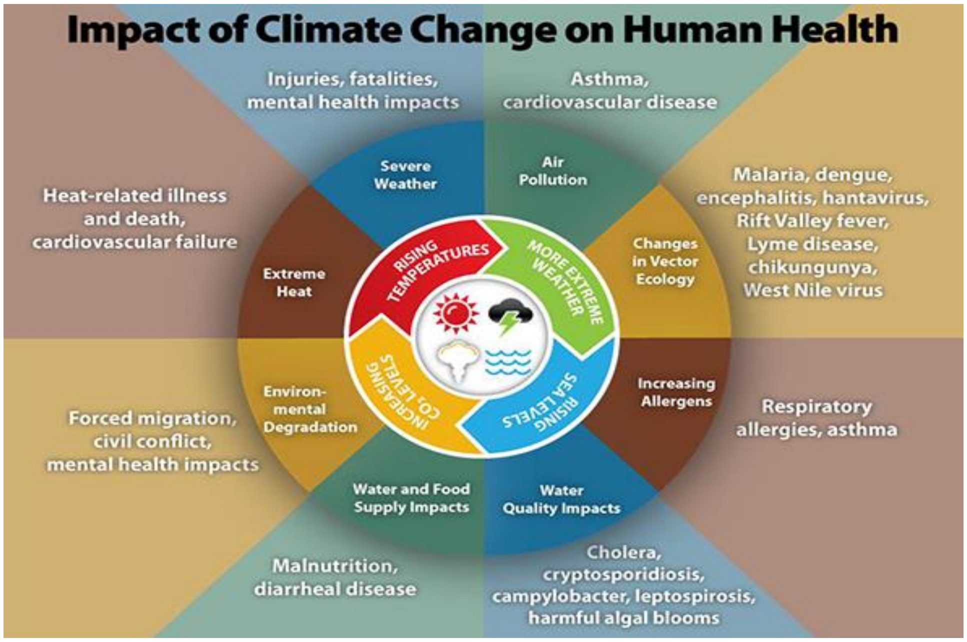

Figure 5. Impact of Climate Change on Human Health (CDC, 2020)

Every sector of the global economy, from manufacturing to agriculture and transportation to power production, contributes GHGs to the atmosphere. Thus, all of them have to diverse from burning fossil fuels in order to avoid the worst effects of climate change. The technologies and countermeasures for restraining the greenhouse gas emissions already exist, including renewable sources, boosting energy efficiency and discouraging carbon emissions by implementing a high price policy on them.

1.2 Reducing greenhouse gas emissions from shipping

Maritime transport is considered by the global markets as the backbone of international trade and economy. More specifically, according to the (UNCTAD / RMT, 2018), around 80% of global trade by volume is carried by sea, and international seaborne trade has been constantly growing for the last decades.

As reported by the (IMO, 2015), GHG emissions from international shipping in 2012 accounted for some 2.2% of anthropogenic CO_2 emissions. It was also recorded that such emissions could probably grow from 50% to 250% by 2050.

The International Maritime Organization contributes to the global fight against climate change and its impacts. Thus, IMO has adopted mandatory measures to reduce GHG emissions from the international shipping industry, under its pollution prevention treaty (MARPOL). In that direction, the Energy Efficiency Design Index (EEDI), which is mandatory for new vessels, and the Ship Energy Efficiency Management Plan (SEEMP) have been established.

Initial Strategy

In 2018, IMO adopted an initial strategy in order to contribute to the reduction of GHG emissions from ships. That Initial Strategy identifies several levels of ambition for the international shipping sector, noting that technological innovation and the global introduction of alternative fuels and energy sources for shipping are crucial in order to achieve the overall ambition. As specified by the (IMO, 2018), the Initial Strategy targets the following objectives:

- Enhancing IMO's contribution to global efforts by addressing GHG emissions from international shipping.

- Identifying actions to be implemented by the international shipping sector, as appropriate, while addressing impacts on States and recognizing the critical role of international shipping in supporting the continued development of global trade and maritime transport services.

- Identifying actions and measures to assist in achieving the set goals, including incentives for research, development and monitoring of GHG emissions from international shipping.

As explained by the (IMO, 2019), reaching the ambitious goals of the Initial GHG strategy requires a mix of technical, operational and innovative solutions applicable on various types of vessels. Some of them, in accordance with the corresponding estimation of the GHG reduction rate, are presented in the following figure:

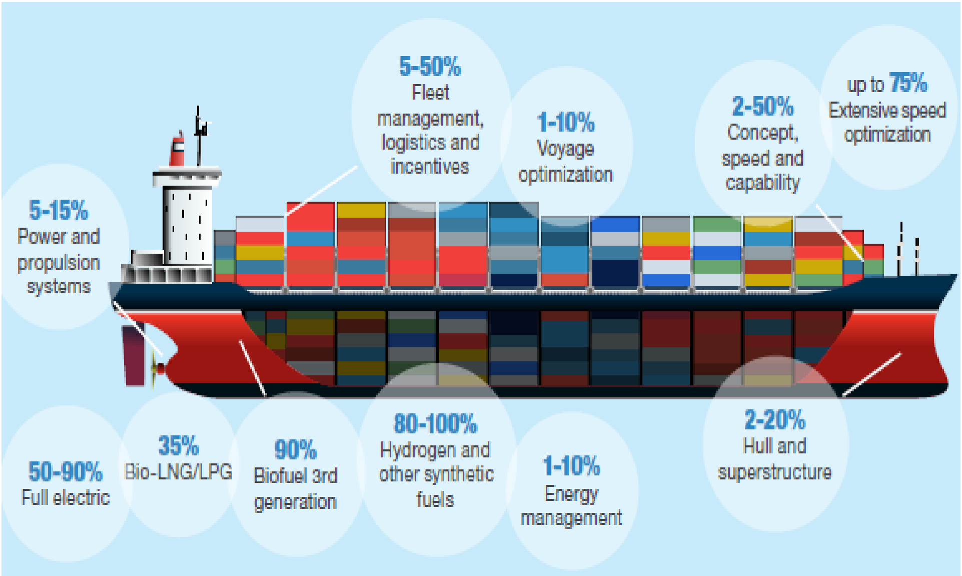

Figure 6. Solutions applicable to ships (IMO, 2019)

Vision and Level of ambition

IMO is focused on reducing GHG emissions from international shipping and urgently aims to eliminate them as soon as possible in this century.

In accordance with the (IMO, 2018), the corresponding levels of ambition leading the Initial Strategy are described as follows:

- Carbon intensity (emissions per transport work) to decline through implementation of further phases of the Energy Efficiency Design Index (EEDI) for new ships

- Reduction of CO_2 emissions per transport work (carbon intensity), as an average across international shipping by at least 40% by 2030, pursuing efforts towards 70% by 2050 compared to 2008.

- Reduction of the total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out, for achieving CO_2 emissions reduction consistent with the Paris Agreement temperature goals.

How to achieve these ambitious goals

The IMO GHG Strategy provides a wide list of possible short-term, mid-term and long-term measures, such as further improvement of the EEDI and the SEEMP, National Action Plans, enhanced technical cooperation, port activities, research and development, support to the effective uptake of alternative low-carbon and zero-carbon fuels, innovative emission reduction mechanisms, etc.

Based on the (IMO, 2018), the possible upcoming measures should be consistent with the timeline presented below:

- Short-term measures would be measures finalized and agreed by the Committee between 2018 and 2023.

- Mid-term measures could be measures finalized and agreed by the Committee between 2023 and 2030, able to reduce carbon intensity by at least 40%.

- Long-term measures could be measures finalized and agreed by the Committee beyond 2030, able to reduce carbon intensity by at least 70%.

In accordance with the (IMO, 2018), a brief but comprehensive list of possible short, middle and long-term measures is presented below:

- **Short-term measures**
  i. Further improvement of the existing energy efficiency framework with a focus on the EEDI and SEEMP
  ii. Develop technical and operational energy efficiency measures for both new and existing vessels, including consideration of indicators in with the three-step approach that can be

utilized to indicate and enhance the energy efficiency performance of shipping, such as the Annual Efficiency Ratio (AER) and the Individual Ship Performance Indicator (ISPI)

iii. Establishment of Existing Fleet Improvement Program

- **Mid-term measures**
  i. Implementation program for the effective uptake of alternative low-carbon and zero-carbon fuels
  ii. Operational energy saving measures for both new and existing vessels including indicators in line with three-step approach that can be utilized to indicate and enhance the energy efficiency performance of ships
  iii. New/Innovative emission reduction mechanisms, possibly including Market-based Measures (MBMs), to incentivize GHG emission reduction

- **Long-term measures**
  i. Pursue the development and provision of zero-carbon and fossil-free fuels to enable the shipping sector to assess and consider decarbonization in the second half of the century
  ii. Encourage and facilitate the general adoption of other possible new/innovative emission reduction mechanisms

A comprehensive illustration of the various possible ways to comply with the IMO's Initial strategy is presented in the following diagram:

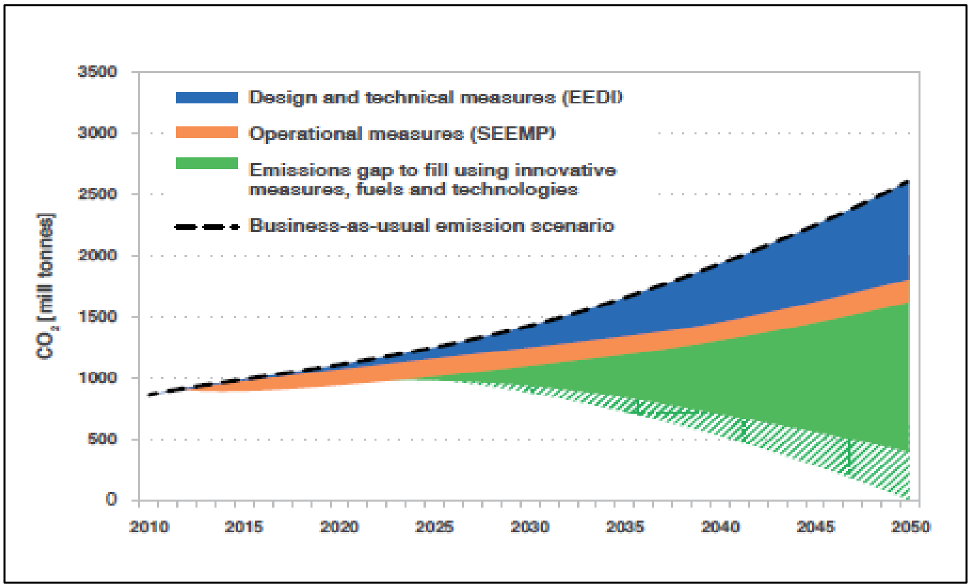

Figure 7. Overall GHG reduction pathway (IMO, 2019)

The main and most ambitious goal the IMO has set is reaching zero greenhouse gas emissions as soon as possible in this century. Shipping community should focus all of its efforts in order to achieve that milestone.

1.3 Objectives and Structure

The purpose of this thesis is to analytically present the upcoming Energy Efficiency Existing Ship Index (EEXI) and to meticulously investigate the effect of the Engine Power Limitation (EPL) on it, in terms of compliance with the requirements and contribution to the reduction of the CO_2 emissions from vessels. More specifically, the main objectives of the current thesis are:

- ✓ The presentation of the issues caused by the Greenhouse Gas emissions
- ✓ The description of the strategy adopted by the IMO to reduce CO_2 emissions from shipping
- ✓ The explanation of the implementation and calculation procedures of the upcoming EEXI
- ✓ The proposal of a wide range of energy efficient technical solutions to comply with the EEXI
- ✓ The comprehensive analysis of the Engine Power Limitation as the most promising mean of compliance
- ✓ The analytical determination of the required Minimum Propulsion Power, in order to ensure the safe application of the Engine Power Limitation
- ✓ The calculation of the EEXI for two vessels of different size and type, in order to assess the corresponding level of compliance, depending on the limitation of the main engine
- ✓ The comparison of the real-time operational data with the theoretical EEXI values, in order to assess the actual effect of the Engine Power Limitation and the EEXI on the CO_2 emissions

In the first part of the report, the EEXI is described from a theoretical point of view. Under this scope, a brief analysis of the International Maritime Organization's (IMO) strategy about the reduction of the CO_2 emissions from shipping is conducted, to reveal the corresponding level of ambition. The theoretical approach to the EEXI consists of three major parts. First and foremost, the EEXI implementation section sets the timeline of the requirements, provides instructions on the survey and verification processes and analyzes the EEXI requirements for different vessels. Secondly, the EEXI calculation section describes the corresponding formula and the included parameters, proposes alternative methods on the estimation of the reference speed and minimum propulsion power and describes a preliminary example of the attained EEXI value calculation process, for a specific vessel. Last but not least, a detailed list of different types of retrofits and modifications is presented, in order to reveal the wide range of the available technical solutions.

In the second part of the thesis, a detailed case study is conducted to provide valid deductions on the effect of the Engine Power Limitation on the EEXI. In that direction, two vessels of different size and type are examined, in order to provide a fair and objective basis for comparison. For each ship, the case study consists of two major steps. In the first step, a hands-on application of the theoretical part of the thesis is performed for the subject vessel. The application aims at calculating the attained EEXI values, for different EPL scenarios, and compare them with the corresponding requirements, in order to verify the level of compliance. In the second step, the real-time open sea data of the subject vessel, provided by the corresponding noon reports, are imported in the EEXI calculation formula, in order for the actual CO_2 emissions of the vessel to be approached. This procedure aims at comparing the theoretical EEXI values calculated in the first step with the real-time CO_2 emissions, in order to study the relationship between the theoretical and the actual emission values.

This thesis, beyond presenting the EEXI requirements and applying the corresponding procedures, aims at revealing the advantages and disadvantages of both the Engine Power Limitation, as a mean of complying, and the EEXI, as a mean of reducing the actual CO_2 emissions from the shipping industry.

At this point, special credits should be given to the following papers for their significant influence on both the concept and the formation of this thesis:

1) **Title**: Limiting engine power to reduce CO_2 emissions from existing ships
   Authors: Dan Rutherford, Xiaoli Mao, Liudmila Osipova, and Bryan Comer
   Date: February 2020

2) **Title**: On the effect of biofouling on the minimum propulsion power of ships for safe navigation in realistic conditions
   Authors: Shukui Liu, Apostolos Papanikolaou, Ana Bezunartea-Barrio, Baoguo Shang & Maya Sreedharan
   Date: March 2021

3) **Title**: An improved formula for estimating the added resistance of ships in engineering applications
   Authors: Shukui Liu, Apostolos Papanikolaou, Victor Bolbot
   Date: June 2016

4) **Title**: The effect of design solutions on the EEDI (Diploma Thesis)
   Authors: Giannis Roussos, Nikolaos Themelis
   Date: 2020

5) **Title**: Determining the EEDI "Minimum Propulsion Power"
   Authors: F. C. Gerhardt, M. Kjellberg, B. Korkmaz, K. Ljungqvist and A. Shiri, SSPA Sweden AB, Sweden
   Date: 2020

2 Energy Efficiency Existing Ship Index (EEXI)

2.1 Introduction to the Energy Efficiency Design Index (EEDI)

The Energy Efficiency Design Index (EEDI) is a rate that estimates the energy efficiency of new vessels (gr-CO_2/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**.**

The need to improve the future efficient of new vessels led the IMO to establish three phases. Each phase affects the EEDI reference line by progressively demanding less energy, and thus CO_2 emissions, for the same transport work. The corresponding phases as mentioned by (Transport & Environment, 2017), in accordance with the applicable time period, are presented below:

- ✓ **Phase 0**: Ships built between 2013-2015 are required to have a design efficiency at least equal to the baseline
- ✓ **Phase 1**: Ships built between 2015-2020 are required to have a design efficiency at least 10% below the reference line
- ✓ **Phase 2**: Ships built between 2021-2025 are required to have a design efficiency at least 20% below the reference line
- ✓ **Phase 3**: Ships built after 2025 are required to have a design efficiency at least 30% below the reference line

The energy efficiency of a vessel increases when the attained EEDI value decreases. As mentioned by the (IMO, 2011), under the condition that a vessel complies with the EEDI requirements, the designer of the ship is able to select the most cost-efficient solution. Furthermore, vessels that comply with the corresponding demands are more likely to sign more profitable chartering contracts.

2.2 Introduction to the EEXI

As reported by (MAN Energy Solutions, 2021), the Energy Efficiency Existing Ship Index (EEXI) is an upcoming IMO technical regulation that follows the concept of the EEDI. Its main purpose is the reduction of the CO_2 emissions produced by existing vessels. The regulation sets minimum requirements for technical efficiency. It is a one-time certification based in the design of the vessel. The EEXI is one measure out of a wide list of suggested solutions to implement IMO Greenhouse Gas Strategy. Other such measures provided by the IMO to reduce the CO_2 emissions from vessels is the Carbon Intensity Indication (CII), which regulates the operational CO_2 emissions from ships, based on the actual fuel oil consumption.

The IMO's MEPC 76 in June 2021 adopted amendments to MARPOL Annex VI, introducing the upcoming EEXI. The planned requirements will enter into force at the 1st of January 2023. According to the (DNV, 2021), the EEXI is applicable for all vessels above 400 GT falling under MARPOL Annex VI. Guidelines on calculations, survey and verification of the EEXI are finalized as per MEPC 76 requirements. The calculation guidelines refer to the corresponding EEDI instructions for new buildings with some important adaptations due to limited access to design data of the existing vessels.

As specified by the (IMO, 2021), the EEXI is defined based on the following crucial parameters of the ship:

- The power of the main and auxiliary engine
- The fuel oil consumption of the engines
- The reference speed of the vessel

As claimed by (MAN Energy Solutions, 2021), the limitation of the power of the main engine is considered the easiest and most efficient way to comply with the EEXI requirements.

According to the (IMO, 2021), the verification of the EEXI compliance will typically be performed by an Administration or organization duly authorized by it, such as a classification society acting on behalf of the flag state. In case that a ship does not comply with the corresponding requirements, technical modifications will be required to improve the EEXI of the vessel. Otherwise, penalties are going to be imposed.

2.3 EEXI implementation

2.3.1 Timeline

As specified by the (ClassNK, 2021), the EEXI enters into force in 2023. The exact timeline of the crucial phases of the EEXI implementation is presented in the following figure:

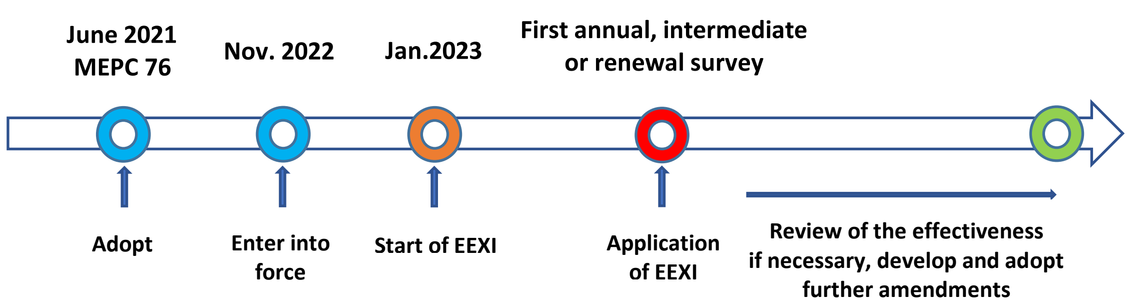

Figure 8. EEXI implementation timeline (ClassNK, 2021)

The IMO's MEPC 76 that took place in June 2021, adopted the following EEXI guidelines:

- ✓ Guidelines on the method of **calculation** of the attained Energy Efficiency Existing Ship Index (EEXI)
- ✓ Guidelines on **survey and certification** of the Energy Efficiency Existing Ship Index (EEXI)
- ✓ Guidelines on the **shaft / engine power limitation** system to comply with the EEXI requirements and use of a power reserve

According to the (DNV, 2021), the key decisions regarding the aforementioned guidelines adopted by the IMO include among others:

1. In case an engine power limitation (EPL) is installed, the engine power in the EEXI calculation (P_{ME}) should be 83% of the maximum limited power (MCR_{lim}) or 75% of maximum power (MCR), whichever is lower.
2. Numerical calculations were accepted as an alternative to tank tests when calculating the reference speed in the EEXI calculation (V_{ref}).
3. Additional options for calculating V_{ref} using in-service speed measurements will be further discussed and may be included at a later stage.
4. Consideration of energy efficiency technologies such as wind propulsion systems was deferred.
5. An additional capacity correction factor for ro-ro cargo ships (vehicle carrier) was agreed.

Entry into force

The amendments to MARPOL Annex VI are expected to enter into force on 1 November 2022. The requirements for EEXI certification are being effective from 1 January 2023 (Fig.8).

Application

As stated in the (ClassNK, 2021), the application of the EEXI follows a specific procedure, which is analytically described in the following chart:

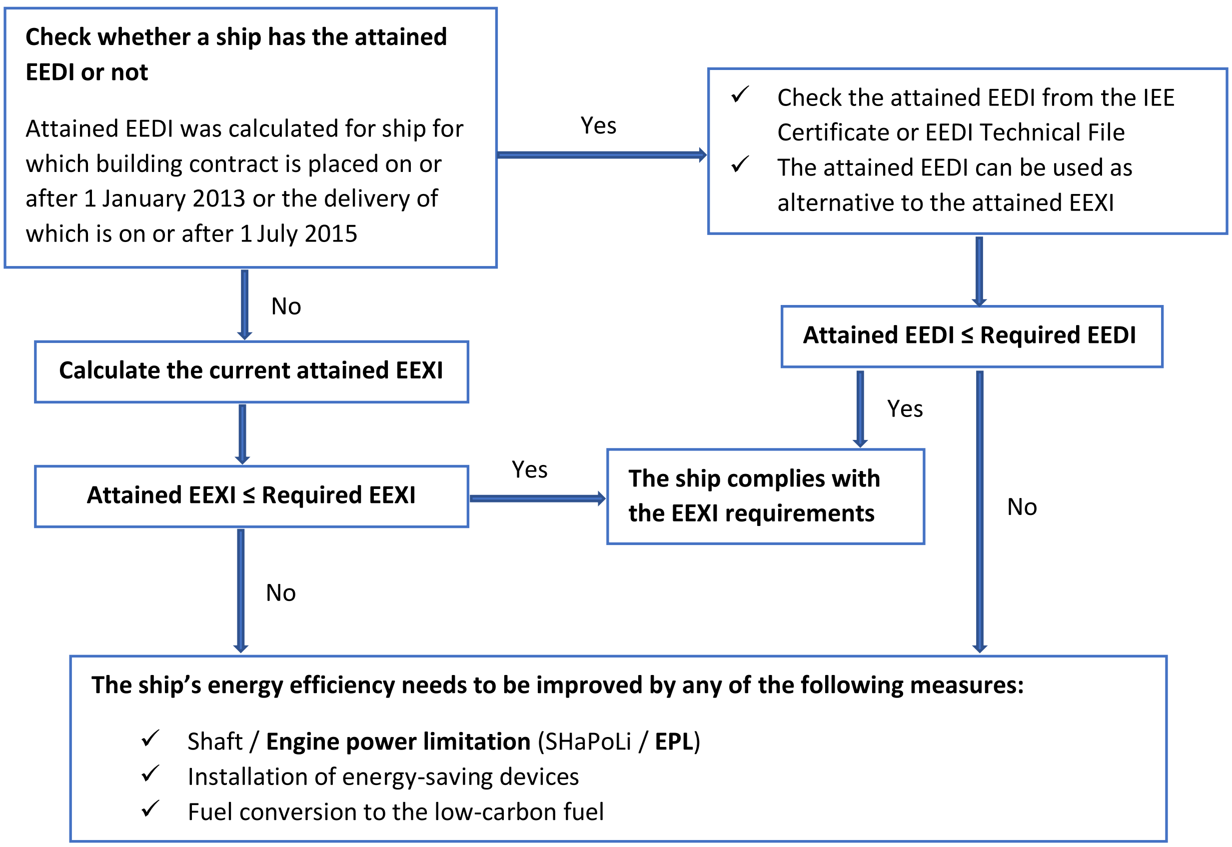

Figure 9. EEXI application procedure (ClassNK, 2021)

Verification

According to (ClassNK, 2021), the EEXI survey and verification must take place at the following timing, based on the delivery date of the vessel (Table 1).

Delivery date of the vessel	Survey and Verification
Before 1 January 2023	Whichever of the following survey of the International Air Pollution Certificate (IAPP Certificate) is first, on or after 1 January 2023: ✓ Annual survey ✓ Intermediate survey ✓ Renewal survey
On or after 1 January 2023	Initial survey of the International Energy Efficiency Certificate (IEE Certificate)

Table 1. EEXI survey and verification (ClassNK, 2021)

Review by 1 January 2026

As the timeline indicates, the IMO is obliged to review the effectiveness of the implementation of the EEXI requirements, by 1 January 2026, and adopt further amendments, if required.

2.3.2 Technical File

As reported by the (DNV, 2021), an EEXI Technical file is required for most types of ships. Vessels that were already built-in accordance with the Energy Efficiency Design Index (EEDI) Phase 2 (2020-2024) or Phase 3 (2025 and onwards) requirements, comply with the EEXI, and thus the technical file is not a prerequisite. The file contains the calculation process of the attained EEXI value, which must be less than the required EEXI. The required value is defined by the EEDI Reference lines, depending on the type and size of the subject vessel. The EEXI requirements are almost in agreement with current new buildings requirements.

As determined by the (IMO, 2021), the verification of the attained EEXI requires an application for survey and the technical file containing the appropriate information, as follows:

- **Deadweight** (DWT) or gross tonnage (GT) for ro-ro passenger ship and cruise passenger ship having non-conventional propulsion
- The rated installed power (**MCR**) of both the main and auxiliary engines
- The limited installed power ($\mathbf{MCR_{lim}}$) in cases where the overridable Engine Power Limitation system is installed
- The speed of the ship ($\mathbf{V_{ref}}$)
- The approximate ship speed ($V_{ref,app}$) for pre-EEDI ships in cases where the speed-power curve is not available
- An approved **speed-power curve** under the EEDI condition
- An estimated speed-power curve under the EEDI condition, or under a different load draught to be calibrated to the EEDI condition, obtained from tank test and/or numerical calculations, if available
- The **estimation process and methodology** of the power curves, as necessary, including documentation on consistency with the defined quality standards and the verification of the numerical setup with parent hull or the reference set of comparable ships in case of using numerical calculations

- A **sea trial report** including sea trial results, which may have been calibrated by the tank test, under the sea condition, if available
- The calculation process of $V_{ref,app}$ for pre-EEDI ships in cases where the speed-power curve is not available
- The type of **fuel**
- The specific fuel consumption (**SFC**) of both the main and auxiliary engines
- The **electric power table** for certain ship types, as necessary
- The documented **record** of annual average figure of the **auxiliary engine load** at sea obtained prior to the date of application for a survey for verification of the ship's EEXI, if applicable
- The calculation process of $P_{AE,app}$, if applicable
- The **principal particulars**, ship type and the relevant information to classify the ship as such a ship type, classification notations and an overview of the propulsion system and electricity supply system on board
- The description of **energy saving equipment**, if available
- The calculated value of the **attained EEXI**, including the calculation summary, which should contain, at least, each value of the calculation parameters and the calculation process used to determine the attained EEXI

As defined by the (DNV, 2021), the EEXI Technical file is submitted to the classification society for approval. It is required to be carried on board. According to the guidelines, the verification shall take place during the first annual, intermediate or renewal survey, on or after 1 January 2023. The new International Energy Efficiency (IEE) Certificate is issued afterwards. The detailed procedure is presented below:

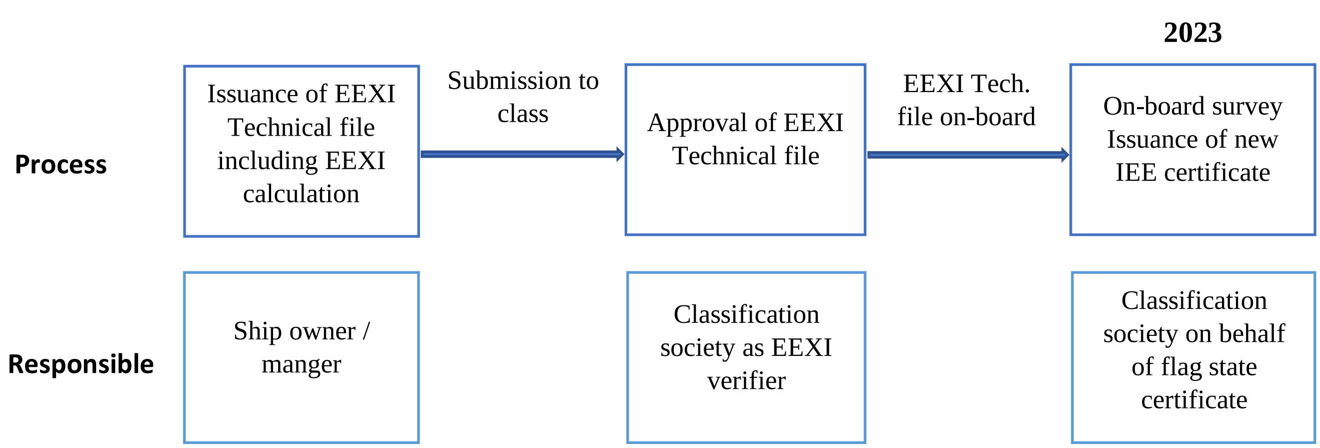

Figure 10. EEXI Technical File verification procedure (DNV, 2021)

2.3.3 Operational approach

Beyond the design approach that refers to the EEXI, short term measures to achieve the IMO 2030 targets also include an operational approach. This approach contains a tool called Carbon Intensity Indicator (CII) rating.

According to the (IMO, 2021), vessels of 5,000 gross tonnage and above have to determine their required annual operational carbon intensity indicator (CII). This indicator determines the annual reduction factor required to ensure constant improvement of the ship's operational carbon intensity within a specific rating level. The actual annual operational CII achieved would be required to be documented and verified in comparison with the required annual operational CII. This would lead to the determination of the operational carbon intensity rating.

CII rating

As explained by the (IMO, 2021), 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. This performance level would be recorded in the ship's Ship Energy Efficiency Management Plan (SEEMP). As the guidelines instruct, a ship rated D for three consecutive years, or E, would have to submit a corrective action plan, to show how the mandatory index (C or above) would be attained. Administrations, port authorities and other stakeholders, are suggested to provide motivations to vessels rated as A or B.

According to the DNV, the implementation of the following alternatives enables a vessel to reduce its carbon intensity rating:

- ✓ Speed reduction
- ✓ Energy efficiency technologies
- ✓ Optimization of operation and logistics
- ✓ Alternative fuels

Based on (Dr. Fabian Kock / DNV, 2021), the required annual operational CII, in accordance with the scale A to E ratings, is presented in the following figure:

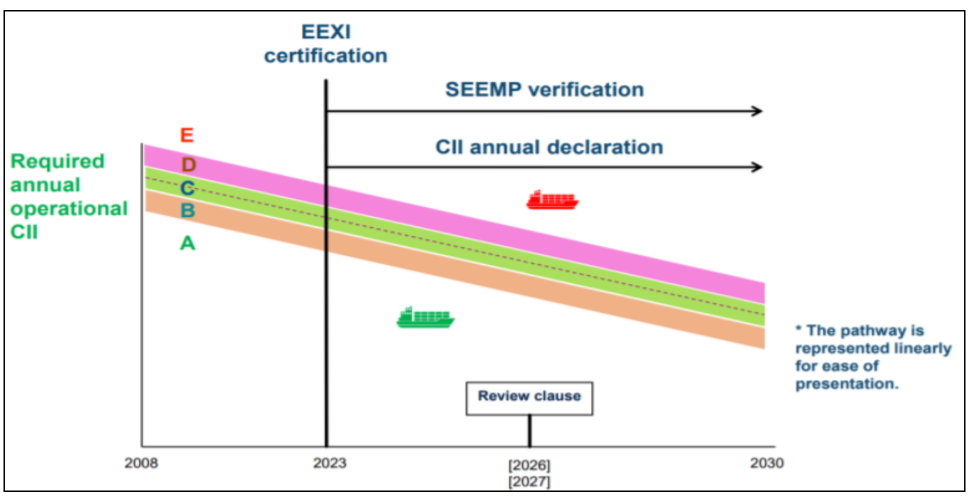

Figure 11. Required annual operational CII (Dr. Fabian Kock / DNV, 2021)

2.3.4 Required EEXI

According to the (ClassNK, 2021), the calculation of the attained and required EEXI value is applied to the following types of ship, in accordance with the deadweight or gross tonnage:

Type of ship	Calculation of Attained EEXI	Conformity to Required EEXI
Bulk carrier	400 GT and above	10,000 DWT and above
Gas carrier	400 GT and above	2,000 DWT and above
Tanker	400 GT and above	4,000 DWT and above
Containership	400 GT and above	10,000 DWT and above
General cargo ship	400 GT and above	3,000 DWT and above
Refrigerated cargo carrier	400 GT and above	3,000 DWT and above
Combination carrier	400 GT and above	4,000 DWT and above
Ro-ro cargo ship (Vehicle carrier)	400 GT and above	10,000 DWT and above
Ro-ro cargo ship	400 GT and above	1,000 DWT and above
Ro-ro passenger ship	400 GT and above	250 DWT and above
LNG carrier	400 GT and above	10,000 DWT and above
Cruise passenger ship (non-conventional)	400 GT and above	25,000 DWT and above

Table 2. Attained / Required EEXI applicability (ClassNK, 2021)

The required EEXI is calculated based on the EEDI Reference Line, as follows:

$$\boldsymbol{Required\ EEXI} = \left(\mathbf{1} - \frac{\boldsymbol{X}}{\mathbf{100}}\right) \times \boldsymbol{EEDI\ Reference\ Line} \quad (\mathbf{1})$$

The reference lines depend on both the type and size of the subject vessel. Furthermore, they depend on the reduction factor X, which has a wide range of values depending on the type and size of the vessel, as well as the required EEDI Phase.

