**NATIONAL TECHNICAL UNIVERSITY OF ATHENS**
SCHOOL OF NAVAL ARCHITECTURE & MARINE ENGINEERING
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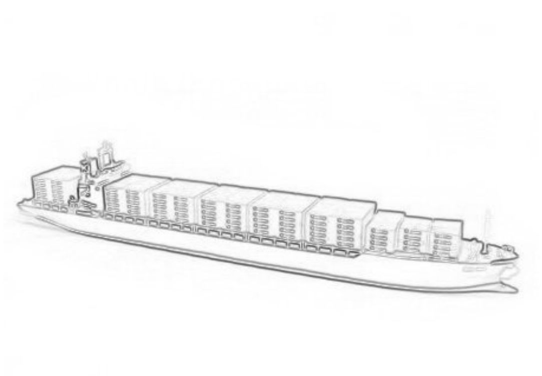

DISSERTATION
OF
NIKOLAOS C. TSEKOURAS

SUPERVISOR: Dr. J.PROUSALIDIS *Assistant Proffessor, NTUA*

ATHENS, JULY 2011

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**NIKOLAOS C. TSEKOURAS**

Naval Architect & Marine Engineer, NTUA

*I am dedicating this dissertation to my father* ***Constantinos N. Tsekouras*** *for inspiring me in studying Naval Architecture & Marine Engineering, being an example for me, for his integrity, responsibility, devotion and passion in serving Maritime as an Engineer and Ship Surveyor.*

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# Acknowledgements

*I would like to express my gratitude especially to my supervisor, Assistant Professor **John M. Prousalidis**, for his guidance on this dissertation, dissemination of his knowledge to me, support and inexhaustible patience.*

*I would like to thank Professor **Christos A. Frangopoulos** & Assistant Professor **Dimitrios V. Lyridis**, co-examiners of this dissertation, for their valuable remarks.*

*I would also like to express my gratitude to my parents **Constantinos N. Tsekouras** & **Eleni I. Alexiou** for advising me and supporting me totally during my studies and my life.*

*Finally, with great pleasure I would like to thank all those who made this thesis possible and especially **Eleni N. Gavriil** for her support, patience and understanding.*

**Nikolaos C. Tsekouras**

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# Abstract

This dissertation analyzes the proposed by the IMO (International Maritime Organization) Energy Efficiency Indices for the Design and Operation of Ships (EEDI & EEOI respectively), focusing on energy efficiency of electric power systems and the arising implementation issues of these indices.

More specifically, the issues considering the Energy Efficiency Design Index (EEDI) are: a) its limited ability to express the energy efficiency of the ship for more than one operating condition, b) the failure to produce comparable results when applied to certain ship categories (Passenger Vessels), c) it is not applicable to ships with non-conventional propulsion systems (Diesel-Electric Propulsion) and d) it produces misleading results driving practically to the design of less energy efficient ships. Additionally: e) the definition of Energy Efficiency Operation Index (EEOI) which is not precise and f) the absence of an index that reflects more accurately the benefits of: i) installing new energy efficient technologies onboard vessels, particularly for electrical power generation and ii) the implementation of optimal operating scenarios; are some of the issues seeking a solution.

Therefore, it is proposed an alternative index VENEFI (Vessel Energy Efficiency Index) for the complete operation of the vessel, as a resultant of individual indices that describe the energy efficiency in each operation mode of the vessel. Individual indices may describe more accurately the energy efficiency of the ship in every activity mode during operation and at design stage for new vessels. In addition, there are proposed specific indices of energy efficiency for the propulsion and the auxiliary power system, individually. All indices are linked through appropriate formulas, while under conditions are comparable with existing indices EEDI & EEOI.

For further investigation on VENEFI, there was developed a spreadsheet for calculating the proposed indices using data from existing ships, performing the calculations and exporting the results. Chapter 4 presents in detail the sample calculation of VENEFI on the ship "BS1", while in Annex 3 are presented additional calculations and an investigation on the effect of the use of shaft generator on VENEFI.

The results showed that through the index VENEFI is possible to investigate optimal operating scenarios and account the benefits of energy efficiency by implementing new technologies, particularly for electric power systems, while the rest of the issues considering indices implementation were resolved.

# Σύνοψη

Στο πλαίσιο της παρούσας διπλωματικής εργασίας, μελετώνται οι Δείκτες Ενεργειακής Απόδοσης, που έχουν προταθεί από τον IMO (International Maritime Organization) και αφορούν στην Σχεδίαση και Λειτουργία των Πλοίων, εστιάζοντας στην απεικόνιση της ενεργειακής απόδοσης των ηλεκτρικών συστημάτων ενέργειας και στα ζητήματα που προκύπτουν γενικότερα κατά την εφαρμογή των δεικτών αυτών.

Συγκεκριμένα για τον Δείκτη Ενεργειακής Απόδοσης που αφορά στην Σχεδίαση Νέων Πλοίων (EEDI), τα ζητήματα αφορούν: α) την περιορισμένη δυνατότητα του να εκφράσει την ενεργειακή απόδοση του πλοίου για περισσότερες από μία καταστάσεις λειτουργίας, β) την έλλειψη εξαγωγής συγκρίσιμων αποτελεσμάτων κατά την εφαρμογή του σε ορισμένες κατηγορίες πλοίων (Επιβατηγά), γ) την ακαταλληλότητα του για πλοία με μη συμβατικά συστήματα πρόωσης (Δηζελοηλεκτρική Πρόωση) και δ) την εξαγωγή πλασματικών αποτελεσμάτων που στην πράξη οδηγούν στην σχεδίαση λιγότερο ενεργειακά αποδοτικών νέων πλοίων. Επιπροσθέτως, ε) η έλλειψη σαφούς ορισμού του Δείκτη Ενεργειακής Απόδοσης για την Λειτουργία των Πλοίων (EEOI) και στ) η απουσία ενός Δείκτη που να απεικονίζει με μεγαλύτερη ακρίβεια τα ενεργειακά οφέλη από την εγκατάσταση νέων τεχνολογιών, ειδικότερα για την παραγωγή ηλεκτρικής ενέργειας, καθώς και από την εφαρμογή βέλτιστων σεναρίων λειτουργίας, είναι μερικά μόνο από τα ζητήματα που επιζητούν λύση.

Για τον λόγο αυτό, προτείνεται η εφαρμογή ενός εναλλακτικού δείκτη VENEFI (Vessel Energy Efficiency Index) για την συνολική λειτουργία του πλοίου που προκύπτει από την σύνθεση επιμέρους δεικτών που περιγράφουν την ενεργειακή απόδοση σε κάθε κατάσταση λειτουργίας. Οι επιμέρους δείκτες δύναται να περιγράψουν με μεγαλύτερη ακρίβεια την ενεργειακή απόδοση του πλοίου σε κάθε κατάσταση ξεχωριστά, τόσο κατά την λειτουργία του όσο και κατά την σχεδίαση ενός νέου πλοίου. Επιπλέον, προτείνονται επιμέρους δείκτες που αξιολογούν την ενεργειακή απόδοση του συστήματος πρόωσης και του ηλεκτρικού συστήματος

παραγωγής. Όλοι οι δείκτες συνδέονται μεταξύ τους μέσω κατάλληλων σχέσεων ενώ είναι συγκρίσιμοι υπό προϋποθέσεις και με τους υφιστάμενους δείκτες EEDI & EEOI.

Για την περεταίρω διερεύνηση, αναπτύχθηκε ένα φύλλο υπολογισμού των δεικτών και χρησιμοποιήθηκαν στοιχεία από υφιστάμενα πλοία για την πραγματοποίηση υπολογισμών και την εξαγωγή αποτελεσμάτων. Στο Κεφάλαιο 4 παρουσιάζεται αναλυτικά ο υπολογισμός του δείκτη VENEFI για το πλοίο “BS1” ενώ στο Παράρτημα 3 παρουσιάζονται επιπλέον υπολογισμοί καθώς και η διερεύνηση βέλτιστου σεναρίου συνολικής λειτουργίας με χρήση ή μη αξονικής γεννήτριας.

Τα αποτελέσματα που προέκυψαν έδειξαν ότι μέσω του δείκτη VENEFI είναι εφικτή η διερεύνηση βέλτιστων σεναρίων λειτουργίας αλλά και η διερεύνηση του μέτρου της ενεργειακής απόδοσης με την εφαρμογή μιας νέας τεχνολογίας, ειδικότερα όσον αφορά την ηλεκτρική ενέργεια, ενώ παράλληλα επιλύθηκαν και τα υπόλοιπα προαναφερθέντα ζητήματα εφαρμογής των Δεικτών.

# Contents

# Chapter 1

# Introduction

## 1.1 Introduction

The present thesis has as its main purpose to investigate the potential of auxiliary (electrical) energy systems optimization, in relation to total vessel energy efficiency optimization.

A thorough literature research has been conducted in order to determine the present progress on the development of an Energy Efficiency Index for seagoing vessels, considering especially electrical energy systems. The research revealed that an important initiative with significant progress has been undertaken by the International Maritime Organization Committee of the United Nations for the establishment of Energy Efficiency Indices considering ship Design and Operation. Focusing, especially in new ships, the Committee during its General Assemblies and Working Groups Meetings has developed an Energy Efficiency Design Index (EEDI) in order to calculate preliminary the emissions of Greenhouse Gases (GHG) that a vessel will emit during its operation. By calculating the index in existing ships that have been recently built, baseline values were established in order to urge to the direction of designing more efficient vessels. New ships will be asked to meet the EEDI requirement baselines as soon as these will be approved by the Organization, affecting, thus, the design parameters of a new vessel. In addition to that, the index intends to serve as a comparison tool between existing vessels indicating and comparing their efficiency.

However, some important issues have not yet been resolved delaying, thus, its establishment. The fact that EEDI describes: 1) only one operating condition of the vessel 2) excludes some ship type categories and 3) doubts that it will lead to the design of new less efficient ships, are some of the major drawbacks of the index.

In addition to the investigation conducted within IMO, other organizations, institutions, universities have been involved in co-operation with IMO or independently, in order to contribute to the development of these indices, propose corrections and improvements.

A second index considering vessel energy efficiency during its operation has also been proposed. However, Energy Efficiency Operation Index (EEOI) has been developed only at the extent of some general guidelines with an urge to ship operators to apply them and return feedback. EEOI seems to have not drawn the attention of other research parties as there is no significant literature research about it as it occurs with EEDI.

In addition to these indices, IMO has also developed the Marginal Abatement Cost (MAC) of implementing a new innovative technology that will reduce GHG emissions and after a period of implementation time will be proven profitable by the benefit of the fuel savings in relation with the steadily increasing fuel prices.

## 1.2 General Approach of the Dissertation

In this study, using as foundation the existing indices we have initiated our research by developing a unique Vessel Energy Efficiency Index for its Complete Operation and determining distinct operation scenarios based on vessel specific activity modes.

With further analysis of the suggested index we developed two different sub indices, suitable for investigation on a specific operation scenario basis. One of those sub indices has been appropriately developed in order under specific conditions and assumptions to match today’s EEDI, creating, thus, a link to until now development.

Renewable energy production has been taken into consideration and its contribution to the optimization of ship’s electric systems and energy production has been represented in a realistic way through the index.

Main engine’s Power-Take-Off (PTO) to the electric system of the ship through shaft generators at specific vessel operating scenarios has been examined and the benefits of these results are depicted on the index encouraging further research on more optimization scenarios.

Distinct sub indices have been introduced for Propulsion Energy and Auxiliary Energy (as part of the Vessel Efficiency Index), in order to enable focusing independently on the optimization of Electric (Auxiliary) Energy Production.

Inclusion of other categories of vessel’s excluded so far from existent indices (EEDI) has been enabled through the proposed index, as Passenger Ships and Vessels using Diesel Electric Propulsion.

All these aspects and more are presented and analyzed in detail in the following Chapters.

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# Chapter 2

# Energy Efficiency Indices for Ships

## 2.1 Energy Efficiency Design Index (EEDI)

### 2.1.1 Introduction

The International Maritime Organization (IMO) is currently developing a regulatory framework to reduce the $CO_2$ emissions from shipping. In this regard, the Marine Environment Protection Committee (MEPC) of IMO, during its 59th session (13 to 17 July 2009), suggested the development of an energy efficiency design index (EEDI) for new ships in order to intrigue technical development and innovation to all parameters affecting the energy efficiency of a ship from its design phase. The MEPC meetings that followed resulted in a formulation of the index which seems satisfactory for conventional vessels larger than 20,000 mt DWT, whilst for smaller and specialized vessels the Committee's 60th meeting concluded that further research is necessary in order to develop an appropriate indexing system.

### 2.1.2 Definition of Energy Efficiency Design Index (EEDI)

The calculation of the Energy Efficiency Design Index (EEDI) of a ship is based merely on ship's design data and it represents $CO_2$ emissions of that particular ship at a single design point and not for its complete operation and other loading profiles. The units EEDI is expressed are grammes of $CO_2$ per tonne of carrying weight per nautical mile ($gCO_2/t{\cdot}nm$).

The Committee has defined two EEDI indices for a ship, both based on the same calculation formula slightly modified for each index. These are the attained Energy Efficiency Design Index ($EEDI_A$) and the required or baseline Energy Efficiency Design Index ($EEDI_{BL}$).

## 2.1.3 Attained Energy Efficiency Design Index ($EEDI_A$)

The attained new ship Energy Efficiency Design Index ($EEDI_A$) is calculated by the following formula:

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

*(2.1)*

Where:

**P (Main Propulsion or Auxiliary Power)**

P is the power of the main or auxiliary engines, measured in kilowatts (kW). The subscripts $_{ME}$ and $_{AE}$ refer to the main and auxiliary engines, respectively. The summation on (i) is for all main engines with the number of engines (nME).

**$P_{ME(i)}$ (Power of Main Engine i)**

$P_{ME(i)}$ is determined as 75% of the rated installed power[1] (MCR) for each main engine (i) after having deducted any power flow to installed shaft generators. The power of the main engine (i) provided for propulsion is given by the formula:

$$P_{ME(i)} = 0.75\cdot\left(MCR_{ME(i)} - P_{PTO(i)}\right) \qquad (2.2)$$

---

[1] The 0.75 factor (75% of MCR) is used to define the required propulsion power for the ship in order to achieve its service speed. The 25% of MCR power availability is justified by considering a power reserve of 15% of MCR due to rough weather conditions and another 10% of MCR power increase due to transmission system power losses.

$MCR_{ME(i)}$ = is the Maximum Continuous Rating of the engine i.

$P_{PTO(i)}$= is 75% power of each shaft generator installed divided by the relevant efficiency of that shaft generator.

### $P_{AE}$ (Power of Auxiliary Engines)

$P_{AE}$ is the required auxiliary engine power to supply normal maximum sea load including necessary power for propulsion machinery systems and accommodation, in design loading condition of Capacity at $V_{ref}$ speed. The power which is not for propulsion is excluded (e.g. thrusters, cargo pumps, cargo gear, ballast pumps). The most accurate way to estimate $P_{AE}$ is by the electric load analysis of the ship. However, if there are no available data to calculate $P_{AE}$, the IMO suggests two formulas for estimating $P_{AE}$ in relation with the installed main engine power of the ship:

- For cargo ships with a total main engine power of 10,000kW or above, $P_{AE}$ is defined as:

$$P_{AE(MCR_{ME})>10000kW)} = \left(0.025 \cdot \sum_{i=1}^{nME} MCR_{ME(i)}\right) + 250 \qquad (2.3)$$

- For cargo ships with a total main engine power of less than 10000kW, $P_{AE}$ is defined as:

$$P_{AE(MCR_{ME}<10000kW]} = 0.05 \cdot \sum_{i=1}^{nME} MCR_{ME(i)} \qquad (2.4)$$

### $P_{PTI(i)}$ (Power-Take-In For Main Propulsion)

$P_{PTI(i)}$ (Power-Take-In) is the power provided to the propulsion shaft by an auxiliary motor (e.g. a shaft generator operating reverse as a booster engine). The value of $P_{PTI(i)}$ is considered 75% of the rated power consumption of each shaft motor divided by the weighted averaged efficiency of the generator or generator(s). In case the ship is using combined PTI/PTO mode the normal operation mode at sea will determine which of these will be used in the calculation.

### $\mathbf{P_{eff(i)}}$

$P_{eff(i)}$ is 75% of the main engine power reduction (kW) due to innovative[2] mechanical energy efficient technology.