As stated by the (ClassNK, 2021), the reference line formula varies for vessels of different size and type. The corresponding baselines are presented as follows:

Type of ship		Reference Line
Bulk carrier	$DWT \leq 279{,}000$	$961.79 \times DWT^{-0.477}$
	$DWT > 279{,}000$	$961.79 \times 279{,}000^{-0.477}$
Gas carrier		$1120.00 \times DWT^{-0.456}$
Tanker		$1218.80 \times DWT^{-0.488}$
Containership		$174.22 \times DWT^{-0.201}$
General cargo ship		$107.48 \times DWT^{-0.216}$
Refrigerated cargo carrier		$227.01 \times DWT^{-0.244}$
Combination carrier		$1219.00 \times DWT^{-0.488}$
Ro-ro cargo ship (Vehicle carrier)	$DWT/GT < 0.3$	$(DWT/GT)^{-0.7} \times 780.36 \times DWT^{-0.471}$
	$DWT/GT \geq 0.3$	$1812.63 \times DWT^{-0.471}$
Ro-ro cargo ship	$DWT \leq 17{,}000$	$1686.17 \times DWT^{-0.498}$
	$DWT > 17{,}000$	$1686.17 \times 17{,}000^{-0.498}$
Ro-ro passenger ship	$DWT \leq 10{,}000$	$902.59 \times DWT^{-0.381}$
	$DWT > 10{,}000$	$902.59 \times 10{,}000^{-0.381}$
LNG carrier		$2253.7 \times DWT^{-0.474}$
Cruise passenger ship (non-conventional)		$170.84 \times GT^{-0.214}$

Table 3. EEDI Reference Line (ClassNK, 2021)

The relationship between the EEDI reference lines and the reduction factor X, is illustrated in the following figure:

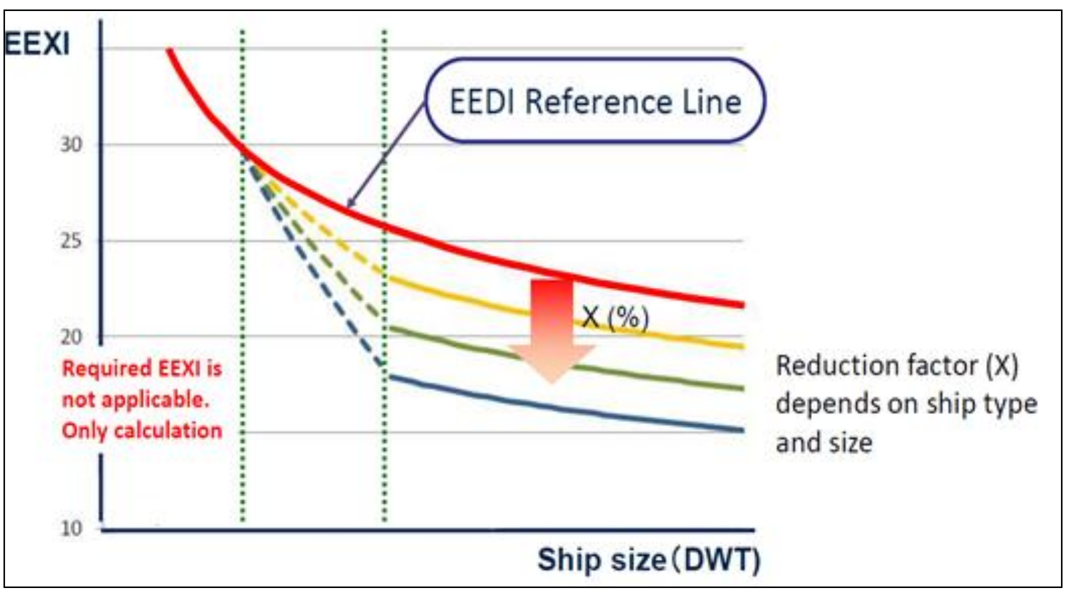

Figure 12. EEDI Reference Line (ClassNK, 2021)

As specified by the (IRCLASS, 2015), the reduction factors X, in accordance with the applicable ship types, are defined according to the following table:

Ship type	Size	Phase 0 1 Jan 2013- 31 Dec 2014	Phase 1 1 Jan 2015- 31 Dec 2019	Phase2 1 Jan 2020- 31 Dec 2024	Phase 0 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*
Containership	15,000 DWT and above	0	10	20	30
	10,000-15,000 DWT	n/a	0-10*	0-20*	0-30*
General cargo ship	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	4,000 GT and above	n/a	5	20	30
	1,000-4,000 GT	n/a	0-5*	0-20*	0-30*
Cruise passenger ship (non-conventional)	85,000 GT and above	n/a	5	20	30
	25,000-85,000 GT	n/a	0-5*	0-20*	0-30*

Table 4. EEDI Reduction factor X (IRCLASS, 2015)

*) The reduction factor needs to be linearly interpolated between the two values, based on the size of the vessel.

2.4 EEXI Calculation

2.4.1 EEXI Calculation formula

As reported by the (IMO, 2018), the EEXI calculation process is fundamentally based on the 2018 calculation guidelines of the EEDI, with several amendments. The EEXI formula is applicable to existing vessels that were not built-in accordance with EEDI Phase 2 or Phase 3 requirements.

According to the (DNV, 2021), the EEXI describes the CO_2 emissions per cargo ton and mile, by determining the standardized emissions related to the installed engine power, transport capacity and ship reference speed. The EEXI is a design index, and thus no measured values of past years are relevant and no on-board measurements are required.

As stated by the IMO, the CO_2 emissions are primarily estimated by the installed power of the main and auxiliary engines, the respective fuel consumption values and the conversion factor between the fuel and CO_2 mass. The transport work of the vessel is defined by the capacity, which is usually equal to the summer load deadweight, and the reference speed.

As far as the installed power is concerned, for most types of vessels the calculation is performed at either the 75% of the original installed power (MCR) or the 83% of the limited installed power (MCR_{lim}), in case of an installed overridable engine power limitation, whichever is lower, as mentioned by the (IMO, 2021).

Furthermore, the calculation process contains several correction factors, in order to provide a valid comparison. Those factors refer to parameters such as the capacity of the vessel, in case of structural enhancement, or the installed power, in case of Ice-class vessel.

In accordance with (IMO, 2021), the proposed formula for the calculation of the attained EEXI is presented as follows:

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

The parameters contained in the EEXI calculation formula are analytically described below:

Parameter	Description
C_F	Non-dimensional conversion factor between fuel consumption and CO_2 emission
V_{ref}	Ship speed in actual nautical miles per hour
Capacity	Computed as a function of Deadweight
P_{ME}	83% of the limited installed power (MCRlim) or 75% of the original installed power (MCR) in kW, whichever is lower
P_{AE}	Auxiliary Engine Power
P_{PTI}	75% of the rated power consumption of shaft motor
P_{eff}	Output of innovative mechanical energy efficient technology for propulsion at 75% main engine power
P_{AEeff}	Auxiliary power reduction due to innovative electrical energy efficient technology
SFC	Certified Specific Fuel Consumption in g/kWh
f_j	Correction factor to account for ship specific design elements. (For e.g., ice classed ships, shuttle tankers)
f_w	Non dimensional coefficient indicating the decrease of speed in representative sea condition of wave height, wave frequency and wind speed
f_i	Capacity factor for any technical / regulatory limitation on capacity
f_c	Cubic capacity correction factor (for chemical tankers and gas carriers)
f_l	Factor for general cargo ships equipped with cranes and other cargo related gear to compensate in a loss of deadweight of the ship
f_{eff}	Availability factor of innovative energy efficiency technology
f_m	Factor for ice-classed ships having IA Super and IA

Table 5. EEXI Formula parameters (IRCLASS, 2015)

2.4.2 Parameters' specifications

The parameters presented in Table 5 are meticulously described in the (IMO, 2018). The most common parameters that are frequently used in the EEXI calculation process for conventional vessels are analytically described below, in accordance with the instructions provided by (IMO, 2018) and (IMO, 2021).

- **C_F : Conversion factor between fuel consumption and CO_2 emission**

  According to the (IMO, 2018), C_F is a non-dimensional conversion factor between fuel consumption measured in gr and CO_2 emission also measured in gr based on carbon content. The subscripts $_{ME(i)}$ and $_{AE(i)}$ refer to the main and auxiliary engine(s) respectively.

The conversion factor for different types of vessels is presented as follows:

Type of fuel		C_F ($t\text{-}CO_2/t\text{-}Fuel$)
Diesel / Gas Oil		3.206
Light Fuel Oil (LFO)		3.151
Heavy Fuel Oil (HFO)		3.114
Liquefied Petroleum Gas (LPG)	Propane	3.000
	Butane	3.300
Liquefied Natural Gas (LNG)		2.750
Methanol		1.375
Ethanol		1.913

Table 6. Fuel Conversion factor (IMO, 2018)

As explained by the (IMO, 2021), for those engines which do not have a test report included in the NO_X Technical File and which do not have the SFC specified by the manufacturer, the C_F corresponding to SFC_{app} should be defined as follows:

C_F = 3.114 ($t\text{-}CO_2/t\text{-}Fuel$), for diesel vessels (including HFO use in practice)

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

According to the (IMO, 2021), in cases where overridable Engine Power Limitation is installed, **$P_{ME(i)}$** 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).

- **$P_{AE(i)}$: Auxiliary engine power**

As stated in the (IMO, 2018), 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 used for propulsion machinery/systems, e.g., thrusters, cargo pumps, cargo gear, ballast pumps, maintaining cargo.

For vessels with total propulsion power of 10,000 kW or more, P_{AE} is defined as follows:

$$P_{AE\,(\Sigma MCR_{ME(i)} \geq 10{,}000kW)} = \left(0.025\ x \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right)\right) + 250 \qquad (3)$$

For vessels with total propulsion power less than 10,000 kW, P_{AE} is defined as follows:

$$P_{AE\,(\Sigma MCR_{ME(i)} < 10{,}000kW)} = \left(0.05\ x \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right)\right) \qquad (4)$$

Where $P_{PTI\,(i)}$, in case that shaft motor(s) are installed, is equal to 75% of the rated power consumption of each shaft motor divided by the weighted average efficiency of the generator(s).

- **SFC: Certified specific fuel consumption**

  As defined by the (IMO, 2021), in cases where an overridable Engine Power Limitation is installed, the SFC corresponding to the P_{ME} should be interpolated by using SFCs listed in applicable test report included in an approved NO_X Technical File of the main engine.

  According to the (IMO, 2018), for auxiliary engines, SFC_{AE} is equal to the power-weighted average among $SFC_{AE(i)}$ of the respective engines (i).

  For those engines that do not have a test report included in the NO_X Technical File and that do not have the SFC specified by the manufacturer or confirmed by the verifier, the SFC can be approximated by SFC_{app} defined as follows:

  $SFC_{ME,app}$ = 190 [g/kWh], for main engines

  $SFC_{AE,app}$ = 215 [g/kWh], for auxiliary engines

- **Capacity**

  As stated by the (IMO, 2018) , 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, the deadweight should be used as capacity. As the guidelines state, deadweight means the difference in tones 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.

- **Correction factors**

  - ✓ **f_w : Factor for speed reduction at sea**

    As specified by the (IMO, 2012), the factor for speed reduction at sea, f_w, can be determined by conducting the ship specific simulation on its performance at representative sea conditions. If the simulation is not conducted f_w should be taken from the "Standard fw " table/curve.

    The standard f_w value is expressed as follows:

    $$\boldsymbol{Standard\ f_w\ value\ =\ a \times ln(Capacity) + b} \quad (\mathbf{5})$$

The parameters a and b of the standard f_w value formula are defined below:

Type of vessel	a	b
Bulk Carrier	0.0429	0.294
Tanker	0.0238	0.526
Containership	0.0208	0.633

Table 7. Parameters for standard f_w value determination (IMO, 2012)

The standard f_w value and the corresponding attained $EEXI_{weather}$, if calculated, should be indicated in the EEXI Technical File, in order to be distinguished from the attained EEXI calculated.

✓ **f_i: Capacity factor for technical/regulatory limitation on capacity**

According to the (IMO, 2018), for bulk carriers and oil tankers, built in accordance with the Common Structural Rules (CSR) of the classification societies and assigned the class notation CSR, the following capacity correction factor fi_{CSR} should apply:

$$f_{iCSR} = 1 + 0.08\frac{LWT_{CSR}}{DWT_{CSR}} \quad (6)$$

Where DWT_{CSR} is the deadweight of the vessel at summer load draught and LWT_{CSR} is the lightweight of the vessel.

Correction factors f_j, f_l, f_{eff}, f_m are assumed equal to one (1.0) if no necessity of the corresponding factors is granted. In special cases, the aforementioned factors are calculated in accordance with the (IMO, 2018) guidelines.

2.4.3 Reference speed

As stated in the (IMO, 2018), the reference speed, V_{ref}, is the ship speed measured in nautical miles per hour (knot), on deep water in the condition corresponding to the capacity. The reference speed, Capacity and Propulsion power (P_{ME}) should be consistent with each other.

According to the (IMO, 2021), there are different ways of calculating the reference speed:

a) For vessels falling into the scope of the EEDI requirements the ship speed V_{ref} 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)

b) For ships not falling into the scope of the EEDI requirements, the ship speed V_{ref} should be obtained from an **estimated** speed-power curve as defined by the (IMO, 2021) and (IMO, 2021).

Based on the guidelines, for pre-EEDI vessels, there are two different cases of speed-power curve:

1. **Case of the pre-EEDI ship**: An estimated speed-power curve obtained from the tank test and/or numerical calculations, if available, is shown in the following figure:

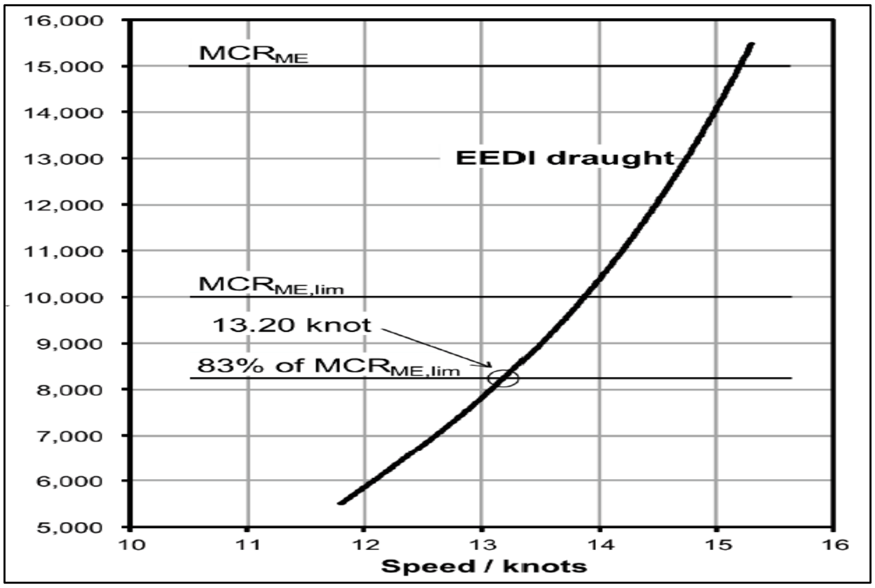

Figure 13. Pre-EEDI ship estimated speed / power curve (IMO, 2021)

2. **Case of the pre-EEDI ship with sea trial result calibrated to a different load draught**:

   As stated in the (ITTC, 2017), it is not always possible to conduct speed trials at full load condition. Thus, the speed trials are performed in ballast condition. The result of the speed trial is converted to that of full load / stipulated condition by using model tank test results, which are required at both the trial condition and the stipulated condition.

   The conversion on vessel's speed from trial condition to other stipulated condition is based on the power ratio $\alpha_{p,}$ which is defined as follows:

- $\boldsymbol{\alpha_{Pi}} = \frac{P_{Trial,Pi}}{P_{Trial,Si}}$ **(7)**
- $\boldsymbol{P_{Full,Si}} = \frac{P_{Full,Pi}}{\alpha_{Pi}}$ **(8)**

Where,

- ✓ $\mathbf{P_{Trial,P}}$**:** Predicted power at trial condition by tank tests
- ✓ $\mathbf{P_{Trial,S}}$ **:** Power at trial condition obtained by the speed trials
- ✓ $\mathbf{P_{Full,P}}$ **:** Predicted power at stipulated condition by tank tests
- ✓ $\mathbf{P_{Full,P}}$ **:** Power at stipulated condition
- ✓ $\mathbf{a_p}$ **:** Power ratio
- ✓ **i** : Index of each power setting

An example of the corresponding conversion is presented below:

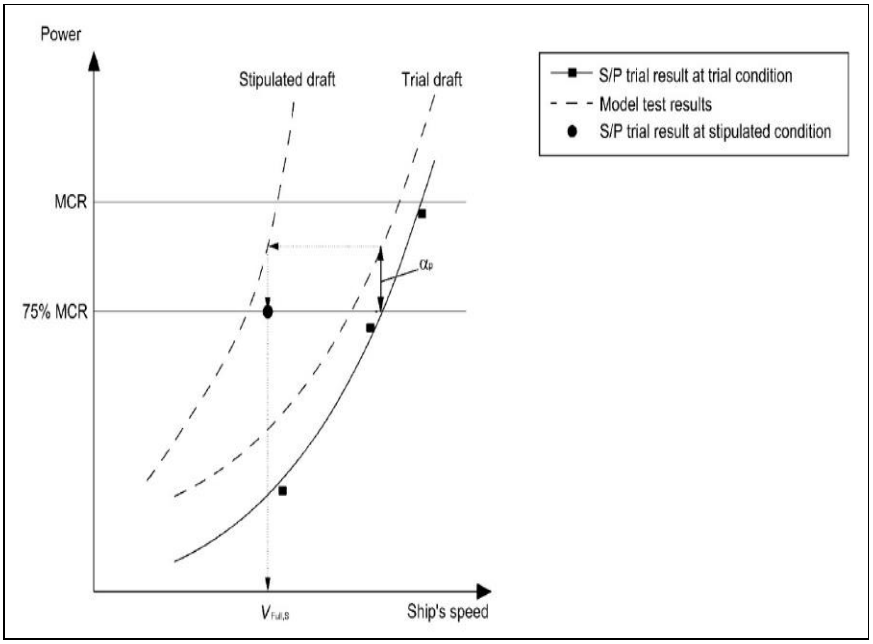

Figure 14. Pre-EEDI ship speed / power curve calibrated to a different load draught (ITTC, 2017)

c) As explained by the (IMO, 2021), 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 are included in the sea trial report, the ship speed V_{ref} may be obtained from the sea trial report, as follows:

$$\boldsymbol{V_{ref} = V_{S,EEDI} \times \left[\frac{P_{ME}}{P_{S,EEDI}}\right]^{\frac{1}{3}} (knot)} \quad \mathbf{(9)}$$

Where:

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

d) According to the (IMO, 2021), 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 are included in the sea trial report, the ship speed V_{ref} may be obtained from the sea trial report, as presented below:

$$\boldsymbol{V_{ref} = k^{\frac{1}{3}} \times \left(\frac{DWT_{S,service}}{Capacity}\right)^{\frac{2}{9}} \times V_{S,service} \times \left[\frac{P_{ME}}{P_{S,service}}\right]^{\frac{1}{3}} (knot)} \quad \mathbf{(10)}$$

Where:

- ✓ $V_{S,service}$ is the sea trial service speed under the design load draught
- ✓ $DWT_{S,service}$ is the deadweight under the design load draught

- ✓ $P_{S,service}$ is the power of the main engine corresponding to $V_{S,service}$
- ✓ k is the scale coefficient, which should be:
  - 0.95 for containerships with 120,000 DWT or less
  - 0.93 for containerships with more than 120,000 DWT
  - 0.97 for bulk carrier with 200,000 DWT or less
  - 1.00 for bulk carrier with more than 200,000 DWT
  - 0.97 for tanker with 100,000 DWT or less
  - 1.00 for tanker with more than 100,000 DWT.

e) As specified by the (IMO, 2021), in cases there 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:

$$\boldsymbol{V_{ref,app}} = \left(\boldsymbol{V_{ref,avg}} - \boldsymbol{m_V}\right) \times \left[\frac{\sum \boldsymbol{P_{ME}}}{\boldsymbol{0.75 \times MCR_{avg}}}\right]^{\frac{1}{3}} \ (\boldsymbol{knot}) \quad (\mathbf{11})$$

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

$$\boldsymbol{V_{ref,avg}} = \boldsymbol{A \times B^C} \quad (\mathbf{12})$$

Where A, B and C are the parameters given in the following matrix:

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 8. Parameters to calculate $V_{ref,avg}$ (IMO, 2021)

- ✓ m_v is a performance margin of a ship, which should be equal to **5% of $V_{ref,avg}$** or **1 (kn)**, whichever is lower

- ✓ MCR_{avg} is a statistical mean of distribution of MCRs for main engines

$$\boldsymbol{MCR_{avg}} = \boldsymbol{D \times E^F} \quad (\mathbf{13})$$

Where D, E and F are the parameters given in the following matrix:

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 9. Parameters to calculate MCR_{avg} (IMO, 2021)

2.4.4 Minimum propulsion power determination

As stated in the (IMO, 2017)**,** a vessel should be considered to have adequate installed power to maintain the maneuverability in adverse weather conditions. In case that the vessel fulfils the corresponding requirements, it is not under the risk of being underpowered, and thus unsafe at sea. The guidelines are applied to all new ships with conventional propulsion systems, of types as listed in Table 10, in case that those vessels are required to comply with regulations on energy efficiency. The following procedures are applicable during Phase 0 and Phase 1 of the EEDI implementation.

According to the IMO, the assessment of the minimum propulsion power to maintain the maneuverability of ships in adverse conditions can be carried out in two different levels:

1. Minimum power lines assessment
2. Simplified assessment

2.4.4.1 Assessment level 1-minimum power lines assessment

As explained by the (IMO, 2017), if the considered vessel has installed at least the power defined by the minimum power line for the corresponding type of ship, it should be considered to have enough power to maintain the maneuverability in adverse weather conditions.

The total installed MCR of all main propulsion engines should not be less than the minimum power line value, which is calculated for various types of vessels, in kW, as follows:

$$\boldsymbol{Minimum\ Power\ Line\ Value} = \boldsymbol{a} \times (\boldsymbol{DWT}) + \boldsymbol{b} \quad (\mathbf{14})$$

Where DWT is the deadweight of the vessel in metric tons. The parameters a and b are defined as follows:

Ship type	a	b
Bulk carrier (DWT<145,000)	0.0763	3374.3
Bulk carrier (DWT>145,000)	0.0490	7329.0
Tanker	0.0652	5960.2
Combination carrier	see tanker above	

Table 10. Minimum power line values' parameters (IMO, 2017)

2.4.4.2 Assessment level 2-Simplified assessment

As explained by the (IMO, 2017), the simplified assessment procedure is based on the idea that if a vessel has sufficient installed power to move with a specific advance speed in head waves and wind, the vessel will also be able to keep course in waves and wind from any other direction. Thus, the minimum ship speed of advance is selected based on the ship's design.

Based on the (IMO, 2017), the simplification of the corresponding procedure is that only the equation of steady motion in longitudinal direction is taken into consideration. Furthermore, the course-keeping in wind and waves requirements are taken into account by adjusting the speed of advance in head wind and waves.

The procedure consists of two major steps, the definition of the required advance speed, and the assessment of whether the installed power is adequate to achieve the corresponding advance speed. The procedures are analytically described below:

Definition of adverse conditions

According to the guidelines, the following adverse condition should be applied for vessels, depending on the length between the perpendiculars:

Ship Length	V_w (m/s)	H_s	T_p (s)
L_{PP}<200m	15.7	4	7-15
200m<L_{PP}<250m	*Linear Interpolation*		
L_{PP}>250m	19	5.5	

Table 11. Adverse conditions parameters (IMO, 2017)

For coastal waters, JONSWAP sea spectrum with peak parameter of 3.3 is taken into consideration for the definition of the sea state.

Definition of required ship speed of advance

As specified by the (IMO, 2017), the required advance speed in head wind and waves, V_s, is set to the larger of:

a. The minimum navigational speed, V_{nav}

This speed enables leaving coastal area within an adequate time before the storm escalates. Its purpose is to reduce navigational risk and risk of excessive motions in waves because of negative heading relating to wind and waves. The minimum navigational speed is set to 4.0 knots

b. The minimum course-keeping speed, V_{ck}

This speed is selected to ease course-keeping of the vessel in wind and waves from all directions. It is calculated based on the reference course-keeping speed, $V_{ck,ref}$, related to vessels with the rudder area equal to 0.9% of the submerged lateral corrected for breadth effect, and an adjustment factor taking into consideration the actual rudder area. The minimum course-keeping speed is calculated as follows:

$$\boldsymbol{V_{ck} = V_{ck,ref} - 10.0 \times (A_{R\%} - 0.9)} \quad (15)$$

The actual rudder area, A_R, as percentage of the submerged lateral area of the vessel corrected for breadth effect $A_{LS,corr}$, is calculated as $\boldsymbol{A_{R\%}} = \frac{\boldsymbol{A_R}}{\boldsymbol{A_{LS,corr}}}\boldsymbol{100\%}$

The submerged lateral area corrected for breadth effect is calculated as $\boldsymbol{A_{LS,corr}} = \boldsymbol{L_{PP}T_m}\left[\boldsymbol{1.0} + \boldsymbol{25.0}\left(\frac{\boldsymbol{B_{WL}}}{\boldsymbol{L_{PP}}}\right)^{\boldsymbol{2}}\right]$, where L_{PP} is the length between perpendiculars in m, B_{WL} is the water line breadth in m and T_m is draft at midship in m.

As determined by the (IMO, 2017), the reference course-keeping speed $V_{ck,ref}$ for bulk carriers and tankers is defined, based on the ration A_{FW}/A_{LW} of the frontal windage area, A_{FW}, to the lateral windage area, A_{LW}, as follows:

1. Reference speed is 9 knots for A_{FW}/A_{LW}=0.1 and below and 4 knots for A_{FW}/A_{LW}=0.4 and above
2. Linearly interpolated between 0.1 and 0.4 for intermediate values of A_{FW}/A_{LW}

Assessment of installed power

As stated in the (IMO, 2017), the assessment procedure is performed in maximum draught condition at the required ship speed of advance, V_s. The required propeller thrust, T in N, is calculated by the sum of the bare hull resistance in calm water R_{cw}, resistance due to appendages Rapp, aerodynamic resistance R_{air} and added resistance in waves R_{aw}, by taking into account the thrust deduction factor t, based on the following formula:

$$\boldsymbol{T} = \frac{\boldsymbol{R_{cw}} + \boldsymbol{R_{air}} + \boldsymbol{R_{aw}} + \boldsymbol{R_{app}}}{\boldsymbol{1-t}} \quad (\boldsymbol{16})$$

1. The calm water resistance R_{cw} for bulk carrier and tankers is calculating neglecting the wave making resistance as follows:

   $$\boldsymbol{R_{cw}} = (\boldsymbol{1}+\boldsymbol{k})\boldsymbol{C_F}\frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{\rho S V_s^2} \quad (\boldsymbol{17})$$

   Where $\boldsymbol{C_F} = \boldsymbol{0.075}/(\boldsymbol{log_{10}Re}-\boldsymbol{2})^{\boldsymbol{2}}$ is the frictional resistance coefficient, $\boldsymbol{Re} = \boldsymbol{V_s\,L_{PP}/\nu}$ is the Reynolds number, ρ is water density in kg/m^3, S is the wetted surface of the bare hull in m^2, Vs is the advance speed of the vessel in m/s, and v is the kinematic viscosity of water in m^2/s.
   The form factor k should be either obtained from the model test reports, or, in case they are not available, by the formula presented below:

   $$\boldsymbol{k} = -\boldsymbol{0.095} + \boldsymbol{25.6}\frac{\boldsymbol{C_B}}{(\boldsymbol{L_{PP}}/\boldsymbol{B_{WL}})^{\boldsymbol{2}}\sqrt{\boldsymbol{B_{WL}}/\boldsymbol{T_m}}}$$

   Where C_B is the block coefficient based on L_{pp}.

2. The aerodynamic resistance R_{air} is defined by the following formula:

   $$\boldsymbol{R_{air}} = \boldsymbol{C_{air}}\frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{\rho_a A_F V_{w,rel}^2} \quad (\boldsymbol{18})$$

   Where C_{air} is the aerodynamic resistance coefficient which is obtained either from the model tests or empirical data. Otherwise, it is assumed equal to 1.0. ρ_α is the density of the air in kg/m^3, A_F is the frontal windage area of the hull and superstructure in m^2, $V_{w,rel}$ is the relative wind speed in m/s, which is calculated by the sum of the ship advance speed V_s and the mean wind speed V_w, as defined by the defined adverse conditions for a vessel of a specific size.

3. The mean added resistance in irregular waves, R_{aw}, defined by the adverse conditions and wave spectrum, is calculated as follows:

$$\boldsymbol{R_{aw} = 2\int_{0}^{\infty} \frac{R_{AW}\,(V_s, \omega)}{\zeta_\alpha^2} S_{\zeta\zeta}(\omega)d\omega} \quad (\mathbf{19})$$

Where the $\mathrm{R_{aw}}(\mathrm{V_s}, \omega)/\zeta_\alpha^2$ is the quadratic transfer function of the added resistance in regular waves, depending on the advance speed V_s in m/s, wave frequency ω in rad/s, the wave amplitude, ζ_a in m and the wave spectrum, $S_{\zeta\zeta}$ in m^2s. The transfer function can be either obtained by tank tests as per ITTC procedures, or from the following semi-empirical methods:

i. Direct correction method STAwave-1

As stated in the (ITTC, 2014), specifically for speed trial conditions with present day vessels a practical method has been developed by STA-JIP to estimate the added resistance in waves, with limited input data.

The increase of the resistance in head waves, under the condition that heave and pitch are small, is calculated based on the following formula:

$$\boldsymbol{R_{AWL} = \frac{1}{16}\rho g H_{W1/3}^2 B\sqrt{\frac{B}{L_{BWL}}}} \quad (\mathbf{20})$$

Where B is the beam of the vessel, $H_{W1/3}$ is the significant wave height and L_{BWL} is the length of the bow on the water line to 95% of the maximum beam.

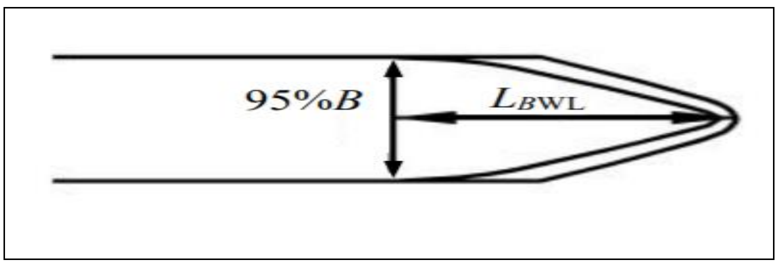

Figure 15. Definition of L_{BWL} (ITTC, 2014)

STAwave-1 has been extensively validated for the following conditions:

- ✓ Significant wave height, $\boldsymbol{H \leq 2.25\sqrt{L_{PP}/100}}$
- ✓ Heave and pitch during speed/power trial are small (vertical acceleration at bow <0.05g)
- ✓ Head waves

The wave correction is restricted to wave directions in the bow sector to ±45(deg.) off bow. Waves within this sector are corrected as head waves. Waves outside the ±45(deg.) sector are not corrected for.

ii. **Liu-Papanikolaou semi-empirical method**

According to (Liu, Papanikolaou, & Bolbot, 2016), the prediction of the added resistance of vessels in head waves, at any wave length, can be calculated based on the following formula:

$$\boldsymbol{R_{WAVE} = R_{AWR} + R_{AWM}} \quad \textbf{(21)}$$

As reported by the (ITTC, 2014), the mean resistance in regular waves, $R_{WAVE,}$ is calculated from the components of the mean resistance increase in regular waves, R_{AWM}, which is mainly included by ship motion, and the mean resistance increase due to wave reflection, R_{AWR}, which should be calculated with accuracy because, in short waves, it is the predominant one.

✓ **Wave Reflection Added Resistance, R_{AWR}**

For the calculation of added resistance in short waves, the following simplified formula is proposed by (Liu, Papanikolaou, & Bolbot, 2016):

$$\boldsymbol{R_{AWR} = \frac{2.25}{2}\rho g B \zeta_{\alpha}^{2} sin^{2}E \left(1+5\sqrt{\frac{L_{PP}}{\lambda}}Fn\right)\left(\frac{0.87}{C_B}\right)^{1+4\sqrt{Fn}}} \quad \textbf{(22)}$$

Where $\mathbf{E = atan(B/2L_E)}$ and L_E is defined as the distance from F.P. to the position where the 99% of the maximum ship breadth (B) is reached.

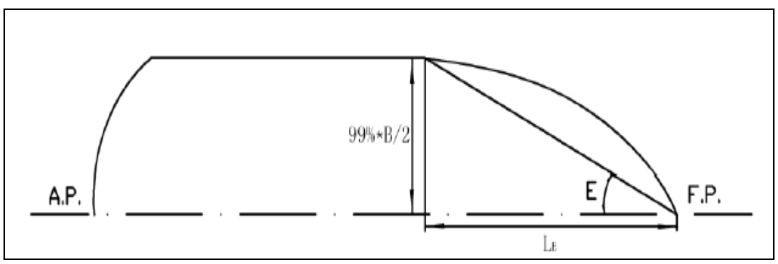

Figure 16. Definition of length L_E and angle E of entrance of waterline (Liu, Papanikolaou, & Bolbot, 2016)

✓ **Ship Motion Added Resistance, R_{AWM}**

For the prediction of Motion Added Resistance the following formula is proposed, as specified by (Liu, Papanikolaou, & Bolbot, 2016):

$$\boldsymbol{R_{AWM} = \frac{4\rho g \zeta_{\alpha}^{2} B^{2}}{L_{PP}} \bar{\omega}^{b_1} exp\left[\frac{b_1}{d_1}\left(1-\bar{\omega}^{b_1}\right)\right]\alpha_1\alpha_2} \quad \textbf{(23)}$$

Where:

- For C_B<0.75

$$b_1 = \begin{cases} 11.0\,, & \bar{\omega} < 1 \\ -8.5\,, & elsewhere \end{cases} \quad (24a)$$

$$d_1 = \begin{cases} 14.0\,, & \bar{\omega} < 1 \\ -566\left(\frac{L_{PP}}{B}\right)^{-2.66} * 6\,, & elsewhere \end{cases} \quad (25a)$$

- For $C_B \geq 0.75$

$$b_1 = \begin{cases} 11.0\,, & \bar{\omega} < 1 \\ -8.5\,, & elsewhere \end{cases} \quad (24b)$$

$$d_1 = \begin{cases} 566\left(\frac{L_{PP}}{B}\right)^{-2.66}\,, & \bar{\omega} < 1 \\ -566\left(\frac{L_{PP}}{B}\right)^{-2.66} * 6\,, & elsewhere \end{cases} \quad (25b)$$

Regarding the peak of the added resistance, the following factor is recommended:

$$\boldsymbol{\alpha_1 = 60.3 C_B{}^{1.34}\left(\frac{0.87}{C_B}\right)^{1+Fn}} \quad (\mathbf{26})$$

For the forward speed factor, the following expression is suggested:

$$\boldsymbol{\alpha_2 = \begin{cases} 0.0072 + 0.1676\, Fn\,, & Fn < 0.12 \\ Fn^{1.5} exp(-3.5 Fn)\,, & Fn \geq 0.12 \end{cases}} \quad (\mathbf{27})$$

For the frequency estimation the following formula is proposed, based on the Froude number:

$$\boldsymbol{\alpha_2 = \begin{cases} \dfrac{\sqrt{L_{PP}/g}\ \sqrt[3]{\dfrac{k_{yy}}{L_{PP}}}\ 0.05^{0.143}}{1.17}\,\omega\,, & Fn < 0.05 \\ \dfrac{\sqrt{L_{PP}/g}\ \sqrt[3]{\dfrac{k_{yy}}{L_{PP}}}\ Fn^{0.143}}{1.17}\,\omega\,, & Fn \geq 0.05 \end{cases}} \quad (\mathbf{28})$$

The mean value of the added resistance in irregular waves is calculated by applying the sea state spectrum to the estimated transfer function $R_{WAVE}/\zeta\alpha^2$.

In accordance with (Liu, Papanikolaou, Bezunartea-Barrio, Shang, & Sreedharan, 2021), the corresponding frequency spectrum is assumed to be of JONSWAP spectrum, as presented below:

$$\boldsymbol{S(H_S, T_P, \gamma) = \frac{\alpha^* H_S^2 \omega^{-5}}{\omega_p^{-4}} exp[\frac{-5}{4}\ (\frac{\omega}{\omega_p})^{-4}]\ \gamma^{exp[\frac{-(\omega-\omega p)^2}{2\sigma^2 \omega p^2}]}} \quad (\mathbf{29})$$

Where:

- $\alpha^* = 0.0624/[0.23 + 0.0336\gamma - 0.185/(1.9+\gamma)]$
- $\sigma = \begin{cases} 0.07\,, & \omega \leq \omega_p \\ 0.09\,, & \omega > \omega_p \end{cases}$
- The peak enhancement factor parameter, γ=3.3

Thus, the mean added resistance in irregular waves is calculated by applying the calculated values to the following formula:

$$R_{AW} = 2\int_{0}^{\infty} \frac{R_{wave}(\omega)}{\zeta_{\alpha}^{2}} S(\omega)d\omega \quad (30)$$

where S(ω) is the wave spectrum, R_{wave} (ω) is the added-resistance response function in regular waves and ζ_{α} the regular wave amplitude

4. The thrust deduction factor t can be either obtained from the model tests or the empirical formula t=0.7w, where w is the wake fraction which can also be obtained from the model tests. Alternatively, the wake factor can be estimated by the following table:

C_B	One propeller	Two Propellers
0.5	0.14	0.15
0.6	0.23	0.17
0.7	0.29	0.19
0.8 and above	0.35	0.23

Table 12. Wake factor (IMO, 2017)

5. As specified by the (IMO, 2017), the required advance coefficient of the propeller is defined as presented below:

$$T = \frac{\rho u_a^2 D_P^2 K_T(J)}{J^2} \quad (31)$$

where D_P is the diameter of the propeller, K_T(J) is the open water propeller thrust coefficient, $J = u_a/nD_P$, and $ua = V_S(1-w)$. J is calculated from the $K_T(J)/J^2$ curve.

The required rotation rate of the propeller, n, in RPS, is defined by the following expression:

$$n = \frac{u_a}{JD_P} \quad (32)$$

The required delivered power to the propeller at the corresponding rotation rate n, P_D in Watts, is defined as follows:

$$P_D = 2\pi\rho n^3 D_P^5 K_Q(J) \quad (33)$$

where K_Q(J) is the open water propeller torque coefficient curve.

6. According to the (IMO, 2017), for diesel engines, the available power is limited because of the torque-speed limitation of the engine. Thus, the required minimum installed MCR is calculated taking into consideration:

    1. The torque-speed limitation curve of the engine which is specified by the engine manufacturer
    2. The transmission efficiency ηs that is to be assumed 0.98 for aft engine and 0.97 for midship engine, unless provided otherwise.

2.4.5 Calculated value of attained EEXI

In this case, a Bulk carrier with a capacity of 150,000 DWT and a reference speed of 13.2 knots is examined. The main data for the calculation process are presented as follows:

Type of vessel	Bulk Carrier
Capacity DWT	150,000
Speed V_{ref} (knots)	13.20
Main Engine Specifications	
MCR_{ME} (kW)	15,000
MCR_{lim} (kW)	9,940
P_{ME} (kW)	8,250
Fuel type	Diesel Oil
C_{FME}	3.206
SFC_{ME} (g/kWh)	166.5
Aux. Engines Specifications	
P_{AE} (kW)	625
Fuel type	Diesel oil
C_{FAE}	3.206
SFC_{AE} (g/kWh)	220.0

Table 13. EEXI calculation parameters (IMO, 2021)

In this case study, for simplicity reasons all non-dimensional correction factors are considered equal to [1]. Furthermore, the calculation does not consider the maximum engine power. In this very case, there is an installed overridable power limitation which sets the MCR_{lim} at 9,940 kW. Thus, the calculation does not consider 75% of MCR, but 83% of $MCR_{lim.}$ As a result, the P_{ME} value is equal to 8,250 kW. Following the procedure determined by (IMO, 2021), the attained EEXI value is calculated as per equation (2):

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

$$= \frac{1 \times (8250 \times 3.206 \times 166.5) + (625 \times 3.206 \times 220.0) + 0 - 0}{1 \times 1 \times 1 \times 150{,}000 \times 1 \times 13.20 \times 1} = 2.45\ (gr - CO_2/ton \cdot mile)$$

The **Attained EEXI** value is equal to **2.45 (gr-CO_2/ton*mile)**.

According to the IMO, the attained EEXI must be less than the required EEXI, in order for the subject vessel to comply with the regulation. The required EEXI is calculated according to equation (1), as follows:

$$\textit{Required EEXI} = \left(1 - \frac{X}{100}\right) \times \textit{EEDI Reference Line}$$

According to Table 3, for a Bulk carrier with a capacity of 150,000 DWT, the reference line is defined as follows:

Reference line = 961.79 x DWT $^{-0.477}$

Based on Table 4, the reduction factor X for the subject vessel is equal to 20%, for EEDI Phase 2. Thus, the **Required EEXI** value is equal to **2.613 (gr-CO_2/ton*mile)**

In this case scenario, the Attained EEXI ≤ Required EEXI. As a result, the ship complies with the EEXI requirements.

In order to present a more comprehensive analysis, the reference speed of the vessel is approximated from statistical mean of distribution of ship speed and engine power, based on equation (11):

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

The parameters of the formula are determined as follows:

- Based on equation (12), the statistical mean of distribution of ship speed is equal to $\boldsymbol{V_{ref,avg}} = \boldsymbol{14.715\ kn}$

  The parameters of equation (12) are defined from Table 8 (Bulk Carrier), as follows:
  - A=10.6585
  - B=150,000 tons
  - C=0.02706

- Based on equation (13), the statistical mean of distribution of MCRs for main engines is equal to $\boldsymbol{MCR_{avg}} = \boldsymbol{14,971.81\ kW}$

  The parameters of equation (13) are defined from Table 9 (Bulk Carrier), as follows:
  - D=23.7510
  - B=150,000 tons
  - C=0.54087

- The performance margin of the vessel is equal to $\boldsymbol{m_v} = \boldsymbol{0.7358}$

Thus, based on equation (11), the approximated speed of the vessel is equal to $\boldsymbol{V_{ref,app}} = \boldsymbol{12.61\ kn}$

For the approximated reference speed, based on equation (2), the Attained EEXI is equal to **2.56 (gr-CO_2/ton*mile)**. The Required EEXI was estimated equal to **2.613 (gr-CO_2/ton*mile)**. Thus, the effect of the reference speed is important, as for the approximated speed the Attained EEXI is marginally lower than the Required EEXI.

3 Means of complying with the EEXI

Nowadays, existing vessels need to compete with new, more energy efficient vessels that enter the global market. According to the (DNV, 2015), a possible negative assessment by a charterer regarding the fuel efficiency of the ship can lead to lower rates, or even worse, to no charter agreement. In order to make vessels competitive in the markets, shipowners need to take immediate action by considering the retrofitting of the older ships in their fleet.

Every ship type can be benefited from an appropriate upgrade. As explained by the DNV, the challenge for ship owners is to detect the measures that ensure the highest savings potential for the company operational profile, vessels type and business models. In that direction, a wide range of retrofitting options is presented below, based on the DNV's Efficiency Finder tool instructions (DNV, 2014) and (MAN PrimeServ, 2016)**.**

3.1 Hull and Propeller Retrofits

- **Bulbous bow modification**

  According to the (DNV, 2014), current operating profiles diverge from the design point that determined the initial design of the ship. Inevitably, the vessel's hull profile is not optimized for current operations. For existing ships, the degrees of freedom in hull form optimization are limited compared to a newbuilding project. Due to that fact, a possible retrofitting of the bulbous bow can bring significant fuel savings.

  In that direction, as mentioned by the (DNV, 2014), it needs to be taken into account that an evaluation from expert needs to be conducted in order to be verified whether the retrofit has the ability to improve the efficiency based on the changed operational profile of the vessel. Furthermore, a CFD analysis of numerous bulb designs is required to optimize the bow form for the new operational target profile.

  As stated by the (DNV, 2014), for existing vessels, exchanging the bulbous bow with an improved design can lead to reduced water resistance for approximately 3-6% in fuel savings.

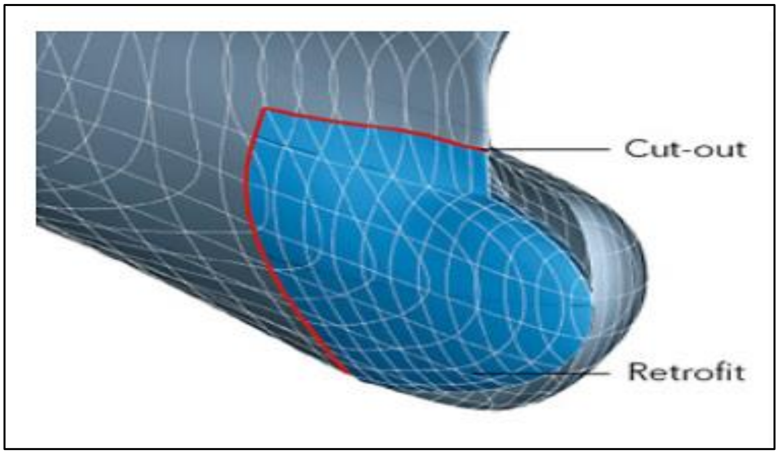

Figure 17. Bulbous bow modification (DNV, 2014)

- **Hull and Propeller Smoothness**

As mentioned by the (DNV, 2014), marine growth on both hull and propeller can lead to added resistance of over 1% a month. The specification of a proper hull coating system or the regular cleaning of the hull and propeller contributes to significant fuel savings.

As stated by the (DNV, 2014), current biocidal anti-fouling systems and ultra-smooth silicone non-stick systems are accessible in the market. However, the release of biocidal products into seawater needs regulatory consideration. Furthermore, it highly affects the choice of the coating system. There are many copper- and silicone-based coatings that are able to maintain and lower the resistance of the hull. The more expensive silicone-based coatings, though, have the privilege of the same results above a minimum speed, without need for replacement unless damaged. The application of the coating system is based on the operational profile of the ship.

Alternatively, hull and propeller cleaning is an effective option. However, it depends on the availability of the resources and port regulations. Furthermore, as claimed by the (DNV, 2014), it has the disadvantage of reducing the life-span of most coatings.

In conclusion, according to the (DNV, 2014), smoothening of anti-fouling coatings or regular hull and propeller cleaning can reduce water resistance for approximately 2-5% in fuel savings.

- **Energy Saving Devices**

According to the (DNV, 2014), based on the type and operational profile of a vessel, there is variety of different energy saving devices (ESD) to be applied in order to improve water velocity distribution to the propeller and minimize wake losses due to swirl in the out-flow of the propeller

There are two main types of ESDs, pre-swirl and post-swirl devices. As explained by the (DNV, 2014), pre-swirl devices aim to improve the propeller inflow, while post-swirl devices are used in order to recover parts of the rotational energy in the propeller slip stream. Possible ESD solutions include, among others: Pre-swirl stator, post-swirl fins, ducts, propeller boss cap fins (PBCF), Grim vane wheel, etc.

As demonstrated by (Technava, 2019), the Propeller Boss Cap Fins (PBCF) is presented as follows:

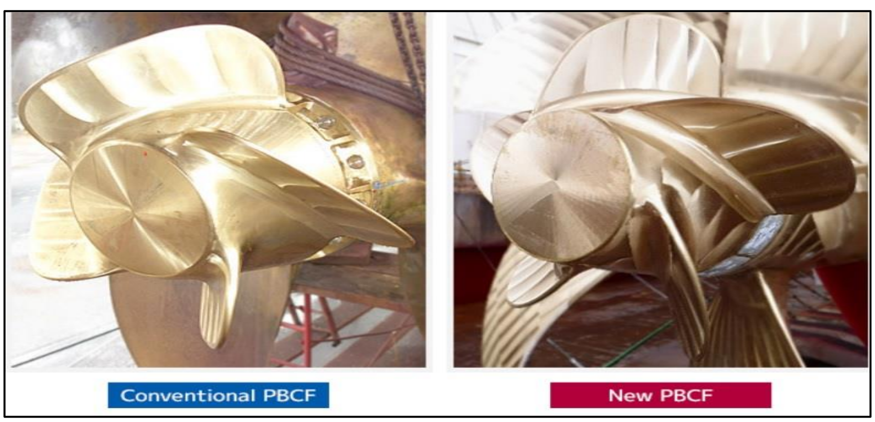

Figure 18. Propeller Boss Cap Fins (Technava, 2019)

As claimed by the (DNV, 2014), mounting or exchanging appendages such as pre-swirl or ducts may count for up to 5% in fuel savings, whereas propeller boss cap fins and rudder bulbs, such as Costa bulbs, may each count for up to 2% in fuel savings.

The applicability of the hull and propeller retrofits on various ship types is presented as follows:

Retrofit / Vessel	CV	CV-Feeder	Bulker	Tanker	MPV
Bulbous bow modification	75%	50%	0%	25%	50%
Hull & Propeller smoothness	50%	50%	75%	75%	50%
Energy Saving Devices	25%	25%	100%	100%	50%

Table 14. Hull & Propeller retrofits' applicability with ship type (DNV, 2014)

In accordance with the (DNV, 2014), the values of interest across all ship types, for the corresponding retrofit solutions, are presented below:

Parameter / Retrofit	Bulbous bow modification	Hull & Propeller smoothness	Energy Saving Devices
Ship Age Fit	0-9 years	0-12+ years	0-12+ years
Investment	M (150-750k USD)	XS-M (0-750k USD)	M-L (150k-3M USD)
Payback Period	1-3 years	0-2 years	2-4 years
Ease of Execution	Drydock	Maintenance, Drydock	Drydock
Pre-Planning Time	3-12 months	0-3 months	3-8 months

Table 15. Hull & Propeller retrofits' values across all ship types (DNV, 2014)

- **Kappel Propeller**

  According to the (MAN PrimeServ, 2016), conventional propellers have blades that deviate only moderately from blades laid out on a helical surface with a straight generating line. The non-planar lifting surfaces of the Kappel Propeller resulted in the development of completely new design methods that are able to handle the subject geometry. In that direction, the blades of a Kappel Propeller have an extended tip that is smoothly curved to the suction side of the blade. As a result, the energy loss from the tip vortex flow is notably reduced. As explained by the (MAN PrimeServ, 2016), the Kappel Propeller can be combined with Rudder Bulb and Fairing Cone in order to provide even better power savings. The calculated saving can be verified by tank tests.

  The Kappel Propeller is applicable to the vast majority of engines and propulsion systems. Furthermore, as mentioned by the (MAN PrimeServ, 2016), it provides a reduction in fuel consumption of around 3% to 5% compared with conventional propellers.

  As specified by the (MAN PrimeServ, 2016), the most promising benefits of the Kappel Propeller are the following:

  - ✓ Up to 5% fuel savings compared to a conventional propeller with the same design standards
  - ✓ Suitability for all vessel speed. Slow steaming is included
  - ✓ Reduced CO_2 emissions
  - ✓ Positive contribution to the effect of other engine tuning methods
  - ✓ Improved performance of the engine

The workshop assembly and testing of the 4,500mm MAN Alpha Kappel propeller with fairing cone is presented as follows:

Figure 19. 4,500mm MAN Alpha Kappel (MAN PrimeServ, 2016)

3.2 Modification of the Main Engine

- **Engine De-Rating**

According to the (DNV, 2014), for a big number of existing vessels the main engine was initially designed for one specific, high vessel speed. By de-rating the main engine of a vessel, the specified maximum continuous rating (SMCR) is changed to lower load points. Thus, higher efficiency with reduced specific oil consumption (SFOC) is attained.

As mentioned by the (DNV, 2014) , the de-rating process changes the engine power and speed distribution rating. Thus, the engine adapts to the vessel speeds of today's slow-steaming market. In order to achieve that, the engine's specified maximum continuous rating is permanently lowered by limiting the power output. The maximum speed of the vessel is limited too. There is a variety of measures to de-rate an engine, such as changing or modifying fuel valves, shimming between x-head and piston rod and re-matching turbochargers. Additionally, deactivating cylinders is a possible solution.

As explained by the (DNV, 2014), there are some issues to be taken into consideration before de-rating an engine. First and foremost, a detailed analysis of the vessel's expected operational profile is required. The analysis should include both the design and maximum speed after the corresponding modification. Secondly, de-rating is often implemented in combination with a propeller exchange. Thus, the optimization of the propeller diameter in order to have better performance at lower engine speeds can shorten the payback time. Last but not least, some de-rating measures, especially for mechanically controlled engines, may require additional de-NOx measures, which have an opposing effect on the SFOC of the engine.

In conclusion, as believed by the (DNV, 2014), in today's slow-steaming market, the modification of the main engine for permanently lower power output can both increase efficiency and reduce specific fuel oil consumption (SFOC) at all loads.

- **Dual Fuel Conversion**

  The upcoming emission target in the shipping industry has contributed to the increased acceptance of alternative fuels. More specifically, according to the (DNV, 2014), LNG offers the prospect of up to a 25% reduction in CO_2 emissions. Furthermore, a nearly complete elimination of sulphur oxides (SOX) and particle emissions, and a 90% reduction in nitrogen oxides (NOX) is possible.

  As stated by the (DNV, 2014), the payback period depends on the exposure to Emission Control Areas (ECAs). For smaller vessels, which have a higher ECA exposure rate, payback time of less than five years in achievable for an LNG system. For example, in the case of a 1,000 TEU vessel, a comparison of payback times for an LNG system and for a scrubber system reveals that LNG is appealing under the condition that its price is lower compared to the HFO's price, when the fuels are compared on their energy content.

  However, there are many terms that need to be taken into consideration. As mentioned by the (DNV, 2014), such a project involves procedures such as the conversion of the engine in order for a complete gas storage and delivery system to be installed. Thus, it is absolutely necessary a feasibility study to be carried out in order to verify whether the conversion is economically feasible. Furthermore, it is essential that both the class rules for safe modification are correctly applied and that the equipment manufactures do also properly implement the corresponding requirements.

The applicability of the main engine modifications on various ship types is presented as follows:

Retrofit / Vessel	CV	CV-Feeder	Bulker	Tanker	MPV
Engine De-Rating	100%	75%	50%	25%	75%
Dual Fuel Conversion	25%	75%	25%	50%	50%

Table 16. M/E retrofits' applicability with ship type (DNV, 2014)

In accordance with the (DNV, 2014), the values of interest across all ship types, for the corresponding retrofit solutions, are presented below:

Parameter / Retrofit	Engine De-Rating	Dual Fuel Conversion
Ship Age Fit	3-12 years	0-12 years
Investment	M-L (150k-3M USD)	XL (> 3M USD)
Payback Time	1-4 years	2-5 years
Ease of Execution	Maintenance, Drydock	Maintenance, Drydock
Pre-Planning Time	3-8 months	8-12 months

Table 17. M/E retrofits' values across all ship types (DNV, 2014)

- **PMI Auto-tuning**

  According to the (MAN PrimeServ, 2016), PMI Auto-tuning is an engine measurement and tuning system for electronically controlled engines. Its purpose is to automate the engine measurement and tuning process, and consequently contribute to significant fuel savings and ensure the optimization of the engine operation. Furthermore, the system contributes to the monitoring and troubleshooting of the combustion process. The monitored performance data are displayed on a screen, and thus the crew is alerted of any potential chance to tune the engine.

  The PMI Auto-tuning enables the vessels to automatically select combustion pressure. As a result, an optimal combustion process, which reduces fuel oil consumption by improving the operation of the main engine, is ensured. The system automatically adjusts to variations of the ambient conditions and fuel properties. Tuning the engine leads to significant fuel savings. As explained by the (MAN PrimeServ, 2016), previous experience shows that savings around 2.0-4.0 gr/kWh are possible, which also lead to a significant reduction in the corresponding CO_2 emissions. MAN's wide list of possible benefits coming out of the Auto-tuning solution, include among others:

  - ✓ Considerable fuel savings
  - ✓ Significantly improved running performance and engine efficiency
  - ✓ Reduced cost of maintenance
  - ✓ The simplified operability eases the workload of the crew. Furthermore, it eliminates the time-consuming manual adjustment
  - ✓ Automatic engine adjustment in case of changes in fuel bunker and ambient conditions
  - ✓ Reduced CO_2 emissions
  - ✓ Avoidance of mechanical and thermal overload of the engine
  - ✓ Installation to be conducted under normal service
  - ✓ Increased reliability
  - ✓ Elimination of human error

4 Engine Power Limitation

4.1 IMO Guidelines on EPL

According to the (IMO, 2021), Overridable Engine Power Limitation is defined as a verified and approved system for the limitation of the maximum engine power by technical means. The engine power is considered as the mechanical power transmitted from the engine to the propeller shaft. In case of multiple engines, the corresponding engine power is the sum of the power transmitted from the engines to the propeller shafts.

As specified by the (IMO, 2021), the Engine Power Limitation can only be overridden either by the master of the vessel or the officer in charge of navigational watch (OICNW) for the purpose of securing the safety of a ship or saving life at sea.

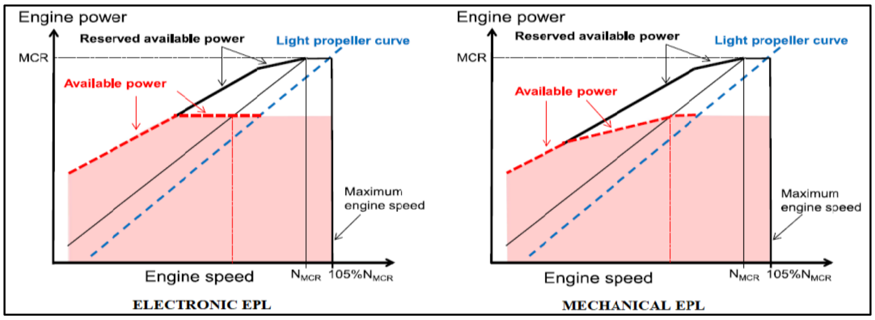

Figure 20. Engine load diagram on Shaft / Engine Power Limitation (IMO, 2021)

The reserved available power presented in the diagrams is the engine power which cannot be used in normal operation, unless the EPL is unlimited for ship safety purposes.

As stated in the (IMO, 2021), the Engine Power Limitation system should consist of the following arrangements, based on the type of the engine:

- **Mechanically controlled engine**

For a mechanically control engine, a sealing device that can physically lock the fuel index by using a mechanical stop screw sealed by wire or an equivalent device with governor limit setting is required. The sealing device should visibly indicate removal of the sealing in case that the vessel's engine power exceeds the limited engine power. Alternatively, the device should be equipped with an alert-monitoring system which can indicate when the engine power exceeds the limit and record the use of unlimited EPL mode (IMO, 2021).

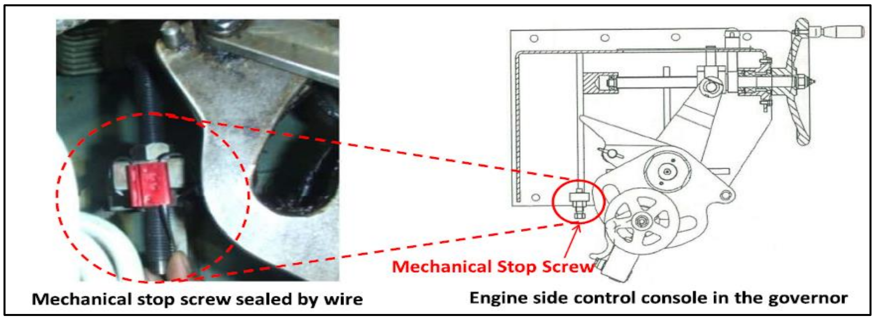

Figure 21. Sealing of mechanical stop screw (IMO, 2021)

➢ **Electronically controlled engine**

For an electronically controlled engine, a fuel index limiter that can electronically lock the fuel index or direct limitation of the power in the engine's control system is required. The use of unlimited mode must be both indicated and recorded by either the fuel index sealing system or the power limitation system. The control unit should inform the master or OICNW clearly and conspicuously in case that the engine power exceeds the limit (IMO, 2021).

As reported by the (IMO, 2021), where it is technically possible and feasible, the EPL system should be controlled remotely from the bridge of the vessel, without the physical attendance of the crew in the engine room. Furthermore, for systems that use a password to control access to the power reserve override, the availability of the password, when override is required, is essential.

4.2 RightShip's EPL acceptance criteria

According to (Skoufalos, 2012), RightShip is considered an independent ship vetting company that provides rating for virtually and commercial vessels. Users log into RightShip's Ship Vetting Information System and enter basic information about the proposed voyage. The company examines the user's request and the information of the corresponding vessel. Based on this, RightShip provides a 1-to-5-star rating, that indicates whether the ship is acceptable for the proposed voyage. As explained by (Skoufalos, 2012), the rating is valid only at the time it is given, and is subject to change, as RightShip constantly update the data in their database.

RightShip's users are mostly charterers. As mentioned by (Skoufalos, 2012), the vetting company helps them choose vessels with a lower risk of lost cargo and delays from casualties and detentions. The company claims that ship owners and managers are also benefited from high ratings in the form of lower insurance costs and higher charter rates.

Beyond vetting, RightShip has also launched Environmental Ratings for vessels. As referred by (Claudia Norrgren / RightShip, 2020), the GHG Rating provided by the company compares the theoretical CO_2 emissions of a peer group of vessels with similar size (± 10% DWT) and type. The groups include bulk carriers, chemical tankers, containerships, crude & product tankers, cruise & passenger ships, general cargo ships, LNG tankers, LPG tankers, refrigerated cargo ships and ro-ro cargo ships.

The GHG rating uses the EVDI (Existing Vessel Design Index), which follows the same calculation process as the EEDI. According to (Claudia Norrgren / RightShip, 2020), a vessel is given a rating based on how its EVDI compares to the average EVDI score of the peer group vessels. If the vessel is more efficient than the average, it earns a higher rating, in scale of A-to-G. Generally, the ratings for a vessel's peer group follow the fixed percentages presented below:

GHG Emissions Rating	G	F	E	D	C	B	A
Size Score	< = -2.0	> -2.0	> -1.0	> -0.5	> 0.5	> 1.0	> 2.0
Area Under Curve	2.5%	13.5%	16%	36%	16%	13.5%	2.5%

Figure 22. RightShip's GHG Emissions Rating / Fixed percentages (Claudia Norrgren / RightShip, 2020)

The size score indicates the position of the vessel in the Rating band. The ratings are dynamic and subject to change as the peer group changes. Thus, a vessel's size score and GHG Rating change over time.

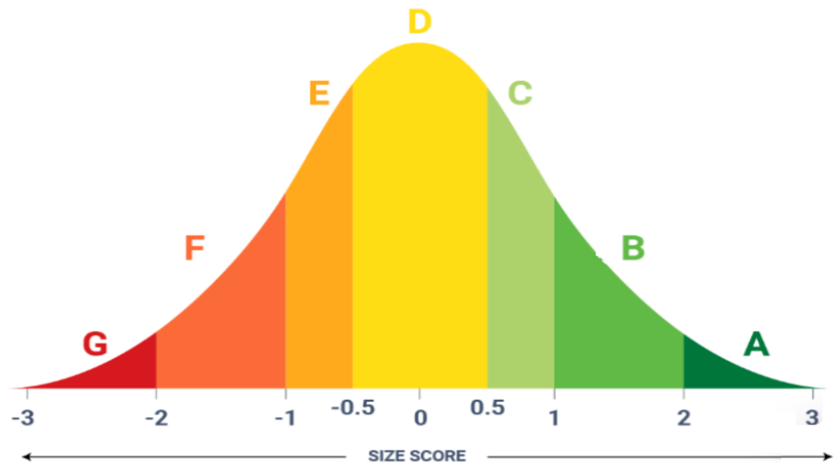

Figure 23. RightShip's Size Score (Claudia Norrgren / RightShip, 2020)

As determined by (RightShip, 2020), the EPL acceptance criteria are designed to maximize the reliability of EPL application on vessels. The company advises that the basis behind the established criteria is the following:

- The significant increase in EPL application, which has affected the peer groups, and thus the dynamic nature of the rating
- The effect of the EPL on a vessel's rating is larger than the corresponding impact on the actual emissions reduction
- Due to the previous facts, the development and investment in other equipment, with a possibly greater impact on emissions reduction, might be put aside.
- Due to the fact that EPL can be reversed, it is vital to ensure the EPL remains intact in normal operation.

Taking into consideration the aforementioned arguments, (RightShip, 2020) has set the following limitations to EPL acceptance:

✓ A vessel must not limit their engine below the IMO's minimum propulsion power guidelines, as indicated in Assessment level 1 – minimum power lines assessment (MEPC.1/Circ.850/Rev.2). Assessment level 2 provided by the IMO guidelines is not applicable. As speculated, the main reason for rejecting Level 2 is the fact that the corresponding minimum propulsion power is by far less than the Level 1 determined power. Thus, a vessel is riskier of being underpowered and, consequently, in danger under adverse weather conditions.

✓ RightShip will only accept one EPL per vessel, thus a vessel is not allowed to undertake more than one EPL

✓ The required documentation must be provided before any benefit will be applied to the vessel's GHG Rating and must prove that the engine has been limited in a 'semi-permanent' way

A clear comparison between RightShip's GHG Rating and EEXI regulation is presented in the following figures. As explained by (RightShip, 2021), Figure 1 shows that GHG Rating provides an efficient comparison of vessels, as there is a clear differentiation between efficiency levels, from A-rated top efficient vessels, to G-rated inefficient vessels.

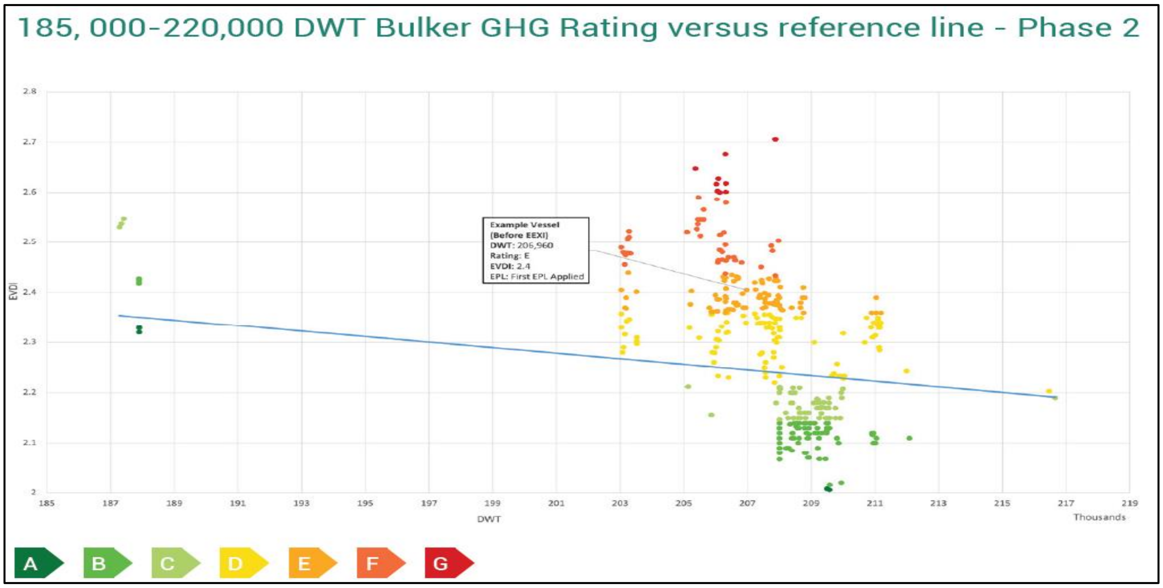

Figure 24. RightShip's 185,000-220,000 DWT Bulker GHG Rating vs Phase 2 Ref. Line (RightShip, 2021)

On the other hand, as claimed by (RightShip, 2021), Figure 2 indicates that as the EEXI enters into force in 2023, in case that all vessels' operators applied overridable Engine Power Limitations to comply with the requirements, this would lead all ships to have similar results in terms of efficiency. Thus, EPL would offer limited differentiation to the market.

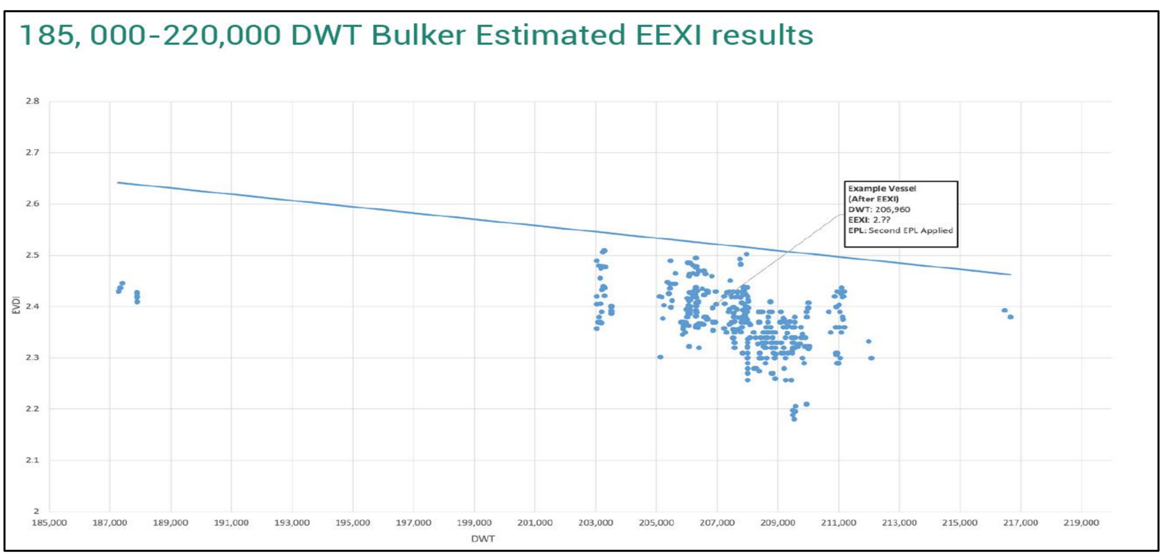

Figure 25. 185,000-220,000 DWT Bulker Estimated EEXI results (RightShip, 2021)

4.3 Hyundai's recommendations on EPL

According to (Hyundai Global Service, 2021), Engine Power Limitation in the easiest way to comply with the upcoming EEXI requirements for vessels that need additional measures to achieve that. However, the EEXI EPL has additional requirements compared to the previous EPL solution which follows RightShip's requirements. The differences between the two EPL solutions are briefly described as follows:

Description	EVDI EPL (Existing Vessel Design Index)	EEXI EPL (Energy Efficiency Existing Ship Index)
Mandatory	Non-Mandatory	Mandatory
Origin	Developed by RightShip	IMO
Limitation	Limited above Minimum Power - Fixed	Limited below Minimum Power - Overridable
Method of Limitation	Mechanical Stopper (Screw Bolt) + BMS/ECS software update for limited mode only	Two Position Stopper Control Unit + BMS/ECS software update for both limited mode and un-limited mode
Method of Release	Removal Screw Bolt by Manual (At Local)	Operation by Remote (at Bridge) - Release Key Switch Installed on the Bridge Control Console
Tamper-Proof	Sealing Wire only	Sealing Wire and Data Recording
Data Logger	Written by hand	Electronic recording system
Alert-Monitoring	Not applied	Interface with AMS adding I/O points
Construction	Installation of Stopper	Installation for the equipment, cables and etc.
Document	EPL Report only	EEXI Technical File, OMM (Onboard Management Manual) and Drawings
Verification	Class Surveyor	Administration or Class Surveyor

Table 18. EVDI / EEXI EPL comparison (Hyundai Global Service, 2021)

As reported by (Hyundai Global Service, 2021), the four main differences of EEXI EPL, compared to EVDI, are concluded as follows:

- ✓ EEXI EPL can limit the output lower than Minimum Power, while EVDI (RightShip) EPL is limited above Minimum Power
- ✓ EEXI EPL is overridable, while EVDI EPL is fixed. Thus, the former allows the master of the vessel to use the unlimited engine power (power reserved) of the ship, in case of emergency.
- ✓ EEXI EPL is capable of self-monitoring. Additionally, it is able to inform the master clearly in any case of malfunction.
- ✓ EEXI EPL system should be controlled by the bridge. Any attendance to the engine room in not required.