### $\mathbf{P_{AEeff(i)}}$

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

### $\mathbf{C_F}$ ($\mathbf{CO_2}$ Emission Factor)

$C_F$ is a conversion factor between consumed fuel and emitted $CO_2$ based on the carbon content of the specific fuel type. They are both measured in the same mass unit (e.g. grammes). Subscripts $_{ME(i)}$ and $_{AE(i)}$ refer to main and auxiliary engines, respectively. The value of $C_F$ factor is provided by Table 2.1 according to the type of fuel:

| | **Type of Fuel** | **Reference** | **Carbon Mass Content** | $\mathbf{C_F}$ **($\mathbf{gCO_2/gF}$)** |
|---|---|---|---|---|
| 1. | Diesel / Gas Oil | ISO 8217 Grades DMX through DMC | 87.5% | 3.206000 |
| 2. | Light Fuel Oil (LFO) | ISO 8217 Grades RMA through RMD | 86.0% | 3.151040 |
| 3. | Heavy Fuel Oil (HFO) | ISO 8217 Grades RME through RMK | 85.0% | 3.114400 |
| 4a. | Liquefied Petroleum Gas (LPG) | Propane | 81.9% | 3.000000 |
| 4b. | Liquefied Petroleum Gas (LPG) | Butane | 82.7% | 3.030000 |
| 5. | Liquefied Natural Gas (LNG) | -- | 75.0% | 2.750000 |

*Table 2.1 Table of $C_F$ values*[3].

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[2] By the term “innovative technology”, is characterized any applied technology that will further reduce fuel consumption. Some of these (ex. Wind Kite) are mentioned at the IMO MEPC 61/INF18, Reduction of GHG Emissions From Ships – Marginal Abatement Costs & Cost-effectiveness of Energy Efficiency Measures, p.13, Table 2-1

## SFC (Specific Fuel Consumption)

SFC is the specific fuel oil consumption of the engine (also abbreviated as SFOC), measured in g/kWh. Subscripts $_{ME(i)}$ and $_{AE(i)}$ refer to main and auxiliary engines respectively. The value of SFC used for the calculation of $EEDI_A$ should be the one recorded on the Engine International Air Pollution Prevention (EIAPP) Certificate[4] at engine's 75% of MCR or torque rating for engines certified for the E2 or E3 duty cycles[5] of the NOx Technical Code 2008 and at 50% MCR or torque rating for D2 or C1 duty cycles.

For vessels where $P_{AE}$ is calculated by the suggested formulas and the value is significantly different from the total power used at normal seagoing, the value of $SFC_{AE}$ of the auxiliary generators is the weighted average among $SFC_{AE(i)}$ of the respective engines i, where $SFC_{AE(i)}$ is the recorded value on the Engine International Air Pollution Prevention (EIAPP) Certificate at generator's engine loading at 75% of MCR or torque rating.

In case of engines with no EIAPP issued certificate, which is due to the fact that their nominal power below 130kW, the SFC used for the calculation is the one specified by the manufacturer and authorities.

## Capacity

Capacity is defined according to the type of ship. For Dry Cargo Carriers, Tankers, Gas Tankers, Ro-Ro Cargo and General Cargo vessels, deadweight (DWT) is used as "Capacity".

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[3] IMO MEPC.1/Circ.681, Interim Guidelines On The Method Of Calculation Of The Energy Efficiency Design Index For New Ships, 17 August 2009, ANNEX, p.2

[4] Detailed information about the Engine International Air Pollution Prevention (EIAPP) is available at IMO MEPC Resolution MEPC.177/(58)/23/Add.1 Annex 14 [NOx Technical Code 2008], Chapter 2, p.13-19.

[5] Detailed information about duty (test) cycles of engine is available at IMO MEPC Resolution MEPC.177/(58)/23/Add.1 Annex 14 [NOx Technical Code 2008], Chapter 3, p.20-22.

For Passenger and Ro-Ro / Passenger ships, gross tonnage[6] (GRT) should be used as “Capacity”.

For Containerships the capacity parameter should be established at 65% of the deadweight (DWT).

### $V_{ref}$ (Reference Speed)

$V_{ref}$ is the ship’s speed measured in nautical miles per hour (knots), at the maximum design load condition[7] (Capacity) on deep water and assuming the weather is calm with no winds and no waves.

### Non-dimensional Factors of EEDI Calculation Formula

The remaining factors of the calculation formula are:

$f_j$ = non-dimensional correction factor to account for ship specific design elements[8].

$f_w$ = non-dimensional coefficient indicating the decrease of speed in representative sea conditions of wave height, wave frequency and wind speed[9].

$f_{eff(i)}$ = availability factor of each innovative energy efficiency technology.

$f_i$ = non-dimensional correction factor to account for ship specific design elements[10].

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[6] Gross Tonnage as defined by the International Convention of Tonnage Measurement of Ships 1969 (ITTC 69) Annex I, Regulation 3.

[7] The maximum design load condition shall be defined by the deepest draught with the associated trim at which the ship is allowed to operate and it is provided by the stability booklet approved by the Administration.

[8] Detailed definition of the $f_j$ factor can be found at IMO MEPC.1/Circ.681 Annex Interim Guidelines On The Method Of Calculation Of The Energy Efficiency Design Index For New Ships, p.5

[9] Detailed definition of the $f_w$ factor can be found at IMO MEPC.1/Circ.681 Annex Interim Guidelines On The Method Of Calculation Of The Energy Efficiency Design Index For New Ships, p.6

[10] Detailed definition of the $f_i$ factor can be found at IMO MEPC.1/Circ.681 Annex Interim Guidelines On The Method Of Calculation Of The Energy Efficiency Design Index For New Ships, p.6-7

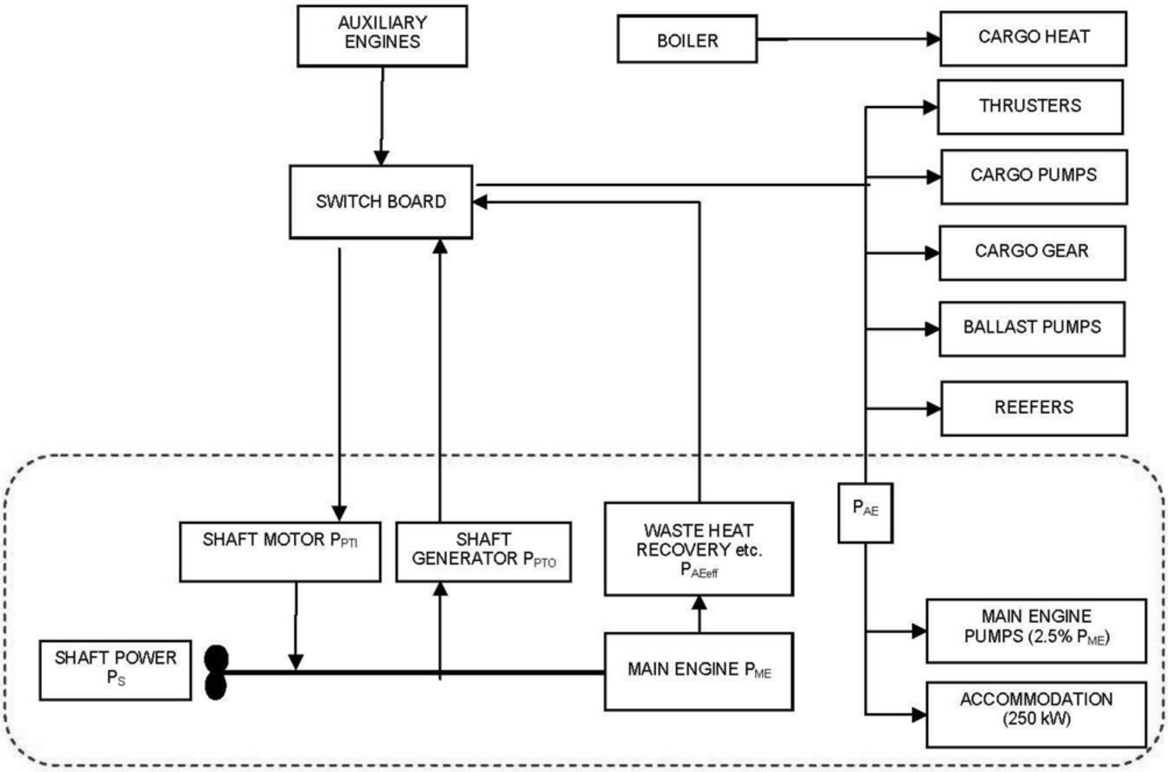

*Figure 2.1 Schematic representation of the calculation items for EEDI*[11]

## 2.1.4 Baseline Energy Efficiency Design Index ($EEDI_{BL}$)

The need of a baseline emissions value, in order to compare whether a ship is designed efficiently in comparison with an average baseline value, was attempted by the IMO MEPC with the introduction of an index called Baseline Energy Efficiency Design Index ($EEDI_{BL}$).

Based on the formula of the attained index ($EEDI_A$), IMO MEPC made assumptions on some of the factors affecting $EEDI_A$ calculation, producing a modified formula named “Average Index Value”. Applying the calculation formula on a wide range of ships-in-service of the same type, resulted in a scattered X-Y graph of emissions ($gCO_2/t{\cdot}nm$) to Capacity (DWT) marks, for each ship category. The values of the

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[11] Figure Source: IMO MEPC.1/Circ.681 Annex Interim Guidelines On The Method Of Calculation Of The Energy Efficiency Design Index For New Ships, p.8

graph are used as the basis for calculating an exponential regression line which expresses the baseline value.

### 2.1.4.1 Calculation of Baseline EEDI

The assumptions on the formula of $EEDI_A$ in order to calculate the “Average Index Value” are:

- Carbon emission factor ($C_F$) for all engines is constant $C_F=3.13$ $gCO_2/gF$
- Specific Fuel Consumption for all ship types is constant for main engines $SFC_{ME}=190g/kWh$ and for auxiliary engines $SFC_{AE}=210g/kWh$
- $P_{ME(i)} = 0.75 \cdot MCR_{ME(i)}$
- None of the ship use innovative energy efficient technology $P_{eff}=0$ or waste heat recovery system $P_{WHR}=0$
- None of the ships uses diesel-electric propulsion from auxiliary engines $P_{PTI}=0$
- All correction factors are set to 1 $f_j = f_i = f_w = 1$
- $P_{AE}$ is calculated only by the estimating formulas defined at the $EEDI_A$ calculation:

$$P_{AE(MCR_{ME}>10000kW)} = \left(0.025 \cdot \sum_{i=1}^{nME} MCR_{ME(i)}\right) + 250 \qquad (2.3)$$

$$P_{AE(MCR_{ME}<10000kW)} = 0.05 \cdot \sum_{i=1}^{nME} MCR_{ME(i)} \qquad (2.4)$$

The equation for calculating the Average Index Value is the following:

$$Average\,Index\,Value = 3.13 \cdot \frac{190 \cdot \sum_{i=1}^{nME}\left(0.75 \cdot MCR_{ME(i)}\right) + 210 \cdot P_{AE}}{Capacity \cdot V_{ref}} \qquad (2.5)$$

Applying the equation of Average Index Value on each ship from a representative selection group of ships from the same category, over a wide range of capacity, the graph in Figure 2.2 is showing the calculation results and the produced regression line:

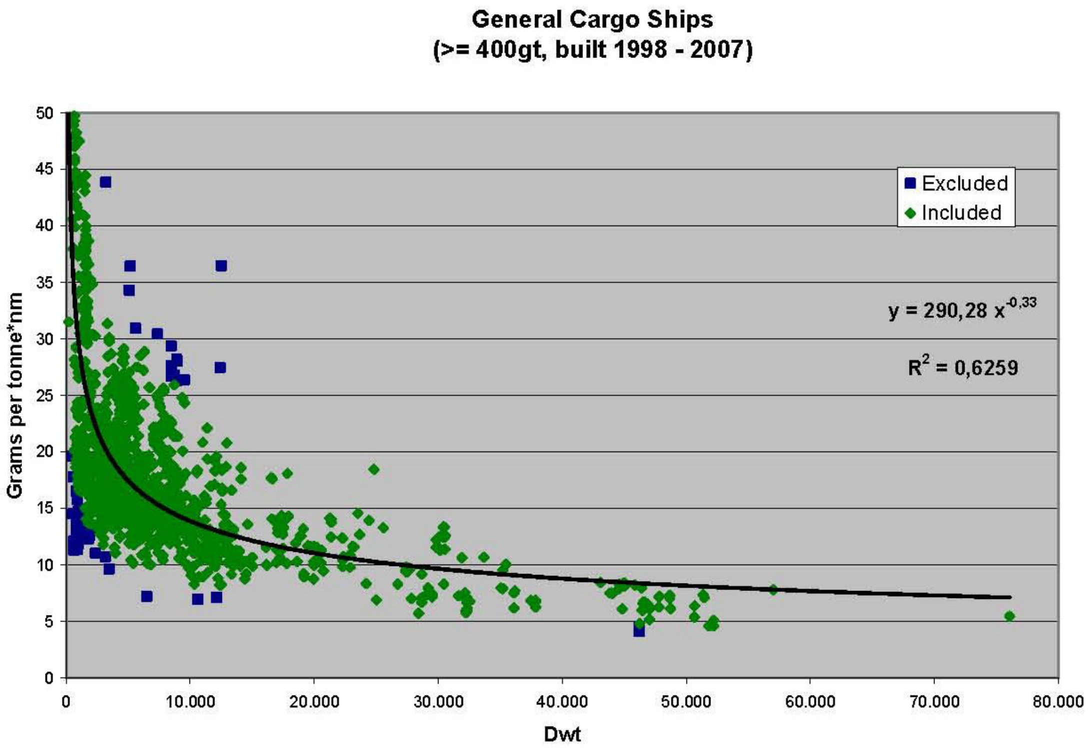

*Figure 2.2 General Cargo Ships Regression Line Graph*[12]

The mathematical calculation of the regression line for every ship category is given by the equation[13]:

$$BaseleineValue = a \cdot Capacity^{-c} \qquad (2.6)$$

The calculation equations of the Baseline Value for six (6) different ships categories are presented in the following table.

| Ship Type | a | Capacity | c | Samples | Excluded |
|---|---|---|---|---|---|
| Dry Bulk Carriers | 1354.00 | DWT | 0.5117 | 2365 | 59 |
| Tankers | 1950.70 | DWT | 0.5337 | 3116 | 59 |
| Gas Carriers | 1252.60 | DWT | 0.4597 | 416 | 11 |
| Container Ships | 139.38 | DWT | 0.2166 | 2189 | 87 |
| General Cargo Ships | 290.28 | DWT | 0.3300 | 1824 | 90 |
| Ro-Ro Cargo Ships | 19788.00 | DWT | 0.7137 | 402 | 27 |

*Table 2.2 Baseline Value Calculation – Parameters Values per Ship Category*[14]

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[12] Figure Source: IMO MEPC GHG-WG 2/2/7 Annex 1, Recalculation Of Energy Efficiency Design Index Baselines For Cargo Ships, 4 February 2009, p.4

[13] IMO MEPC GHG-WG 2/2/7, Consideration Of The Energy Efficiency Design Index For New Ships, 4 February 2009, p.3

[14] IMO MEPC GHG-WG 2/2/7, Consideration Of The Energy Efficiency Design Index For New Ships, 4 February 2009, p.3

Consulting Table 2.2, the baseline $EEDI_{BL}$ for a specific ship is calculated by equation 2.6 where the capacity of the vessel is known and the values for parameters a & c are obtained from 2.2 according to the category the ship.

The Energy Efficiency Design Index Baselines ($EEDI_{BL}$) can be recalculated over time for every category by modifying (increasing) the numbers of the ships and/or re-determining the period within the ships of the sample were built, excluding, thus, older ships and replacing them with newer in the sample[15]. Moreover, calculating both $EEDI_A$ and $EEDI_{BL}$ for a specific vessel and comparing the two indices, there can be a comparison of how efficient is the specific vessel in relation with other vessels of the same category.

## 2.2 Energy Efficiency Operation Index (EEOI)

### 2.2.1 Introduction

The establishment of an Energy Efficiency Design Index (EEDI) is an action to the right direction considering the effort on reducing emissions from marine industry; however this index is not designed to accurately account the GHG emissions of a ship during its lifetime operation. The real emissions produced by a vessel might be quite different from those that EEDI indicates. This fact, urged the Marine Environment Protection Committee (MEPC) of International Maritime Organization (IMO) to identify and develop the mechanism or mechanisms needed to achieve the limitation or reduction of Greenhouse Gas (GHG) emissions from international shipping and, in doing so, to give priority to the establishment of a GHG baseline; and the development of a methodology to describe the GHG efficiency of a ship in terms of GHG emission indicator for that ship during its operation.