Engine Power Limitation for Electronically Controlled Engine (Hyundai-MAN ME Type)

As specified by (Hyundai Global Service, 2021), for electronically controlled engines (ME), the governing system for each cylinder is controlled by Engine Control Station (ECS). The Password/Pin to control the power reserve override should be implemented by the manufacturer.

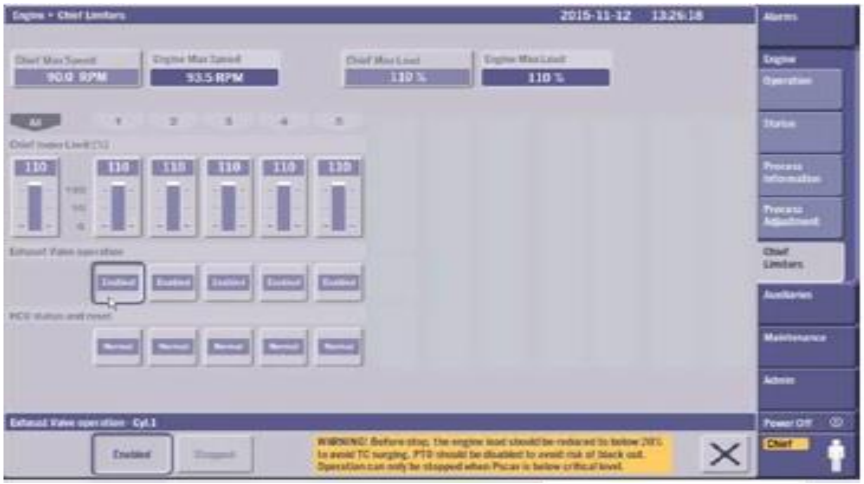

Figure 26. Hyundai's Engine Control Station software (Hyundai Global Service, 2021)

Engine Power Limitation for Mechanically Controlled Engine (Hyundai-MAN MC Type)

As explained by (Hyundai Global Service, 2021), for existing vessels, engine power is being limited by adjusting stopper bolt height in order to limit the rotation of governor regulating shaft mechanically.

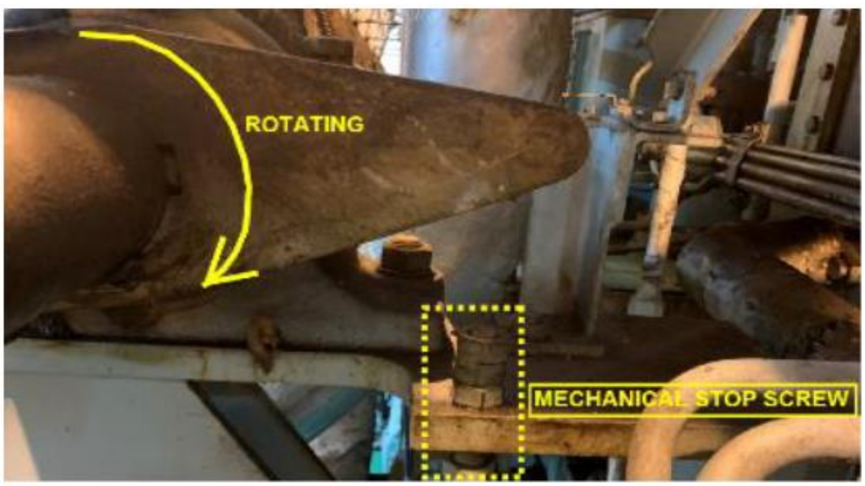

Figure 27. Mechanical stop screw (Hyundai Global Service, 2021)

The new EEXI guidelines require that the engine of a vessel shall have two power limitations. The first one is limited power by EEXI and the second one is reserve power, which demands that the ship shall instantly return to the original power in case of emergency situation. As mentioned by (Hyundai Global Service, 2021), the two power modes shall be converted by remote operation, so that the master of the vessel can release the limit from the bridge with electro-pneumatic controlled two position unit on engine. The event must always be recorded in the logbook.

Monitoring and recording

According to (Hyundai Global Service, 2021), for both electronically and mechanically controlled engines, the Data Acquisition & Transmission System (DATS) provided by Hyundai can be applied for the easiest monitoring and automatic recording function. In case that DATS is combined with EPL system, the data are recorded as the regulation requires and are automatically logged in the system so they can be read by the monitor and printed out. Furthermore, the data is unable to be modified. The configuration diagram of the system is presented below, as per HGS:

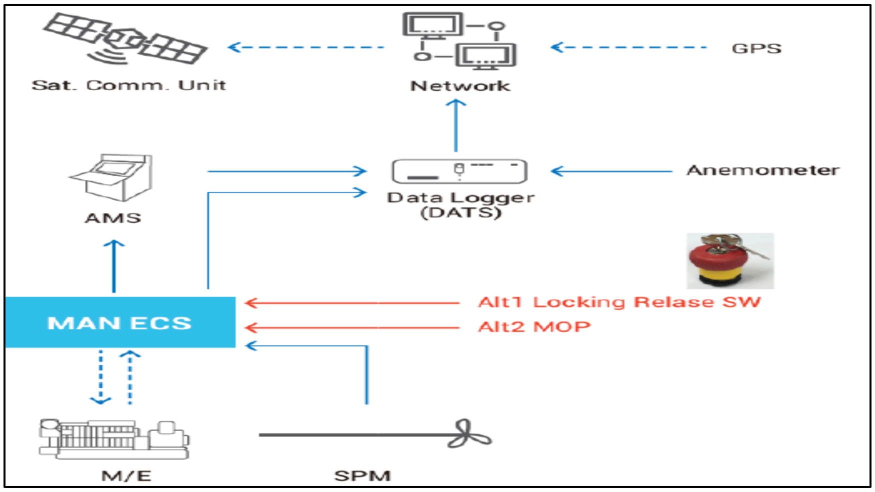

Figure 28. Hyundai's Data Acquisition and Transmission System (Hyundai Global Service, 2021)

4.4 The disadvantage of Engine Power Limitation

As explained by (RightShip, 2021), the most likely recommendation, for existing vessels, to comply with the upcoming EEXI requirements will be an overridable Engine Power Limitation. However, EPL is not sufficient in terms of achieving the innovation required for the industry to decarbonize in accordance with the ambitious IMO's GHG reduction strategy. As believed by (RightShip, 2021), the main reason for that is the fact that vessels, nowadays, are generally slow steaming and rarely use their full engine power. Thus, the effect of Engine Power Limitation on emission reduction will probably be minimal, due to the fact that their operational profile will not change, as ships already operate slower than the speed limit applied by EPL. As a result, in order for Engine Power Limitation to contribute to the IMO's GHG reduction goals, it needs to be really antagonistic.

5 Case study: The effect of EPL on the EEXI and CO_2 emissions

In this case study, two different vessels are about to be examined. The first one is a 180,000 DWT Bulk Carrier, built in 2011, equipped with an electronically controlled engine of 18660 kW @ 91 RPM. The second vessel is a 75,000 DWT Product Carrier, built in 2008, with a mechanically controlled engine of 12240 kW @ 105 RPM.

In the first part of the following report, an extended calculation process is conducted for a range of Engine Power Limitation scenarios in order to test the effect of the limitation on the attained EEXI values and to verify whether the subject vessel complies with the upcoming EEXI requirements. For that purpose, the following parameters are determined based on the procedures described by the guidelines:

1. **Minimum Propulsion Power**
   The minimum propulsion power is calculated based on the Level 1-minimum power lines assessment and Level 2-simplified assessment procedures, as they are provided by the IMO.

2. **Speed / Power curve at scantling draught**
   The power curve at the stipulated/scantling draught condition is calculated from the results of the speed trial condition using the power curves predicted by the model tank tests, according to the ITTC's and IMO's procedures.

3. **Attained EEXI**
   The attained Energy Efficiency Design Index is calculated by the formula provided by the IMO's MEPC 76.

4. **Required EEXI / EEDI values**
   The required EEXI values are obtained from the EEDI reference lines, which are calculated accordingly for vessels of different type and size.

In the second part of the report, a comparison between the attained theoretical values and the real-time data obtained by the noon reports is conducted. In that direction, an extended analysis of the noon reports' data is performed, in order to estimate the real-time average speed of the subject vessel for the Jan 20 – Dec 21 period, as well as the corresponding "EEXI" [gr-CO_2/t*nm] emissions. The purpose of the study is to investigate the relationship between the predicted EEXI values and the real-time "EEXI" emissions in order to provide a reliable deduction about the effect of the upcoming EEXI regulation on the actual GHG emissions.

5.1 180,000 DWT Bulk Carrier

5.1.1 Data

In the first part of the calculation report, a **180,000 DWT Bulk Carrier** is about to be examined. The main particulars of the subject vessel are presented in the following table:

Particulars	
Type	Bulk Carrier
Length Over All	292.00 m
Length between perpendiculars	283.50 m
Breadth moulded	45.00 m
Depth moulded	24.80 m
Draught moulded (Summer load line draught)	18.32 m
Deadweight (at Summer load line draught)	179107 tons
Lightship	26361 tons
Year of Build	2011
Ice class	No

Table 19. Bulker's main particulars

The subject vessel was built in **2011**, according to the owner. Thus, it is under the scope of the upcoming EEXI requirements. Furthermore, due to the fact that it is a Bulk Carrier vessel, it extensively falls under the scope of RightShip's requirements regarding the Engine Power Limitation acceptance criteria.

The crucial parameters of the main and auxiliary engines of the vessel are presented in the following tables. A further investigation in the shop tests is about to be done in a later stage to obtain more specific parameters of the engines.

MAIN ENGINE	
Maker	Hyundai-MAN B&W
Engine type	6S70ME-C7
Maximum continuous rating (kW)	18660
Speed @ MCR (RPM)	91
Fuel type	Diesel Oil

Table 20. Bulker's main engine particulars

AUXILIARY ENGINE	
Maker	YANMAR CO., LTD.
Engine type	6EY18ALW x 730 kW
Maximum continuous rating (kW)	800
Speed @ MCR (RPM)	900
Fuel type	Diesel Oil

Table 21. Bulker's aux. engines particulars

5.1.2 Minimum Propulsion Power Calculation

IMO suggest two different methods to determine the minimum propulsion power a ship should have in order to be considered to have sufficient power to maintain maneuverability in adverse weather conditions. The assessment can be carried out in the two following levels:

1. Level 1: Minimum Power Lines Assessment
2. Level 2: Simplified Assessment

Level 1 assessment of a 180,000 DWT Bulk Carrier

The "Bulk Carrier" parameters a and b for the determination of the minimum power line value for the corresponding DWT of the subject vessel are defined by Table 10 and presented as follows:

- ✓ a = 0.0490
- ✓ b = 7329.0
- ✓ DWT = 179107.4 tons

Based on the defined parameters and equation (14), the calculated minimum power is defined as follows:

Minimum Power = 16106 kW

This minimum power value refers to the total installed MCR of the main engine

Level 2 assessment of a 180,000 DWT Bulk Carrier

The main particulars of the hull and the propeller of the subject vessel, for the minimum propulsive power determination, based on the simplified assessment, are presented below:

HULL	
L_{PP} (m)	283.5
Beam, B (m)	45
Summer Draft, T (m)	18.32
Disp, Δ (tons)	205429
Disp, V (m3)	199962
Wetted Surface Hull, S_H (m2)	20772.3
Wetted Surface Rudder, S_R (m2)	188.5
Wetted surface, S (m2) (Hull+Rudder)	20960.8
Actual Rudder Area, A_R (m2)	74.15
Block coeff., C_B	0.857
Deadweight, DWT (tons)	179107
Frontal wind area, A_{FW} (m2)	1027
Lateral wind area, A_{LW} (m2)	2781
PROPELLER	
No. blades	4
D (m)	8.2
P/D (0.7R)	0.732
A_e/A_o	0.459
Model	P2517

Table 22. Bulker's assessment level 2 particulars

- **Spectrum determination**

Based on Table 11, the significant wave height, Hs, for a vessel larger than **250 m**, is considered equal to **5.5 m**. The environmental conditions are defined for various sea states. Each sea state is defined by the aforementioned significant wave height and the peak spectral period, which ranges from 7 to 15 seconds.

According to the guidelines, the frequency spectrum is considered to be of **JONSWAP** spectrum with the peak enhancement factor, γ=3.3.

- **Speed of advance**

The required ship advance speed through the water in head wind and waves, V_s, is set the larger of:

- **Minimum navigational speed, V_{nav}**

  In accordance with the IMO, the minimum navigational speed is set to **4 kn**.

- **Minimum course keeping speed, V_{ck}**

  The minimum course keeping speed for the subject vessel is specified by equation (15), as follows:

  $$\boldsymbol{V_{ck} = V_{ck,ref} - 10.0} \times (\boldsymbol{A_{R\%} - 0.9})$$

  Where,

  - ✓ $V_{ck,\, ref}$ = 4.517 kn, for A_{FW}/A_{LW} = 0.369.
  - ✓ $A_{R\%}$ = 0.876
    - A_R = 74.15 m^2
    - $A_{LS,CORR}$ = *8466.1* m^2

  Thus, the minimum course keeping speed, V_{ck} is equal to **4.76 kn**.

The required ship speed of advance is the larger the aforementioned ones, thus Vs is equal to **4.76 kn**

- **Calm Water Resistance**

The calm water resistance for bulk carriers can be calculated according to equation (17) , neglecting the wave-making resistance, as follows:

$$\boldsymbol{R_{cw} = (1 + k)C_F \frac{1}{2}\rho S V_s^2}$$

Where,

- ✓ Re = $5.83*10^8$
- ✓ C_F= $1.64*10^{-3}$
- ✓ k= 0.2575
- ✓ ρ = 1025 kg/m^3
- ✓ S = 20960.78 m^2
- ✓ Vs = 2.447 m/s

Thus, the calculated Calm water resistance, $\mathbf{R_{cw}}$, is equal to **132.52 kN**

- **Aerodynamic Resistance**

The aerodynamic resistance is calculated based on equation 18, as follows:

$$R_{air} = C_{air}\frac{1}{2}\rho_a A_F V_{w,rel}^2$$

Where,

- ✓ $C_{air} = 1$
- ✓ $\rho_a = 1.2$ kg/m^3
- ✓ $A_F = 1026.8$ m^2
- ✓ $V_{w,rel} = 21.447$ m/s

Thus, the calculated Aerodynamic resistance, $\mathbf{R_{air}}$, is equal to **283.38 kN**

- **Added resistance in waves**

The mean added resistance in irregular waves, Raw, defined by the adverse conditions and wave spectrum, is calculated as per equation (19). The resistance increase due to waves could be determined by the following alternative methods:

i. <u>Direct correction method STAwave-1</u>

The increase of the resistance in head waves, given that heave and pitching are small, is calculated according to equation (20), as follows:

$$R_{AWL} = \frac{1}{16}\rho g H_{W1/3}^2 B\sqrt{\frac{B}{L_{BWL}}}$$

Where,

- ✓ B: Beam of the vessel, **45m**
- ✓ $H_{W1/3}$: significant wave height, **5.5m**
- ✓ L_{BWL}: Length of the bow on the water line to 95% of maximum beam, **42.95m**

The added resistance due to waves, R_{AWL}, according to the method STAwave-1, is equal to **875.66 kN**.

The STAwave-1 method, in order to be exclusively valid, also requires that $H_s \leq 2.25\sqrt{L_{PP}/100}$ For the subject vessel, Hs is equal to **5.5m**. The equation is equal to **3.79,** and thus the condition is not verified. As a result, the STAwave-1 offers a preliminary but uncertain estimation of the mean added resistance in irregular waves and, thus, a second method is required in order to verify the validity of the calculated results.

ii. Liu-Papanikolaou semi-empirical formula

In order to calculate the added resistance of ships in head waves at any wave length, the equation (21) developed by (Liu, Papanikolaou, & Bolbot, 2016), can be used**:**

$$\boldsymbol{R_{WAVE} = R_{AWR} + R_{AWM}}$$

For short waves, the mean added resistance increase due to wave reflection, R_{AWR}, is the predominant one. The simplified equation (22) has been developed by Liu-Papanikolaou, for the calculation of the corresponding added resistance:

$$\boldsymbol{R_{AWR} = \frac{2.25}{2} \rho g B \zeta_\alpha^2 sin^2 E \left(1 + 5\sqrt{\frac{L_{PP}}{\lambda}} Fn\right) \left(\frac{0.87}{C_B}\right)^{1+4\sqrt{Fn}}}$$

Where $\mathbf{E = atan(B/2L_E)}$ and L_E is defined as the distance from F.P. to the position where the 99% of the maximum ship breadth (B) is reached. For the subject vessel $\mathbf{L_E}$ is equal to **51.14m.**

For the calculation of the mean added resistance due to ship motion, the equation (23) is proposed by Liu-Papanikolaou:

$$\boldsymbol{R_{AWM} = \frac{4\rho g \zeta_\alpha^2 B^2}{L_{PP}} \bar{\omega}^{b_1} exp\left[\frac{b_1}{d_1}(1 - \bar{\omega}^{b_1})\right] \alpha_1 \alpha_2}$$

The parameters included in the aforementioned formula, as they are described by (Liu, Papanikolaou, & Bolbot, 2016), are defined by the equations (24)-(28)

The added resistance in regular head waves R_{WAVE}, as a dimensionless quantity, is presented in the following diagram:

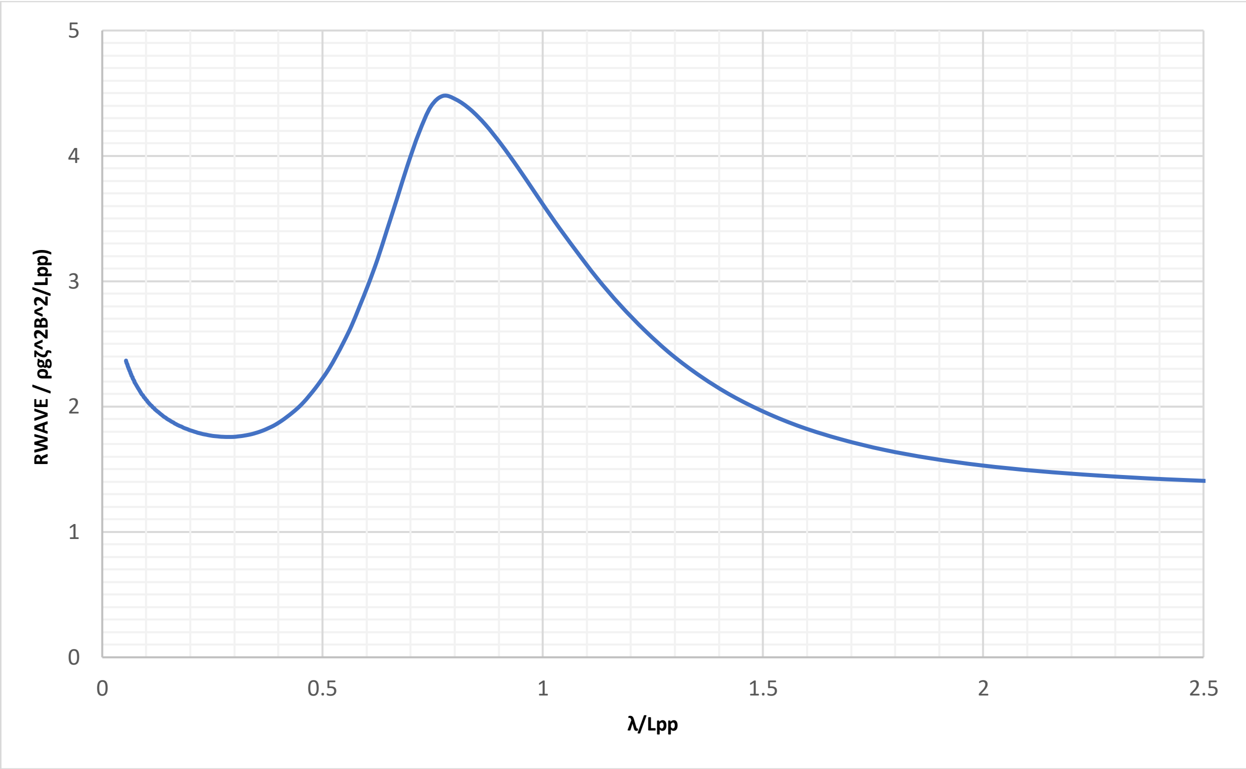

Figure 29. Added resistance in regular waves

The mean value of the added resistance in irregular waves is calculated by applying some standards JONSWAP spectrums to the estimated transfer function $R_{aw}(V_s, \omega)/\zeta_\alpha^2$. Thus, the mean added resistance in irregular waves is calculated in accordance with equation (30), as follows:

$$\boldsymbol{R_{AW}} = \mathbf{2}\int_{0}^{\infty} \frac{\boldsymbol{R_{wave}(\omega)}}{\boldsymbol{\zeta_\alpha^2}} \boldsymbol{S(\omega)d\omega}$$

where **ζα** is equal to **2.75m** for the subject sea state. The JONSWAP spectrum is calculated according to equation (29), taking into consideration that **H**$_s$ is equal to **5.5m**, as follows:

$$\boldsymbol{S(H_S, T_P, \gamma)} = \frac{\mathbf{6.183}\ \boldsymbol{\omega^{-5}}}{\boldsymbol{\omega_p^{-4}}} \boldsymbol{exp}\left[\frac{-\mathbf{5}}{\mathbf{4}}\left(\frac{\boldsymbol{\omega}}{\boldsymbol{\omega_p}}\right)^{-4}\right] \boldsymbol{\gamma}^{\boldsymbol{exp}\left[\frac{-(\omega-\omega p)^2}{2\sigma^2 \omega p^2}\right]}$$

Where the peak enhancement factor parameter, γ=3.3

In order for the results to be valid, every possible wave spectrum, with peak period ranging from 7 to 15 seconds, needs to be examined. The added resistance in regular waves, R_{WAVE}, and the various sea states that were taken into consideration are presented in the following diagram:

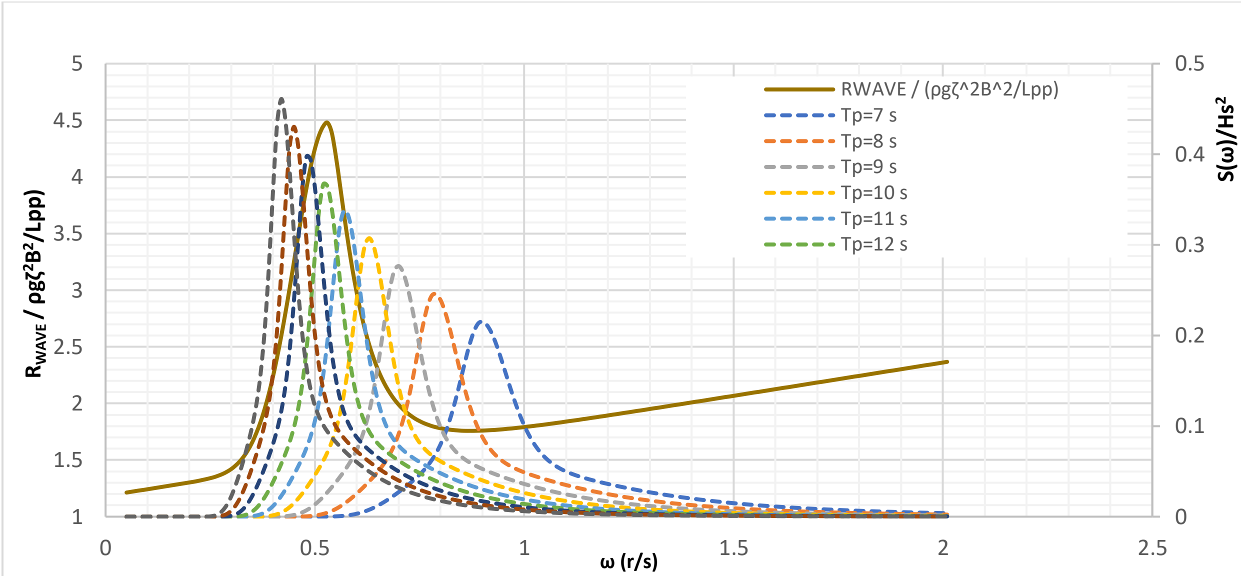

Figure 30. JONSWAP spectrums-Added resistance in regular waves

In order to calculate the maximum mean added resistance in irregular waves for the subject vessel the corresponding formula needs to applied for all the sea states. The calculated values of the mean added resistance, as a function of the corresponding peak period, is presented in the following diagram:

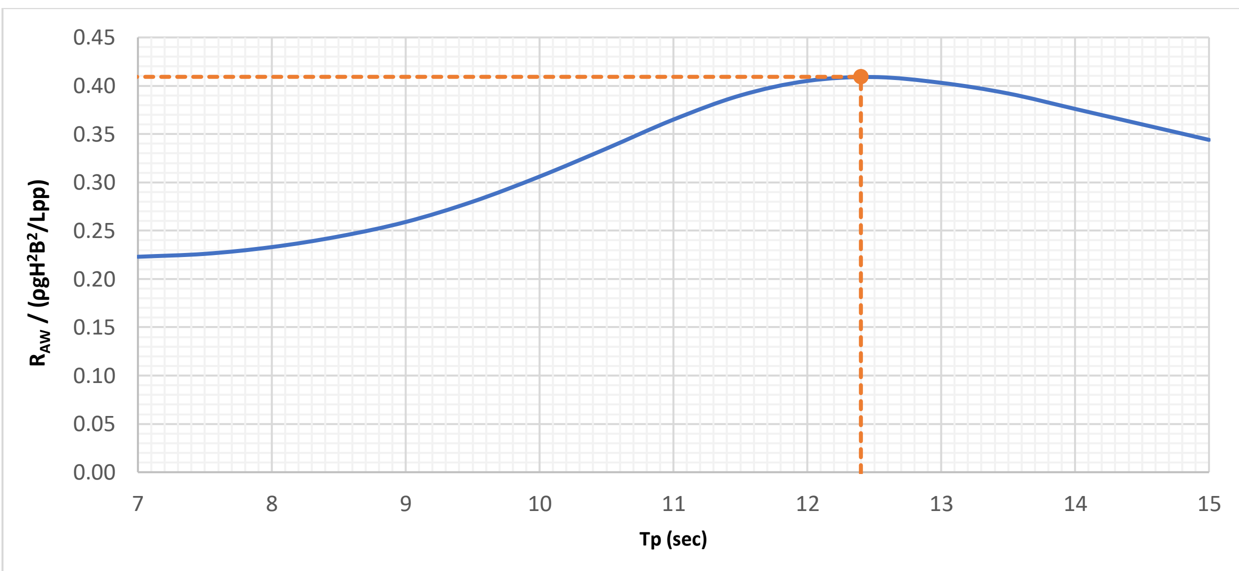

Figure 31. Mean added resistance in irregular waves

According to the diagram, the maximum mean added resistance in irregular waves is calculated for the JONSWAP spectrum with a peak period, T_p, equal to **12.4 sec**. The corresponding value, R_{AW}, is equal to **889 kN.**

- **Total Resistance**

The total resistance of the vessel, R_{TOT}, takes two different values, depending on the method that was used to calculate the added resistance due to waves, STAwave-1 or Liu-Papanikolaou semi-empirical formula. Those values are presented in the following diagram.

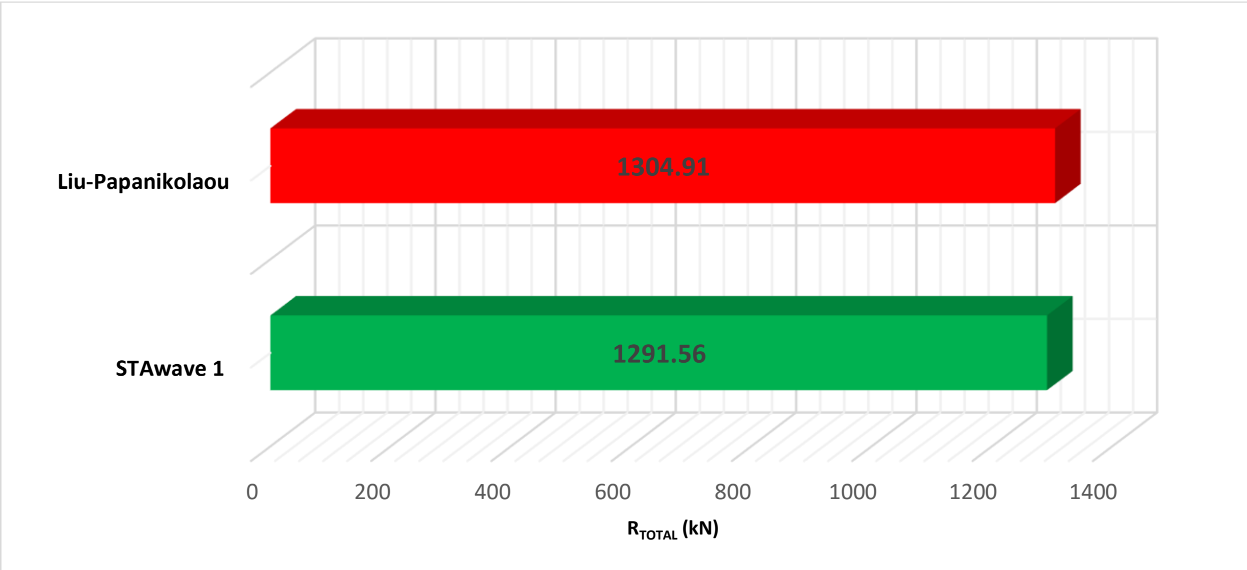

Figure 32. STAwave 1 – Liu Papanikolaou Total Resistance Comparison

The diagram indicates that the total resistance calculated based on the Liu-Papanikolaou method is larger than the STAwave-1 respective one. As a result, in order to make a more conservative estimation of the Level 2 Minimum Propulsion Power, the total resistance, $\mathbf{R_{TOT}}$, is considered equal to **1304.91 kN**.

- **Propeller Thrust**

The required propeller thrust, T in N, is defined from the sum of bare hull resistance in calm water R_{cw}, resistance due to appendages Rapp, aerodynamic resistance R_{air}, and added resistance in waves R_{aw}, taking into consideration the thrust deduction factor, t. In this case, the resistance due to appendages is included in the calm water resistance calculation. The propeller thrust is calculated based on equation (16), as follows:

$$\boldsymbol{T = R_{cw} + R_{air} + R_{aw} \;/(1-t)}$$

According to the total resistance estimation process, the most conservative summarize of the aforementioned resistance parameters, $\mathbf{R_{TOT}}$, is equal to **1304.91 kN**.

The thrust deduction factor, t, for the subject vessel, is estimated from the model tests report and is equal to **0.169.** The corresponding wake fraction, w, is **0.369**. Despite the fact that these model test values correspond to a larger speed of advance than the examined one (4.76 kn), they are considered to be a conservative and thus reliable approach. As a result, the Propeller Thrust, **T**, is equal to **1570.29 kN.**

- **Advance coefficient**

The power prediction is based on the "K_T/J^2 method" provided by the ITTC. Thus, the required advance coefficient is calculated from the propeller loading K_T/J^2, in accordance with equation (31), as follows:

$$\mathbf{K_T/J^2} = \mathrm{T}/\rho u_\alpha^2 D_P^2 \;\; = \mathbf{9.557}$$

Based on the following model scale open water diagram that was obtained from the model tests report of the vessel, the propeller required values are defined as follows:

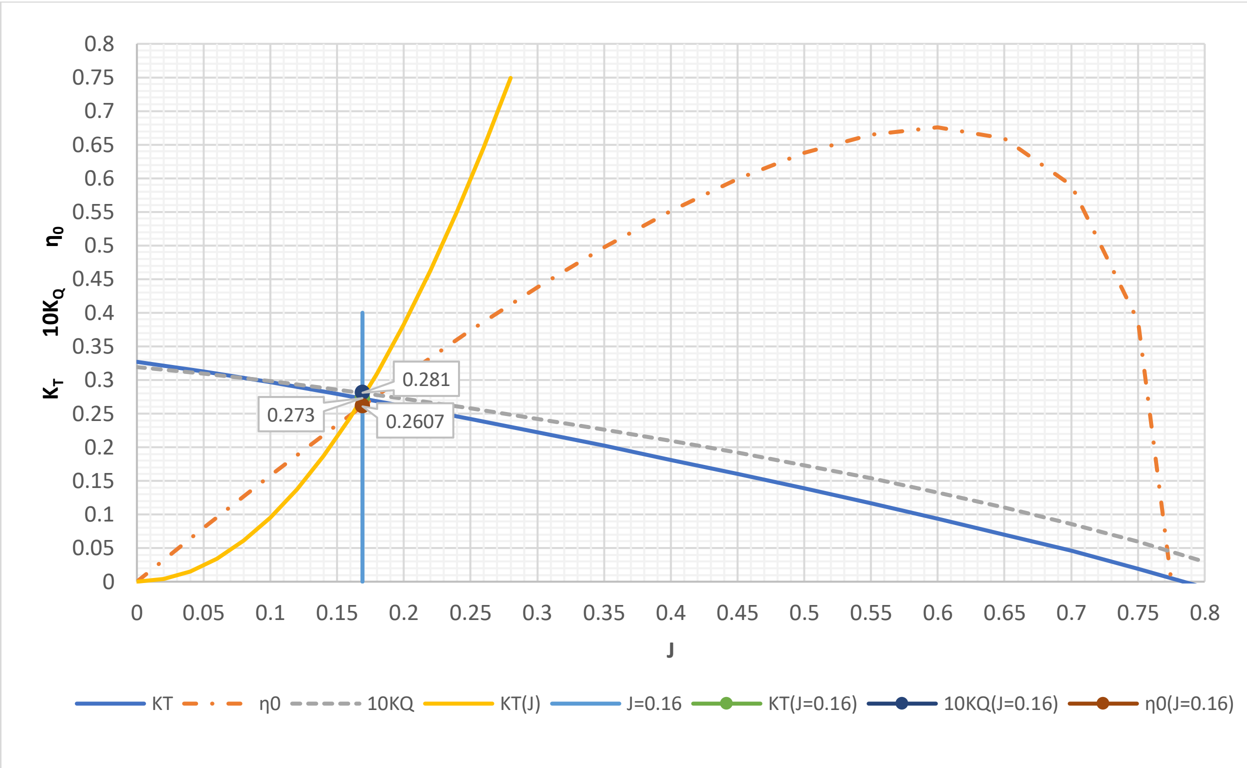

Figure 33. Propeller model scale open water diagram

J	K_T	K_Q	η_o
0.169	0.273	0.0281	0.2607

Table 23. Open water diagram parameters

- **Rotation rate**

The required rotation rate of the propeller, n, in revolutions per second, is calculated according to equation (32), as follows:

$$\boldsymbol{n} = \frac{u_a}{JD_P} = \boldsymbol{1.114\ r/s}$$

Thus, the required propeller rotation rate, n, in revolutions per minute, is equal to **66.8 RPM**.

- **Delivery Power**

The required delivery power to the propeller at this rate n, P_D in Watt, is defined by equation (33), as follows:

$$\boldsymbol{P_D} = 2\pi\rho n^3 D_P^5 K_Q(J) = \boldsymbol{9275448 Watts}$$

Thus, the delivered power P_D, in kW, is equal to **9275 kW**.

- **Diesel engine available power**

In order to verify that the maximum torque that the engine can deliver at the calculated propeller rotation rate n is adequate, it is necessary to design the torque/speed limit of the MAN B&W 6S70ME-C7 Engine. Considering that the transmission efficiency, η_s, is equal to 0.98, the minimum power that the diesel engine should provide at **66.8 RPM** is equal to **9465 kW**.

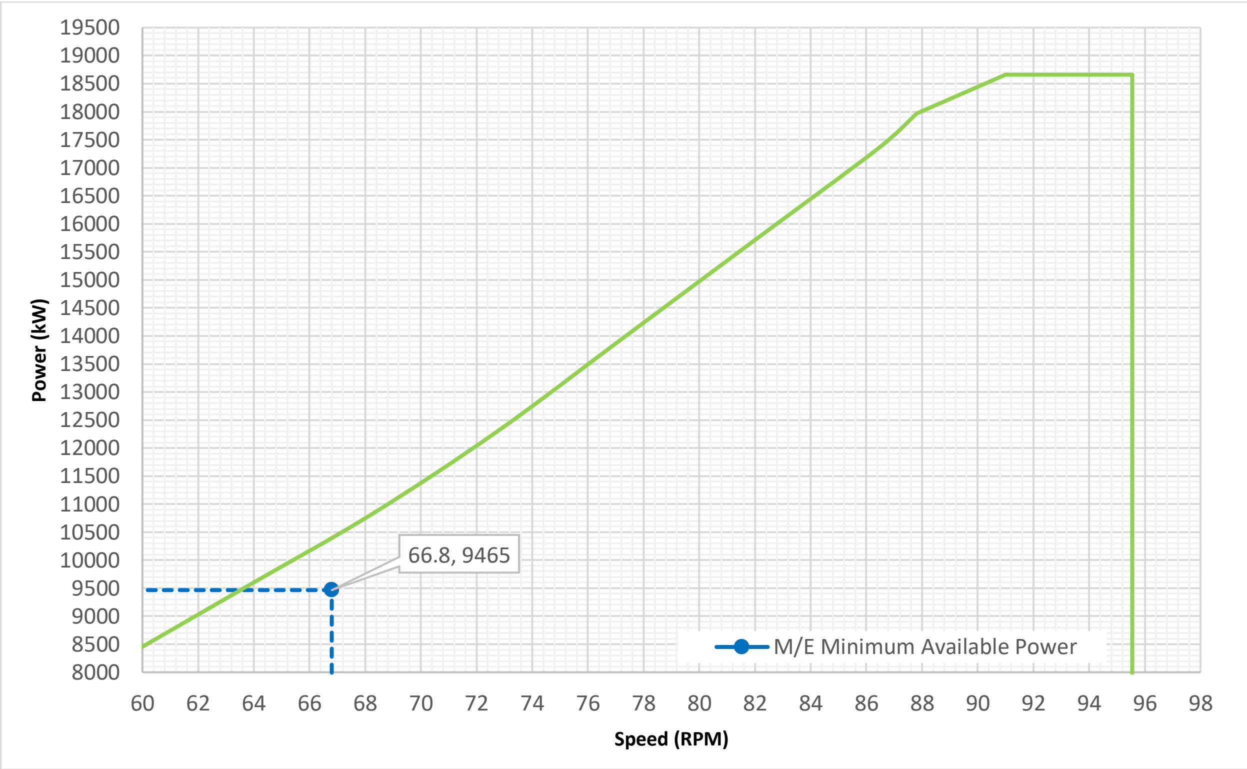

Figure 34. MAN B&W 6S70ME-C7 Load diagram / Engine Minimum Available Power

The estimated load diagram indicates that the diesel engine will deal effortlessly with the required torque for Vs = 4.76 kn. Furthermore, the conservative estimation process of the Level 2 Minimum Propulsion Power of the subject vessel ensures that the diesel engine, even in the worst-case scenario that was examined, is able to provide the required power at the corresponding rotation rate.

5.1.3 Power / Speed Curve

The subject vessel was built in 2011, thus the corresponding case refers to a pre-EEDI vessel.

For the subject vessel, six case scenarios are about to be examined in order to provide a clear picture of the way that the EEXI responds on various limitations of the engine.

The examined case scenarios are briefly described below:

- ✓ **Case 1**: In this scenario the engine in not limited (0% EPL).
- ✓ **Case 2**: The engine is limited to the Level 1 Minimum Propulsion Power (13.69% EPL)
- ✓ **Case 3**: The engine is limited to the Level 2 Minimum Propulsion Power (49.28% EPL).
- ✓ **Case 4**: The engine is limited to a level that applies to IMO's EEDI Phase 2 (41.05%) requirements
- ✓ **Case 5**: The engine is limited to a level that applies to IMO's EEDI Phase 3 (53.05%) requirements
- ✓ **Case 6**: In this scenario the engine is limited to a level that the reference speed matches the average speed of the daily noon reports, 11 kn. The corresponding EPL is 64.13%.

RightShip's EPL acceptance criteria only applies to Case 1 and Case 2, where the engine is not limited lower than the Level 1 Minimum Propulsion Power.

According to the ITTC, it is difficult, especially for dry cargo vessels, to conduct speed trials at full load condition. As a result, in the examined case the speed trial was performed at heavy ballast condition. The result of the trial needs to be converted to that of the scantling load condition**.**

The power curve at scantling load condition is obtained from the results of the speed trials at heavy ballast condition using the power curves that were predicted by the model tank tests that were carried out at both the heavy ballast and scantling load condition.

The speed-power curve values predicted by the model tank test at the scantling load condition are presented as follows:

V (kn)	$P_{FULL,P}$ (kW)
11	5893
12	7690
13	9754
14	12156
15	15214
16	19054

Table 24. Scantling draught model tank test speed/power values

The conversion on vessel's speed from heavy ballast trial condition to scantling load condition is carried out by using the power ratio, α_p, in accordance with the equations (7)-(8) :

- $\boldsymbol{a_p = P_{Trial,P} / P_{Trial,S}}$

- $\boldsymbol{P_{Full,S} = P_{Full,P} / a_p}$

Where,

- ✓ $\mathbf{P_{Trial,P}}$: Predicted power at heavy ballast condition by tank tests
- ✓ $\mathbf{P_{Trial,S}}$: Power at heavy ballast condition obtained by the speed trials
- ✓ $\mathbf{P_{Full,P}}$: Predicted power at scantling load condition by tank tests
- ✓ $\mathbf{P_{Full,P}}$: Power at scantling load condition

V (kn)	$P_{Full,P}$ (kN)	$P_{Trial,P}$ (kN)	$P_{Trial,S}$ (kN)	a_p	$P_{Full,P}$ (kN)
11	5893	4053	3850	1.0527	5598
12	7690	5320	5054	1.0526	7306
13	9754	6810	6469	1.0527	9266
14	12156	8673	8240	1.0525	11549
15	15214	10996	10447	1.0526	14454
16	19054	13920	13224	1.0526	18101

Table 25. Speed/power curve conversion from Heavy ballast to Scantling draught

The estimated power-speed curve and the Propulsion power-Reference speed values for the five studied cases, at scantling draught, based on the procedure previously described, is presented below:

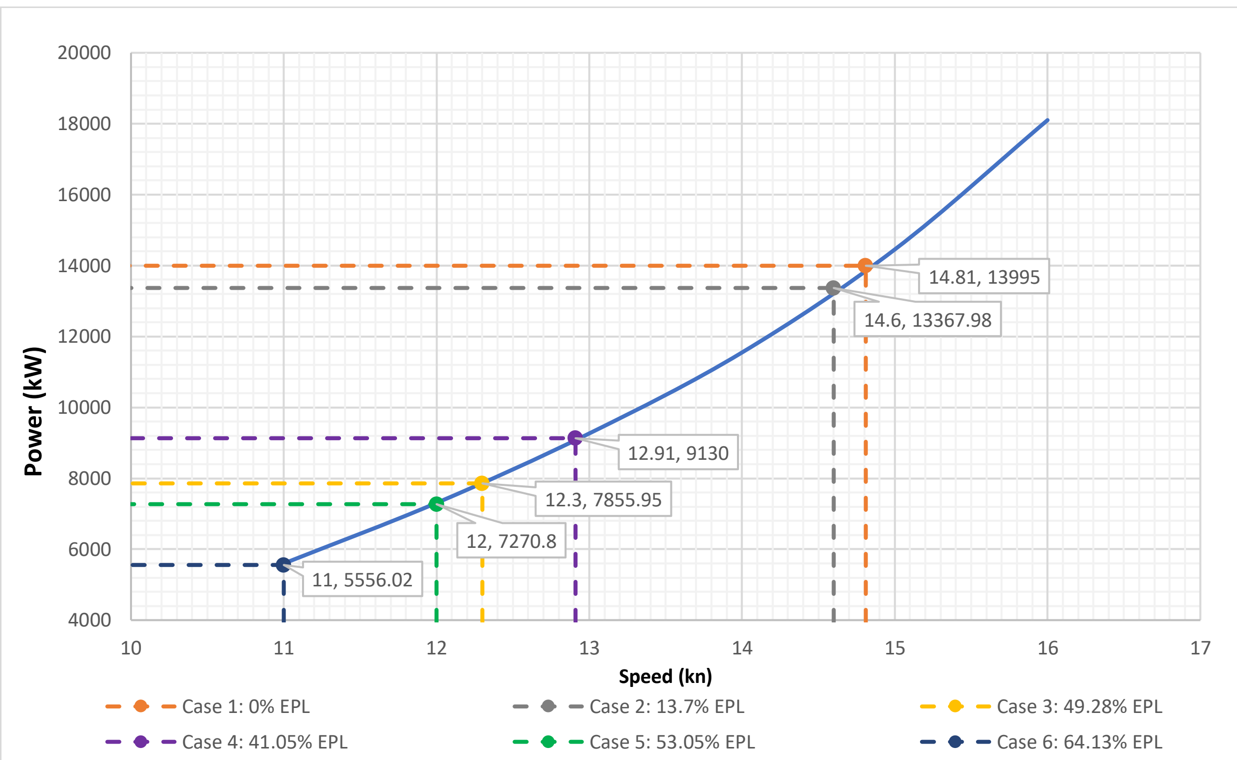

Figure 35. Speed-Power curve (@ scantling draught)

The speed-power curve is well described by the following equation:

$$Power(kW) = 3.248 * Speed\ (kn)^{3.1045}$$

Furthermore, it is essential to estimate the corresponding rotational rate for each power and speed value. The required data is obtained from the sea trial report and the model test. The Rotation Rate (RPM) – Speed (kn) curve is presented in the following diagram:

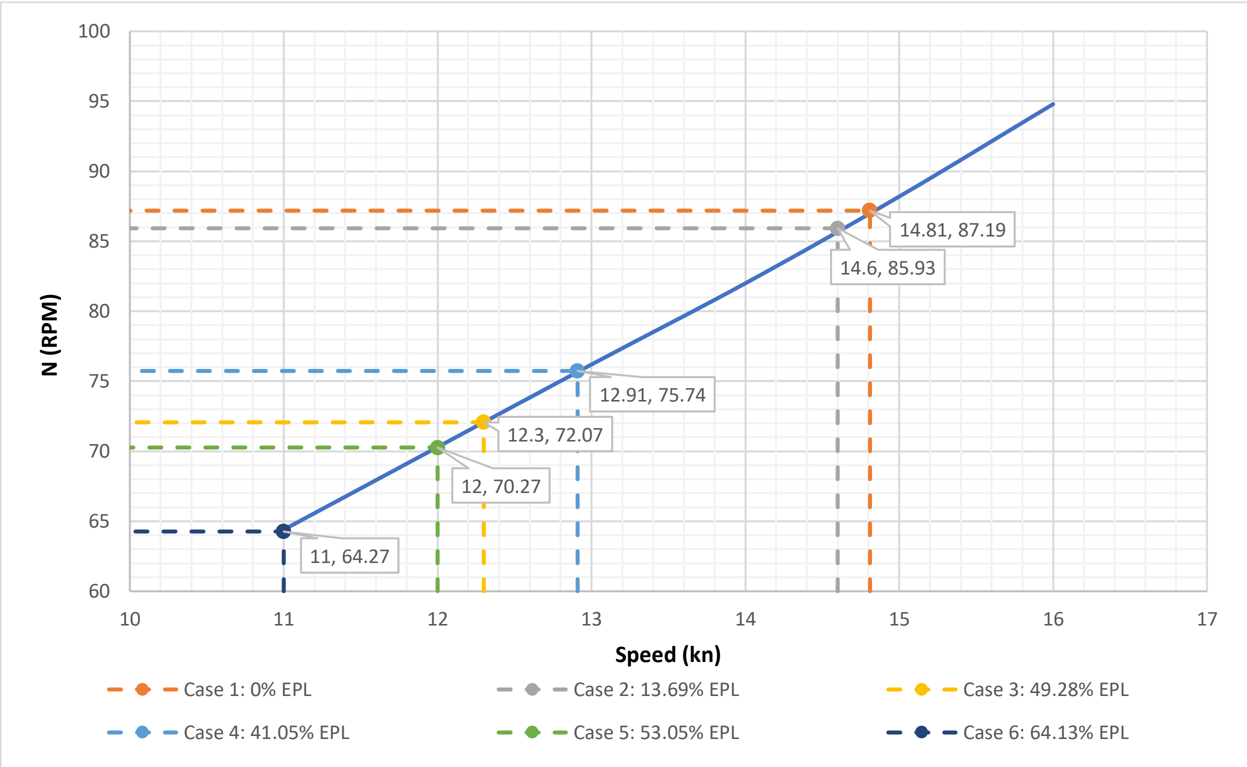

Figure 36. RPM-Speed curve (@ scantling draught)

The RPM-speed curve is well described by the following equation:

$$N\ (RPM) = 5.492 * Speed\ (kn)^{1.0258}$$

Based on the aforementioned equations and the corresponding curves, the reference speed and rotation rate for the examined propulsive power values, at scantling draught, are estimated as follows:

Case	MCR_{LIM} (kW)	EPL (%)	P_{ME} (kW)	V_{REF} (knots)	N (RPM)
1	18660	0	13995	14.81	87.19
2	16106	13.69	13368	14.6	85.93
3	9465	49.28	7856	12.3	72.07
4	11000	41.05	9130	12.91	75.74
5	8760	53.05	7271	12.00	70.27
6	6694	64.13	5556	11.00	64.27

Table 26. Power/Speed/RPM values (@ Scantling draught)

The load diagram of the engine and the examined propulsion power values, P_{ME} (kW), with the corresponding rotation rate, N (RPM), are presented in the following diagram:

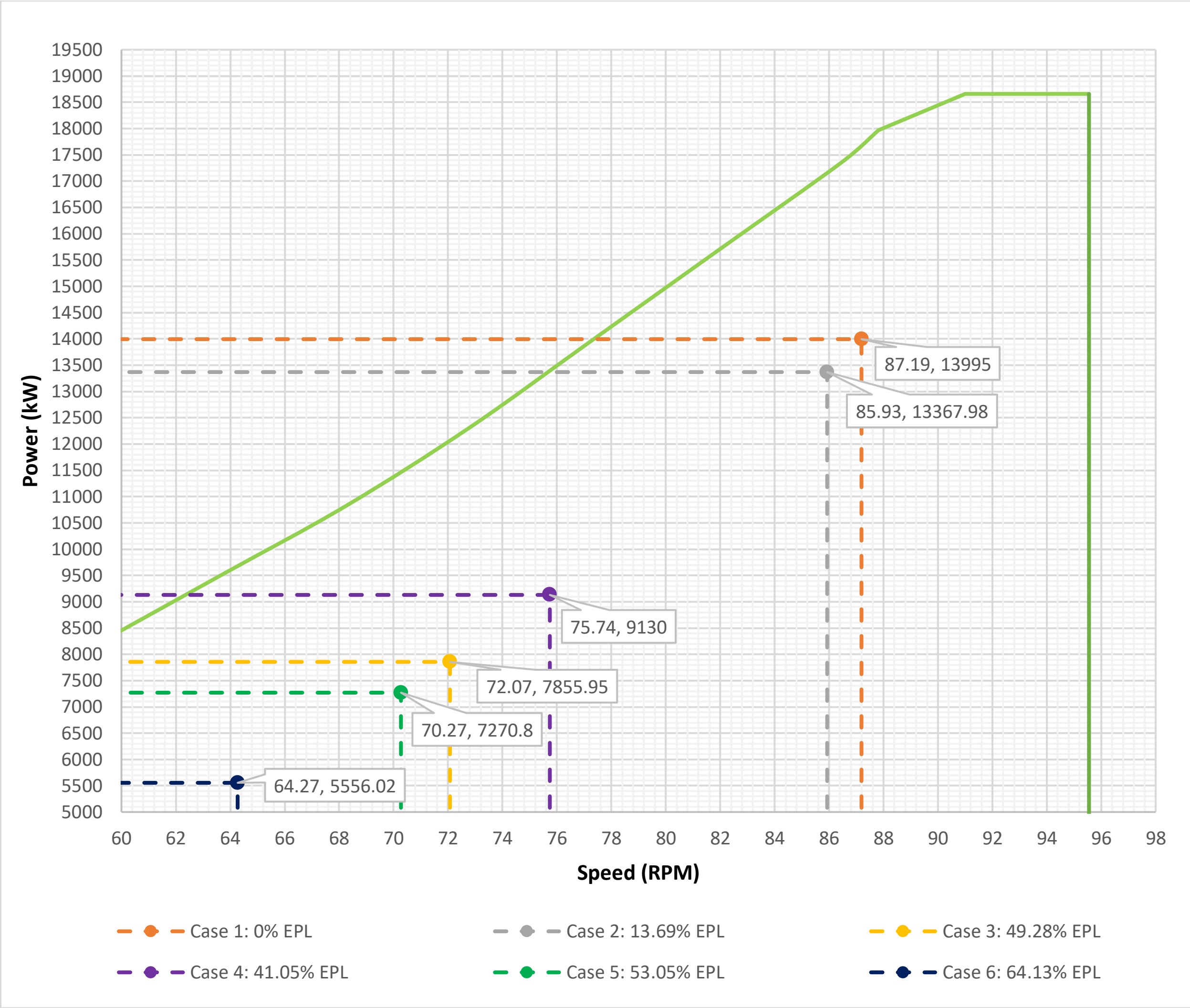

Figure 37. MAN B&W 6S70ME-C7 Load Diagram

The torque/speed limit of the corresponding diagram indicates that the engine can deal effortlessly with the six examined cases and, thus, that even the most aggressive Engine Power Limitation of 64.13% is considered to be safe and effective.

5.1.4 EEXI Calculation

The collected documents of the vessel were obtained from the owner and used, accordingly, for the calculation of the EEXI. The calculation process took place for five different case scenarios, based on different Engine Power Limitations on the MCR of the main engine. The relevant documents are presented below:

- ✓ Capacity Plan
- ✓ Sea trial report
- ✓ Main engine shop test result
- ✓ Aux. Engine test records
- ✓ Model tests report
- ✓ Noon reports

The main data for the calculation of the EEXI in each case scenario were extracted from the aforementioned documents and are presented in the following tables, for each case scenario:

GENERAL SPECS	
Shaft Generator	No
Shaft motor	No
Innovative electrical energy efficiency technology	No
Ice class	No
CSR Design	Yes

Table 27. Bulker's general specifications

MAIN ENGINE SPECS	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
MCR_{ME} (kW)	18660	18660	18660	18660	18660	18660
MCR_{LIM} (kW)	18660	16106	9465	11000	8760	6694
P_{ME} (kW)	13995	13368	7856	9130	7271	5556
V_{REF} (kn)	14.81	14.6	12.3	12.91	12	11
Fuel type	D.O.	D.O.	D.O.	D.O.	D.O.	D.O.
Conversion factor, C_{FME}	3.206	3.206	3.206	3.206	3.206	3.206
SFC_{ME} (@ P_{ME}) (g/kWh)	173	173.22	181.68	179.25	182.95	187.41

Table 28. Bulker's M/E specifications

AUX. ENGINE	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
P_{AE} (kW)	716.5	652.7	473.3	525	438	334.7
Fuel type	D.O.	D.O.	D.O.	D.O.	D.O.	D.O.
Conversion factor, C_{FAE}	3.206	3.206	3.206	3.206	3.206	3.206
Number of sets	3	3	3	3	3	3
SFC_{AE} (@50%MCR_{AE}) (g/kWh)	208.3	208.3	208.3	208.3	208.3	208.3

Table 29. Bulker's A/E specifications

The final parameters of the calculation formula provided by the IMO are presented in the following table

EEXI Parameters final	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
CF: conversion factor between fuel consumption and CO_2 emission						
CF_{ME}	3.206	3.206	3.206	3.206	3.206	3.206
CF_{AE}	3.206	3.206	3.206	3.206	3.206	3.206
Vref: ship speed						
V_{REF} (kn)	14.81	14.6	12.3	12.91	12	11
Capacity						
Capacity (@DWT at summer load draught) (tons)	179107	179107	179107	179107	179107	179107
P: Power of main and auxiliary engines						
P_{ME} (kW)	13995	13368	7856	9130	7271	5556
P_{PTO} (kW)	0	0	0	0	0	0
P_{PTI} (kW)	0	0	0	0	0	0
P_{eff} (kW)	0	0	0	0	0	0
P_{AEeff} (kW)	0	0	0	0	0	0
P_{AE} (kW)	716.5	652.7	473.3	525	438	334.7
SFC: Specific fuel consumption						
SFC_{ME} (g/kWh)	173	173.2	181.7	179.3	182.95	187.4
SFC_{AE} (g/kWh)	208.3	208.3	208.3	208.3	208.3	208.3
Correction factors						
f_j	1	1	1	1	1	1
f_w	1	1	1	1	1	1
f_i	1.012	1.012	1.012	1.012	1.012	1.012
f_c	1	1	1	1	1	1
f_l	1	1	1	1	1	1
f_m	1	1	1	1	1	1

Table 30. Bulker's EEXI calculation parameters

The attained EEXI is calculated for each case scenario according to equation (2), as follows:

EEXI attained (g/ton*nm)	3.07	2.971	2.195	2.393	2.096	1.787

Table 31. Attained EEXI values

Furthermore, the calculation of the coefficient f_w is required. Since the subject vessel is a bulk carrier, the standard f_w value is defined by equation (5) and Table 7, as follows:

$$\boldsymbol{f_w = 0.0429 \times ln(Capacity) + 0.294}$$

The capacity of the vessel at summer load line draught is 179107.4 tons, thus the standard f_w value is equal to **0.8129**.

In case the standard f_w value is co-estimated in the calculation process, a special reference ($EEXI_{WEATHER}$) needs to be made. Thus, the calculated EEXI value under weather conditions is estimated as follows:

EEXI weather (g/ton*nm)	3.777	3.654	2.7	2.943	2.578	2.198

Table 32. Attained $EEXI_{WEATHER}$ values

5.1.5 EEXI Requirements

Since the subject is a bulk carrier, the reference line value shall be calculated according to Table 3, as follows:

$$\boldsymbol{Reference\ Line = 961.79 \times DWT^{-0.477}}$$

The required EEDI for each one of the three phase is calculated according to equation (1), as follows:

$$\boldsymbol{Required\ EEXI = \left(1 - \frac{X}{100}\right) \times 961.79 \times DWT^{-0.477}}$$

In order to calculate the EEDI reference lines for each phase and, thus, the required EEDI values for the subject vessel, various DWTs are included in the calculation process. The correction factor, X, is different in each phase (Table 4). For a bulk carrier the corresponding values of the X factor are presented below:

- ✓ X=0 (EEDI Phase 0)
- ✓ X=10 (EEDI Phase 1)
- ✓ X=20 (EEDI Phase 2)
- ✓ X=30 (EEDI Phase 3)

The required EEDI values for the subject vessel for the four EEDI Phases are calculated as follows:

- ✓ EEDI Phase 0: $EEXI_{Req}$ = 3.0 [gr-CO_2/t*nm]
- ✓ EEDI Phase 1: $EEXI_{Req}$ = 2.7 [gr-CO_2/t*nm]
- ✓ EEDI Phase 2: $EEXI_{Req}$ = 2.4 [gr-CO_2/t*nm]
- ✓ EEDI Phase 3: $EEXI_{Req}$ = 2.1 [gr-CO_2/t*nm]

The comparison among the four phases and especially between Phase 0 and the upcoming Phase 3 reveals the IMO's ambition regarding the CO_2 reduction, as the emission ratings for a 180,000 DWT Bulk Carrier have decreased from 3 [gr-CO_2/t*nm], in 2008 (Phase 0), to 2.1 [gr-CO_2/t*nm] after 2025 (Phase 3).

The EEDI reference lines and the attained EEXI values are presented in the following diagram:

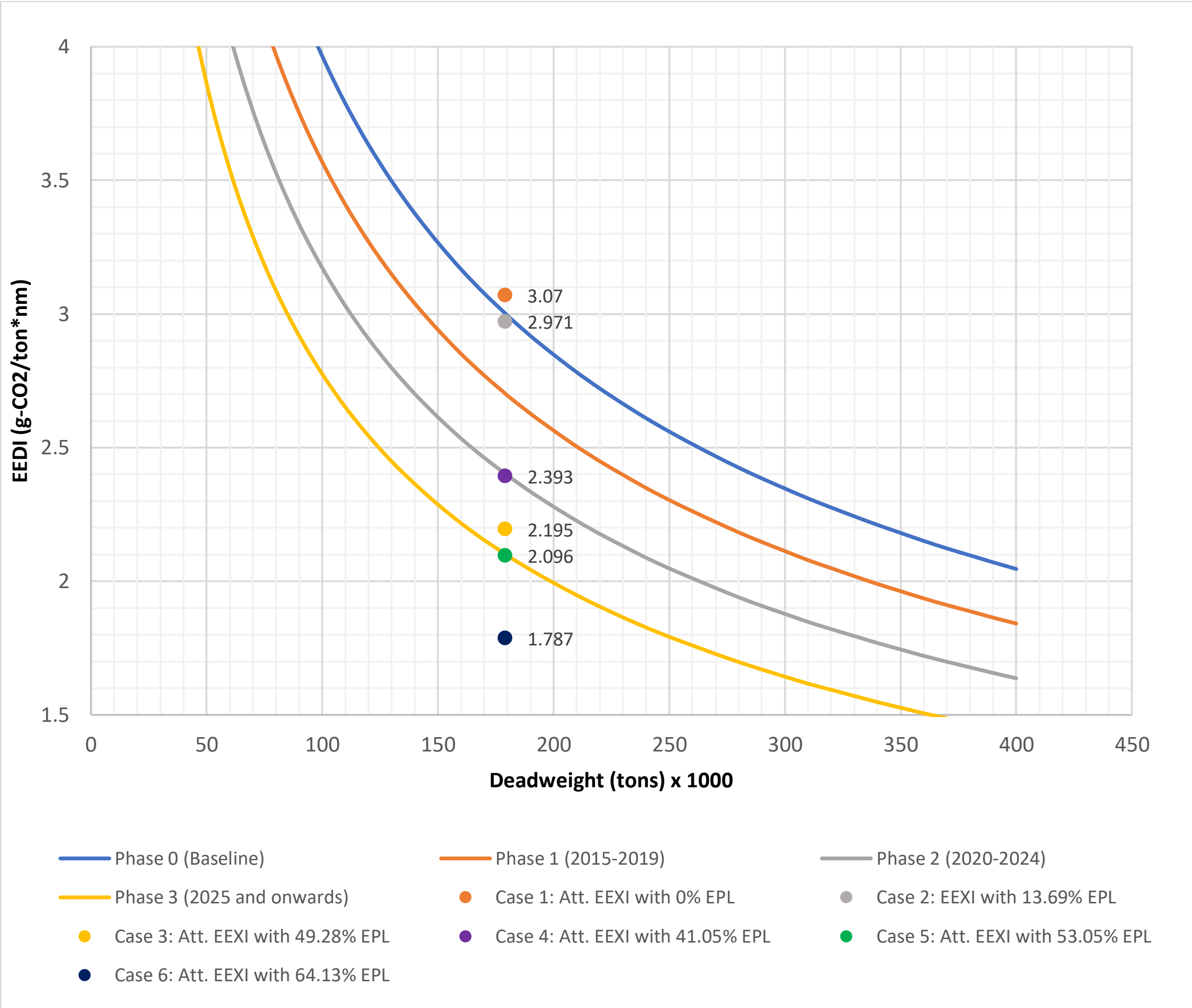

Figure 38. EEDI Reference Lines / Attained EEXI

According to Fig.38, in order for the subject vessel to comply with the current Phase 2 EEDI requirements, a very aggressive Engine Power Limitation of at least 41.05% is required. The requirements are more demanding for the upcoming Phase 3, where a Limitation of at least 53.05% is required to comply with the regulation.

Based on RightShip's requirements, those limitation rates, except 0% and 13.69% EPL, do not comply with their EPL acceptance criteria. However, they do comply with the IMO's EEXI guidelines, considering that the Minimum Propulsion Power previously estimated is overridable, according to the corresponding regulation.

5.1.6 Comparison with operational data from the noon reports

The purpose of this analysis is to provide a fair basis for comparison between the theoretical values (Reference speeds, Attained EEXIs) and the real-time values (Speed distribution, "EEXI" [gr-CO_2/t*nm]) as they were estimated by the noon reports' data of the subject vessel. The comparison aims at providing a clear understanding about the relation between the reference speed values and the actual speed distribution of the ship. Furthermore, it estimates the contribution of the Attained EEXI values for each Engine Power Limitation Case 1 to 6 to the reduction of the CO_2 emissions. In order to achieve that, the study calculates the real-time "EEXI" [gr-CO_2/t*nm] values, in accordance with the actual speed and fuel oil consumption. The estimated values are compared with the attained EEXIs. In case that the number of the real-time "EEXI" values that are above a specific Attained EEXI corresponds to a certain percentage, it is considered that the respective EPL Case contributes to the CO_2 emissions' reduction. In order for similar quantities to be compared, the reports of the vessel have been filtered so that the requested values correspond to daily report type and laden loading condition.

By editing the aforementioned data, the histogram of the daily open sea speed distribution for the Jan 2020-Dec 2021 period, in accordance with the reference speed values, is presented below:

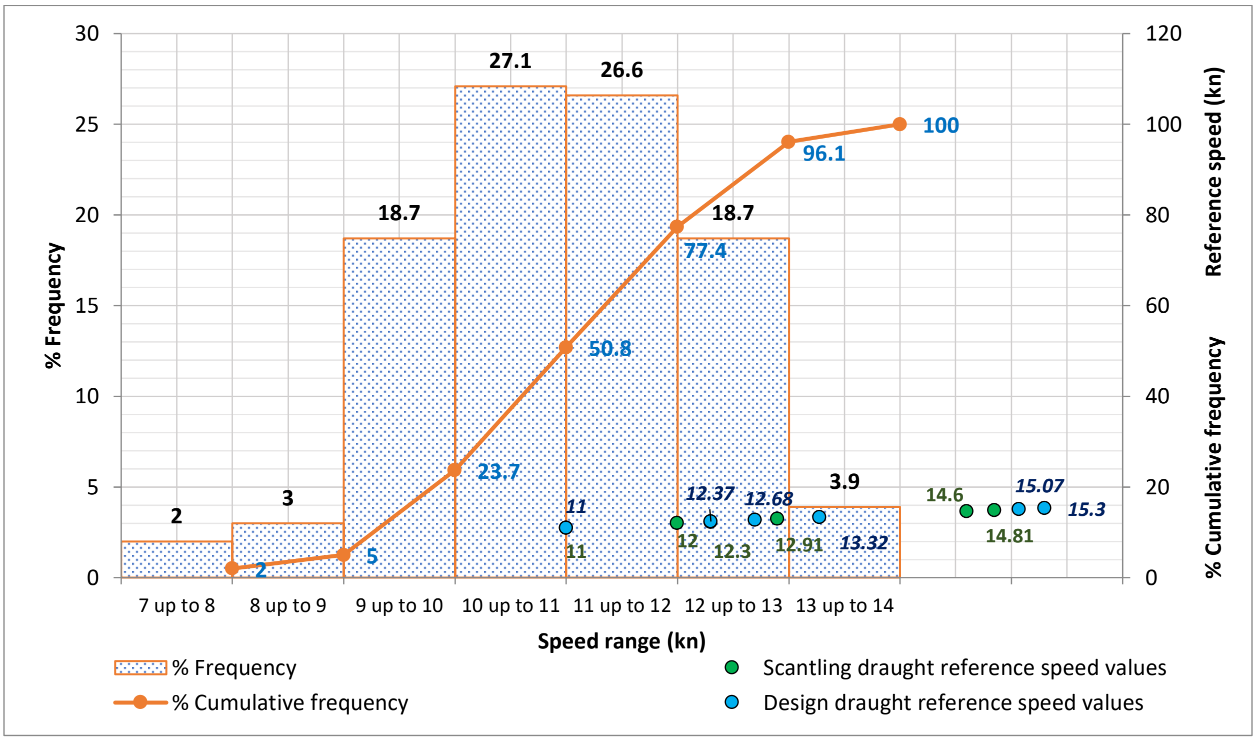

Figure 39. Histogram of Speed distribution Jan 20-Dec 21

The basic statistics of the speed distribution for the Jan 20-Dec 21 period are presented as follows:

Mean value	11.00
Standard Deviation	1.257
25% percentile	10.04
75% percentile	11.83
90% percentile	12.596

Table 33. Speed's basic statistics

Based on the cumulative curve (Fig.39), the reference speed values as they are calculated for the examined Cases 1 to 6, at both scantling and design load conditions, are compared with the actual speed values, as follows:

Scantling Load Reference Speed

1. The Case 1 Reference speed is equal to **14.81 knots**. Thus, **100%** of the reported to the noon report actual speeds are below this value.
2. The Case 2 Reference speed is equal to **14.6 knots**. Thus, **100%** of the reported actual speeds are below this value.
3. The Case 3 Reference speed is equal to **12.3 knots**. Thus, **83.01%** of the reported actual speeds are below this value.
4. The Case 4 Reference speed is equal to **12.91 knots**. Thus, **94.42%** of the reported actual speeds are below this value.
5. The Case 5 Reference speed is equal to **12 knots**. Thus, **77.4%** of the reported actual speeds are below this value.
6. The Case 6 Reference speed is equal to **11 knots**. Thus, **50.8%** of the reported actual speeds are below this value.

Design Load Reference Speed

1. The Case 1 Reference speed is equal to **15.3 knots**. Thus, **100%** of the reported to the noon report actual speeds are below this value.
2. The Case 2 Reference speed is equal to **15.07 knots**. Thus, **100%** of the reported actual speeds are below this value.
3. The Case 3 Reference speed is equal to **12.68 knots**. Thus, **90.12%** of the reported actual speeds are below this value.
4. The Case 4 Reference speed is equal to **13.32 knots**. Thus, **97.35%** of the reported actual speeds are below this value.
5. The Case 5 Reference speed is equal to **12.37 knots**. Thus, **84.32%** of the reported actual speeds are below this value.
6. The Case 6 Reference speed is equal to **11 knots**. Thus, **50.8%** of the reported actual speeds are below this value.

As it is indicated by the comparison, the EPL Cases 1 and 2 do not correspond to any reported actual speed values. The actual speed of the vessel is low, as **50.8%** of the reported speeds are below 11 knots.

The noon reports do not provide information regarding the details of the laden condition. Thus, two different cases need to be examined, in order for the final results to be as objective as possible.