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[15] IMO MEPC GHG-WG 2/2/7 Annex 2, Recalculation Of Energy Efficiency Design Index Baselines For Cargo Ships, 4 February 2009, p.1

## 2.2.2 Definition of Energy Efficiency Operation Index

In its most simple form the Energy Efficient Operation Index or alternatively expressed as the Carbon Dioxide Transport Efficiency Index is defined as the ratio of mass of $CO_2$ per unit of transport work:

$$EEOI = \frac{mCO_2}{transport\ work} \qquad (2.7)$$

### 2.2.2.1 Single Voyage EEOI

The formula of EEOI for the time period of a specific voyage is defined as:

$$EEOI = \frac{\sum_j FC_j \cdot C_{Fj}}{m_{cargo} \cdot D} \qquad (2.8)$$

$FC_j$ = is the mass of consumed fuel type j at the voyage.

$C_{Fj}$ = is the fuel mass to $CO_2$ mass conversion factor for fuel j.

$m_{cargo}$ = is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships.

D = is the distance in nautical miles corresponding to the cargo carried or work done.

### 2.2.2.2 Average EEOI

Equation 2.8 expresses the index of a specific voyage. An average operation index based on the previous formula can be more of interest. Considering a number of voyages n where i = (1,n) the Average Energy Efficiency Operation Index will be:

$$Average\,EEOI = \frac{\sum_i \sum_j (FC_j \cdot C_{Fj})}{\sum_i (m_{\text{cargo},i} \cdot D_i)} \qquad (2.9)$$

#### 2.2.2.3 Rolling Average of EEOI

A rolling average of EEOI can be even more useful in order to compare the operation indices of vessels, when a suitable time of period is selected. For example it can be one year closest to the end of a voyage for that period, or a specific number of voyages, which are agreed as statistically relevant to the initial averaging period. The EEOI will be calculated by the Equation 2.9.

## 2.3 EEDI and Diesel Electric Propulsion

### 2.3.1 Introduction

During the MEPC 60 meeting discussion about EEDI framework, ships with diesel electric propulsion systems were excluded from the index. The reason for this exclusion is that the EEDI formula is based on the installed propulsion power, which cannot be determined in a straightforward way for diesel electric propulsion systems. The generator sets are designed to provide power to a number of applications with varying demand of electric power, including the vessel main propulsors. Thus, the power of these generators may not be considered as equivalent to the main engine power in the calculation of the EEDI. The MEPC 59 has agreed on selecting a limited number of ship types for which the EEDI framework will be further developed. However, within this selection some ships like tankers, Ro-Ro carriers and container ships may be equipped with diesel electric propulsion systems. If these ships have to be included in the framework, a solution has to be found for determination of the equivalent of installed power. In this section, a proposal will be discussed on how to calculate the EEDI for these ships.

Diesel electric propulsion systems are applied on vessels of various ship types and the most common application of these systems is on vessels with special operational profiles (ex. large passenger ships). These vessels are characterized by a very high demand of electrical power for their primary functions, which is variable in time. Passenger vessels are not yet included in the EEDI framework. A recent trend is to apply diesel electric configurations to cargo carrying vessel like tankers.

Considering the fact that the application of the current EEDI formula will be applied to a limited group of ship categories (bulk carriers, tankers, container vessels and ro-ro carriers), the study of CMTI (Centrum Maritieme Technologie en Innovativie)[16] describes a method of how to derive a EEDI value for the diesel electric vessels in these categories. The two initial points for developing this method are:

- The EEDI formula should not be changed.
- Comparison with conventional propelled ships should be feasible.

## 2.3.2 Simplified Diesel Electric System

To explain the proposed method of CMTI, a short description of a diesel electric propulsion plant is given.

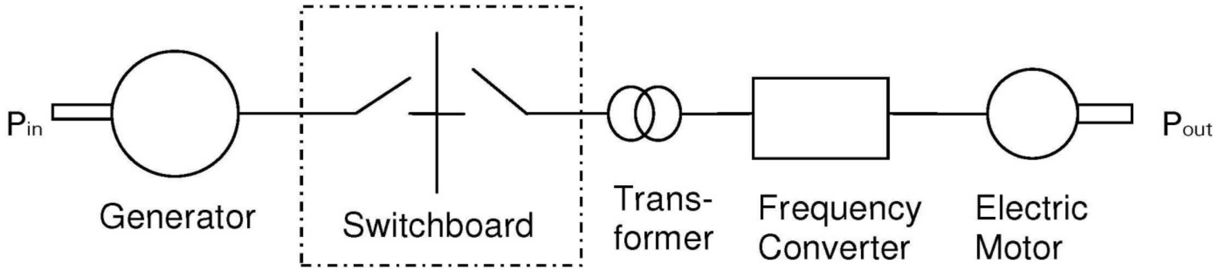

*Figure 2.3 Diesel Electric Propulsion Plant Scheme*[17]

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[16] CMTI (Centrum Maritieme Technologie en Innovativie), Energy efficiency of small ships and non conventional propelled ships, Report No.3075 Study 2010, p.27-32

[17] Figure Source: CMTI (Centrum Maritieme Technologie en Innovativie), Energy efficiency of small ships and non conventional propelled ships, Report No.3075 Study 2010, p.28

Except for the prime movers, a simplified diesel electric propulsion plant, excluding the prime movers, consists of the components presented in Figure 2.3.

The prime movers (e.g. diesel engines or gas turbines) supply power to the electric generator shaft. The electric motor, which could be the propulsion motor, is loaded by a power from its connected load. The power lost in the components between the shaft of the diesel engine and the shaft of the electric motor is composed of mechanical and electrical losses which result in heat and temperature increase in equipment and ambient area. The electrical efficiency of the system will be:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{losses}} \qquad (2.10)$$

The electrical efficiency of each component can be calculated and the typical values at full rated power are presented at the following table:

| **Component** | **η** |
|---|---|
| Generator | 0.95 - 0.97 |
| Switchboard | 0.999 |
| Transformer | 0.99 - 0.995 |
| Frequency Converter | 0.98 - 0.99 |
| Electric Motor | 0.95 - 0.97 |

*Table 2.3 Diesel Electric Propulsion System Components Efficiency*

Inspecting Table 2.3, the efficiency of a diesel electric system, from diesel engine shaft, to electric propulsion motor shaft, is between 0.875 and 0.926 at full load. The variation on the efficiency depends on the loading of the system.

The additional components between the prime mover and the propeller shaft in a diesel electric propulsion system contributes to a total of approximately 10% losses. According to the study the fuel savings potential might not be feasible due to these power losses. Also, it is suggested to be investigated a) how the hydrodynamic efficiency of a fixed pitch propeller (FPP) compared to a controllable pitch propeller

(CPP) should be regarded and b) the fuel efficiency of the prime mover when installed in a diesel electric system with constant speed and high loading, compared to the fuel efficiency of a mechanical propulsion system with varying load. These differences may be significant, especially on low thrust, e.g. during maneuvering.

## 2.3.3 CMTI Proposal for Calculating EEDI at Diesel Electric Ships

The calculation is conducted using the Equation 2.1:

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

The fundamental approach in this method is to calculate 75% of the "equivalent" installed power, as deducted from the power at the propeller shaft, required to achieve the reference speed in the maximum load condition. The "equivalent" installed power is, in general, a part of the real installed power, and is calculated as follows:

$P_{elecmax}$ = Installed electric propulsion power

$P_{elec}$ = 75% of $P_{elecmax}$

$f_{elec}$ = loss of diesel engine power to electric motor shaft power

$$\eta=\frac{P_{out}}{P_{in}}=\frac{P_{out}}{P_{out}+P_{losses}}=\frac{1}{f_{elec}} \qquad (2.11)$$

$f_{elec}$ is set by the study somewhere between 1.10 and 1.20

Now the equivalent installed main engine power is calculated by the formula:

$$P_{ME(i)}=f_{elec}\cdot P_{elec} \qquad (2.12)$$

$MCR_{ME(i)}$ = the theoretic maximum continuous rating for main engines = $P_{ME(i)} / 0.75$

The auxiliary power will be calculated by equations 2.3 or 2.4 depending on the theoretic installed $MCR_{ME}$ of the vessel.

$$P_{AE(MCR_{ME}>10000kW)} = \left(0.025 \cdot \sum_{i=1}^{nME} MCR_{ME(i)}\right) + 250 \qquad (2.3)$$

$$P_{AE(MCR_{ME}<10000kW)} = 0.05 \cdot \sum_{i=1}^{nME} MCR_{ME(i)} \qquad (2.4]$$

To verify the proposed new method, the study conducts calculations for a number of diesel electric ships. A number of diesel electric tankers have been compared with tankers of the same size, equipped with mechanical propulsion systems. Both groups of vessels were part of the same fleet of a chemical tanker operator. An exact value for $f_{elec}$ was not available; hence, an average value from the literature equal to 1.15 was assumed.

The study concludes on commenting on the results and more specifically that with elimination of the electrical efficiency factor, the EEDI values for individual ships of both groups as well as the trend lines are very close. Also, states that the diesel electric ships seem to be less efficient than the mechanical propelled ships and the amount of reduction of efficiency is directly in line with the factor $f_{elec}$. In this case, the diesel electrics ships are about 15% less efficient than their mechanical propelled versions. However, this is suggesting the development of a verification procedure for the electrical efficiency factor.

# Chapter 3

# Vessel Energy Efficiency Index Proposal

## 3.1. Introduction

In Chapter 2, it is thoroughly examined and analyzed the existing efficiency indices of shipping GHG emissions. The Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operation Index (EEOI) proposed by the International Maritime Organization (IMO) are focused on developing a regulatory framework to reduce the $CO_2$ emissions from shipping. In addition to these indices, IMO has developed the Marginal Abatement Cost (MAC) of implementing a new innovative technology that will reduce GHG emissions and after a period of implementation time will be proven profitable by the benefit of the fuel savings in relation with the steadily increasing fuel prices.

This regulatory framework however is still in the process of early development and there is only an urge to shipping community to voluntarily adopt some of the abatement measures. In addition to that the process and the parameters of EEDI calculation are still under discussion and the precision of the calculated emissions are still questionable. This phenomenon is more intense when EEOI is to be calculated for which only some general guidelines are proposed. A more accurate calculation of vessel real-time operation index, which would be uniformly applied and easily verified by the authorities, seems to be needed. The development of an index like that and the establishment of a GHG exchange market for shipping industry emissions will increase competitiveness, decrease drastically GHG emissions and lead to a major reformation of the world fleet, as it is known till nowadays.

The proposed Vessel Energy Efficiency Index (VENEFI[18]) will take into account

existing indices in an effort to combine them and evolve them to the direction of creating a unified index for use with every ship at both design stage and operation.

The issues the proposed index is striving to solve are the following:

- Comparisons between vessels of the same or different categories will be feasible.
- Vessels with Diesel Electric Propulsion and Large Passenger ships will be included in the framework of the index.
- Ad-hoc analysis on a specific route considering transport demand will enable comparison and optimum selection of the most suitable energy efficient vessel.
- The accuracy of the index could be set by determining calculation assumptions. Thus, it can be used either as a comparison or baseline rule or an optimization tool (ex. from shipping companies or vessel operators).
- Introduction of the benefits of renewable forms of energy production.
- More precise modeling of energy flows in order to depict optimization benefits.

The key features of the new proposed index are:

- Categorization of the produced energy for the vessel needs in two major categories according to energy final use, Propulsion Energy (PE) and Auxiliary Energy (AE) as existing indices do. However, the Auxiliary Energy category will include the total of auxiliary energy and not part of it as EEDI suggested.
- Introduction of efficiency coefficients for energy production and distribution.
- Particular indices for Propulsion Energy and Auxiliary Energy efficiency as also for each power plant, applied on each part of produced energy

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[18] The proposed name of the index will be the acronym VENEFI from the phrase **V**essel's **En**ergy **Ef**ficiency **I**ndex. Moreover, in Latin the word "venefi-cium" means "poisoning". As the index will express the mass of GHG [$CO_2$] emissions per transport work, a vessel with a higher VENEFI will emit more GHG per transport work justifying, thus, the name of the index.

considering the final use of this part either as PE or AE and all intermediate energy transformation efficiency from production to consumption.

- Distinction of the index in complete operation index calculated over a predefined period of time and single operation scenario index which will be a part of the complete index focusing on a specific operation scenario.
- The single operation scenario index can replace EEDI in a case study approach and yet be in complete uniformity with the operation index.

## 3.2 Definition of Proposed Vessel Energy Efficiency Index

In this section, a generic definition of Vessel Energy Efficiency Index considering the Complete Operation of the vessel (VENEFI or $VENEFI_{CO}$) is given as the starting point of the index development, which will follow in the next paragraphs.

The index will be calculated over a predefined period of time (T) and will express the total of the vessel $CO_2$ emissions per its productivity. Productivity definition can vary for each type of ship, however, it can be defined, in general, as the product of carried units and distance.

A generic expression of the index will be[19]:

$$Vessel\ Energy\ Efficiency\ Index\ (T) = \frac{Mass\ of\ CO_2\ Total\ Emissions}{Carried\ Units \cdot Distance}$$

*(3.1)*

The units used will be grammes (g) for the mass of $CO_2$ emissions, nautical miles (nm) for distance and metric tons (t) for the carried units[20]. ($gCO_2/t{\cdot}nm$).

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[19] This definition of the index is in accordance with IMO proposed guidelines for the EEOI. IMO MEPC.1/Circ.684 Guidelines For Voluntary Use Of The Ship Energy Efficiency Operational Indicator (EEOI), 17 August 2009

[20] Correlation of carried units for Passenger Ships & Cruise Vessels is presented in Chapter 4.

### 3.2.1 Determination of Calculation Time Period (T)

The period of time accounted for the calculation of the index should be a predefined continuous time period (T), at which the ship is operating normally. From that period there will be excluded time for drydocking or accidents, which cannot be considered as vessel normal operation. For instance:

- **A single trip period.** This period is starting at departure time from port A and ending at departure time from port B (in order to include the time vessel spends at port B). This option seems more appropriate for vessels on the spot market with variable routes according to their freight.

- **A round trip period.** This period starting at departure time from home port and ending at departure time from home port again after a round trip. This approach can include multi leg trips during a round trip and can be best applied to liners which have a standard route schedule (e.g. Passenger Ferries & Ro-Ro Carriers).

- **A custom period of time.** This can be a 24 hour period, a week period, a month or even a year period. In general, any period between two different custom time marks can be used, for example the period between two consecutive drydockings of the vessel[21].

### 3.2.2 Vessel Activity Modes (VAM)

Within the predefined period of time the vessel operates in different modes with different power demands. The description of a vessel movement can be determined taking into consideration the suggestion of (ICF & U.S. Environmental Protection

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[21] As proposed by IMO EEOI Proposal. IMO MEPC.1/Circ.684 Guidelines For Voluntary Use Of The Ship Energy Efficiency Operational Indicator (EEOI), 17 August 2009

Agency 2006)[22]. According to the report, the vessel movements are described by four different distinct modes, each one of them associated with a speed and, therefore, an engine load that has unique emission characteristics. The four modes referred as Vessel Activity Modes (VAM) are:

1. **Cruise Mode ($t_1$)**

The vessel is moving at service speed (also called sea speed or normal cruising speed), which is usually considered to be equal to 94 percent of the vessel maximum speed. Service speed is achieved when main propulsion engines are loaded at about 83 percent of their maximum continuous rating (MCR). Cruise speed mode is applied, when vessel is out of port boundary, a waterway or a Reduced Speed Zone.

2. **Reduced Speed Mode ($t_2$)**

The vessel is moving at a speed less than cruise speed and greater than maneuvering speed. This is a maximum safe speed the vessel uses to traverse distances within a waterway leading to a port. Some ports are instituting Reduced Speed Zones (RSZs), to reduce emissions from oceangoing vessels as they enter their port.

3. **Manoeuvre Mode ($t_3$)**

The vessel is moving at a speed spectrum with even slower speeds than reduced speed as described above, as it reaches its dock, pier, wharf or anchorage. The Manoeuvre Mode, occurs when the vessel is within port boundaries or an inland waterway. In case the vessel is assisted by tug boats, the propulsion engines are still in operation, thus, this scenario is also

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[22] ICF Consulting, *Current Methodologies and Best Practices in Preparing Port Emission Inventories*, Report, prepared for U.S. Environmental Protection Agency, January 2006, p.16-17. Available at http://www.nescaum.org/documents/northeast-clean-ports-workshop/ports-workshop-documents/preparing-port-emission-inventories-final-1-5-06.pdf

characterized as Manoeuvre Mode. In addition, Passenger / Ro-Ro Carriers that perform short time approaches to ports to embark and disembark passengers and vehicles, are also considered that they do not terminate the operation of their main engines, so the time period for that action is considered as Manoeuvre Mode and not as Port Time Mode, which will be described at the next mark.

4. **Port Time Mode ($t_4$)**

Port Time Mode is the Activity Mode applied at the time the vessel spends at dock, pier, wharf or anchorage when the vessel is operating auxiliary engines only or is cold ironing. Auxiliary engines are operating at partial load conditions while the entire time the vessel is manned, but peak loads will occur after the shutdown of propulsion engines. The auxiliary engines are then committed for all onboard power or/and are used to power off-loading equipment.

Cold ironing uses shore power to provide electricity to the ship instead of using the auxiliary engines. Port mode is further divided into cold ironing and active mode to accurately account for reduced emissions from cold ironing. Port times can also be determined from pilot records of vessel arrival and departure times when other data is not available.

### 3.2.3 Power Production Operation Scenarios (PPOS)

In the process of determining the emissions of a vessel, the described Vessel Activity Modes (VAM) offers the basis on which Power Production Operation Scenarios (PPOS) will be designed.

A Power Production Operation Scenario (PPOS) is the complete operation description of all power production plants and power import (ex. Cold Ironing), if any, at a specific time. This description consists of the power each power plant produces, the emissions produced as a side effect of this production and the flow of the produced energy described by the respective efficiency factors.

Considering the proposed index, the main principle is that a Vessel Activity Mode (VAM) power demand can be fulfilled at least by one Power Production Operation Scenario (PPOS) or alternatives which each one of them corresponds to the power demands of that mode. As an example, considering the fourth Vessel Activity Mode (VAM) "Port Time Mode" which describes the power demand of the vessel during docking, the required power can be provided by two different Power Production Operation Scenarios (PPOS) either with energy produced by vessel auxiliary engines or through cold ironing using shore connection.

While Vessel Activity Modes (VAM) and Power Production Operation Scenarios (PPOS) can be infinite, for the definition of the proposed efficiency index and for most vessels, especially conventional ones, the hypothesis made that for each Vessel Activity Mode (VAM) there is only one Power Production Operation Scenario (PPOS) and the adoption of the four (4) basic Vessel Activity Modes seems adequate for calculating with greater precision vessel emissions in the proposed index.

### 3.2.4 Correlation of Vessel Activity Modes and Index Calculation Time Period (T)

The summation of the total time that the vessel operates at each Activity Mode (always considering the one to one relation with the Power Production Operation Scenario) should be equal with the predefined period of time (T) and is described by the following formula:

$$\sum_{i=1}^{n} t_i = T \qquad (3.2)$$

where:

i = the activity mode (i)

n = the total number of Vessel Activity Modes

$t_i$ = the total time (summation) of operation at activity mode (i) during period T

T = the predefined period of time for vessel operation. This period must be continuous.

Considering that vessel operation can be described only by the four (4) activity modes described above, a definition of the respective time periods follows:

$t_1$ = is the total time that the vessel is at Cruise Mode during predefined period (T).

$t_2$ = is the total time that the vessel operates at Reduced Speed Mode during predefined period (T).

$t_3$ = is the total time that the vessel operates at Maneuver Mode during predefined period (T). This can be divided in two subcategories 3a & 3b to indicate maneuvering mode in port where main engines are loaded at almost 50% of MCR and maneuvering mode with ship's main engines at 10%-20% MCR (dead slow) during loading/unloading or tug towing of the ship.

$t_4$ = is the total time that the vessel operates at Port Time Mode during predefined period (T).

The following equation describes the relation of the predefined period of time (T) with the time that each Activity Mode is active:

$$\sum_{i=1}^{n=4} t_i = T \Rightarrow t_1 + t_2 + t_3 + t_4 = T \qquad (3.3)$$

Many variables affect one or more calculations on the time. These variables cannot be accurately predicted for a single vessel or a ship-type category over a period of time (T) that is very long (e.g. an entire year). Traffic conditions, weather, vessel schedule, and sea currents are some of the most important variables that dictate how much time is required at each activity mode, especially considering maneuvering[23].

# 3.3 Vessel Energy Efficiency Index Development

## 3.3.1 Development of the Complete Operation Vessel Energy Efficiency Index VENEFI

The calculation of the $CO_2$ emissions at each activity mode during the period (T) and the sum of them express the total $CO_2$ emissions the vessel produced at the predefined period (T). Considering the period T is equal with the period of one voyage starting at departure from port A and ending at departure from port B the efficiency index is given by the formula:

$$VENEFI(\mathrm{T}=t_j)=\frac{\sum_{i=1}^{4} mCO_{2(t_i)}}{CU_j\cdot D_j}= \qquad (3.4)$$

Equation 3.4 is suitable for use with real time data and its result will be the operation efficiency index of the vessel at the specific voyage j. By choosing a period (T) that includes more voyages (completed) the index will be expressed as an average index of the period (T) by Equation 3.5:

$$VENEFI(T)=\frac{\sum_{j=1}^{n}\sum_{i=1}^{4} mCO_{2(t_i)}}{\sum_{j=1}^{n} CU_j\cdot D_j}= \qquad (3.5)$$

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[23] More information about these variables can be found at: ICF Consulting, *Current Methodologies and Best Practices in Preparing Port Emission Inventories*, Report, prepared for U.S. Environmental Protection Agency, January 2006, p.18-19.

Both equations are in accordance with IMO EEOI[24] proposal.

Working on Equation 3.4 for one voyage it is yielded that:

$$VENEFI(\mathrm{T}=t_j)=\frac{\sum_{i=1}^{4} mCO_{2(t_i)}}{CU_j\cdot D_j}=\frac{mCO_{2(t_1)}+mCO_{2(t_2)}+mCO_{2(t_3)}+mCO_{2(t_4)}}{CU\cdot D}=$$

$$=\frac{\left[t_1\cdot\frac{mCO_{2(t_1)}}{t_1}+t_2\cdot\frac{mCO_{2(t_2)}}{t_2}+t_3\cdot\frac{mCO_{2(t_3)}}{t_3}+t_4\cdot\frac{mCO_{2(t_4)}}{t_4}\right]}{CU\cdot D}=$$

$$=\frac{\left[t_1\cdot\frac{mCO_{2(t_1)}}{t_1}+t_2\cdot\frac{mCO_{2(t_2)}}{t_2}\right]}{CU\cdot D}+\frac{\left[t_3\cdot\frac{mCO_{2(t_3)}}{t_3}+t_4\cdot\frac{mCO_{2(t_4)}}{t_4}\right]}{CU\cdot D}=$$

$$=\frac{1}{CU\cdot D}\sum_{i=1}^{2}\left[t_i\cdot CU\cdot D_i\cdot\frac{\left(\frac{mCO_{2(t_i)}}{t_i}\right)}{CU\cdot D_i}\right]+\frac{1}{CU\cdot\frac{D}{T}}\cdot\sum_{i=3}^{4}\left[\frac{t_i}{T}\cdot\left(\frac{mCO_{2(t_i)}}{t_i}\right)\right]=$$

$$=\sum_{i=1}^{2}\left(\frac{D_i}{D}\right)\cdot\left[\frac{\left(\frac{mCO_{2(t_i)}}{t_i}\right)}{CU\cdot V_i}\right]+\left(\frac{1}{CU\cdot\frac{D}{T}}\right)\cdot\sum_{i=3}^{4}\left(\frac{t_i}{T}\right)\cdot\left[\frac{mCO_{2(t_i)}}{t_i}\right]= \qquad (3.6)$$

$$VENEFI(T=t_j)=\sum_{i=1}^{2}\left[\frac{D_i}{D}\cdot VENEFI_{OS(D)}(V_i)\right]+\frac{1}{CU\cdot\frac{D}{T}}\cdot\sum_{i=3}^{4}\left[\frac{t_i}{T}\cdot VENEFI_{OS(S)}(i)\right]$$

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[24] IMO MEPC.1/Circ.684 Guidelines For Voluntary Use Of The Ship Energy Efficiency Operational Indicator (EEOI), 17 August 2009

These calculations divided the Complete Operation Index into two parts, distinct activity modes, where the ship covers a significant distance (ex. Cruise Speed Mode) and those, where the ship is operating but is not moving in a specific direction (ex. Manoeuvring Mode, Port Time Mode). This is to the direction of determining partial efficiency indices, which, however, will be correlated with the Complete Operation Index of the Vessel.

Defining these partial indices will enable optimization on an activity mode base, whose effect will be obviously depicted on the complete operation Index.

On a closer consideration on Equation 3.6, it can be seen that the quantity in brackets $\left[\frac{\left(\frac{mCO_{2(t_i)}}{t_i}\right)}{CU \cdot V_i}\right]$ expresses the energy efficiency of the vessel at activity mode (i), given the speed of the vessel at this mode and the loading of the ship. This expression in its general form is the same with EEDI definition. Therefore, we can define an Operation Scenario (Dynamic) Index, which will indicate the energy efficiency of the vessel at this scenario and could be used both for design and operation study.

$$VENEFI_{OS(D)}(t_i) = \frac{mCO_{2(t_i)}}{CU \cdot V_i} \qquad (3.7)$$

where:

i = the vessel activity mode (in this case it is the Cruise Speed of Reduced Speed Mode).

The units of the index are ($gCO_2/t \cdot nm$).

Assuming that Carried Units are the DWT of the vessel and $V_i$ is the service speed, $VENEFI_{OS}(t_1)$ is in close relation with EEDI. However, as it will be seen in the following sections, the approach on inclusion of $CO_2$ emissions in VENEFI is different from that in EEDI.

In Equation 3.6 observing closely the quantity in brackets $\left[\frac{mCO_{2(t_i)}}{t_i}\right]$ it can be a suitable way to express vessel efficiency on activity modes where there is no significant movement of the vessel, as it is not related with the travelled distance. The partial Operation Scenario (Static) Index in this case will be:

$$VENEFI_{OS(S)}(t_i) = \frac{mCO_{2(t_i)}}{t_i} \qquad (3.8)$$

The units of the index are ($gCO_2/h$).

The time factor $n_{t(i)}=t_i/T$ indicates the time vessel spent in this mode as a fraction of the total time of the complete operation efficiency index.

Now replacing part indices in Equation 3.6 the relation between these partial indices and the estimated Complete Operation Efficiency Index will be yielded:

$$VENEFI(T=t_j) = \sum_{i=1}^{2}\left[\frac{D_i}{D}\cdot VENEFI_{OS(D)}(V_i)\right] + \frac{1}{CU\cdot\frac{D}{T}}\cdot\sum_{i=3}^{4}\left[\frac{t_i}{T}\cdot VENEFI_{OS(S)}(i)\right] \qquad (3.9)$$

Now comparing the average $VENEFI_{CO}$ of Equation 3.9 with the one that is calculated from real time data, a comparison tool between Design and Operation can be obtained.

## 3.3.2 Complete Operation Vessel Energy Efficiency Index Calculation from Real Data

Calculating the carbon dioxide emissions for each engine onboard the vessel with the proposed methodology and summing up the results, the total emissions of the vessel at the specific period (T) are obtained. The following equation is indenting to calculate all emissions from engines onboard the vessel irrelevantly to the existence of PTI, PTO or the presence of methods for renewable energy production, as their effect is already included by a respective decrease of power at engines included in the calculation:

$$mCO_{2\,(Total\ Emissions)} = \sum_{i=1}^{m}\left(mCO_{2(i)}(T)\right) = \sum_{i=1}^{m}\sum_{k=1}^{n}\left[\frac{t_{(i,k)}}{T}\cdot(LF_{(i,k)}\cdot MCR_{(i)})\cdot SFC_{(i,k)}\cdot C_{F(i,k)}\right] \tag{3.10}$$

where:

i = the power plant (engine) i of the vessel

m = the vessel total power plants (engines)

k = operation scenario of engine i

n = total operation scenarios of engine i

Given the ship's transport work and distance traveled over the same period, the calculation of Complete Operation Vessel Energy Efficiency Index is feasible. This index is based on real data collected onboard the vessel and can be used to verify the VENEFI$_{CO}$ as calculated.

$$VENEFI_{CO(RT)}\ (T) = \frac{mCO_{2\,(Total\ Emissions)}}{Carried\,Units\cdot Distance}$$

$$VENEFI_{CO(RT)}\ (T) = \frac{\sum_{i=1}^{m}\sum_{k=1}^{n}\left[\frac{t_{(i,k)}}{T}\cdot(LF_{(i,k)}\cdot MCR_{(i)})\cdot SFC_{(i,k)}\cdot C_{F(i,k)}\right]}{\sum_{j=1}^{l}\left(CU_j\cdot D_j\right)} \tag{3.11}$$

where:

T = index calculation time period

$t_{(i,k)}$ = time of the applied operating condition (k) on engine (i)

i = the power plant (engine) i of the the vessel

m = the vessel total power plants (engines)

k = operation scenario of engine i

n = total operation scenarios of engine i

j = total voyages of the vessel during period (T)

$MCR_{ME(i)}$ = the rated installed power of the main engine (i). [kW]

$LF_{(i,k)}$ = Load factor of engine (i) at operating condition (k) as percentage of $MCR_{(i)}$

$SFC_{(i,k)}$ = the specific fuel consumption of engine (i) at operating condition (k). This value can be calculated according to manufacturer's engine data relatively to the loading of the main engine. [gF/kWh]

$C_{F(i,k)}$ = conversion factor indicating the produced mass of $CO_2$ gases by the use of 1 unit of mass of fuel. This value depends on the type of fuel used from the engine (i) and in case of a dual-fuel engine, the operating condition (k) regarding the type of the fuel used at that condition.

The units of the index are ($gCO_2/t \cdot nm$). The index is suitable for vessel real time operation where data will be available by measurements conducted from engines monitoring systems or alternatively from crew and recorded on the ship log books.

The advantages of this energy efficiency index are:

- It considers all operation activity of the ship within the calculation time period (T)

- Suitable for determining the real $CO_2$ emissions the vessel produces per its transport work.

On the other hand, the disadvantages of this index expression are:

- It provides no information about efficiency of Propulsion Energy and Auxiliary Energy separately, especially when there is PTI/PTO, something which will be useful as an additional indication (ex. for identifying how the implementation of a $CO_2$ reduction measure will affect the efficiency of energy at each category separately).

- It provides no information on optimizing vessel energy efficiency apart from service maintenance of every engine separately.

- The correlation of engines operation profile and ship's activity mode is not depicted during index calculation. Thus, operation scenarios (vessel activity mode and engines loading profile) which will optimize the index cannot be pursued.

- Not many vessels have installed monitoring or data recording systems.

### 3.3.3 Propulsion Energy & Auxiliary Energy Efficiency Sub-Indices

The $CO_2$ total mass emissions can be divided into two major categories according to the purpose they are produced of, either for vessel main propulsion or vessel auxiliary energy demands:

$$mCO_{2\ (Total\ Emissions)} = mCO_{2\ (Propulsion\ Energy)} + mCO_{2\ (Auxiliary\ Energy)}$$

*(3.12)*

Now the formula of $VENEFI_{CO}$ will become:

$$VENEFI\ (T) = \frac{mCO_{2\ (Propulsion\ Energy)} + mCO_{2\ (Auxiliary\ Energy)}}{Carried\,Units \cdot Distance}$$

*(3.13)*

At this point, VENEFI can be expressed as the sum of two separate indices, one for emissions due to the production of energy for main propulsion and one for emissions of auxiliary energy production.

$$VENEFI\ (T) = \frac{mCO_{2\ (Propulsion\ Energy)}}{Carried\,Units \cdot Distance} + \frac{mCO_{2\ (Auxiliary\ Energy)}}{Carried\,Units \cdot Distance} \Rightarrow$$

$$VENEFI\ (T) = VENEFI_{PE}(T) + VENEFI_{AE}(T) \qquad (3.14)$$

The two sub-indices could be regarded as an indication of the efficiency of each energy category separately. There can also be used as a comparison tool between similar vessels of the same category and be exploited for optimization of the efficiency of a specific energy category (ex. Auxiliary Energy).