- ✓ **Scenario 1**: In this case, the laden condition referred in the noon reports of the vessel corresponds to the Scantling Load Condition of the subject vessel, with a draught equal to **18.32 m**. The deadweight of the vessel is equal to **179107 tons**

- ✓ **Scenario 2**: In this case, the laden condition referred in the speed reports of the vessel corresponds to the Design Load Condition of the subject vessel, with a draught equal to **16.52 m**. The deadweight of the vessel is equal to **157175 tons**

Scenario 1: Noon reports refer to Scantling Load condition

In this case, the DWT of the vessel, for the daily noon reports, is considered equal to the DWT of the scantling load condition, **179107 tons**. Under this condition, the speed distribution of the vessel, for the Jan 20 – Dec 21 period, is compared to the reference speed values as they were estimated during the calculation process of the attained EEXI at Scantling draught. The corresponding diagram is presented below:

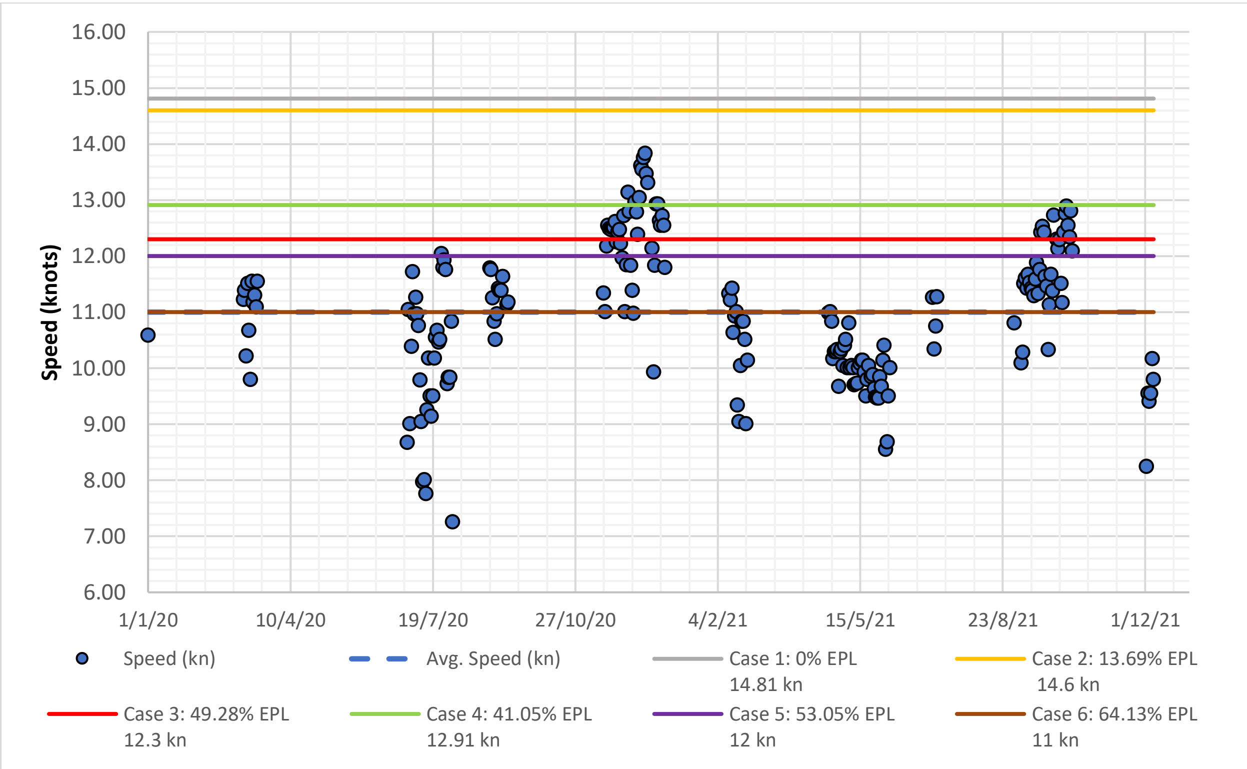

Figure 40. Scantling Draught Ref. Speed-Daily Speed distribution comparison

As indicated by Fig.40, the average real-time speed of the subject vessel, at laden condition, is equal to **11 knots**. Thus, none of the examined EPL Cases 1 to 5 provide lower estimated speed than the actual one. The EPL Case 6 indicates that in order for the vessel to reach a reference speed equal to the average real-time speed (11 kn), a very aggressive EPL of 64.13% is required.

Furthermore, a comparison between the real-time "EEXI" [gr-CO_2/t*nm] and the attained EEXI is required, in order to provide a clear understanding of the actual CO_2 emissions' reduction. The real-time "EEXI" is estimated by importing the daily Speed, the Fuel Oil Consumption of the main and auxiliary engines, the Scantling DWT of the vessel and the corresponding correction factors, to the EEXI formula.

Based on that, the histogram of the daily "EEXI" distribution, at scantling load condition, is presented as follows:

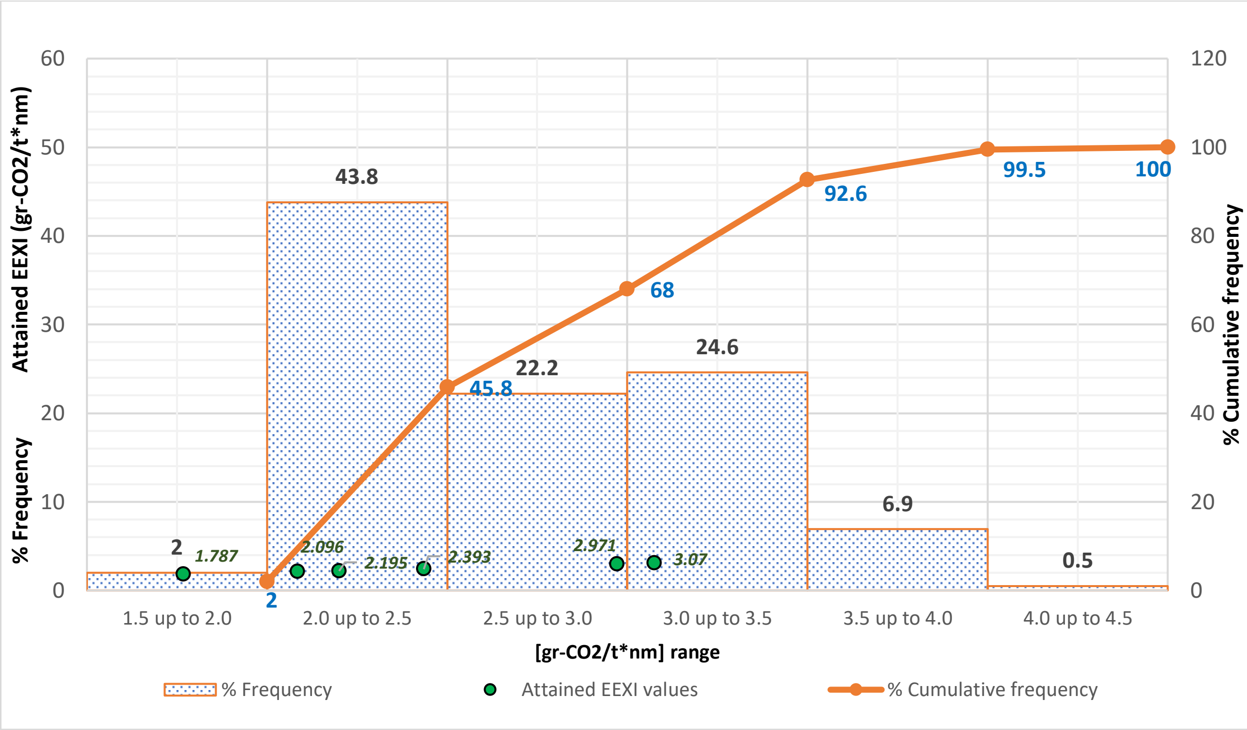

*Figure 41. Histogram of Scantling draught "EEXI" [gr-CO_2/t*nm] distribution Jan 20-Dec 21*

According to the cumulative curve (Fig.41), the Attained EEXI values as they are calculated for the examined Cases 1 to 6, for scantling load condition, are compared with the Real-time "EEXI" values, as follows:

Scantling Load "EEXI" with regular operational data

1. The Case 1 Attained EEXI is equal to **3.07 [gr-CO_2/t*nm]**. Thus, **71.44%** of the real-time "EEXIs" are below this value and **28.56%** are affected by the EPL Case 1.
2. The Case 2 Attained EEXI is equal to **2.971 [gr-CO_2/t*nm]**. Thus, **66.71%** of the real-time "EEXIs" are below this value (**33.29%** affected).
3. The Case 3 Attained EEXI is equal to **2.195 [gr-CO_2/t*nm]**. Thus, **19.08%** of the real-time "EEXIs" are below this value (**80.92%** affected).
4. The Case 4 Attained EEXI is equal to **2.393 [gr-CO_2/t*nm]**. Thus, **36.43%** of the real-time "EEXIs" are below this value (**63.57%** affected).
5. The Case 5 Attained EEXI is equal to **2.096 [gr-CO_2/t*nm]**. Thus, **10.41%** of the real-time "EEXIs" are below this value (**89.59%** affected).
6. The Case 6 Attained EEXI is equal to **1.787 [gr-CO_2/t*nm]**. Thus, **less than 2%** of the real-time "EEXIs" are below this value (more than **98%** affected).

Based on the comparison, the EPL Cases 1 and 2 do not contribute to the reduction of the actual emissions, as they affect only **28.56%** and **33.29%** of the estimated [gr-CO_2/t*nm] emissions, which means that they are not effective enough. The rest of the examined cases seem to improve the CO_2 emissions, but a further investigation is required.

In order to verify the reliability of the previous results, the real-time "EEXI" calculation is also performed considering that the diesel engines' fuel oil consumption is equal to a theoretical value. This value corresponds to the examined EPL Case 6, which has the lowest fuel consumption among the EPL Cases 1 to 6, and thus provides the most conservative estimation. For this case, the Specific Fuel Consumption is equal to **208.33 gr/kWh**, and the corresponding power value is equal to **334.7 kW**. Thus, the theoretical fuel oil consumption of the auxiliary engines is equal to **6.973 x 10^4 gr/hr**.

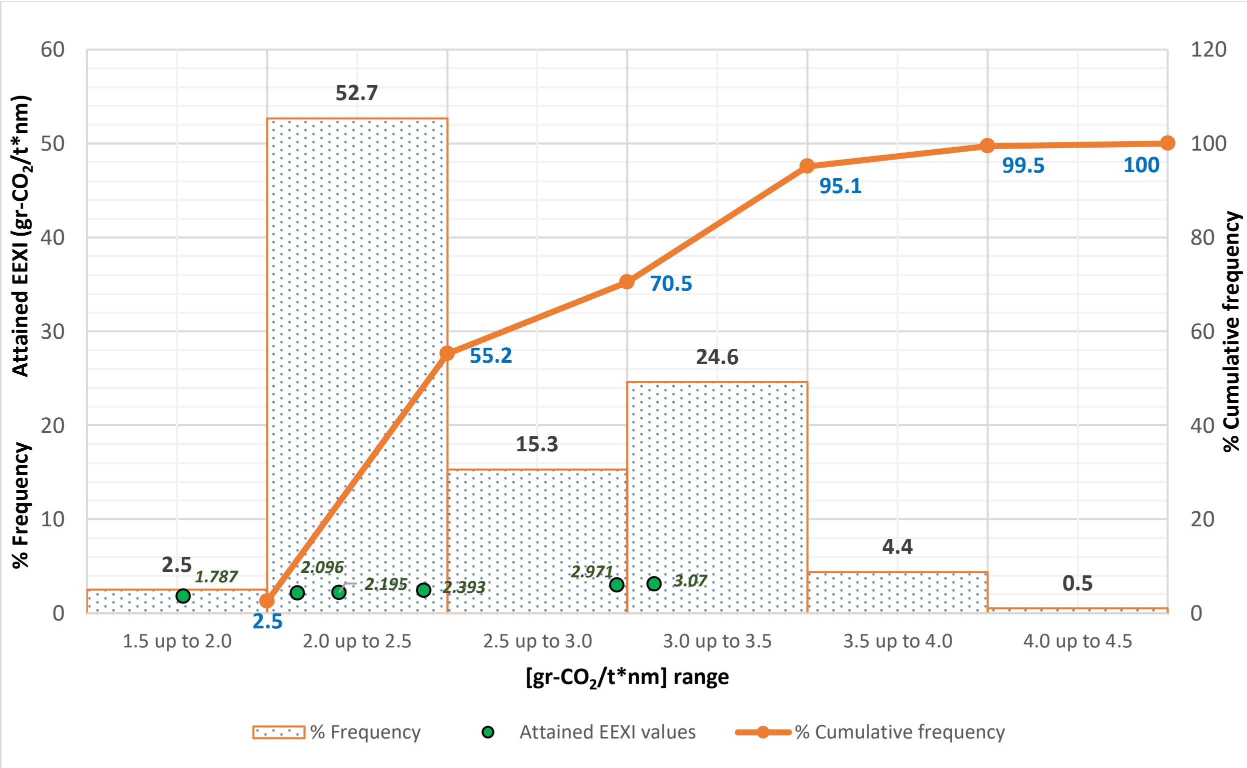

*Figure 42. Histogram of Scantling draught "EEXI" [gr-CO_2/t*nm] distribution with Theoretical FOC_{AE} Jan 20-Dec 21*

Based on the respective cumulative curve (Fig.42), the Attained EEXI values as calculated for the examined Cases 1 to 6, for scantling load condition, are compared with the Real-time "EEXI" values estimated for the theoretical FOC_{AE} value, as follows:

Scantling Load "EEXI" with Theoretical D/G Fuel Consumption

1. **73.94%** of the real-time "EEXIs" are below the Case 1 Attained EEXI value (**26.06%** affected).
2. **69.61%** of the real-time "EEXIs" are below the Case 2 Attained EEXI value (**30.39%** affected).
3. **23.05%** of the real-time "EEXIs" are below the Case 3 Attained EEXI value (**76.95%** affected).
4. **43.92%** of the real-time "EEXIs" are below the Case 4 Attained EEXI value (**56.08%** affected).
5. **12.62%** of the real-time "EEXIs" are below the Case 5 Attained EEXI value (**87.38%** affected).
6. **Less than 2.5%** of the real-time "EEXIs" are below the Case 6 Attained EEXI value (more than **97.5%** affected).

Based on the comparison, it is verified that the EPL Cases 1 and 2 certainly do not contribute to the reduction, as their effectiveness reduced to **26.06%** and **30.39%**, respectively. Furthermore, regarding Case 4, the corresponding effectiveness reduced to **56.08%**, and thus it is considered slightly effective. The rest of the cases are still significantly contributing to the CO_2 reduction.

Scenario 2: Noon reports refer to Design Load condition

In this case, the laden condition DWT of the vessel is considered equal to the DWT of the design load condition, **157175 tons**. Thus, the speed distribution of the vessel, for the examined period, is compared to the reference speed values as they were estimated during the calculation process of the attained EEXI at Design draught. The estimation process followed the same pattern as in the case of the Scantling Load Condition attained EEXI.

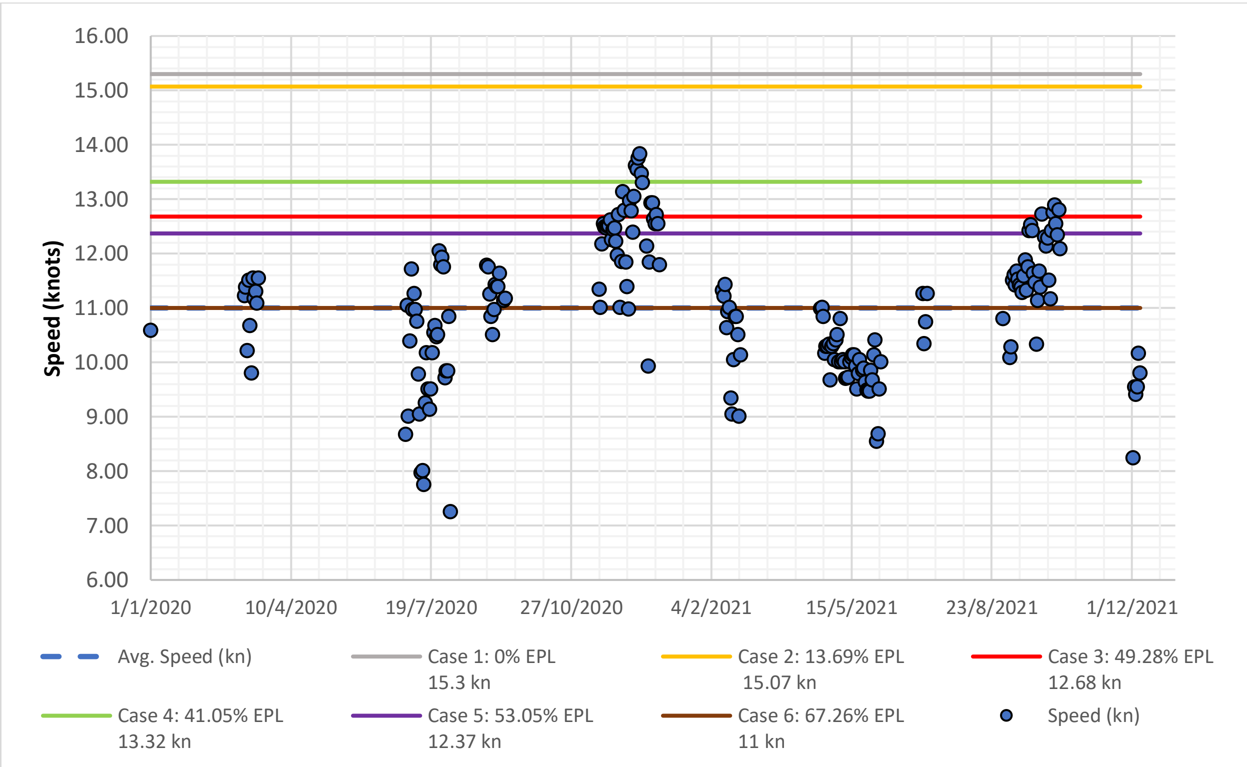

Figure 43. Design Draught Ref. Speed-Daily Speed distribution comparison

Based on Fig.43, the average real-time speed of the subject vessel, at laden condition, remains equal to 11 knots. In Design load condition, none of the examined EPL Cases 1 to 5 provide lower estimated speed than the actual one. The EPL Case 6 indicates that in order for the vessel to reach a reference speed equal to the average one, an even more aggressive EPL of 67.26% is required.

The comparison between the real-time "EEXI" [gr-CO_2/t*nm], for the design load condition, and the attained EEXI is crucial, in order to provide a clearer understanding of the actual GHG emission reduction, for the examined laden condition. Following the same procedure as in Scenario 1, and by assuming that the laden deadweight corresponds to the Design Load DWT, 157175 tons, the histogram of the daily "EEXI" distribution is presented as follows:

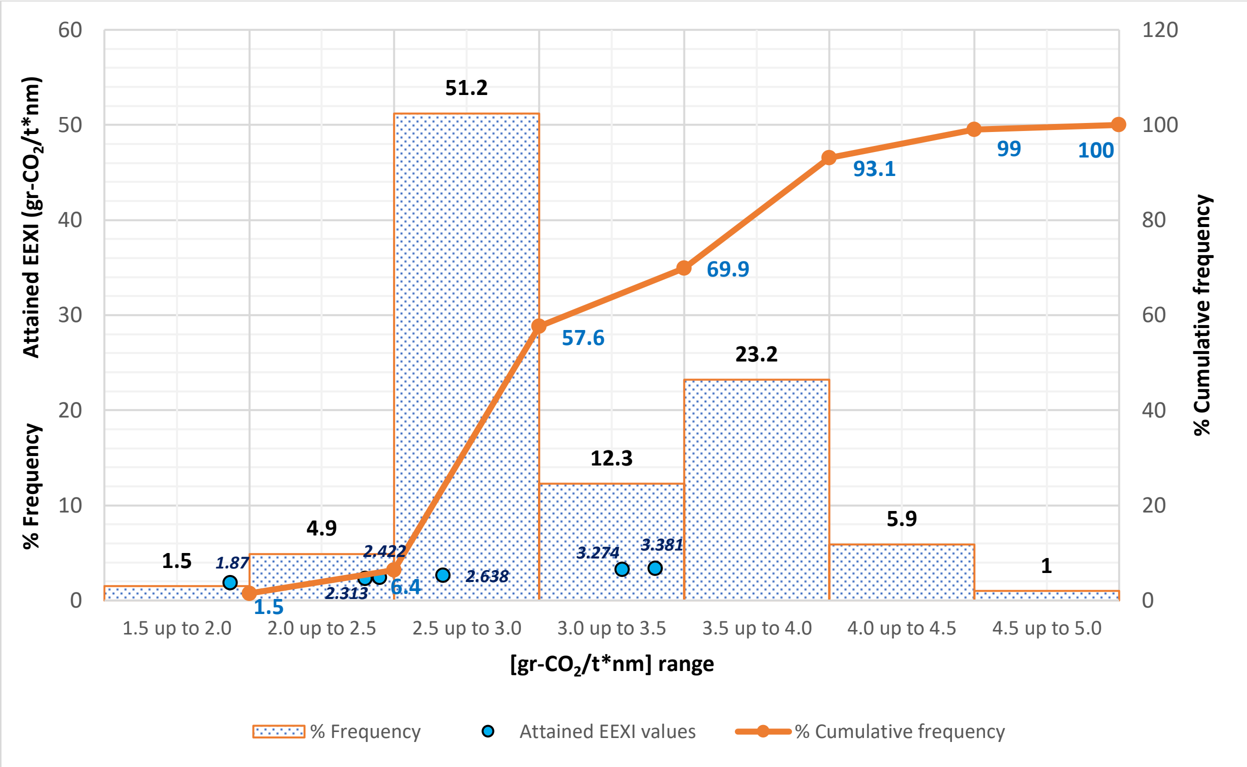

*Figure 44. Histogram of Design draught "EEXI" [gr-CO_2/t*nm] distribution Jan 20-Dec 21*

Based on the cumulative curve (Fig.44), the Attained EEXI values as they are calculated for the examined Cases 1 to 6, for design load condition, are compared with the corresponding Real-time "EEXI" values, as follows:

Design Load "EEXI" with regular operational data

1. The Case 1 Attained EEXI is equal to **3.381 [gr-CO_2/t*nm]**. Thus, **66.97%** of the real-time "EEXIs" are below this value (**33.03%** affected).
2. The Case 2 Attained EEXI is equal to **3.274 [gr-CO_2/t*nm]**. Thus, **64.34%** of the real-time "EEXIs" are below this value (**35.66%** affected).
3. The Case 3 Attained EEXI is equal to **2.422 [gr-CO_2/t*nm]**. Thus, **5.64%** of the real-time "EEXIs" are below this value (**94.36%** affected).
4. The Case 4 Attained EEXI is equal to **2.638 [gr-CO_2/t*nm]**. Thus, **20.53%** of the real-time "EEXIs" are below this value (**79.47%** affected).
5. The Case 5 Attained EEXI is equal to **2.313 [gr-CO_2/t*nm]**. Thus, **4.57%** of the real-time "EEXIs" are below this value (**95.43%** affected).
6. The Case 6 Attained EEXI is equal to **1.87 [gr-CO_2/t*nm]**. Thus, **less than 1.5%** of the real-time "EEXIs" are below this value (more than **98.5%** affected).

In accordance with the comparison, the EPL Cases 1 and 2 do not contribute to the reduction of the actual emissions, as they affect only **33.03%** and **35.66%** of the estimated [gr-CO_2/t*nm] emissions. The rest of the examined cases seem to significantly improve the reduction of the CO_2 emissions.

The reliability of the previous deduction is verified as per Scenario 1, considering that the auxiliary engines' fuel oil consumption is equal to the respective theoretical value. For the examined Case 6, at design draught, the Specific Fuel Consumption is equal to **208.33 gr/kWh**, and the corresponding Power value is equal to **305.5 kW**. Thus, the fuel oil consumption of the auxiliary engines is equal to **6.364×10^4 gr/hr.**

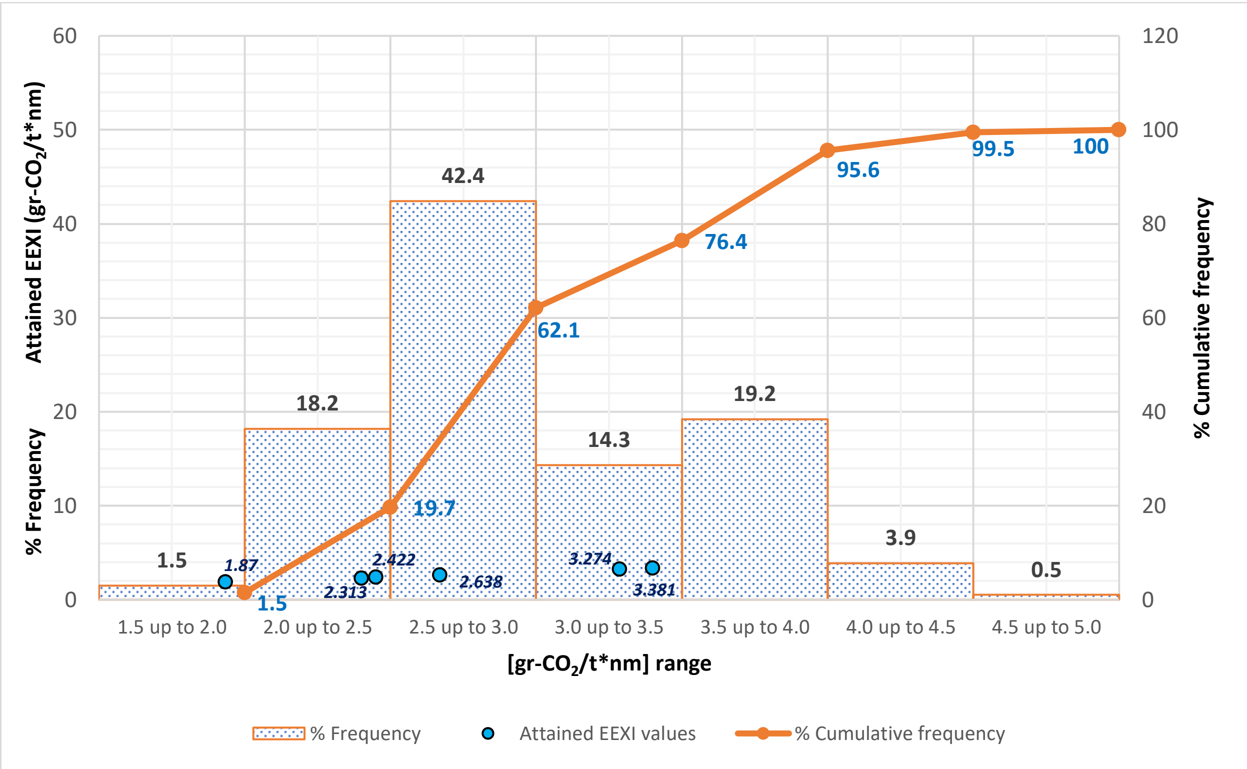

*Figure 45. Histogram of Design draught "EEXI" [gr-CO_2/t*nm] distribution with Theoretical FOC_{AE} Jan 20-Dec 21*

In accordance with the respective cumulative curve (Fig.45), the Attained EEXI values as they are calculated for the examined Cases 1 to 6, for design load condition, are compared with the Real-time "EEXI" values calculated for the theoretical FOC_{AE} value, as follows:

Design Load "EEXI" with Theoretical D/G Fuel Consumption

1. **73%** of the real-time "EEXIs" are below the Case 1 Attained EEXI value (**27%** affected).
2. **69.94%** of the real-time "EEXIs" are below the Case 2 Attained EEXI value (**30.06%** affected).
3. **16.86%** of the real-time "EEXIs" are below the Case 3 Attained EEXI value (**83.14%** affected).
4. **31.4%** of the real-time "EEXIs" are below the Case 4 Attained EEXI value (**68.6%** affected).
5. **12.89%** of the real-time "EEXIs" are below the Case 5 Attained EEXI value (**87.11%** affected).
6. **Less than 1.5%** of the real-time "EEXIs" are below the Case 6 Attained EEXI value (more than **98.5%** affected).

The comparison verifies that the EPL Cases 1 and 2 do not contribute to the reduction, as the effectiveness reduced to **27%** and **30.06%**, respectively. As far as Case 4 is concerned, the corresponding effectiveness also reduced to **68.6%**. Thus, it is considered effective, but relatively unreliable. The rest of the cases are still significantly effective.

For the Design load condition, which is considered more realistic in terms of real-time operation, it is essential to evaluate the effect of the wind force. Thus, the "EEXI" [gr-CO_2/t*nm] values are calculated for the EPL Cases 1 to 6 by using the real-time data that correspond to wind force equal to 4.0 BFT or less.

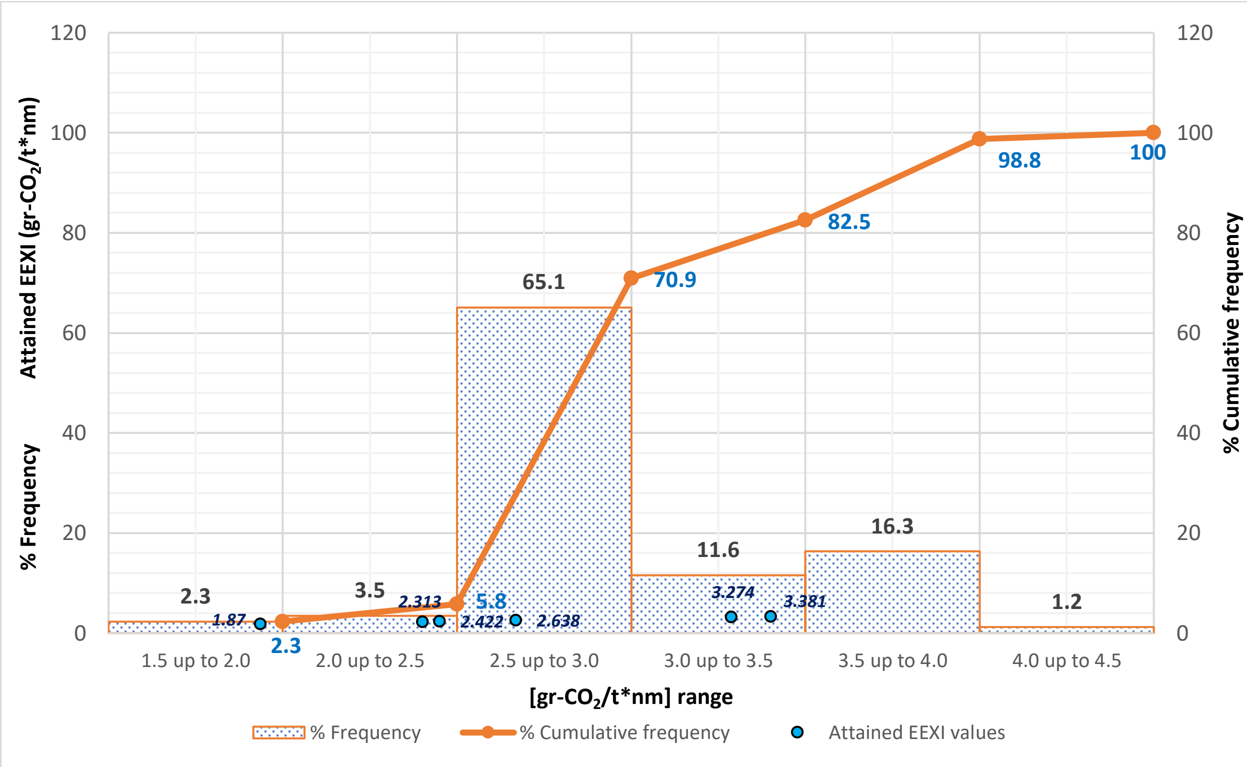

*Figure 46. Histogram of Design draught "EEXI" [gr-CO_2/t*nm] distribution with Wind Force ≤ 4 BFT Jan 20-Dec 21*

Based on the respective cumulative curve (Fig.46), the Attained EEXI values as they are calculated for the examined Cases 1 to 6, for design load condition, are compared with the Real-time "EEXI" values calculated for wind force equal or less than 4 BFT, as follows:

Design Load "EEXI" with Wind Force ≤ 4 BFT

1. **79.74%** of the real-time "EEXIs" are below the Case 1 Attained EEXI value (**20.26%** affected).
2. **77.26%** of the real-time "EEXIs" are below the Case 2 Attained EEXI value (**22.74%** affected).
3. **5.25%** of the real-time "EEXIs" are below the Case 3 Attained EEXI value (**94.75%** affected).
4. **23.77%** of the real-time "EEXIs" are below the Case 4 Attained EEXI value (**76.23%** affected).
5. **4.49%** of the real-time "EEXIs" are below the Case 5 Attained EEXI value (**95.51%** affected).
6. **Less than 2.3%** of the real-time "EEXIs" are below the Case 6 Attained EEXI value (**more than 97.7%** affected).

The wind force mostly affects the highest "EEXI" values. Thus, the EPL Cases 1 and 2 are mostly affected, as their effectiveness reduced to **20.26%** and **22.74%**, respectively. Furthermore, Case 4 is slightly affected, as the corresponding percentage reduced to **76.23%**. For the rest of the cases, the influence of the wind force is minor.

Case	%EPL	Scantling Load Condition		Design Load Condition		
		%Effect	%Effect (Theoretical FOC_{AE})	**%Effect**	%Effect (Theoretical FOC_{AE})	%Effect (Wind Force ≤ 4BFT)
1	**0.00**	28.56	26.06	33.03	27.00	20.26
2	**13.69**	33.29	30.39	35.66	30.06	22.74
3	**49.28**	80.92	76.95	94.36	83.14	94.75
4	**41.05**	63.57	56.08	79.47	68.60	76.23
5	**53.05**	89.59	87.38	95.43	87.11	95.51
6	> **64.13**	98.00	97.50	98.50	98.50	97.7

*Table 34. The %Effect of each EPL Case on the "EEXI" [gr-CO_2/t*nm] emissions*

Based on Table 34, the following deductions can be made:

1. Cases 1 and 2 should be rejected as a possible mean of reducing the actual [gr-CO_2/t*nm] emissions, as the corresponding effects have a [**20.26%, 33.03%]** range for Case 1 and [**22.74%, 35.66%]** range for Case 2, which are considered low. Furthermore, neither of the two cases complies with the EEDI Phase 2 and Phase 3 requirements (Fig.38).

2. Cases 3 and 4, which both comply with the EEDI Phase 2 requirements (Fig.38), are considered effective in terms of reducing the actual [gr-CO_2/t*nm] emissions, and thus contributing to the CO_2 reduction. The corresponding effects have a [**76.95%, 94.75%]** range for Case 3 and [**56.08%, 79.47%]** range for Case 4, which are fairly high. Comparing the two cases, Case 3 is more sufficient, as the limitation of the main engine is more aggressive (49.28%) and the corresponding [gr-CO_2/t*nm] effect range ([76.95%, 94.75%]) contains larger values.

3. Cases 5 and 6, which both comply with the EEDI Phase 3 requirements (Fig.38), are considered highly effective in terms of reducing the actual [gr-CO_2/t*nm] emissions, and thus contributing to the CO_2 reduction. The corresponding effects have a [**87.11%, 95.51%]** range for Case 5 and [**97.5%, 98.5%]** range for Case 5, which are extremely high.