## 3.4 Calculation of Vessel $CO_2$ Emissions

The GHG emissions in the index will be expressed by the Carbon Dioxide ($CO_2$) mass released in the environment from energy production plants, the mission of which is the operation of the vessel. This includes energy produced onboard the vessel but also energy produced off-board and transferred onboard for use (ex. through an Offshore Power Connection - Cold Ironing).

### 3.4.1 GHG Emitting Power Plants & Renewable Energy Production

An energy efficiency index should take into consideration all energy producing plants onboard the vessel, conventional and renewable. This approach will allow to the renewable forms of energy production in shipping to be considered and their benefits to be accounted in this index.

The proposed distinction of power plants is between those which produce significant amount of GHG and those which do not. In the first category, all known fossil fuel powered combustion engines as diesel engines, gas turbines or steam engines are , while in the second one, renewable energy sources like solar panels, wind generators or waste heat recovery systems can be considered.

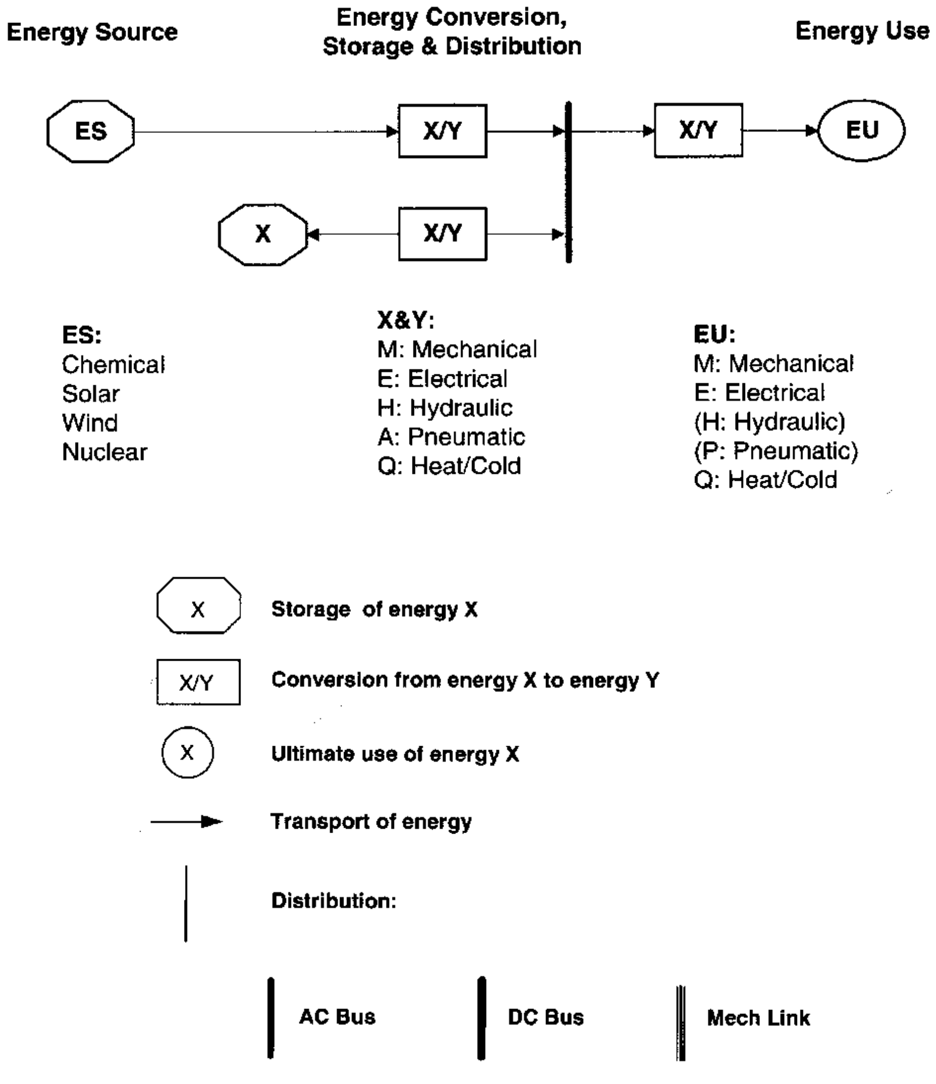

*Figure 3.1 Generic Energy Flow Diagram*[25]

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[25] Figure Source: Hans Klein Woud & Douwe Stapersma, Design of Propulsion and Electric Power Generation Systems, IMarEST Publications, London, 2002, p.98-99

### 3.4.2 GHG Emitting Power Plants

During the process of transforming its fuel chemical energy to any other applicable form of energy (kinetic, electric or heat) in a power plant, GHG emissions are produced as a side effect. Hence, the plant can be characterized as GHG Emitting Power Plant (GHG-EPP) and, thus, included in the index as a major contributor of both power production and $CO_2$ emissions. This category includes the majority of ship power plants as they produce energy for main propulsion or auxiliary purposes. The majority of power plants onboard ships, as mentioned before, are combustion engines using fossil fuel like Diesel Engines or Gas Turbines, which are used as prime movers of electric power generators. Also, shore-ship power connection will be taken into account in this category provided there is significant information about the power imported onboard and the respective emissions released for the production of that energy on land.

### 3.4.3 Calculation of Emissions from GHG Emitting Power Plants

According to the index calculation, the total emissions of the engine over the predefined period of time (T) should be included. The emissions are related with engine's fuel type and given the fuel consumption of the engine at a period (T) can be calculated by the conversion factor $C_F$.

The simplest and most accurate way of acquiring information about engine's emissions is by measuring the fuel consumption of the engine over the predefined period (T). This can be possible by conducting only two measurements of the engine's fuel; one at the beginning and one at the end of period (T). While this method is accurate, it has some major disadvantages, as it does not provide any information about fuel consumption variations in relation with the operation scheme of the engine. A solution to that is provided by adding interim measurements at key points of engine's operation as the change of its loading profile. However, this introduces complexity and practically is only feasible with a monitoring or data recording system. Alternatively, this method could be proven very useful for verifying an estimated index and determine its declination.

At a given operating condition (k), fuel consumption (FC) can be estimated by the specific fuel oil consumption (SFC) at that specific loading point and the power the engine delivers; this will be the Maximum Continuous Rating (MCR) multiplied be the loading factor (LF) at that condition.

$$FC_{(i,k)} = P_{(i,k)} \cdot SFC_{(i,k)} \Rightarrow FC_{(i,k)} = (LF_{(i,k)} \cdot MCR_{(i)}) \cdot SFC_{(i,k)} \qquad (3.15)$$

where: i = the engine i

k = the loading condition k

It is clear that the engine is not loaded in the same way over the predefined period of index calculation. Different loading conditions may be applied so the fuel consumption over each period will vary. This fact is taken into account by considering the summation of all different operation periods and their respective fuel consumption. The formula of engine's fuel consumption will become:

$$FC_{(i)} = \sum_{k=1}^{n} \frac{t_{(i,k)}}{T} (LF_{(i,k)} \cdot MCR_{(i)}) \cdot SFC_{(i,k)} \qquad (3.16)$$

where:

n = the engine's total different loading profiles

The conversion of the consumed fuel mass to carbon dioxide mass will be made by multiplying the calculated engine's fuel consumption (FC) with the conversion factor $C_F$. The formula of $gCO_2$ emissions of the specific engine (i) over the period (T) will be:

$$mCO_{2(i)}(T) = C_{F(i)} \cdot FC_{(i)} = C_{F(i)} \cdot \sum_{k=1}^{n} \left[ \frac{t_{(i,k)}}{T} \cdot (LF_{(i,k)} \cdot MCR_{(i)}) \cdot SFC_{(i,k)} \right] \qquad (3.17)$$

However the above formula does not cover dual-fuel engines. To correct this, the $C_F$ factor is not considered constant for an engine but will vary according to engine's operation scenario and fuel type, so the formula will become:

$$mCO_{2(i)}(T)=\sum_{k=1}^{n}\left[\frac{t_{(i,k)}}{T}\cdot(LF_{(i,k)}\cdot MCR_{(i)})\cdot SFC_{(i,k)}\cdot C_{F(i,k)}\right] \qquad (3.18)$$

This method of calculation is approaching closer to real-time produced emissions. The fact that the formula describes only the various steady-state operation profiles of the engine, while, also within the same time period (T) transitional operating conditions occur which might affect, in an extend, the calculated fuel consumption, should not be considered as a major drawback. Dividing the transitional period of time in two equal or even weighted time intervals and embodying them respectively to the previous and the following steady state operation profiles, will reclaim accuracy. Moreover, selecting a greater period of calculation time (T) is expected to decrease any probable inaccuracy.

### SFC

All existing indices are using only one value of SFC, usually the one for loading factor equal to 75% of MCR and is referred to the EIAPP Certificate of the engine or the one that corresponds to a specific operating point (loading factor) of the engine.

SFC however can vary significantly over the operation spectrum of the engine, making indices using a single value SFC quite inaccurate. The SFC – %MCR curve should be calculated either during EIAPP tests or provided by the engine's manufacturer for the specific configuration of the engine. According to vessel activity mode for example the main engine's loading can vary from 20% - 95% of engines MCR (Maximum Continuous Rating). In each activity mode and relative loading of the engine, the respective SFC should be used.

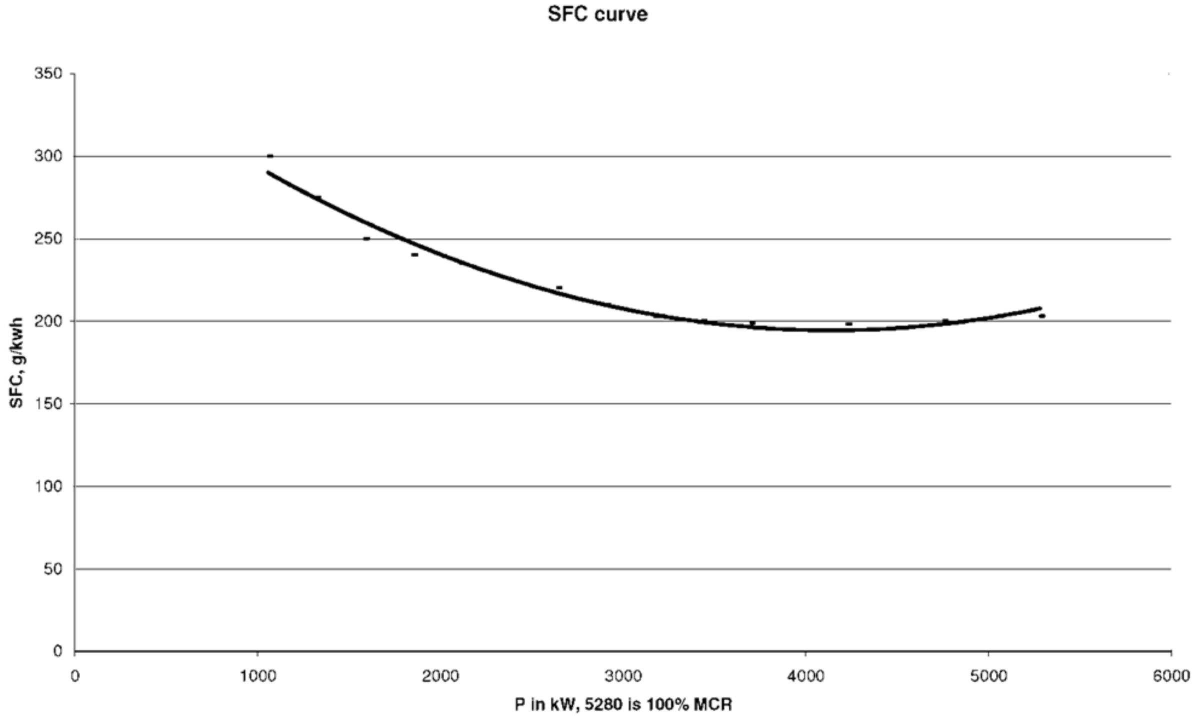

*Figure 3.2 Sample Form of Specific Oil Consumption Curve*

### 3.4.4 Renewable Energy Production

Nowadays, there are energy production methods (solar panels, wind generators, wind kites and many other innovative renewable energy production methods) that do not release significant GHG emissions in the environment[26]. These methods provide energy without increasing the mass of $CO_2$ included in the index. The contribution of Renewable energy production onboard the vessel will be analyzed in the following paragraph.

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[26] Renewable energy production also emits a negligible amount of GHG during generation, but it is only compared to human's body relative emissions. A potential inclusion of emissions produced during the construction process of the equipment (ex. solar panels, wind generators) would only be useful at a Life Cycle Assessment (LCA) Analysis of the vessel and not at this Energy Efficiency Index Approach.

### 3.4.5 Calculation of GHG Emissions Decrease Due to Renewable Energy Production

Whilst, EEDI has introduced the $-\left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right)$ *(3.19)* and $-\left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)} \cdot C_{FAE} \cdot SFC_{AE}\right)$ *(3.20)* quantities to account carbon dioxide reduce due to innovative technologies that reduce fuel consumption of main or auxiliary energy production engines, this method seems best to apply at innovative technologies that intervene directly to the specific category of energy production. For example, installation of common rail injection system at the main engine will optimize fuel efficiency and reduce consumption. However, the use of a renewable energy technology like a wind kite which will provide additional power to the propulsion of the ship will be considered beneficial only by a simultaneous deliberate decrease of the power of the main engine. This can also be depicted in EEDI through $-\left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right)$, but now, the loading of the main engine should be decreased in order not to exceed the required propulsion power. This will lead to a new operating point of the engine and a change of the SFC according to the %MCR-SFC curve. Thus, the fuel savings calculated at the new operating point will be different from those calculated with the SFC of the previous engine's operating point before renewable power contribution. Therefore, the proposition for calculating the benefits on the index is to omit the $f_{eff}$ factor and recalculate the index, considering the power contribution of the renewable energy production (ex. wind kite) and recalculate the emissions of main engine at the new decreased operating point.

# 3.5 Power Production and Demand for VENEFI

Considering power production, demand and flow (or else transformation) is essential for defining an efficiency index. This can be described by the following equation:

$$P_{Energy\,Use} = \eta_{eff} \cdot P_{Energy\,Source} \qquad (3.21)$$

$$P' = \eta_{eff} \cdot P \qquad (3.22)$$

In order to optimize an operation scenario, the vessel total energy demand for that specific scenario should be known. The total energy demand can be divided into two major categories as mentioned before, the Propulsion Energy and the Auxiliary Energy.

## 3.5.1 Propulsion Energy Demand

The propulsion energy demand ($P_{PE}$) will be the required amount of energy required to move the main propulsors of the vessel (ex. propellers, waterjets and other, excluding thrusters which are considered as auxiliary equipment), so that the vessel attains a specific speed under specific conditions. This energy should be equal to the amount of power delivered at the main propulsors of the vessel in order to achieve the specified speed. These conditions are considered to be the sea trials conditions as determined by ITTC (International Tank Towing Committee)[27].

## 3.5.2 Propulsion Energy Production

Taking into consideration all power losses that occur during production and transfer of propulsion power from the engines to the propulsors, there will be:

$$P_{PE} = P'_{PE} + P_{PE(losses)} \qquad (3.23)$$

---

[27] Sea Trials conditions are presented at ITTC Recommended Procedures 7.5-04-01-01.5 available at http://ittc.sname.org/2002_recomm_proc/7.5-04-01-01.5.pdf

The propulsion efficiency coefficient will express the effect of these power losses:

$$\eta_{eff(PE)} = \frac{P'_{PE}}{P_{PE}} = \frac{P'_{PE}}{P'_{PE} + P_{PE(losses)}} \quad (3.24)$$

where:

$\eta_{eff\ (PE)}$ = Propulsion Efficiency Coefficient.

$P_{PE}$ = Power produced by propulsion engines. In case of conventional propulsion systems the Engine Horse Power (EHP). (Energy Source)

$P'_{PE}$ = Power delivered to propulsors. In case of conventional propulsion systems the Shaft Horse Power (SHP). (Energy Use)

The correlation between vessel speed and required Engine Power (EHP) or $P_{PE}$ is described by the Speed-Power Curves for every ship. The curves depend on the hull resistance of the ship at specific conditions (cargo loading condition of the ship, weather conditions etc). These curves are described by the formula:

$$c = \frac{P_{PE}}{V^{c_1}} \quad (3.25)$$

where: c = constant

V = Ship's Velocity

$P_{PE}$ = Required Engine Power to develop velocity V

$c_1$= Constant depending on hull form. For conventional hull forms $c_1 = 3$

It is very important to note that Equation 3.25 takes into account the required power in achieving a specific velocity. This means that this part of the required power might be originated from other sources than the main engines. Given the exact point of PTI on the main propulsion transmission system (which may vary according to the type of the shaft generator/booster engine), we are able to examine potential benefits on the index by balancing the mixture of propulsion power and the effect it has on ship's velocity and $CO_2$ emissions.