In order for the results to be as reliable as possible, it needs to be clarified that the previous deductions are based on a theoretical comparison. The actual %Effect of the Attained EEXI to the real-time "EEXI" [gr-CO_2/t*nm] is expected to be less than the reported values in Table 34, for any examined EPL Case. This is justified by the following reasons:

- The quality of the fuel used for the specification of the theoretical fuel oil consumption values is different compared to the real-time fuel quality. Thus, the theoretical EEXI is not as objective as required in order to reliably determine the effect on the CO_2 emissions reduction.
- The noon reports have a shortage of information regarding the power of the Main / Aux. engine(s) that corresponds to the reported fuel oil consumption. Considering that the EPL Cases 1 to 6 correspond to a wide range of power values, the comparison would have been more comprehensive in case that the required information was available.
- The laden condition mentioned in the noon reports, is not necessarily either Scantling or Design, as it was assumed in the case study. The actual capacity would contribute to a more reliable estimation of the real-time "EEXI" values.
- The effect of the weather on both the theoretical and real-time values need to be further investigated.

However, the theoretical comparison is considered reliable, as all the %Effect values are expected to decrease in proportion to each other. Thus, the study provides an objective perspective of the EPL contribution to the reduction of the actual [gr-CO_2/t*nm] emissions.

5.2 75,000 DWT Product Carrier

5.2.1 Data

In the second part of this calculation report, a **75,000 DWT Product Carrier** is examined. The main particulars of the vessel are presented as follows:

Particulars	
Type	Product Carrier
Length Over All	228.16
Length between perpendiculars	219
Breadth moulded	32.24
Depth moulded	20.9
Draught moulded (Summer load line draught)	14.41
Deadweight (at Summer load line draught)	74995.1
Lightship	13824
Year of Build	2008
Ice class	No

Table 35. Tanker's main particulars

The subject vessel was built in 2008 and, thus, it is under the scope of the upcoming EEXI requirements. Considering that it is a Product Carrier vessel, it does not extensively fall under the scope of RightShip's requirements regarding the Engine Power Limitation acceptance criteria. However, given that RightShip has extended their target group in the latest years, their limitations need to be taken into account.

The basic parameters of the main and auxiliary engines of the vessel are presented in the following tables.

MAIN ENGINE	
Maker	STX-MAN B&W
Engine type	6S60MC
Maximum continuous rating (kW)	12240
Speed @ MCR (RPM)	105
Fuel type	Diesel Oil

Table 36. Tanker's main engine particulars

AUXILIARY ENGINE	
Maker	YANMAR CO. , LTD.
Engine type	6N21AL-EV x 900 kW
Maximum continuous rating (kW)	970
Speed @ MCR (RPM)	900
Fuel type	Diesel Oil

Table 37. Tanker's aux. engines particulars

5.2.2 Minimum Propulsion Power Calculation

Following the same procedure as in the minimum power determination of the 180,000 DWT, the minimum propulsion power for a 75,000 DWT Product Carrier is calculated according to Level 1 and Level 2 requirements, as follows:

Level 1 assessment of a 75,000 DWT Product Carrier

The "Product Carrier" parameters a and b for the determination of the minimum power line value for the corresponding DWT of the subject vessel are defined by Table 10 presented below:

- ✓ a = 0.0652
- ✓ b = 5969.2
- ✓ DWT = 74995 tons

Based on the defined parameters and equation (14), the calculated minimum power is defined as follows:

Minimum Power = 10850 kW

Level 2 assessment of a 75,000 DWT Product Carrier

The subject vessel has a 4-blade propeller with a diameter of 7m. Following the STAwave-1 and Liu-Papanikolaou procedures, as they provided by the guidelines, and using the model scale open water diagram, the minimum power that the diesel engine of the vessel should provide is **5390 kW @ 70.8 RPM.**

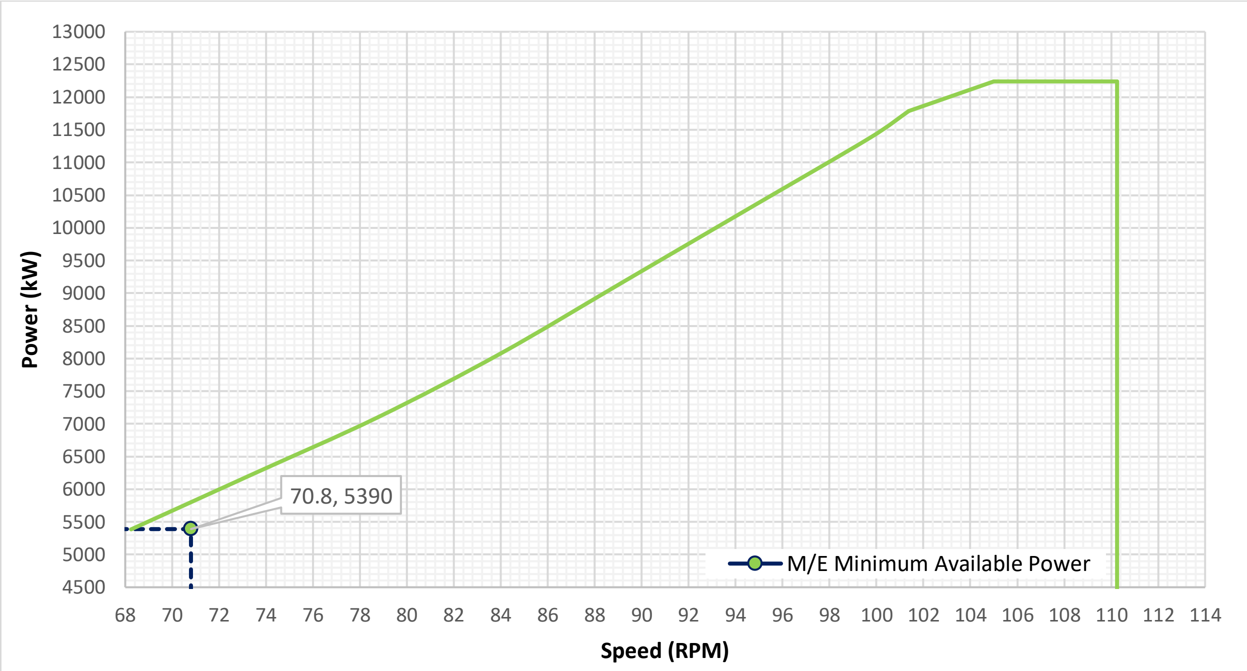

Figure 47. MAN B&W 6S60MC Load diagram / Engine Minimum Available Power

The estimated load diagram indicates that the diesel engine will deal effortlessly with the required torque for advance speed, Vs, equal to 4.0 kn.

5.2.3 Power/Speed Curve

For the subject vessel, in accordance with the Bulk Carrier procedure, six cases are examined. In Case 1 the engine in not limited. In Cases 2 and 3 the engine is limited to the Level 1 and 2 Minimum Propulsion Power, respectively. In Cases 4 and 5, the engine is limited to a level that applies to IMO's EEDI Phase 2 and 3. In Case's 6 scenario the engine is limited to a level that the reference speed matches the average speed of the daily noon reports, 12.21 kn.

RightShip's EPL acceptance criteria only applies to Case 1 and Case 2, where the engine is not limited lower than the Level 1 Minimum Propulsion Power.

The reference speed and rotation rate for the examined propulsive power values, at scantling draught, are estimated as follows:

Case	MCR_{LIM} (kW)	EPL (%)	P_{ME} (kW)	V_{REF} (knots)	N (RPM)
1	12240	0	9180	15.01	99
2	10850	11.36	9006	14.92	98.4
3	5390	55.96	4474	12.01	77.1
4	8520	30.39	7072	13.85	90.5
5	6840	44.12	5677	12.93	83.8
6	5680	53.59	4714	12.21	78.6

Table 38. Power/Speed/RPM values (@ Scantling draught)

The load diagram of the engine and the examined propulsion power values, P_{ME} (kW), with the corresponding rotation rate, N (RPM), are presented in the following diagram:

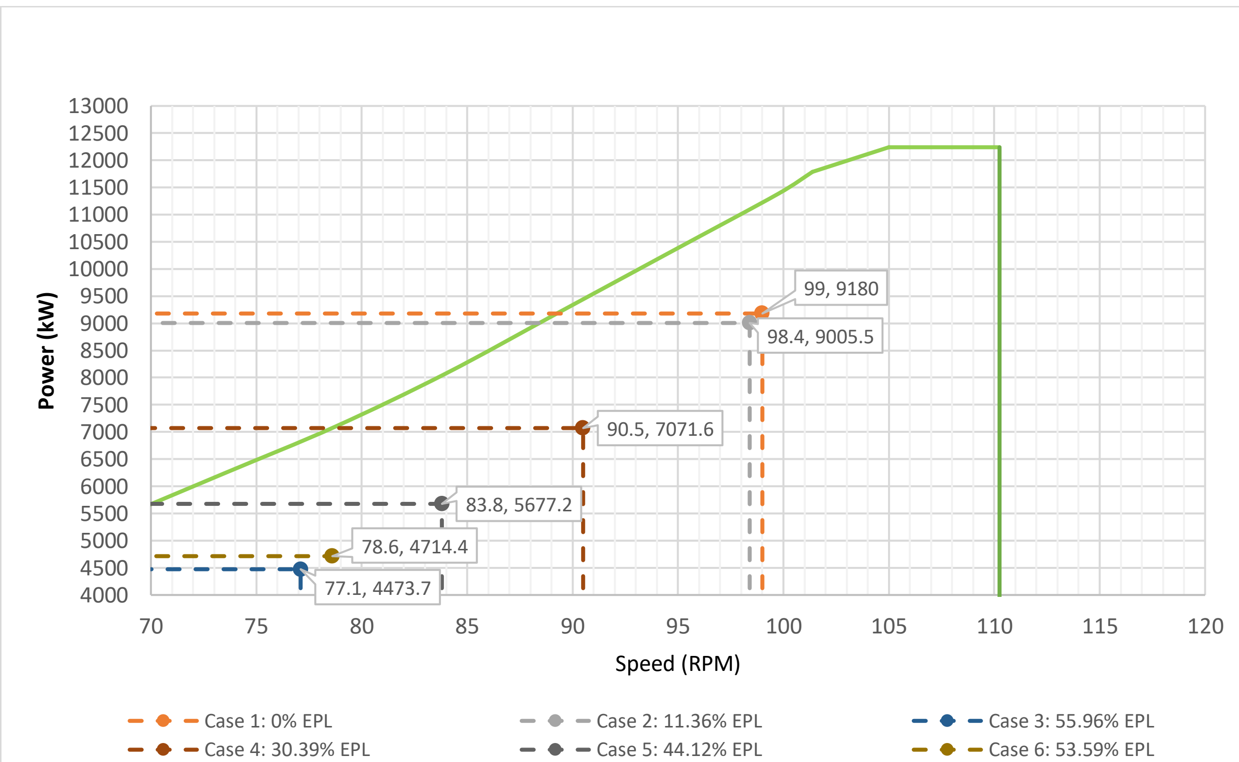

Figure 48. MAN B&W 6S60MC Load Diagram

5.2.4 EEXI Calculation

By exploiting the data provided by the owner, the final parameters of the calculation formula provided by the IMO's guidelines are presented as follows:

EEXI Parameters final	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
CF: conversion factor between fuel consumption and CO_2 emission						
CF_{ME}	3.206	3.206	3.206	3.206	3.206	3.206
CF_{AE}	3.206	3.206	3.206	3.206	3.206	3.206
Vref: ship speed						
V_{REF} (kn)	15.01	14.92	12.01	13.85	12.93	12.21
Capacity (@DWT at summer load draught) (tons)	74995	74995	74995	74995	74995	74995
P: Power of main and auxiliary engines						
P_{ME} (kW)	9180	9006	4474	7072	5677	4714
P_{AE} (kW)	556	521.3	269.5	426	342	284
SFC: Specific fuel consumption						
SFC_{ME} (g/kWh)	172.15	172.69	183.18	176.25	179.54	182.37
SFC_{AE} (g/kWh)	214.1	214.1	214.1	214.1	214.1	214.1
Correction factors						
f_j	1	1	1	1	1	1
f_w	1	1	1	1	1	1
f_i	1.015	1.015	1.015	1.015	1.015	1.015
f_c	1	1	1	1	1	1
f_l	1	1	1	1	1	1
f_m	1	1	1	1	1	1

Table 39. Tanker's EEXI calculation parameters

The attained EEXI values are estimated for each case scenario according to equation (2), as follows:

EEXI attained (g/ton*nm)	4.77	4.71	3.08	4.07	3.56	3.18

Table 40. Attained EEXI values

For the subject Product Carrier vessel, with a capacity at summer load line draught equal to **74995 tons**, the standard f_w value is equal to **0.7932**. The calculated EEXI value under weather conditions is estimated as follows:

EEXI weather (g/ton*nm)	6.01	5.93	3.88	5.13	4.49	4

Table 41. Attained $EEXI_{WEATHER}$ values

5.2.5 EEXI Requirements

Since the subject is a product carrier, the reference line value shall be calculated according to Table 3, as follows:

$$\boldsymbol{Reference\ Line} = \mathbf{1218.8} \times \boldsymbol{DWT}^{-0.488}$$

The required EEDI for each one of the three phase is calculated based on equation (1), as follows:

$$\boldsymbol{Required\ EEXI} = \left(\mathbf{1} - \frac{\boldsymbol{X}}{\mathbf{100}}\right) \times \mathbf{1218.8} \times \boldsymbol{DWT}^{-0.488}$$

For a 20,000 DWT and above Tanker, the corresponding values of the X factor are equal to 0, 10, 20, 30 for Phases 0, 1, 2 and 3, respectively (Table 4).

The required EEDI values for the subject vessel for the four EEDI Phases are calculated as follows:

- ✓ EEDI Phase 0: $EEXI_{Req}$ = 5.092 [gr-CO_2/t*nm]
- ✓ EEDI Phase 1: $EEXI_{Req}$ = 4.583 [gr-CO_2/t*nm]
- ✓ EEDI Phase 2: $EEXI_{Req}$ = 4.074 [gr-CO_2/t*nm]
- ✓ EEDI Phase 3: $EEXI_{Req}$ = 3.565 [gr-CO_2/t*nm]

The EEDI reference lines and the attained EEXI values are presented in the following diagram:

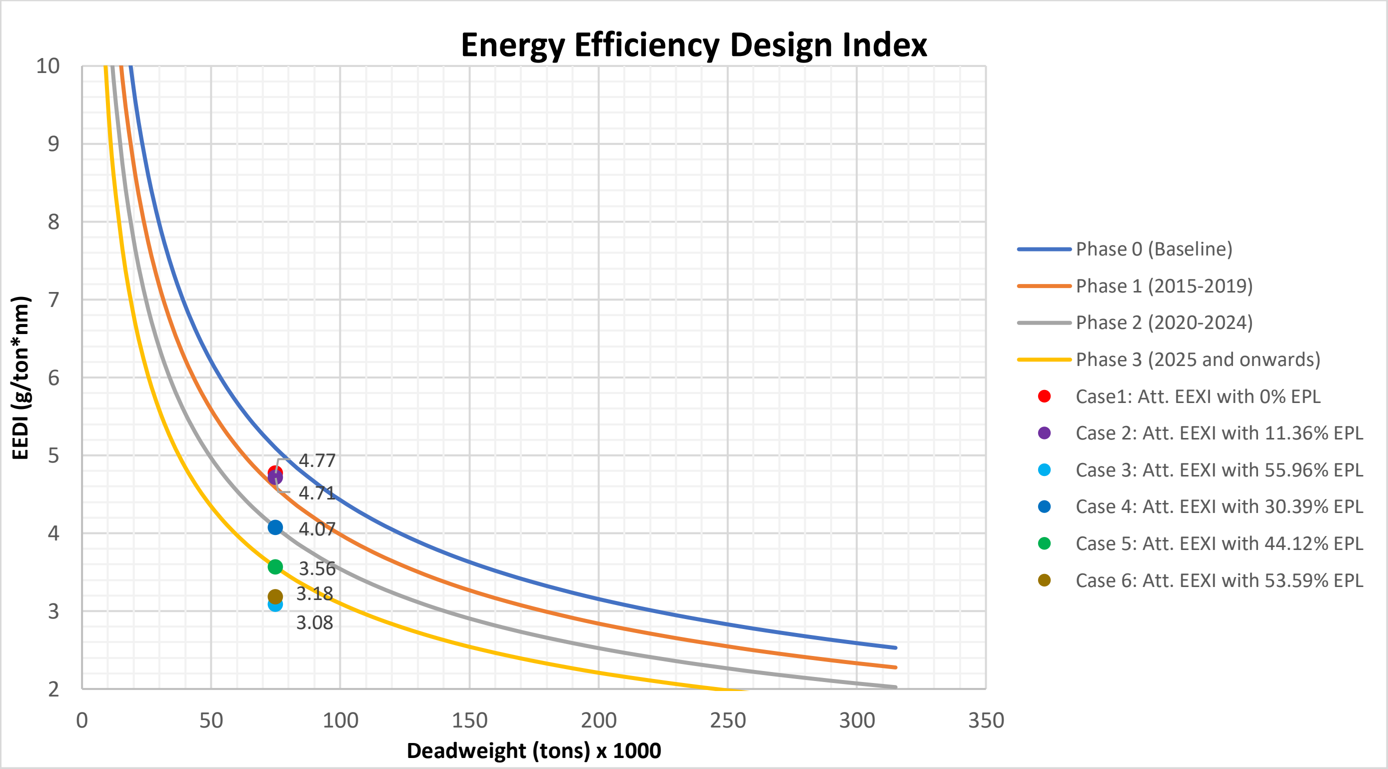

Figure 49. EEDI Reference Lines / Attained EEXI

According to Fig.49, in order for the subject vessel to comply with the current Phase 2 EEDI requirements, an Engine Power Limitation of at least 30.39% is required. The requirements are more demanding for the upcoming Phase 3, where a Limitation of at least 44.12% is required to comply with the regulation.

5.2.6 Comparison with operational data from the noon reports

In this section, the calculated EEXI values and the respective reference speed are about to be compared with the real-time corresponding values as they are calculated by the data provided from the daily noon reports. The reports of the vessel have been filtered so that the requested values are isolated based on the following criteria:

- ✓ Report type: Daily
- ✓ Condition: Laden

By editing the aforementioned data, the histogram of the daily open sea speed distribution for the Jan 2020-Dec 2021 period is presented below:

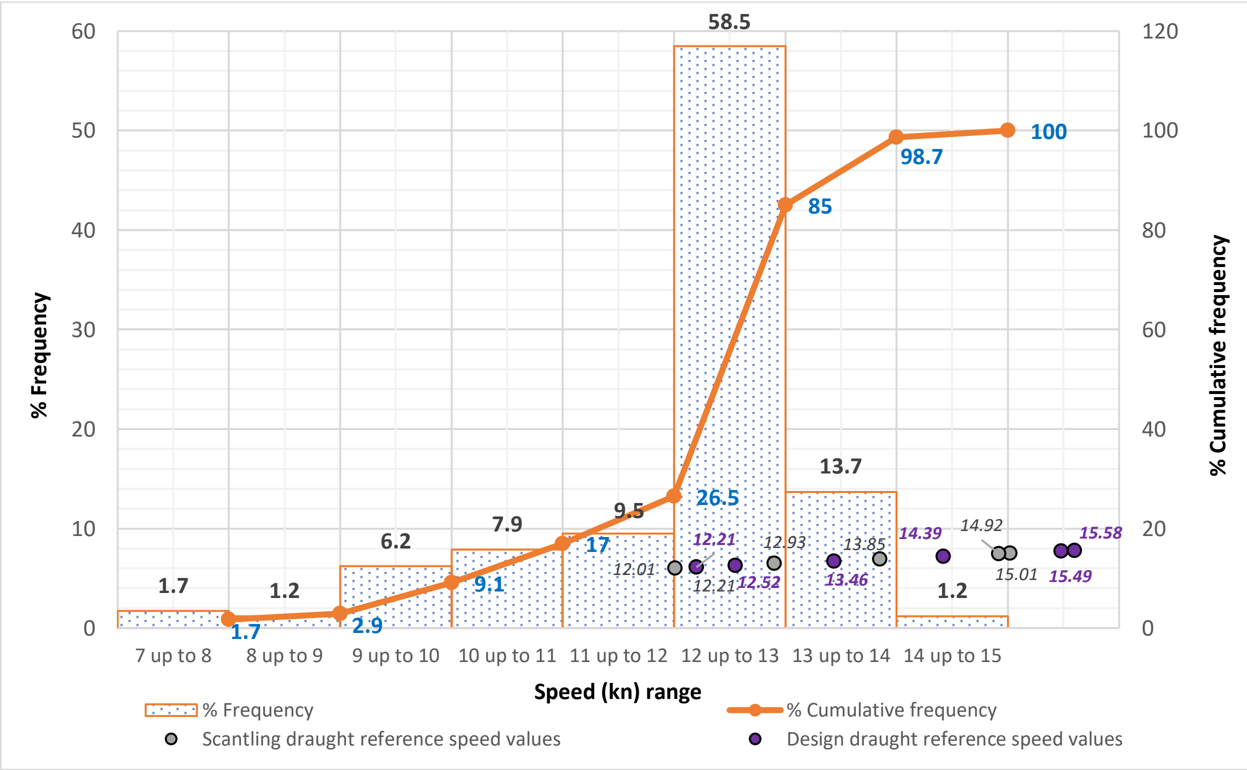

Figure 50. Histogram of Speed distribution Jan 20-Dec 21

The basic statistics of the speed distribution for the Jan 20-Dec 21 period are presented as follows:

Mean value	12.21
Standard Deviation	1.246
25% percentile	12
75% percentile	13
90% percentile	13.2

Table 42. Speed's basic statistics

According to (Fig.50), the reference speed values as they are calculated for the examined Cases 1 to 6, for both scantling and design load conditions, are compared with the actual speed distribution as follows:

Scantling Load Reference Speed

1. The Case 1 Reference speed is equal to **15.01 knots**. Thus, **100%** of the reported actual speeds are below this value.
2. The Case 2 Reference speed is equal to **14.92 knots**. Thus, **99.9%** of the reported actual speeds are below this value.
3. The Case 3 Reference speed is equal to **12.01 knots**. Thus, **27.09%** of the reported actual speeds are below this value.
4. The Case 4 Reference speed is equal to **13.85 knots**. Thus, **96.65%** of the reported actual speeds are below this value.
5. The Case 5 Reference speed is equal to **12.93 knots**. Thus, **80.91%** of the reported actual speeds are below this value.
6. The Case 6 Reference speed is equal to **12.21 knots**. Thus, **38.79%** of the reported actual speeds are below this value.

Design Load Reference Speed

1. The Case 1 Reference speed is equal to **15.58 knots**. Thus, **100%** of the reported actual speeds are below this value.
2. The Case 2 Reference speed is equal to **15.49 knots**. Thus, **100%** of the reported actual speeds are below this value.
3. The Case 3 Reference speed is equal to **12.52 knots**. Thus, **56.92%** of the reported actual speeds are below this value.
4. The Case 4 Reference speed is equal to **14.39 knots**. Thus, **99.21%** of the reported actual speeds are below this value.
5. The Case 5 Reference speed is equal to **13.46 knots**. Thus, **91.3%** of the reported actual speeds are below this value.
6. The Case 6 Reference speed is equal to **12.21 knots**. Thus, **38.79%** of the reported actual speeds are below this value.

Based on the comparison, the actual speed of the vessel is relatively high, as only **26.5%** of the reported speed values are below 12 knots. Furthermore, **58.5%** and **13.7%** of the reported speeds belong to the [12, 13] and [13, 14] bins, respectively.

For the subject vessel the noon reports do not provide information regarding the details of the laden condition. Thus, two following alternative cases are about to be examined:

✓ **Scenario 1**: In this case, the laden condition referred in the noon reports of the vessel corresponds to the Scantling Load Condition of the subject vessel, with a draught equal to **14.41 m**. The deadweight of the vessel is equal to **74995 tons**

✓ **Scenario 2:** In this case, the laden condition referred in the speed reports of the vessel corresponds to the Design Load Condition of the subject vessel, with a draught equal to **12.2 m**. The deadweight of the vessel is equal to **59967 tons**

Scenario 1: Noon reports refer to Scantling Load condition

In this case, the DWT of the vessel, for the daily noon reports, is considered equal to the DWT of the scantling load condition, **74995 tons**. Under this condition, the speed distribution of the vessel, for the Jan 20 – Dec 21 period, is compared to the reference speed values as they were estimated during the calculation process of the attained EEXI at Scantling draught. The corresponding diagram is presented below:

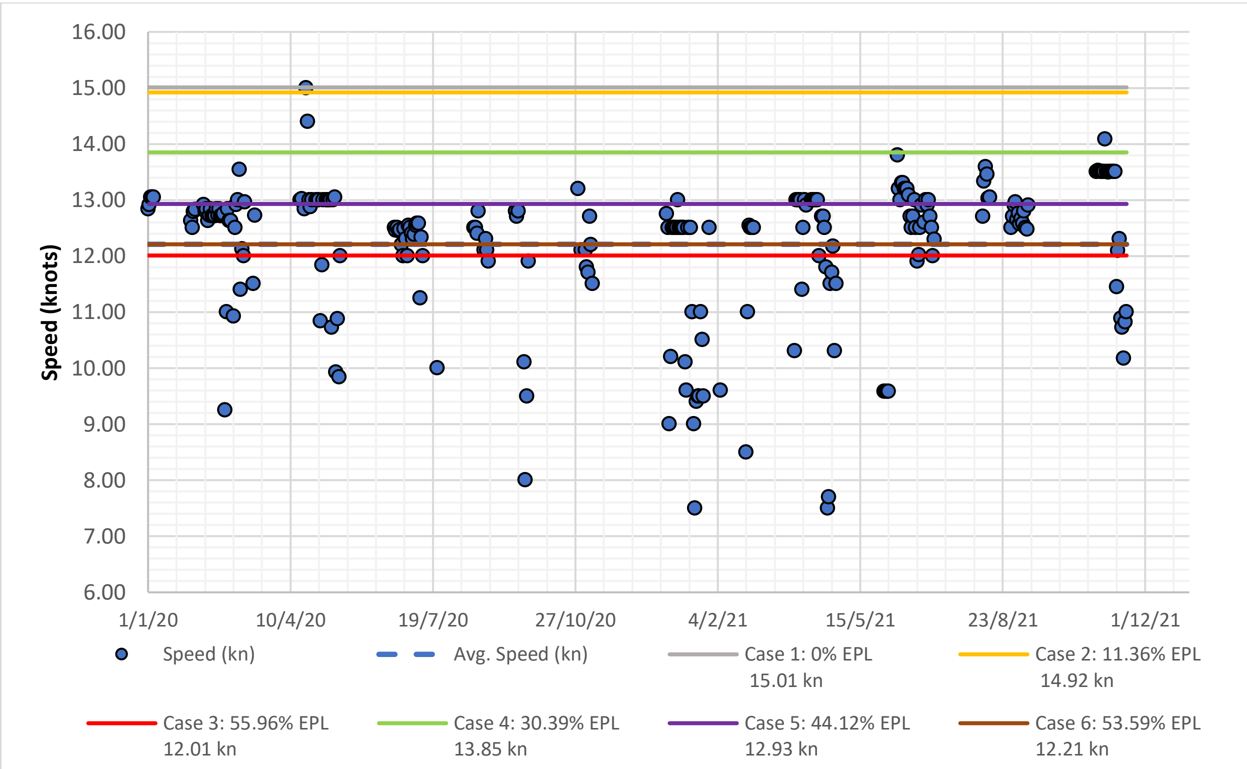

Figure 51. Scantling Draught Ref. Speed-Daily Speed distribution comparison

As illustrated by Fig.51, the average real-time speed of the subject vessel, at laden condition, is equal to **12.21 knots**. Thus, only the examined EPL Case 3 provides lower estimated speed than the actual one. The EPL Case 6 indicates that in order for the vessel to reach a reference speed equal to the average real-time speed (12.21kn), an aggressive EPL of **53.59%** is required.

Furthermore, a comparison between the real-time "EEXI" [gr-CO_2/t*nm] and the attained EEXI is required, in order to provide a clear understanding of the actual GHG emission reduction. The real-time "EEXI" is estimated by importing the daily Speed, the Fuel Oil Consumption of the main and auxiliary engines, the Scantling DWT of the vessel and the corresponding correction factors, to the EEXI formula.

Based on that, the histogram of the daily "EEXI" distribution, at scantling load condition, is presented as follows:

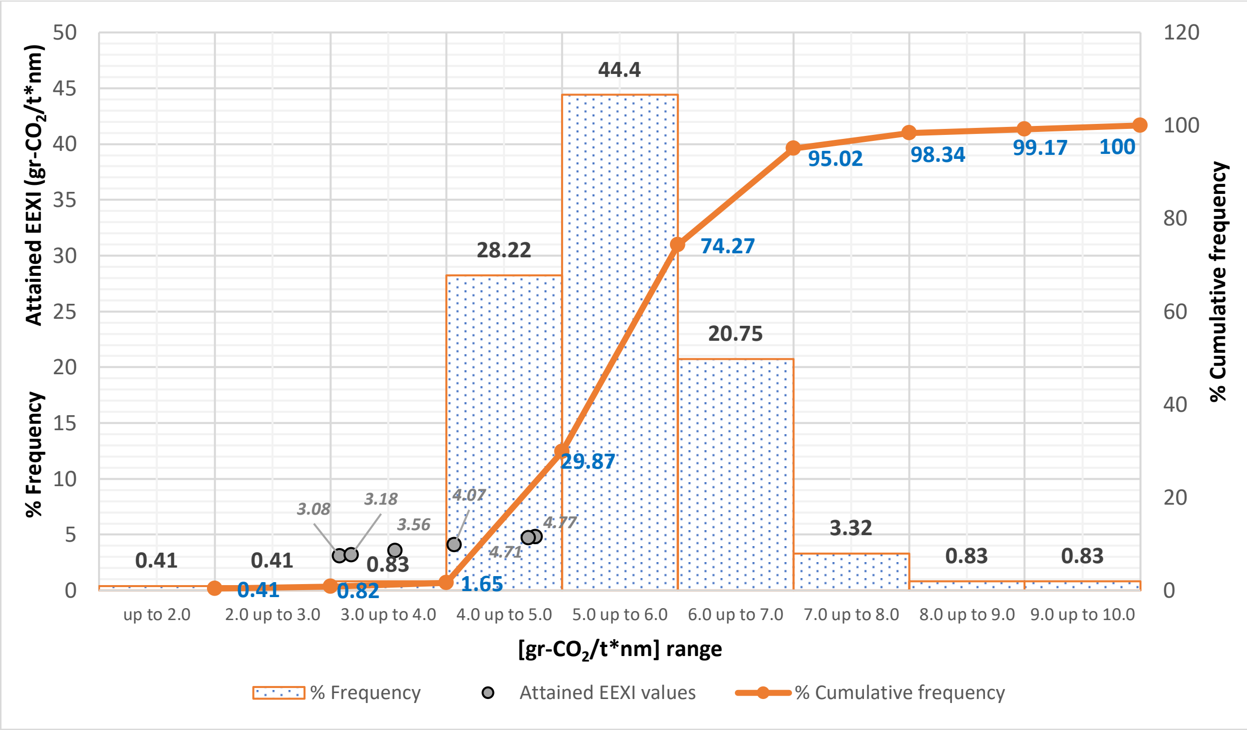

*Figure 52. Histogram of Scantling draught "EEXI" [gr-CO_2/t*nm] distribution Jan 20-Dec 21*

According to the cumulative curve (Fig.52), the Attained EEXI values as they are calculated for the examined Cases 1 to 6, for scantling load condition, are compared with the Real-time "EEXI" values, as follows:

Scantling Load "EEXI" with regular operational data

1. The Case 1 Attained EEXI is equal to **4.77 [gr-CO_2/t*nm]**. Thus, **23.38%** of the real-time "EEXIs" are below this value (**76.62%** affected).
2. The Case 2 Attained EEXI is equal to **4.71 [gr-CO_2/t*nm]**. Thus, **21.69%** of the real-time "EEXIs" are below this value (**78.31%** affected).
3. The Case 3 Attained EEXI is equal to **3.08 [gr-CO_2/t*nm]**. Thus, **0.89%** of the real-time "EEXIs" are below this value (**99.11%** affected).
4. The Case 4 Attained EEXI is equal to **4.07 [gr-CO_2/t*nm]**. Thus, **3.63%** of the real-time "EEXIs" are below this value (**96.37%** affected).
5. The Case 5 Attained EEXI is equal to **3.56 [gr-CO_2/t*nm]**. Thus, **1.28%** of the real-time "EEXIs" are below this value (**98.72%** affected).
6. The Case 6 Attained EEXI is equal to **3.18 [gr-CO_2/t*nm]**. Thus, **0.97%** of the real-time "EEXIs" are below this value (**99.03%** affected).

Based on the comparison, the examined EPL Cases 1 to 6 seem to contribute to the [gr-CO_2/t*nm] reduction. A closer look reveals that even the EPL Cases 1 and 2, where the limitation of the main engine is either not applied or minor, significantly contribute to the reduction, as their effect is **76.62%** and **78.31%**, respectively. This contradiction requires further investigation.

In order to verify the reliability of the previous results, the real-time "EEXI" calculation is also performed considering that the auxiliary engines' Fuel Oil Consumption is equal to the theoretical value used in the calculation of the examined EPL Case 6 attained EEXI. For this case, the Specific Fuel Consumption is equal to **214.1 gr/kWh**, and the corresponding power value is equal to **284 kW**. Thus, the theoretical fuel oil consumption of the auxiliary engines is equal to **6.08 x 10^4 gr/hr**.