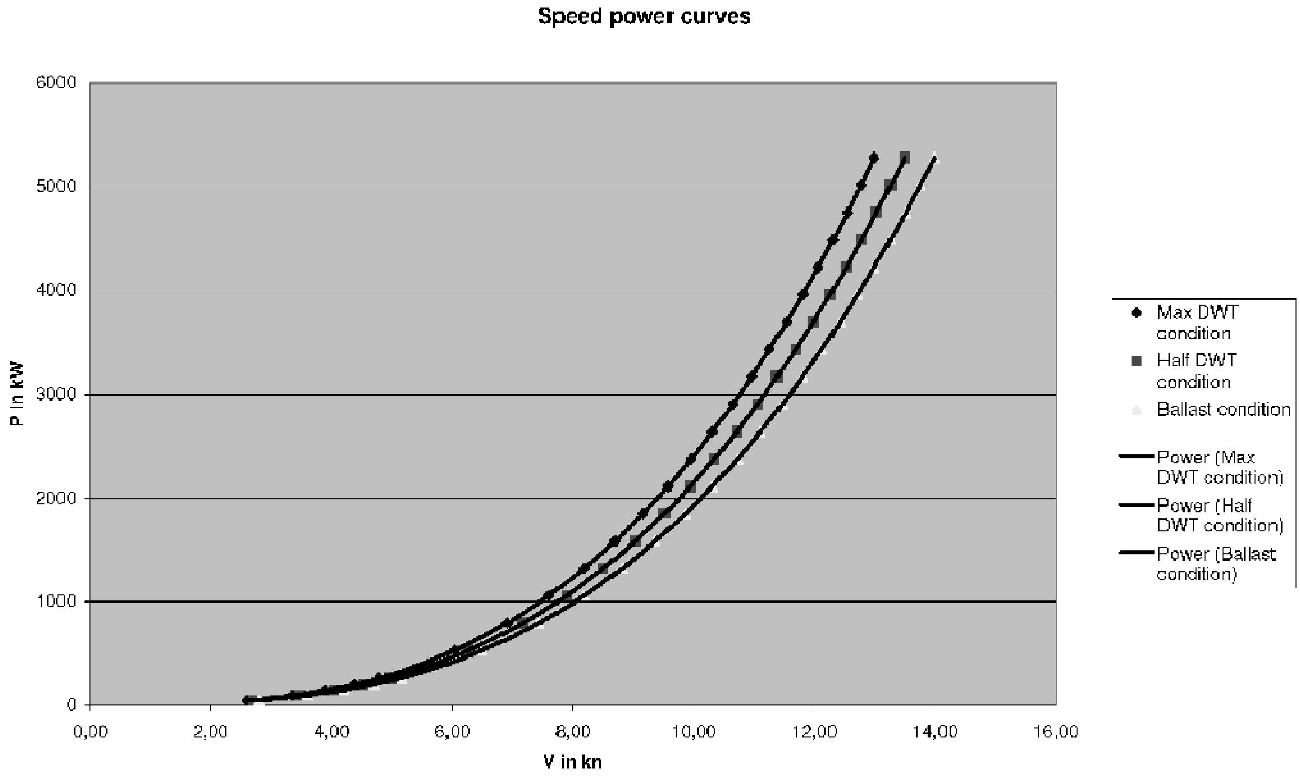

*Figure 3.3 Speed – Power Curves of a Ship*[28]

## 3.5.3 Propulsion Energy Production Analysis

Specifically, the Produced Propulsion Energy ($P_{PE}$) can be analyzed:

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[28] Figure Source: CMTI (Centrum Maritieme Technologie en Innovativie), Energy efficiency of small ships and non conventional propelled ships, Report No.3075 Study 2010, p.21

$$P_{PE} = P_{ME} + \left(P_{PTI} - P_{PTO}\right) + P_{REN(PE)} \qquad (3.26)$$

$P_{PE}$ = Propulsion Energy Production

$P_{ME}$ = Total Power Production of Main Propulsion Engines

$P_{PTO}$ = Part of power from $P_{PE}$ that is transferred through PTO (ex. Shaft Generator) to $P_{AE}$.

$P_{PTI}$ = Part of power from $P_{AE}$ that is transferred through PTI (ex. Booster Engine) to $P_{PE}$.

$P_{REN(PE)}$ = The power produced by renewable methods of power production and contribute to $P_{PE}$.

## 3.5.4 Auxiliary Energy Demand

The auxiliary energy demand ($P'_{AE}$) is the total required power for vessel auxiliary purposes. That includes any energy demand on-board the vessel apart from main propulsion. However, auxiliary machinery connected to main engines that require power from the auxiliary engines, will be accounted in the $P'_{AE}$. PTI will be excluded from $P'_{AE}$.

### 3.5.4.1 Auxiliary Energy Demand Analysis

The required auxiliary energy of the vessel can be defined by the following formula.

$$P'_{AE} = P'_{AE(Propulsion)} + P'_{AE(Machinery)} + P'_{AE(Cargo)} + P'_{AE(Accomodation)} \qquad (3.27)$$

$P'_{AE(Propulsion)}$ = The required auxiliary energy for all machinery systems of the main engines and the secondary propulsion systems, as thrusters and stabilizers. The quantity of this power may vary according to engine’s loading and always considering the operation scenario. The auxiliary propulsion energy can be divided in two subcategories.

$$P'_{AE(Propulsion)} = P'_{AE(MainPropulsion)} + P'_{AE(SecondaryPropulsion)} \qquad (3.28)$$

$P'_{AE(Machinery)}$ = The required energy for the all other machinery systems excluding those dedicated to propulsion or maneuvering and cargo handling or maintenance. These systems might be chain winches, boilers & other.

$P'_{AE(Cargo)}$ = The required energy for cargo handling or maintenance.

$P'_{AE(Accomodation)}$ = The required auxiliary power for accommodation or hotel services.

The required auxiliary power can be calculated by the electrical tables of the ship for each activity mode. This is the most appropriate method in order to select an optimized energy production scenario.

## 3.5.5 Auxiliary Energy Production

As auxiliary energy production ($P_{AE}$) will be considered the amount of energy produced to cover all the energy demands of the vessel excluding propulsion power.

Taking into consideration all power losses that occur during production and transfer of auxiliary power from the generators and other forms of auxiliary energy production, there will be:

$$P_{AE} = P'_{AE} + P_{AE(losses)} \qquad (3.29)$$

The auxiliary energy efficiency coefficient will express the effect of these power losses:

$$\eta_{eff(AE)} = \frac{P'_{AE}}{P_{AE}} = \frac{P'_{AE}}{P'_{AE} + P_{AE(losses)}} \qquad (3.30)$$

where:

| | |
|---|---|
| $\eta_{eff.(AE)}$ = | Auxiliary Energy Efficiency Coefficient. |
| $P_{AE}$ = | Power produced for auxiliary purposes (Energy Source) |
| $P'_{AE}$ = | Power delivered to auxiliary equipment (Energy Use) |

### 3.5.5.1 Analysis of Auxiliary Energy Production for Use with the Index

The majority of the auxiliary energy will be produced by the established and well known methods of production (Diesel Generators, Shaft Generators) and new innovative methods, all of them producing, at an extent, GHG emissions. Specifically, the Produced Auxiliary Energy ($P_{AE}$) can be analyzed:

$$P_{AE} = P_{EG} + \left(P_{PTO} - P_{PTI}\right) + P_{REN(AE)} + P_{CI} \qquad (3.31)$$

where:

| | |
|---|---|
| $P_{AE}$ = | Auxiliary Energy Production |
| $P_{EG}$ = | Total Power Production of Electricity Generators |
| $P_{PTO}$ = | Part of power from $P_{ME}$ that is transferred through PTO (ex. Shaft Generator) to $P_{AE}$. |
| $P_{PTI}$ = | Part of power from $P_{AE}$ that is transferred through PTI (ex. Booster Engine) to $P_{PE}$. |

$P_{REN(AE)}$ = The power produced by renewable methods of power production and contribute to $P_{AE}$.

$P_{CI}$ = The power from Cold Ironing supplied to the vessel.

The Power from Electricity Generators is further analysed:

$$P_{EG} = P_{DG} + P_{GT} + \sum_i P_{EG(i)} \qquad (3.32)$$

$P_{DG}$ = Total Power Production of Diesel Generators

$P_{GT}$ = Total Power Production of Gas Turbine Generators

$P_{EG(i)}$ = Total Power Production of any other type of electricity generators using fossil fuel.

The production of auxiliary energy that creates GHG emissions is based mainly on electric power generators using as a prime mover diesel engines, gas turbines or steam turbines. The philosophy of the index is to calculate separately the produced emissions for each auxiliary energy production installation within the calculation time period (T).

In case of PTO power is supplied to the auxiliary energy network of the ship by a shaft generator, which transforms mechanical power originally produced at the main propulsion engine. This portion of power produced by the main engine should be considered to contribute to auxiliary energy GHG emissions, while the energy available for use by auxiliary equipment should be decreased by the respective total efficiency factor $\eta_{eff.PTO}$

The $\eta_{eff.PTO}$ includes all intermediate efficiency factors from the production of the respective amount of energy to the consumption of it.

$$\eta_{eff(PTO)} = \frac{P'_{PTO}}{P_{PTO}} \qquad (3.33)$$

On the contrary when PTI occurs part of the auxiliary energy produced by power plant is supplied to the main engine, and, thus, is considered as main propulsion energy.

Power flow from main engine to auxiliary energy and vice versa appears in both formulas of power summation (Propulsion Power & Auxiliary Power), subtracted from one group and added to the other respectively.

$$P_{PE} = P_{ME} + \left(P_{PTI} - P_{PTO}\right) + P_{REN(PE)} \qquad (3.34)$$

$$P_{AE} = P_{EG} + \left(P_{PTO} - P_{PTI}\right) + P_{REN(AE)} \qquad (3.35)$$

In reality, both PTO and PTI do not directly produce energy, but rather transform it from mechanical to electrical and vice versa.

## 3.6 Diesel Electric Propulsion Vessels Inclusion in Index Calculation

In the literature, there is the CMTI study about the EEDI calculation of ships with diesel electric propulsion. However, although the diesel electric propulsion plant has well been modelled and the EEDI calculation methodology is quite accurate, the propulsion coefficient has not been taken into consideration. From the EEDI formula is concluded that the calculated emissions are based on the $P_{ME}$, meaning that this is the power the engine delivers to its prime mover and not the one to the vessel propulsor. Thus, the first step is to introduce the propulsion coefficient to EEDI calculation for conventional propulsion systems as it has been taken for diesel electric with $\eta_{elec} = 1/f_{elec}$.

***Conventional Propulsion System Power Flow***

$$MCR_{ME} \rightarrow \frac{MCR_{ME}}{0.75} = P_{ME} \rightarrow P_{ME} \cdot \left[\eta_{PC}\right] = P_{ME@Shaft}$$

***Diesel Electric Propulsion System Power Flow***

$$MCR_{ME} \rightarrow \frac{MCR_{ME}}{0.75} = P_{ME} \rightarrow P_{ME} \cdot \left[\frac{1}{f_{elec}}\right] = P_{elec}$$

*Figure 3.4 Comparison scheme of Conventional and Diesel Electric Propulsion Power Conversion*

The second step is to define the required power in order the vessel to acquire a specific speed. The diagrams should match in order to make comparisons, meaning that either $P_{ME}$ should be used or $P_{ME@Shaft}$ ($P_{elec}$) for all ships participating at the comparison table.

In this way more accurate comparisons can be conducted. Moreover, this is a unique approach for all ships either they are equipped with diesel-electric or conventional propulsion systems can be made.

## 3.7 Optimization Scenarios for Examination with the Index

The development of the index can enable the examination of custom operation scenarios under the scope of the index and the results can indicate firstly the feasibility of the optimization and secondly the scale of the profits.

Some generic energy efficiency optimization scenarios, which could have lead to interesting results are proposed to be examined by the index:

- Vessel main engines are using Heavy Fuel Oil (HFO), while Diesel Generators Marine Diesel Oil (MDO). The installation and operation at specific operation scenarios of a suitable shaft generator (PTO) can increase vessel efficiency, which will be depicted in the index.
- Considering vessel main engines are using HFO, but there are installed gas turbine electric generators using LNG as fuel. The application of PTI through booster engines might also increase efficiency of the vessel at specific operation scenarios.

The process indicates first the calculation of the Operation Scenario Index $\text{VENEFI}_{OS}$ considering existing scenario and then the calculation of the same index with the proposed optimized scenario. Then, the calculation of the complete operation index $\text{VENEFI}_{CO}$ should follow under the same circumstances, but taking into consideration the potential effect the different operation scenarios might have on the other operating conditions of the index.

# Chapter 4

# Calculation Example of VENEFI

## 4.1 Calculation Example of VENEFI for Passenger/ Ro-Ro Cargo Ship “BS1”

The vessel selected for the calculation is a Passenger / Ro-Ro Cargo Ship performing the round route Piraeus – Thira – Kos – Rhodes – Kos – Thira – Piraeus. She is selected from a category that has not yet been included in present indices (EEDI) in order to investigate the results. Detailed information on Ship Specifications is presented in Appendix 2.

### 4.1.1 Vessel Movements

The first step was to acquire data about vessel movements. The selected vessel is equipped with an AIS (Automatic Identification System) transmitter so data records describing its movements are available[29].

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[29] Data collected from website: http://www.marinetraffic.com/ais/

| Date | Time | Event | Port | Duration | Duration | Activity | V |
|---|---|---|---|---|---|---|---|
| | [hh:mm] | | | (h):(m) | (h) | | (kn) |
| 10/5/2011 | 16:07 | Departure | PIRAEUS | 00:00 | | | |
| 10/5/2011 | 22:02 | Arrival | THIRA | 05:55 | 5.92 | Full Speed | |
| 10/5/2011 | 22:55 | Departure | THIRA | 00:53 | 0.88 | Port [Stop-by] | |
| 11/5/2011 | 00:59 | Midnight position | | | | | 26.1 |
| 11/5/2011 | 03:03 | Arrival | KOS | 04:08 | 4.13 | Full Speed | |
| 11/5/2011 | 03:49 | Departure | KOS | 00:46 | 0.77 | Port [Stop-by] | |
| 11/5/2011 | 06:38 | Arrival | RHODES | 02:49 | 2.82 | Full Speed | |
| 11/5/2011 | 12:59 | Midday position | | | | | 0 |
| 11/5/2011 | 14:04 | Departure | RHODES | 07:26 | 7.43 | Port Idle | |
| 11/5/2011 | 16:46 | Arrival | KOS | 02:42 | 2.70 | Full Speed | |
| 11/5/2011 | 17:40 | Departure | KOS | 00:54 | 0.90 | Port [Stop-by] | |
| 11/5/2011 | 22:23 | Arrival | THIRA | 04:17 | 4.28 | Full Speed | |
| 11/5/2011 | 23:05 | Departure | THIRA | 00:42 | 0.70 | Port [Stop-by] | |
| 12/5/2011 | 00:59 | Midnight position | | | | | 22.4 |
| 12/5/2011 | 04:56 | Arrival | PIRAEUS | 05:51 | 5.85 | Full Speed | |
| 12/5/2011 | 12:54 | Midday position | | | | | 0 |
| 12/5/2011 | 16:15 | Departure | PIRAEUS | 11:39 | 11.65 | Port Idle | |
| **Total** | | | | 40:08 | 48.03 | | |

*Table 4.1 Vessel Movements (According to AIS Data)*

| Vessel Activity Mode | Duration | $t_k$ (h) |
|---|---|---|
| Cruise Speed | $t_1$ | 22.70 |
| Reduced Speed | $t_2$ | 0 |
| Maneuvering | $t_3$ | 6.25 |
| Port Time | $t_4$ | 19.08 |
| Total | T | 48.03 |

*Table 4.2 Vessel Activity Modes (VAM) Time Share*

### 4.1.2 Definition of Time Period for the Calculation

The calculation period of time (T) for the calculation is a round trip as defined in Chapter 3. More specifically, the period (T) is starting at vessel departing time from the port of Piraeus and ending at vessel departure again from port of Piraeus after a complete round trip. According to the data presented at Table 4.2 the predefined period will be equal to 48.03h. As the vessel has an exact time of departure from home port of Piraeus at the same time every two (2) days, the period (T) will be rounded to 48h.

$$\mathrm{T} = 48h$$

The voyages the vessel conducts in this period are six (6).

### 4.1.3 Duration of Vessel Activity Modes

1. **Cruise Speed Mode**

The cruise speed mode is derived by the data of Table 4.2:

$$t_1 = 22.7h$$

The value in this example is derived after calculating all other mode's time.

2. **Reduced Speed Mode**

The route does not contain any reduced speed zones. During arrival at Piraeus port, sometimes there are, though, some delays caused by vessels arriving simultaneously (*traffic jam*) outside the harbour. This fact forces the Harbour Master suggest to incoming vessels to sail in reduced speed for an interval before arriving at the entrance of the port. The time of arrival of the vessel at Piraeus port suggests that at this time, there is no traffic. This is verified examining the voyage duration of the trip legs Piraeus – Thira & Thira – Piraeus, which are, actually, quite the same. Thus, the reduced speed time is considered:

$$t_2 = 0h$$

3. **Manoeuvring Mode Time**

During the vessel round trip period (T), which lasts 48h, the vessel conducts 6 port to port leg trips. Considering that the time required for manoeuvring in order to approach or depart from the ports of the specific route is 15 minutes[30], the corresponding total duration is:

$$t_{3a} = t_{Docking/Undocking} = n_{LegTrips} \cdot \left(2t\right) = 6 \cdot (2 \cdot 15\min) = 180\min = 3h \qquad (4.1)$$

The time that the vessel remains in the ports of Thira & Kos must be added upon this value $t_{3\alpha}$. There is a stop-over for loading and unloading vehicles and passengers, while the vessel engines are still operating during that time. This interval calculated from Table 4.2 is:

$$t_{3b} = t_{PortEng.On} = 3.25h \qquad (4.2)$$

Thus, the total manoeuvring time is:

$$t_3 = t_{3\alpha} + t_{3b} = 3h + 3.25h = 6.25h \qquad (4.3)$$

#### 4. Port Time Mode

The time that the vessel has her propulsion engines shut down and consumes power only from auxiliary engines is during its presence at ports of Piraeus and Rhodes. The data of Table 4.2 indicates that Port Time Mode is 19.08h. However due to the rounding of the predefined period T the only value that will be affected will be Port Mode time, from which the value δT=48.03-48.00=0.03h will be subtracted.

$$t_4 = 19.08h - 0.03h = 19.05h \qquad (4.4)$$

The new time periods for each activity mode of the vessel that will be used in the calculation are presented:

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[30] California Air Resources Board Planning and Technical Support Division, *Emissions Estimation Methodology for Ocean-Going Vessels – Appendix D, 2.Operating Mode Specific Activity Hours, b.Maneuvering,* May 2008, p.D-15

| Operation Scenario Description | k | $t_k$ (h) |
|---|---|---|
| Cruise Speed | $t_1$ | 22.70 |
| Reduced Speed | $t_2$ | 0 |
| Maneuvering | $t_3$ | 6.25 |
| Port Time Mode | $t_4$ | 19.05 |
| Total | T | 48.00 |

*Table 4.3 Vessel Activity Modes (VAM's) Time Shares for Index Calculation*

## 4.1.4 Distance Covered

The distance covered is presented in Table 4.4:

| Port Distances | D (nm) |
|---|---|
| Piraeus - Thira | 130 |
| Thira - Kos | 108 |
| Kos - Rhodes | 65 |
| Total Route Distance (One Way) | 303 |
| Total Route Distance (Round Trip) | 606 |

*Table 4.4 Port Distances*[31]

Greater precision can be achieved by obtaining data from the log book of the vessel, however, the calculated distance corresponds to reality and can be corroborated by the real data of the ship; moreover considering that the vessel is covering the total distance at Cruise Speed, then $V_{Average}$=303nm/(22.7h/2)=26.7kn

The instant speed interval recorded from AIS on 11/5/2011 00:59 indicates a speed of 26.1kn. Therefore, the accuracy of Activity Mode Time and Distances is satisfactory.

The registered service speed of the ship is equal to 28kn.

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[31] Distance data is collected as published from Port Authorities, while some of them are provided by measurements of typical ship routes for these voyages.

### 4.1.5 Calculation of Transport Work

The “BS1” is a Passenger Ro-Ro Cargo ship. At most ship types, the transport work is defined as the product of vessel payload (and not the DWT as EEDI) at one specific voyage and the distance it transfers this cargo. If more voyages are included in the index the summation of all voyages transport work must be used for the calculation.

$$\sum_{j=1}^{6}\left(CU_j \cdot D_j\right) \qquad (4.5)$$

In order to define the carried units in a journey for a vessel of the same type like the Passenger Ro-Ro Cargo considered, an equivalent unit as percentage of GT and maximum capacity of the vessel considering passengers and vehicles.

The Gross Registered Tonnes of “BS1” are:

$$GT = 29415t$$

The maximum capacity of “BS1” is:

$$\text{Maximum Passengers} = 1802$$

$$\text{Maximum Vehicles} = 640$$

A function between passengers and vehicles is defined in order to obtain a regulated value of the total cargo. It is recommended to use a weight factor, which for passenger will be equal to 100kg = (75kg human weight + 25kg luggage weight) and 1000kg for a car. The total capacity of the vessel will be:

$$W_{payload} = 1802*0.01t + 640 * 1t = 820.2t \qquad (4.6)$$

Now the vessel loading coefficient is defined, which is related to vessel GT:

$$c_{VL} = \frac{GT}{W_{payload}} = \frac{29415t}{820.2t} = 35.8632 \qquad (4.7)$$

The coefficient $c_{VL}$, which is unique for each vessel, can be also written:

$$c_{VL} = \frac{GT}{W_{payload}} = \frac{GT}{0.1 \cdot n_{passengers} + n_{cars}} \qquad (4.8)$$

The equivalent carried units for a passenger Ro-Ro ship can be calculated for each voyage by the formula.

$$CU_j = c_{VL} \cdot (0.1 \cdot n_{passengers(j)} + n_{cars(j)}) \qquad (4.9)$$

The calculation is presented in Table 4.5.

| **Voyage (j)** | **$n_{passengers}$** | **$n_{cars}$** | **CU (%GT)** | **D (nm)** | **CU*D (t*nm)** |
|---|---|---|---|---|---|
| PIRAEUS –THIRA | 1,500 | 600 | 25,553 | 130 | 3,321,890 |
| THIRA – KOS | 1,118 | 401 | 17,388 | 108 | 1,877,904 |
| KOS – RHODES | 952 | 284 | 12,746 | 65 | 828,490 |
| RHODES – KOS | 952 | 284 | 12,746 | 65 | 828,490 |
| KOS – THIRA | 1,118 | 401 | 17,388 | 108 | 1,877,904 |
| THIRA – PIRAEUS | 1,500 | 600 | 25,553 | 130 | 3,321,890 |
| | | | Transport Work= | | 12,056,578 |

*Table 4.5 Transport Work Calculation*

The total transport work of the vessel for the period (T) is:

Transport Work = 12,056,578 t*nm

### 4.1.6 Calculation of Emissions due to Propulsion Energy

At this simple case study, no PTO is considered, although the vessel is equipped with a shaft generator. Another case study is provided in the Appendix 2 which takes into account the operation of shaft generators.

The total propulsion emissions for all activity modes are calculated by the following formula, which, due to the fact that there are 4 identical main propulsion engines, MAN B&W 8L58/64 of 11200kW will become:

$$mCO_{2(PE)} = \left( \sum_{i=1}^{nME} \left( C_{FME(i)} \cdot \frac{1}{T} \sum_{k=1}^{K_i} t_{(i,k)} \cdot P_{ME(i,k)} \cdot SFC_{ME(i,k)} \right) \right) \Rightarrow$$

$$mCO_{2(PE)} = C_{FME} \cdot \frac{1}{T} \sum_{k=1}^{5} t_{(k)} \cdot P_{ME(k)} \cdot SFC_{ME(k)} \qquad (4.10)$$

**$P_{ME}$**

The vessel is equipped with 4 identical main engines MAN B&W 8L58/64 of 11200kW each, and all of them are loaded in the same way according to each operating scenario. Thus, the equation of $P_{ME(i,k)}$ will take the formation:

$$P_{ME(i,k)} = P_{ME(k)} = 4 \cdot LF_{ME(k)} \cdot MCR_{ME} \qquad (4.11)$$

According to the operation scheme, all engines are loaded in the same way which is expressed by the Load Factor ($LF_{ME}$). For each operation mode:

$$P_{ME(1)} = 4 \cdot 0.85 \cdot MCR_{ME} = 4 \cdot 0.85 \cdot 11200kW = 38080kW$$
$$P_{ME(2)} = 4 \cdot 0.50 \cdot MCR_{ME} = 4 \cdot 0.50 \cdot 11200kW = 22400kW$$
$$P_{ME(3a)} = 4 \cdot 0.50 \cdot MCR_{ME} = 4 \cdot 0.50 \cdot 11200kW = 22400kW$$
$$P_{ME(3b)} = 4 \cdot 0.20 \cdot MCR_{ME} = 4 \cdot 0.20 \cdot 11200kW = 8960kW$$
$$P_{ME(4)} = 4 \cdot 0 \cdot MCR_{ME} = 4 \cdot 0 \cdot 11200kW = 0kW$$

**$C_{FME}$**

The fuel used for the main engines according to manufacturer is HFO380. For that type of fuel the MEPC.1/Circ.681 suggests

$C_F$ = 3.1144 (tonnes of $CO_2$ / tonne of Fuel)

**$SFC_{ME}$**

The manufacturer of the engines indicates that SFC is equal to 174g/kWh@100%MCR and 173g/kWh@85%MCR.

In Figure 4.1 the curves of SFC - %MCR of engine loading are developed by the 4 values of SFC the manufacturer provides for 4 different operating points of the engines. Also, the curve of the Diesel engines generators is presented in the same diagram.

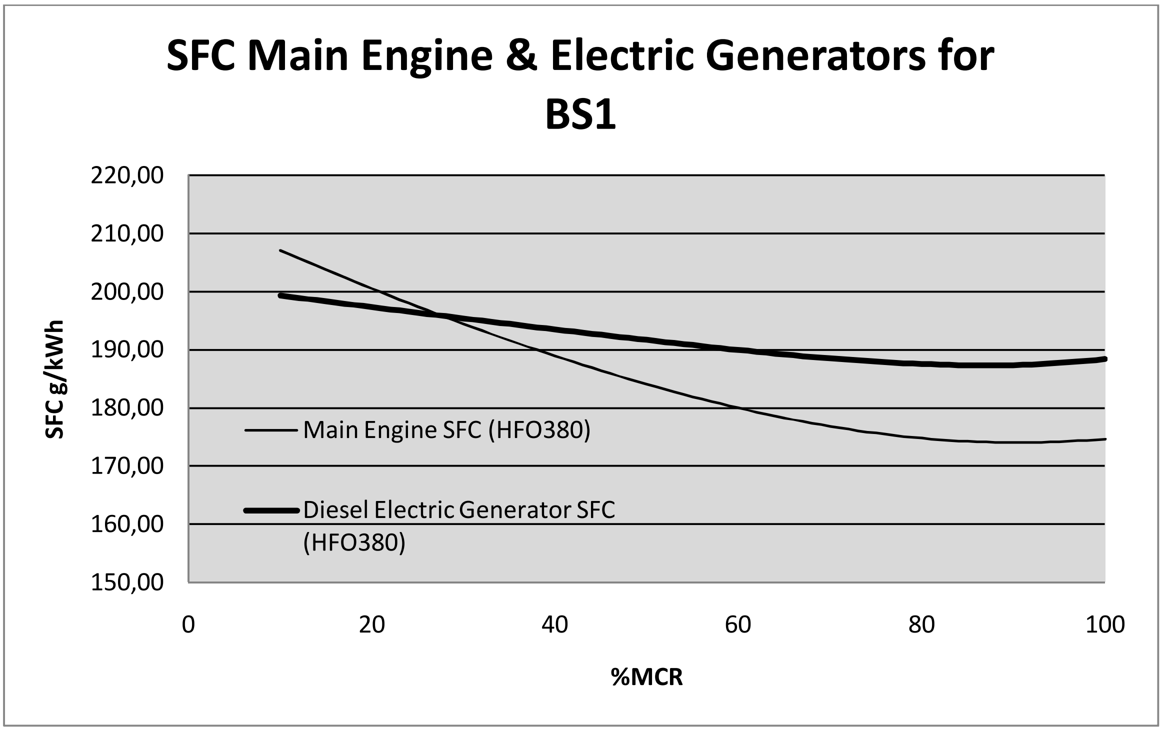

*Figure 4.1 Specific Fuel Consumption of Main Engine and Electric Power Generators*

Consulting the chart the values of SFC that will be used in the calculations are:

SFC 85%MCR =174.24 g/kWh

SFC 50%MCR =184.02 g/kWh

SFC 20%MCR =200.57 g/kWh

Considering the mentioned assumptions, the emissions of the main propulsion engines can be calculated by the formula:

$$mCO_{2(ME)} = \sum_{i=1}^{nME}\left(\sum_{k=1}^{K_i}\left(t_{(k,i)} \cdot P_{ME(k,i)} \cdot SFC_{ME(k,i)} \cdot C_{FME(i)}\right)\right) \Rightarrow$$

$$mCO_{2(ME)} = \sum_{k=1}^{5}\left(t_{(k)} \cdot P_{ME(k)} \cdot SFC_{ME(k)} \cdot C_{FME}\right) \qquad (4.12)$$

| $\sum_{k=1}^{5}\left(t_{(k)} \cdot P_{ME(k)} \cdot SFC_{ME(k)}\right)$ | | | | | |
|---|---|---|---|---|---|
| k | $t_k$ | $LF_{(k)}$ | $P_{ME(k)}$ | $SFC_{ME(k)}$ | Fuel Consumed |
| - | h | - | kW | g/kWh | g Fuel |
| 1 | 22.7 | 85% | 38,080 | 174.24 | 150,615,844 |
| 2 | 0 | 50% | 0 | 184.02 | 0 |
| 3a | 3 | 50% | 22,400 | 184.02 | 12,366,144 |
| 3b | 3.25 | 20% | 8,960 | 200.57 | 5,840,599 |
| 4 | 19.0 | 0% | 0 | 0 | 0 |
| | 48 | | -- | -- | 168,822,587 |

*Table 4.6 Propulsion Energy Emissions Calculation For All Activity Modes*

The carbon dioxide emissions for time period (T) are:

$$mCO_{2(PE)} = C_{FME} \cdot \sum_{k=1}^{5}\left(t_{(k)} \cdot P_{ME(k)} \cdot SFC_{ME(k)}\right) = 3.1144 \cdot 168{,}822{,}587 gF = 525{,}781{,}065 gCO_2$$

*( 4.13)*

An indicating average emission rate of propulsion energy emissions for period (T) can also be calculated:

$$mCO_{2(PE)} = \frac{1}{T} \cdot C_{FME} \cdot \sum_{k=1}^{5} \left( t_{(k)} \cdot P_{ME(k)} \cdot SFC_{ME(k)} \right) = \frac{1}{48h} \cdot 525,781,065 gCO_2 =$$

$$mCO_{2(PE)} = 10.954 \, {}^{tCO_2}\!/_{h} \qquad \textit{(4.14)}$$

## 4.1.7 Calculation of Emissions due to Auxiliary Energy

As stated at the calculation of Propulsion Energy, it is assumed that there is no PTO, although the vessel is equipped with a shaft generator. Therefore the calculation will be conducted only for the installed auxiliary diesel generators. The vessel is equipped with three (3) MAN B&W 6L28/32 Diesel Gensets of 1200kW power each.

$$mCO_{2(AE)} = \sum_{i=1}^{nAE} \left( \sum_{k=1}^{K_i} t_{(i,k)} \cdot P_{AE(i,k)} \cdot SFC_{AE(i,k)} \cdot C_{FAE(i)} \right) \Rightarrow$$

$$mCO_{2(AE)} = \sum_{k=1}^{5} (t_{(k)} \cdot P_{AE(k)} \cdot SFC_{AE(k)} \cdot C_{FAE}) \qquad \textit{(4.15)}$$

Working in the same way, the auxiliary power generators emissions are calculated. It is assumed that only two (2) of the three (3) installed diesel-engine generators of 1200kW each, suffice to cover the required load and sustain energy stability; thus will be included in the calculation.