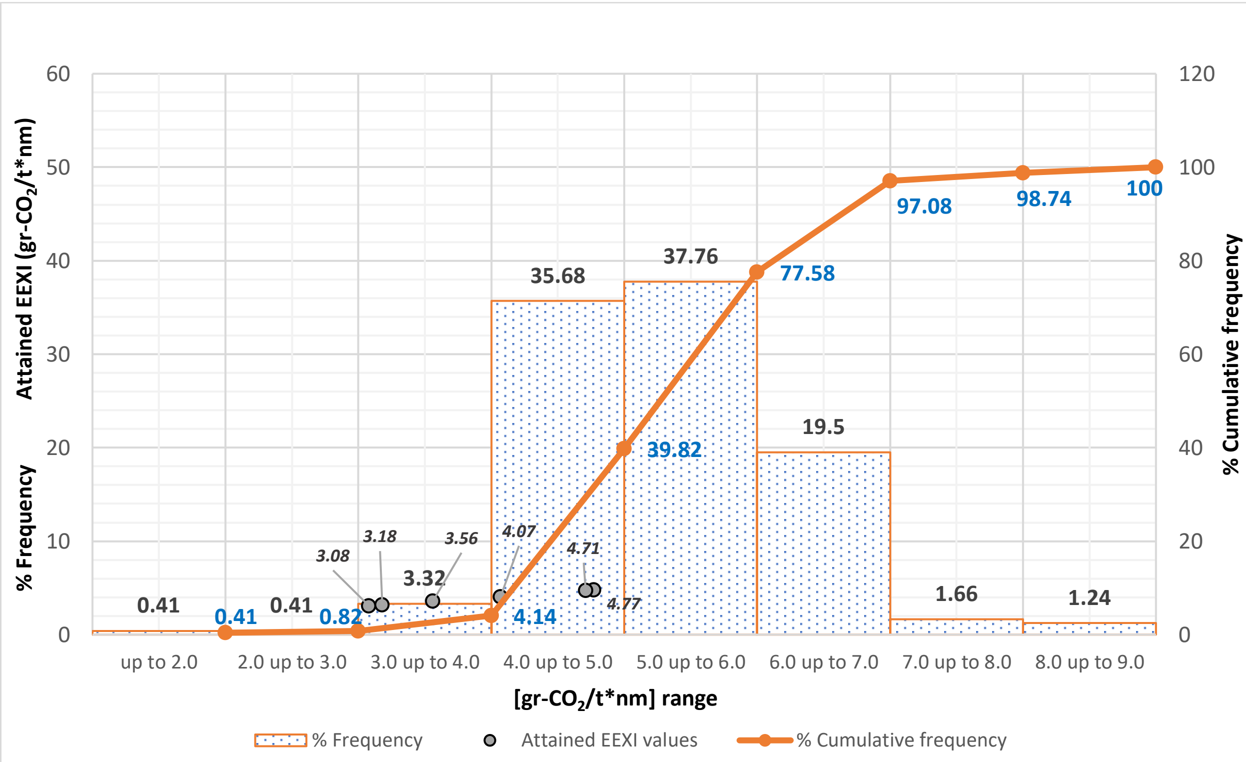

*Figure 53. Histogram of Scantling draught "EEXI" [gr-CO_2/t*nm] distribution with Theoretical FOC_{AE} Jan 20-Dec 21*

Based on the cumulative curve (Fig.53), the Attained EEXI values as they are calculated for the examined Cases 1 to 6, for scantling load condition, are compared with the Real-time "EEXI" values calculated for the theoretical FOC_{AE}, as follows:

Scantling Load "EEXI" with Theoretical D/G Fuel consumption

1. **31.61%** of the real-time "EEXIs" are below the Case 1 Att. EEXI (**68.39%** affected).
2. **29.47%** of the real-time "EEXIs" are below the Case 2 Att. EEXI (**70.53%** affected).
3. **1.09%** of the real-time "EEXIs" are below the Case 3 Att. EEXI (**98.91%** affected).
4. **6.64%** of the real-time "EEXIs" are below the Case 4 Att. EEXI (**93.36%** affected).
5. **2.68%** of the real-time "EEXIs" are below the Case 5 Att. EEXI (**97.32%** affected).
6. **1.42%** of the real-time "EEXIs" are below the Case 6 Att. EEXI (**98.58%** affected).

The comparison reveals that the examined Cases 3 to 6 remain highly effective in terms of affecting the [gr-CO_2/t*nm] emissions. On the other hand, for Cases 1 and 2, despite the fact that they remain significantly effective, the influence of the theoretical fuel oil consumption of the Aux. engines on their effectiveness is strong. For Case 1 the effectiveness reduced to **68.39%**, and for Case 2 to **70.53%**.

Scenario 2: Noon reports refer to Design Load condition

In this case, the laden condition DWT of the vessel is considered equal to the DWT of the design load condition, **59967 tons**. Thus, the speed distribution of the vessel, for the examined period, is compared to the reference speed values as they were estimated during the calculation process of the attained EEXI at Design draught. The estimation process followed the same pattern as in the case of the Scantling Load Condition attained EEXI.

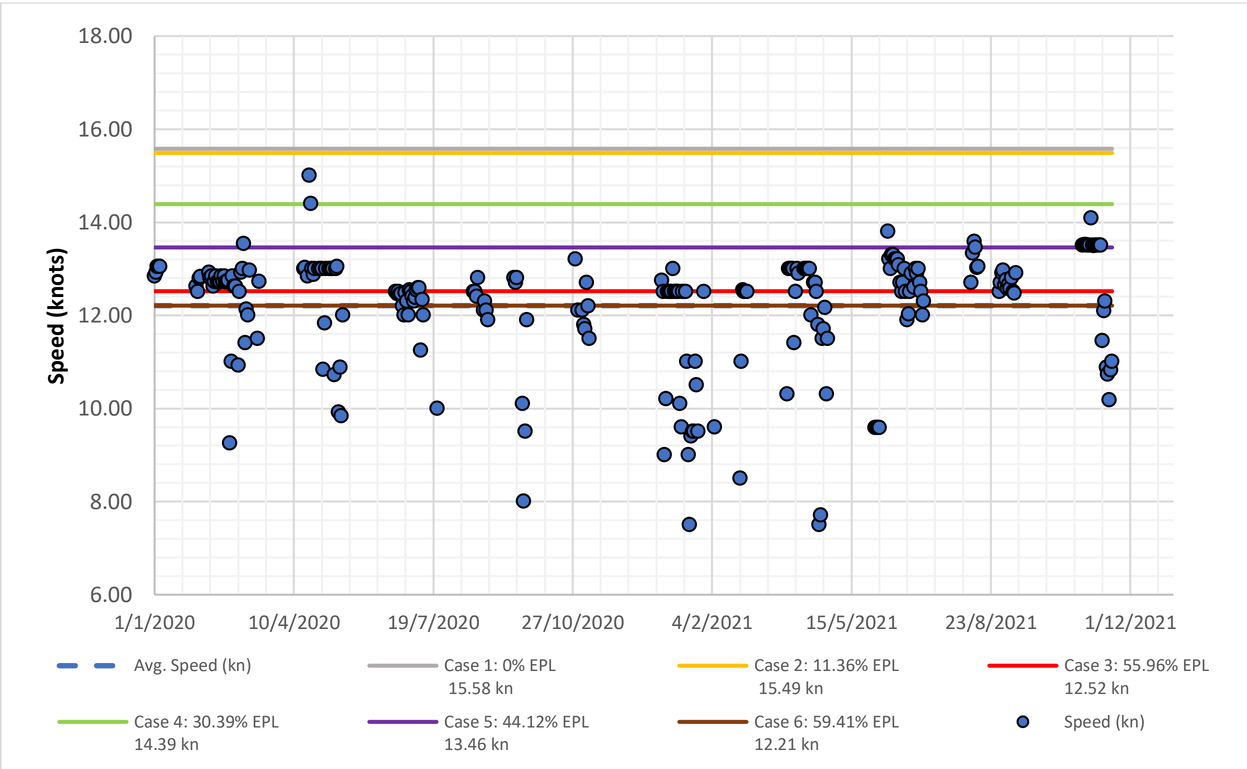

Figure 54. Design Draught Ref. Speed-Daily Speed distribution comparison

In accordance with Fig.54, the average real-time speed of the subject vessel, at laden condition, remains equal to **12.21 knots**. In Design load condition, none of the examined EPL Cases 1 to 5 provide lower estimated speed than the actual one. The EPL Case 6 indicates that in order for the vessel to reach a reference speed equal to the average one, an even more aggressive EPL of **59.41%** is required.

The comparison between the real-time “EEXI” [gr-CO_2/t*nm], for the design load condition, and the attained EEXI is crucial, in order to provide a clearer image of the actual GHG emission reduction, for the examined laden condition. Following the same procedure as in Scenario 1, and by assuming that the laden deadweight corresponds to the Design Load DWT, **59967 tons**, the histogram of the daily “EEXI” distribution is presented as follows:

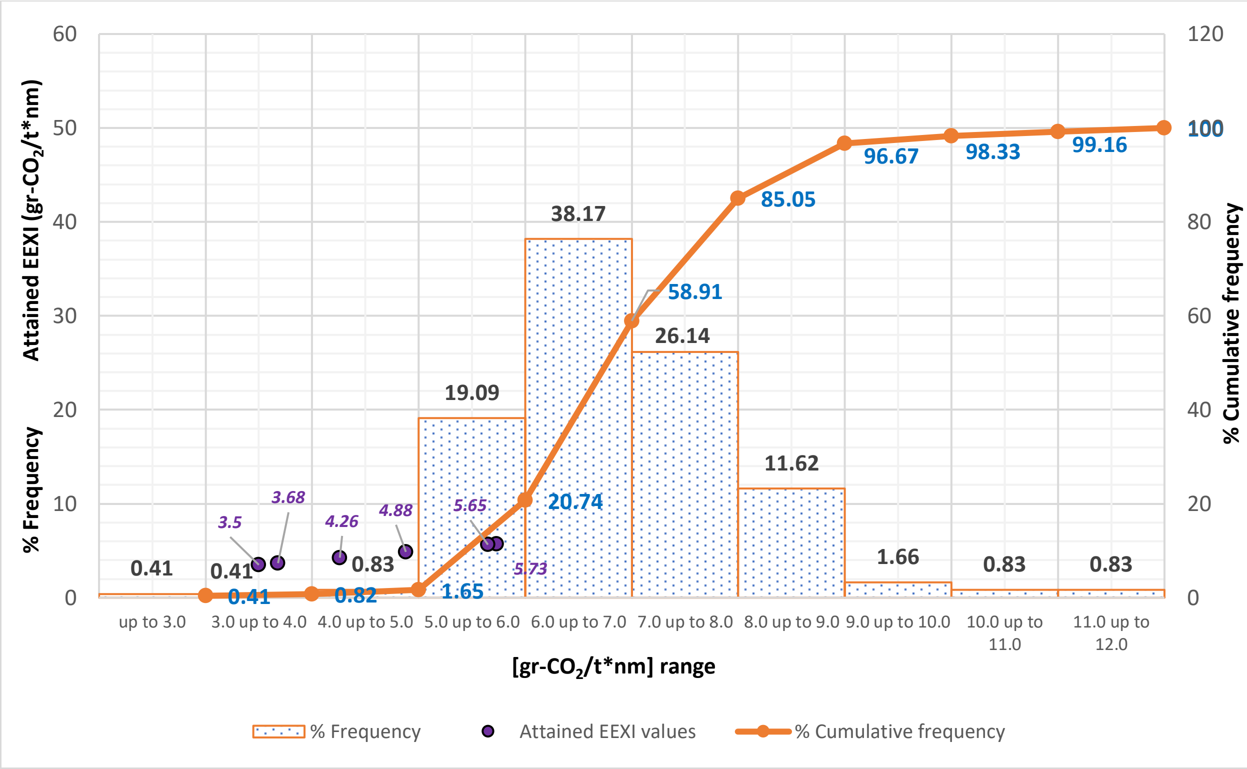

*Figure 55. Histogram of Design draught "EEXI" [gr-CO_2/t*nm] distribution Jan 20-Dec 21*

According to the cumulative curve (Fig.55), the Attained EEXI values as they are calculated for the examined Cases 1 to 6, for design load condition, are compared with the Real-time "EEXI" values, as follows:

Design Load "EEXI" with regular operational data

1. The Case 1 Attained EEXI is equal to **5.73 [gr-CO_2/t*nm]**. Thus, **15.59%** of the real-time "EEXIs" are below this value (**84.41%** affected).
2. The Case 2 Attained EEXI is equal to **5.65 [gr-CO_2/t*nm]**. Thus, **14.06%** of the real-time "EEXIs" are below this value (**85.94%** affected).
3. The Case 3 Attained EEXI is equal to **3.68 [gr-CO_2/t*nm]**. Thus, **0.69%** of the real-time "EEXIs" are below this value (**99.31%** affected).
4. The Case 4 Attained EEXI is equal to **4.88 [gr-CO_2/t*nm]**. Thus, **1.55%** of the real-time "EEXIs" are below this value (**98.45%** affected).
5. The Case 5 Attained EEXI is equal to **4.26 [gr-CO_2/t*nm]**. Thus, **1.04%** of the real-time "EEXIs" are below this value (**98.96%** affected).
6. The Case 6 Attained EEXI is equal to **3.50 [gr-CO_2/t*nm]**. Thus, **0.62%** of the real-time "EEXIs" are below this value (**99.38%** affected).

As was also observed in Scenario 1, the effect of both the EPL Case 1 and 2 is significantly high. The corresponding values are **84.41%** and **85.94%**, respectively.

The reliability of the previous deduction is verified as per Scenario 1, considering that the auxiliary engines' fuel oil consumption is equal to the respective theoretical value. For the examined Case 6, at design draught, the Specific Fuel Consumption is equal to **214.1 gr/kWh**, and the corresponding power value is equal to **248.4 kW**. Thus, the fuel oil consumption of the auxiliary engines is equal to **5.32 x 10^4 gr/hr.**

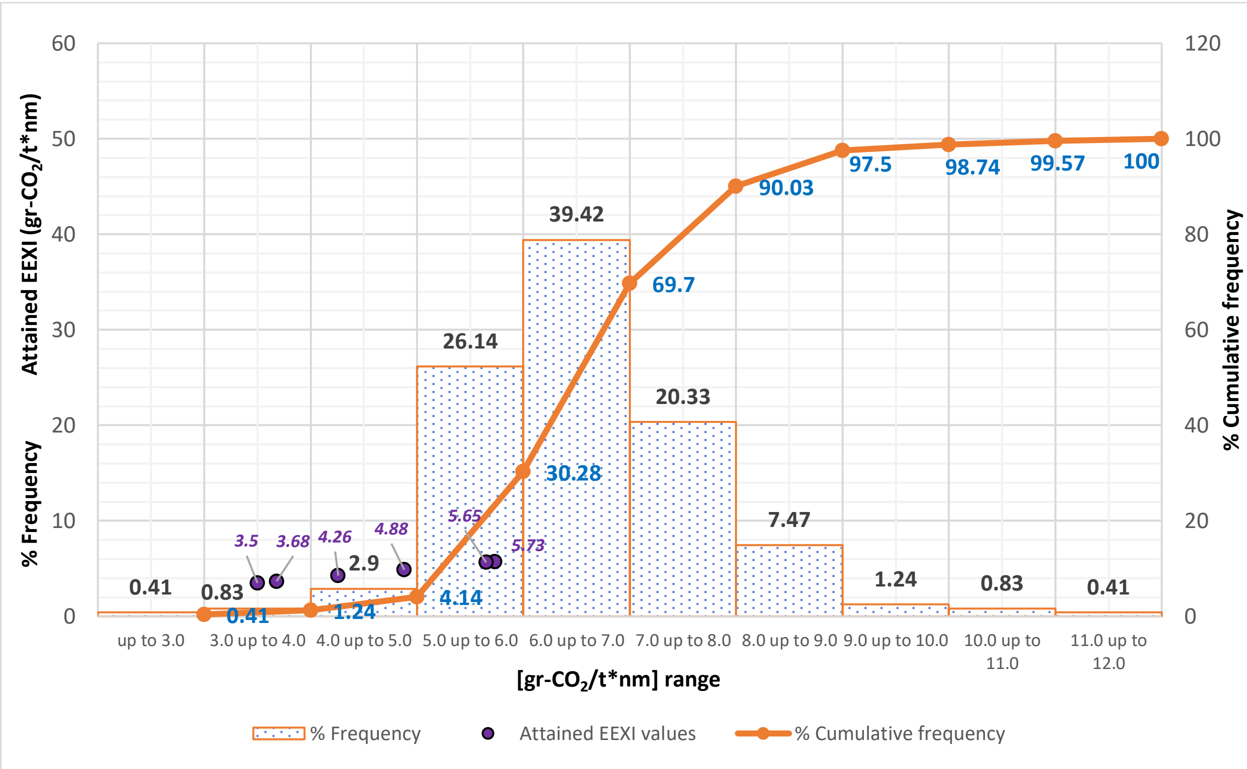

*Figure 56. Histogram of Design draught "EEXI" [gr-CO_2/t*nm] distribution with Theoretical FOC_{AE} Jan 20-Dec 21*

Based on the cumulative curve (Fig.56), the Attained EEXI values as they are calculated for the examined Cases 1 to 6, for design load condition, are compared with the Real-time "EEXI" values calculated for the theoretical FOC_{AE}, as follows:

Design Load "EEXI" with Theoretical D/G Fuel consumption

1. **23.22%** of the real-time "EEXIs" are below the Case 1 Att. EEXI (**76.78%** affected).
2. **21.13%** of the real-time "EEXIs" are below the Case 2 Att. EEXI (**78.87%** affected).
3. **0.97%** of the real-time "EEXIs" are below the Case 3 Att. EEXI (**99.03%** affected).
4. **3.79%** of the real-time "EEXIs" are below the Case 4 Att. EEXI (**96.21%** affected).
5. **1.99%** of the real-time "EEXIs" are below the Case 5 Att. EEXI (**98.01%** affected).
6. **0.83%** of the real-time "EEXIs" are below the Case 6 Att. EEXI (**99.17%** affected).

As observed in the first scenario, the effectives of the Cases 1 and 2 is reduced by applying the theoretical D/G fuel consumption. The corresponding percentages reduced to **76.78%** for Case 1 and **78.87%** for Case 2.

For the Design load condition, it is useful to evaluate the wind force effect. Thus, the "EEXI" [gr-CO_2/t*nm] values are calculated by using the real-time data that correspond to wind force equal to 4.0 BFT or less.

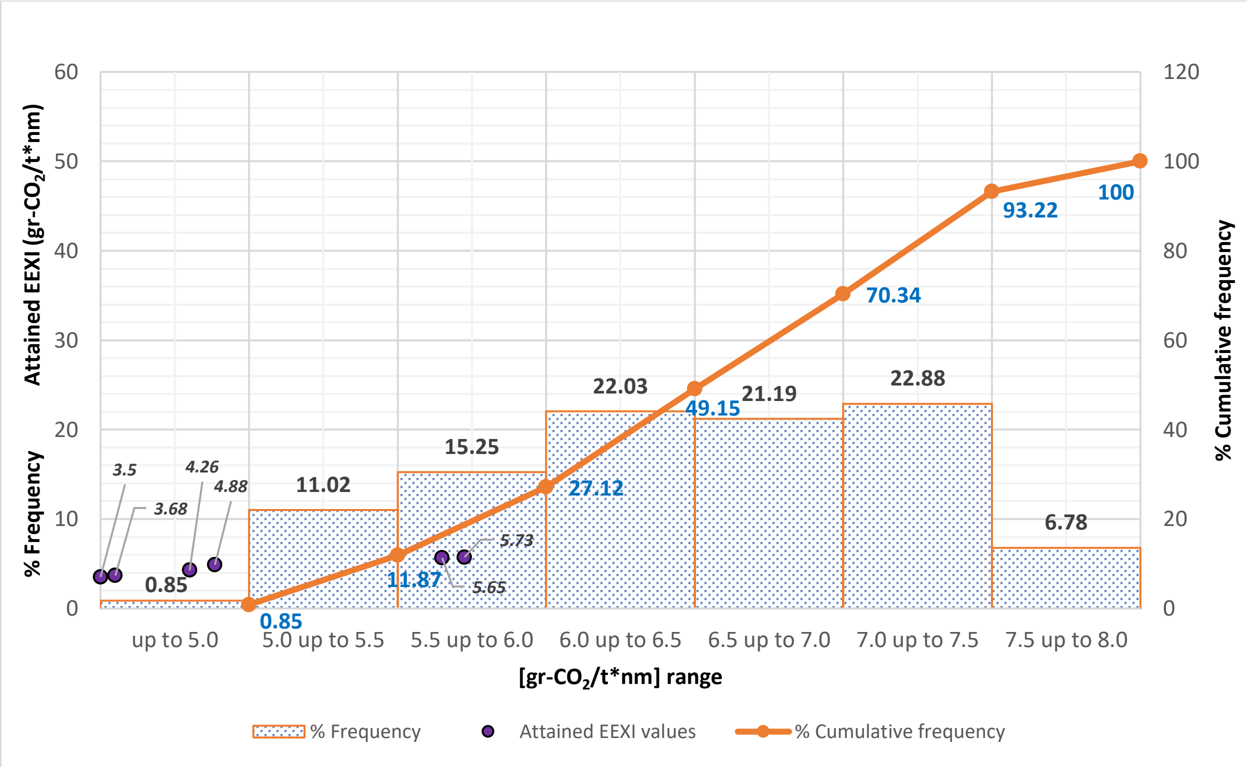

*Figure 57. Histogram of Design draught "EEXI" [gr-CO_2/t*nm] distribution with Wind Force ≤ 4 BFT Jan 20-Dec 21*

Based on the respective cumulative curve (Fig.57), the Attained EEXI values as they are calculated for the examined Cases 1 to 6, for design load condition, are compared with the Real-time "EEXI" values calculated for wind force equal or less than 4 BFT, as follows:

Design Load "EEXI" with Wind Force ≤ 4 BFT

1. **18.89%** of the real-time "EEXIs" are below the Case 1 Att. EEXI (**81.11%** affected).
2. **16.45%** of the real-time "EEXIs" are below the Case 2 Att. EEXI (**83.55%** affected by EPL).
3. Less than **0.85%** of the real-time "EEXIs" are below the Case 3 Att. EEXI (>**99.15%** affected).
4. Less than **0.85%** of the real-time "EEXIs" are below the Case 4 Att. EEXI (>**99.15%** affected).
5. Less than **0.85%** of the real-time "EEXIs" are below the Case 5 Att. EEXI (>**99.15%** affected).
6. Less than **0.85%** of the real-time "EEXIs" are below the Case 6 Att. EEXI (>**99.15%** affected).

According to the comparison, the wind force has a subtle influence on the %Effect of the EPL Cases 1 and 2, as the corresponding values reduced to **81.11%** and **83.55%**, respectively.

Based on the previous comparisons, a comprehensive list of the results is presented below:

Case	%EPL	Scantling Load Condition		Design Load Condition		
		%Effect	%Effect (Theoretical FOC_{AE})	**%Effect**	%Effect (Theoretical FOC_{AE})	%Effect (Wind Force ≤ 4BFT)
1	**0.00**	76.62	68.39	84.41	76.78	81.11
2	**11.36**	78.31	70.53	85.94	78.87	83.55
3	**55.96**	99.11	98.91	99.31	99.03	99.15
4	**30.39**	96.37	93.36	98.45	96.21	99.15
5	**44.12**	98.72	97.32	98.96	98.01	99.15
6	**>53.59**	99.03	98.58	99.38	99.17	99.15

*Table 43. The %Effect of each EPL Case on the "EEXI" [gr-CO_2/t*nm] emissions*

In accordance with the 180,000 DWT Bulk Carrier, it needs to be defined that the %Effect of each EPL Case is not totally accurate. However, it provides an objective understanding of the way that the Engine Power Limitation and the EEXI affect the real-time [gr-CO_2/t*nm] emissions. Based on Table 43, the following results are extracted:

1. The examined EPL Cases 3, 4, 5 and 6 significantly contribute to both the EEDI Phase 2 or 3 compliance and to the reduction of the real-time [gr-CO_2/t*nm] emissions. The influence of both the theoretical D/G consumption and the wind force on the effectiveness of those cases is considered minor.

2. The contradiction regarding the effect of the EPL Cases 1 and 2 on the [gr-CO_2/t*nm] reduction needs to be explained. For the subject cases, according to Table 43, the corresponding effectiveness belongs to the **[68.39%, 84.11%]** range for Case 1 and to the **[70.53%, 85.94%]** range for Case 2. Those values are unjustifiably high, considering that the limitation of the main engine is 0% and 11.36%, respectively, and thus those cases are not supposed to affect the real-time [gr-CO_2/t*nm] emissions, in terms of Engine Power Limitation.

   However, there is a rational explanation on the issue. By observing the "EEXI" [gr-CO_2/t*nm] histograms of the subject vessel, it is revealed that the real-time [gr-CO_2/t*nm] emissions are extremely high. That indicates that the performance of the vessel regarding the carbon emissions is poor, which can be justified as follows:

   - According to Table 42, the average real-time speed of the vessel is **12.21** knots. Furthermore, **72.2%** of the reported speed values belong to the **[12, 14] (kn)** range. This reveals that the subject vessel does not extensively use slow steaming to cut down carbon emissions.
   - The relatively high speed of the vessel severely increases the power demands of the propeller, and thus the required power from the main engine. The increases requirements lead to higher fuel oil consumption.
   - Based on the noon reports of the vessel, it is observed that the real-time fuel oil consumption of the main engine is significantly high, although this is partially justified the high speed and the increased power demands. This indicates that the quality of the fuel used is poor and probably of high carbon intensity, which heavily increases the real-time [gr-CO_2/t*nm] emissions.

The justification of the controversial Cases 1 and 2 reveals that it is not exclusively the Engine Power Limitation that has an influence of the %Effect of each examined case. The quality of the theoretical fuel used in the calculation of the Attained EEXI values is considered a crucial parameter. As it is specified by the IMO and reported by the M/E shop tests, the Fuel Oil Consumption of the Main Engine is corrected to Lower Calorific Value 42,700 kJ/kg for ISO conditions. However, the noon reports do not provide information about the specification of the real-time fuel. Usually, the burnt fuel is of poor standards compared to the theoretical values. Thus, it contributes to the extensive increase of the real-time [gr-CO_2/t*nm] emissions, in combination with the increased power demands of the subject vessel. Inevitably, the real-time poor performance of the subject vessel contributes to the increased %Effect of the EPL Cases.

This assumption is also verified by the effect of the Theoretical D/G fuel consumption. For Cases 1 and 2, the theoretical FOC value decreases the corresponding %Effect by around **8%**. This happens because a fuel of higher quality (theoretical) reduces the real-time [gr-CO_2/t*nm] emissions. Thus, the EPL Cases are not required to contribute to the reduction so extensively as they do in the case of poor performance (real-time fuel).

In conclusion, it is revealed that it not only the limitation of the main engine that affects the real-time “EEXI” [gr-CO_2/t*nm]. The quality of the burnt fuel also plays a major role in the reduction of the actual emissions.

6 Conclusion

This thesis aimed to extensively describe the upcoming EEXI regulation, as part of the IMO's strategy to reduce the CO_2 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 corresponding requirements. Among the suggested proposals, the most promising solution was considered to be the limitation of the main engine. Thus, a number of applications based on the EPL was conducted in order to verify its actual effect on both the EEXI compliance and the reduction of the actual CO_2 emissions.

In that direction, the limitation of the main engine applied on two vessels of different type and size. By comparing the examined cases, the following conclusions can be made:

- Regarding the determination of the minimum propulsion power, the Level 2-simplified assessment gives significantly lower requirements compared to Level 1 assessment. Under the condition that the main engine can deal effortlessly with the corresponding requirements, the Level 2 minimum propulsion power allows the engine to be extensively limited, and thus complying with the EEDI Phase 2 requirements.

- The calculation process conducted for the two vessels revealed that the Engine Power Limitation requirements, in order to comply with EEDI Phase 2 or 3, are remarkably lower for the smaller Product Carrier vessel.

- For both the examined vessels, the EPL acceptance criteria established by RightShip do not allow an extended limitation of the main engine. Thus, it is considered impossible for a ship to both comply with RightShip's and IMO's requirements by exclusively limiting the power of the main engine.

- As revealed by the comparison between the real-time and theoretical values of the two vessels, an aggressive Engine Power Limitation, in combination with a high-quality fuel, contributes to the reduction of the actual CO_2 emissions.

Based on these conclusions, a number of concerns arise, which are considered essential to be further investigated in a future study. More specifically:

- The safe application of the Engine Power Limitation is critical. Due to that fact, it is essential to determine the Minimum Propulsion Power based on both the Level 1 and Level 2 assessment guidelines, as they provided by the IMO. It is crucial to ensure that the calculated values are below the torque / speed limit of the engine, in order to verify the safe operation of the vessel under adverse weather conditions. Especially for the Level 2 assessment, it is considered important to co-estimate the effect of the real-time condition of the hull. More specifically, the hull of the vessel is usually fouled during operation, and thus the vessel has increased power demands. Despite the fact that the regulations suggest the minimum power to be determined for clean hull condition, it is certain that a fouled hull would increase the required power for the same rotational rate, and thus could set the corresponding operational point above the torque / speed limit of the engine. That would set the safe operation of the ship in danger.

- The compliance with the EEXI requirements demands really aggressive limitation of the main engine, as it was specified for both the examined vessels. By limiting the engine in such levels, the safe operation of the ship is set under risk. Despite the fact that the guidelines include minimum power requirements, which are overridable in case of bad weather, the wear of the engine throughout the years is not taken into consideration. The vast majority of vessels affected by the EEXI are more than 10 years old, and thus their engines are fatigued. This needs to be co-estimated in the definition of the minimum power requirements, in order to avoid extensive limitations of the main engine that can endanger the vessel.

- The EPL acceptance criteria established by RightShip are considered a game changer regarding the applicability of the EPL, as they do not allow a limitation below the Level 1 requirements. This restriction does not allow the majority of vessels to comply with the EEDI Phase 2 requirements by inclusively limiting their engine. Although RightShip's requirements are not mandatory, a possible noncompliance would discourage charterers from signing a contract with the shipowner.

- The reduction of the actual CO_2 emissions is not inclusively determined by the limitation of the main engine. Due to that fact, the effect of the quality and type of the burnt fuel on the GHG emissions should be further investigated, in order to provide more comprehensive results.

In conclusion, under specific and strict conditions, it is certain that the Engine Power Limitation eases the compliance of the existing vessels with the upcoming EEXI. However, it is considered essential the limitation of the main engine to be combined with other efficient technical and operational solutions, in order to both comply with the requirements and strongly affect the actual CO_2 emissions, which is the main goal of the IMO's policy.

7 References

CDC. (2020). *Preparing for the regional health impacts of climate change in the United States.* https://www.cdc.gov/climateandhealth/docs/Health_Impacts_Climate_Change-508_final.pdf

ClassNK. (2021). *Outlines of EEXI regulation*. https://www.classnk.or.jp/hp/pdf/activities/statutory/eexi/eexi_rev3e.pdf

Claudia Norrgren / RightShip. (2020). *The GHG model methodology*. https://help.rightship.com/en/articles/4248831-the-ghg-model-methodology

Cook, J. (2016). *Myth 5: Climate change isn't harmful*. https://www.beforetheflood.com/explore/the-deniers/fact-climate-change-is-very-very-dangerous/

DNV. (2014). *Efficiency Finder*. https://www.dnv.com/maritime/energy-efficiency/efficiency-finder.html

DNV. (2015). *ECO RETROFIT Improve your vessel's performance for today's market.* http://production.presstogo.com/fileroot6/gallery/dnvgl/files/original/f930de242ecc6336e04385ee5e4d49eb/f930de242ecc6336e04385ee5e4d49eb_low.pdf

DNV. (2021). *EEXI – Energy Efficiency Existing Ship Index*. https://www.dnv.com/maritime/insights/topics/eexi/index.html

DNV. (2021). *IMO update: Marine Environment Protection Committee – MEPC 76.* https://www.dnv.com/news/imo-update-marine-environment-protection-committee-mepc-76-203128

Dr. Fabian Kock / DNV. (2021). *Alternative Fuels: Biofuels in international shipping.* https://www.maritimes-zentrum.de/fileadmin/data/contentgrafiken/Aufgaben_und_Aktivitaeten/Weiterbildung_und_Veranstaltungen/ISF_Tagung/2021/Vortraege/Kock_Alternative_Fuels_-_Biofuels.pdf

EPA & NOAA. (2021). *Climate Change Indicators: Climate Forcing.* https://www.epa.gov/climate-indicators/climate-change-indicators-climate-forcing

EPA. (2021). *Overview of Greenhouse Gases.* https://www.epa.gov/ghgemissions/overview-greenhouse-gases

Hyundai Global Service. (2021). *EEXI Compliance Solution.* https://www.hyundai-gs.com/eng/Main.do

IMO. (2011). *Energy Efficiency Measures.* https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx

IMO. (2012). *MEPC.1/Circ. 796: IMO Guidelines for the calculation of the coefficient fw for decrease in ship speed in a representative sea condition for trial use.* https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Circ-796.pdf

IMO. (2013). *MEPC 65/22/Annex 14: 2013 Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI).* https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.231(65).pdf

IMO. (2015). *Third IMO Greenhouse Gas Study 2014.* https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf

IMO. (2017). *MEPC.1/Circ.850/Rev.2: 2013 Interim guidelines for determining minimum propulsion power to maintain the maneuverability of ships in adverse conditions, as amended.* https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/MEPC.1-CIRC.850-REV2.pdf

IMO. (2018). *MEPC 72/17/Add.1/Annex 11: Initial IMO Strategy on reduction of GHG emissions from ships.* https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304(72).pdf

IMO. (2018). *MEPC 73/19/Add.1/Annex 5: 2018 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships.* https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.308(73).pdf

IMO. (2019). *IMO Action to reduce Greenhouse Gas emissions from international shipping.* https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/IMO%20ACTION%20TO%20REDUCE%20GHG%20EMISSIONS%20FROM%20INTERNATIONAL%20SHIPPING.pdf

IMO. (2021). *IMO working group agrees guidelines to support new GHG measures*. https://www.imo.org/en/MediaCentre/PressBriefings/pages/ISWG-GHG-8.aspx

IMO. (2021). *MEPC 76/15/Add.2/Annex 7: 2021 Guidelines on the method of calculation of the attained Energy Efficiency Existing Ship Index (EEXI).* https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.333(76).pdf

IMO. (2021). *MEPC 76/15/Add.2/Annex 8: 2021 Guidelines on survey and certification of the attained Energy Efficiency Existing Ship Index (EEXI).* https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.334(76).pdf

IMO. (2021). *MEPC 76/15/Add.2/Annex 9: 2021 Guidelines of the Shaft / Engine Power Limitation system to comply with the EEXI requirements and use of a power reserve.* https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.335(76).pdf

IRCLASS. (2015). *Implementing Energy Efficiency Design Index (EEDI).* https://www.irclass.org/media/1393/energy-efficiency-design-index.pdf

ITTC. (2014). *ITTC 7.5-04-01-01.2: Analysis of Speed/Power Trial Data.* https://ittc.info/media/4210/75-04-01-012.pdf

ITTC. (2017). *ITTC 7.5-04-01-01.1: Preperation, Conduct and Analysis of Speed / Power Trials.* https://www.ittc.info/media/7691/75-04-01-011.pdf

Liu, S., Papanikolaou, A., & Bolbot, V. (2016). *An improved formula for estimating the added resistance of ships in engineering applications. Journal of Marine Science and Application.* https://www.researchgate.net/publication/303880878

Liu, S., Papanikolaou, A., Bezunartea-Barrio, A., Shang, B., & Sreedharan, M. (2021). *On the effect of biofouling on the minimum propulsion power of ships for safe navigation in realistic conditions. The Journal of Bioadhesion and Biofilm Research*. https://doi.org/10.1080/08927014.2021.1890044

MAN Energy Solutions. (2021). *Everything you need for EEXI compliance.* https://www.man-es.com/services/new-service-solutions/eexi

MAN PrimeServ. (2016). *Retrofit & Upgrade MAN PrimeServ Products & Services Portfolio.* https://www.man-es.com/services/industries/marine/retrofit-upgrade

RightShip. (2020). *RIGHTSHIP ENGINE POWER LIMITATION (EPL) - ACCEPTANCE CRITERIA UPDATE.* https://www.rightship.com/resources/news/rightship-engine-power-limitation-epl-acceptance-criteria-update/

RightShip. (2021). *RightShip's GHG Rating and the EEXI / CII regulation.* https://www.rightship.com/?utm_source=google&utm_medium=ppc-sem&utm_campaign=brand&utm_content=brand

Skoufalos, P. (2012). *RightShip Apprival Clauses-The Right Idea?* https://www.steamshipmutual.com/publications/Articles/RightShip0212.htm

Technava. (2019). *MOL Techno-Trade | Mitsui PBCF.* https://www.technava.gr/company.php?id=5a93f4ecbc97d

Transport & Environment. (2017). *Statistical analysis of the energy efficiency performance (EEDI) of new ships.* https://www.transportenvironment.org/wp-content/uploads/2021/07/Statistical%20analysis%20of%20the%20energy%20efficiency%20performance%20(EEDI)%20of%20new%20ships.pdf

UNCTAD / RMT. (2018). *Review of Maritime Transport.* https://unctad.org/system/files/official-document/rmt2018_en.pdf

WHO. (2021). *Climate change and health.* https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health