<table>
<tr><th colspan="8">$\sum_{k=1}^{5}(t_{(k)} \cdot P_{AE(k)} \cdot SFC_{AE(k)} \cdot C_{FAE})$</th></tr>
<tr><th>k</th><th>$t_k$</th><th>nAE</th><th>$LF_{(AEk)}$</th><th>$P_{AE(k)}$</th><th>$P'_{AE}$</th><th>$SFC_{AE(k)}$</th><th>Fuel Consumed</th></tr>
<tr><td>-</td><td>h</td><td></td><td>-</td><td>kW</td><td>kW</td><td>g/kWh</td><td>g Fuel</td></tr>
<tr><td>1</td><td>22.7</td><td>2</td><td>75%</td><td>1,890</td><td>1,850</td><td>187.84</td><td>8,058,900</td></tr>
<tr><td>2</td><td>0</td><td>2</td><td>75%</td><td>1,872</td><td>1,750</td><td>187.84</td><td>0</td></tr>
<tr><td>3a</td><td>3</td><td>2</td><td>55%</td><td>1,386</td><td>1,300</td><td>190.85</td><td>793,554</td></tr>
<tr><td>3b</td><td>3.25</td><td>2</td><td>55%</td><td>1,386</td><td>1,300</td><td>190.85</td><td>859,684</td></tr>
<tr><td>4</td><td>19.05</td><td>1</td><td>75%</td><td>900</td><td>900</td><td>187.84</td><td>3,220,517</td></tr>
<tr><td></td><td>48</td><td></td><td></td><td>--</td><td></td><td>--</td><td>12,932,655</td></tr>
</table>

*Table 4.7 Auxiliary Energy Emissions Calculation For All Activity Modes*

The carbon dioxide emissions due to auxiliary energy for the time period (T) are:

$$mCO_{2(AE)} = \sum_{k=1}^{5}\left(t_{(k)} \cdot P_{AE(k)} \cdot SFC_{AE(k)} \cdot C_{FAE}\right) = 3.1144 \cdot 12,932,655 gF = 40,277,461 gCO_2$$

*(4.16)*

An indicating average emission rate of auxiliary energy emissions for period (T) can also be calculated:

$$mCO_{2(AE)} = \frac{1}{T} \cdot \sum_{k=1}^{5}\left(t_{(k)} \cdot P_{AE(k)} \cdot SFC_{AE(k)} \cdot C_{FAE}\right) = \frac{1}{48h} \cdot 40,277,461 gCO_2 =$$

$$= 0.83912 \, {}^{tCO_2}\!/_{h} \qquad (4.17)$$

The total emissions of the vessel in the period (T) are:

$$mCO_2 = mCO_{2(PE)} + mCO_{2(AE)} = 525,781,065 gCO_2 + 40,277,461 gCO_2 =$$

$$mCO_2 = 566,058,526 gCO_2 \qquad (4.18)$$

### 4.1.8 Calculation of VENEFI$_{CO}$

VENEFI$_{CO}$ can be now calculated:

$$VENEFI_{CO} = \frac{mCO_2}{\sum_{j=1}^{6}(CU_j \cdot D_j)} = \frac{566,058,526gCO_2}{12,056,578t \cdot nm} = 46.95\frac{gCO_2}{t \cdot nm}$$

*(4.19)*

The respective VENEFI$_{CO}$ with PTO has resulted in an index of 44.85gCO$_2$/t·nm, which indicates the efficiency of PTO during the complete operation of the vessel.

It is clear that for the same operation conditions the VENEFI is suitable to be used as an optimization investigation tool while it also depicts the real CO$_2$ emissions released to the environment.

### 4.1.9 Spreadsheet for Calculation of VENEFI$_{CO}$

For the calculation of the example presented in this chapter, a spreadsheet has been developed, where using as input the ship specifications, operating scenarios and voyage data, performs the calculation of VENEFI. The spreadsheet can be also used to calculate indices for different ships on the same route, or the index for a specific operation scenario.

In Appendix 3 the developed spreadsheet has been used to calculate two different complete operation scenarios of “BS1”, one with the use of shaft generator and one without. The results depicted in the index the expected benefits from the use of shaft generator, showing that VENEFI is suitable as an optimization tool considering vessel’s operation.

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# Chapter 5

# Conclusions

In this chapter the main conclusive remarks drawn throughout this dissertation are summarized and discussed to some extent. Furthermore, some hints are made towards further research investigation.

## 5.1 Conclusive Remarks

- The first step at this dissertation has been the performance of a literature survey on today's efforts to establish Energy Efficiency Indices of ships, which will be able to indicate the energy efficiency of a vessel as designed and during its operation life cycle.

- The mathematical formulae of calculating these ship efficiency indices are of primary importance as they intrigue, an investment boom on innovative energy efficiency technologies and the adoption of optimized operation decisions. This will result in the decrease of worldwide shipping industry GHG emissions. During this diploma thesis performance, it was discovered that IMO's proposals of the establishment of two different indices, Energy Efficiency Design Index (EEDI) and Energy Efficiency Operation Index (EEOI) has concentrated the attention of several research institutions, organizations, universities and of course flag state members of IMO. These indices are still under discussion and/or ratification: discussion on applying EEDI has been significantly developed and discussed; in contrast, EEOI remains in a general description stage by proposed guidelines, as some issues have not yet resolved.

- EEDI refers to only one loading condition of the vessel (Full Load Condition) and to a unique velocity of the vessel (Service Speed). Also, it allows an estimation of onboard auxiliary energy, which leads to a higher inaccuracy when calculating the index, as it is not able to depict real GHG emissions due to electrical (auxiliary) energy production of the vessel at that specific condition. Many flag states, like Greece[32], raised objections that today's form of the index leads to distortions, as it encourages the design of smaller and less efficient ships with reduced operational capabilities rather than promoting the larger vessels, which, intentionally, will operate on slow steaming, while in difficult conditions it will use its reserved power.

- EEDI cannot be applied to passenger ships due to varied auxiliary energy demands of this type of vessels; moreover, ships with diesel-electric propulsion are also excluded due to the complexity in energy distribution and varying power demand.

- On the other hand, the discussion on application of EEOI seems to be neglected in the favour of EEDI's discussions.

- Within the frame of this dissertation, it was decided to revert the process and start investigating first the capabilities to *develop an operation index keeping the general guidelines of EEOI*. Using as a starting point the generic form of EEOI, a novel index has been developed the *Complete Operation Vessel Energy Efficiency Index* $VENEFI_{CO}$, by determining distinct operation scenarios based on the activity modes of the vessel and by calculating the $CO_2$ emissions at each one of them. These *vessel activity modes* have been divided into two categories, the *dynamic ones*, when the ship is conducting

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[32] IMO MEPC 60/4/17, Prevention of Air Polution From Ships, The Energy Efficiency Design Index (EEDI) and Underpowered Ships, 15 January 2010.

transport work (Cruise Mode, Reduced Speed Mode) and the static ones, when the vessel is not directly producing transport work but is operating in a mode, which is necessary for transiting in a producing transport mode (Manoeuvring Mode, Port Time Mode).

- By analysing the $VENEFI_{CO}$ to an activity scenario level, two different *sub-indices have been developed, one for dynamic modes* ***$VENEFI_{OS(D)}$*** *and one for static activity modes* ***$VENEFI_{OS(S)}$***. The $VENEFI_{OS(D)}$ is appropriately developed in order to match the current EEDI expression under specific conditions and assumptions, creating, thus, a link to the eventual development of EEDI's up-to-date. In this way, a unified index is introduced and the design of the vessel is transferred to the optimization of its complete operation index $VENEFI_{CO}$ leading to a more accurate confrontation of vessel efficiency at the design stage. By adding more operation scenarios, calculating $VENEFI_{CO}$ at design stage can improve the calculation accuracy of the vessel energy efficiency even more.

- More specifically, focusing on a single voyage, the Vessel Energy Optimization can be based on the $VENEFI_{OS}$. By minimizing the $VENEFI_{OS}$ at each scenario, either the ship is in a Dynamic Activity Mode (e.g. Cruise Speed Mode) expressed by $VENEFI_{OS(D)}$ in (gCO2/t·nm) or in a Static Activity Mode (e.g. Port Time Mode) expressed by $VENEFI_{OS(S)}$ in ($gCO_2$/h), the vessel energy efficiency can be significantly optimized. Then, modeling of the vessel voyage is performed by determining the quantity of Carried Units, Distance Covered, Voyage Duration and Specific Time under each Vessel Activity Mode. Via Equation 4.9, the Complete Operation Vessel Energy Efficiency Index is calculated for that particular voyage.

$$VENEFI_{CO}(T) = \frac{1}{D} \cdot \sum_{i=1}^{4} \left[ D_i \cdot VENEFI_{OS(A)}(V_i) \right] + \frac{1}{CU \cdot \frac{D}{T}} \cdot \sum_{i=3}^{4} \left[ n_{t(i)} \cdot VENEFI_{OS(S)}(i) \right]$$

- The same index $VENEFI_{CO(RT)}$ can be calculated from real time data, e.g. recorded via engine's monitoring systems and ship's log books subject to the inspection of Authorities. Thus, verification of index calculation results can be achieved.

- The same optimization method can be applied also on a multi leg round trip. This time an ***Average*** $\boldsymbol{VENEFI_{CO}}$ must be calculated considering separately the sum of $CO_2$ emissions at the several activity modes and the sum on the transport work. Then, a comparison with $VENEFI_{CO(RT)}$ based on real time data for the same time period can be conducted.

- Calculating the $VENEFI_{CO(RT)}$ in a significant period of time including several voyages by real time data can become a vessel energy efficiency comparison tool between ships in service of various categories. The time period suggested for this calculation is a *Rolling Average* considering the period of the past year from the calculation date with an interval between calculations equal to three months.

- The above might also be the basis for the creation of a *$CO_2$ exchange market* in shipping industry in order to award energy efficient vessels and penalize the less efficient.

- Considering only the dynamic activity modes of the vessel and ignoring the static ones, an index for a voyage combining multiple operation scenarios is obtained:

$$VENEFI_{CO(D)} = \frac{1}{D} \cdot \sum_{i=1}^{n} \left[ D_i \cdot VENEFI_{OS(D)}(V_i) \right]$$

- This index can also model different weather conditions during voyage by adding respective scenarios without the need of determining a specific weather factor ($f_W$) as in EEDI.

- During the calculation of $CO_2$ emission provoked by the prime movers of electricity generators, the SFC should be taken into consideration in relation with the loading of the engine using the %MCR-SFC curve.

- Partial indices have been introduced for Propulsion Energy and Auxiliary Energy efficiency as also for each power plant, applied on each part of produced energy the final use of this part either as PE or AE and all intermediate energy transformation efficiency from production to consumption.

- Renewable forms of energy production that do not emit GHG have been considered to contribute power, which will lead to a respective and deliberate decrease of power in other highly $CO_2$ emitting power plants that produce power for the same purpose (ex. Auxiliary Energy). Thus, the efficiency factor $f_{eff}$ of EEDI is not used, but a new index calculation is performed considering the same amount of demanded energy. Then, the two indices can be compared acknowledging the benefits of the applied innovative renewable form of energy production at that specific operation scheme.

- In calculation of emissions due to produced energy, efficiency factors have been introduced in order to indicate whether power flow and energy transformation can be proven beneficial to efficiency or not according to the power demand and the operation scenario. In this way, energy flow and transformation efficiency through PTO/PTI can be depicted at the index.

  This can resolve the issue of calculating the efficiency of diesel electric propulsion vessels and comparing them with conventional ships.

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# Figures

Figure 2.1 Schematic representation of the calculation items for EEDI (p.11)

Source: IMO MEPC.1/Circ.681 Annex Interim Guidelines On The Method Of Calculation Of The Energy Efficiency Design Index For New Ships, p.8

Figure 2.2 General Cargo Ships Regression Line Graph (p.13)

Source: IMO MEPC GHG-WG 2/2/7 Annex 1, Recalculation Of Energy Efficiency Design Index Baselines For Cargo Ships, 4 February 2009, p.4

Figure 2.3 Diesel Electric Propulsion Plant Scheme (p.17)

Figure Source: CMTI (Centrum Maritieme Technologie en Innovativie), Energy efficiency of small ships and non conventional propelled ships, Report No.3075 Study 2010, p.28

Figure 3.1 Generic Energy Flow Diagram (p.37)

Figure Source: Hans Klein Woud & Douwe Stapersma, Design of Propulsion and Electric Power Generation Systems, IMarEST Publications, London, 2002, p.98-99

Figure 3.2 Sample Form of Specific Oil Consumption Curve (p.41)

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Source: CMTI (Centrum Maritieme Technologie en Innovativie), Energy efficiency of small ships and non conventional propelled ships, Report No.3075 Study 2010, p.21

Figure 3.4 Comparison scheme of Conventional and Diesel Electric Propulsion Power Conversion (p.51)

# Tables

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# Appendix 2

# Abbreviations

| | |
|---|---|
| AE | Auxiliary Energy |
| AIS | Automatic Identification System |
| CF | Carbon emission Factor |
| CI | Cold Ironing |
| CMTI | (Centrum Maritieme Technologie en Innovativie [ Centre of Maritime Technology & Inovation (Netherlands) ] |
| $CO_2$ | Carbon Dioxide |
| CPP | Controllable Pitch Propeller |
| CU | Carried Units |
| D | Distance |
| DG | Diesel Generator |
| DWT | Dead WeighT |
| ECA | Emissions Control Area |
| EEDI | Energy Efficiency Design Index |
| $EEDI_A$ | Energy Efficiency Design Index - Attained |
| $EEDI_{BL}$ | Energy Efficiency Design Index - Baseline |
| EEOI | Energy Efficiency Operation Index |

| | |
|---|---|
| eff. | efficiency |
| EG | Electricity Generators |
| EHP | Engine Horse Power |
| EIAPP | Engine International Air Pollution Prevention |
| elec | electric |
| elecmax | electric maximum |
| EPA | Environmental Protection Agency |
| FC | Fuel Consumption |
| FPP | Fixed Pitch Propeller |
| GHG | Greenhouse Gases |
| GHG-EPP | GreenHouse Gases Emitting Power Plant |
| GRT or GT | Gross Registered Tones |
| GT | Gas Turbine [ (appeared only as index ($P_{GT}$) ] |
| HFO | Heavy Fuel Oil |
| IMO | International Maritime Organization |
| ISO | International Organization for Standardization |
| ITTC | International Tank Towing Committee |
| LCA | Life Cycle Assessment |
| LF | Load Factor |
| LFO | Light Fuel Oil |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| MAC | Marginal Abatement Cost |

| | |
|---|---|
| MCR | Maximum Continuous Rating |
| MDO | Marine Diesel Oil |
| ME | Main Engine |
| MEPC | Marine Environment Protection Committee |
| NOx | Nitrous Oxide |
| P | Power |
| PC | Propulsion Coefficient |
| PE | Propulsion Energy |
| PPOS | Power Production Operation Scenarios |
| PTI | Power Take In |
| PTO | Power Take Off |
| ref. | Reference |
| REN | Renewable |
| Ro-Ro | Roll On Roll Off (Ships) |
| RSZ | Reduced Speed Zones |
| SFC | Specific Fuel Consumption |
| SFOC | Specific Fuel Oil Consumption |
| T | Time (Period) |
| US | United States (Of America) |
| V | Velocity |
| VAM | Vessel Activity Mode |
| VENEFI | Vessel Energy Efficiency Index |
| $VENEFI_{CO}$ | Vessel Energy Efficiency Index in Complete Operation |

| | |
|---|---|
| $\mathrm{VENEFI}_{\mathrm{CO(RT)}}$ | Vessel Energy Efficiency Index in Complete Operation calculated exclusively with Real Time data |
| $\mathrm{VENEFI}_{\mathrm{OS}}$ | Vessel Energy Efficiency Index in Operation Scenario |
| $\mathrm{VENEFI}_{\mathrm{OS(D)}}$ | Vessel Energy Efficiency Index in Dynamic Operation Scenario |
| $\mathrm{VENEFI}_{\mathrm{OS(S)}}$ | Vessel Energy Efficiency Index in Static Operation Scenario |
| $\mathrm{VENEFI}_{\mathrm{PE}}$ | Vessel Energy Efficiency Index of Propulsion Energy |
| $\mathrm{VENEFI}_{\mathrm{AE}}$ | Vessel Energy Efficiency Index of Auxiliary Energy |
| VL | Vessel Loading |
| W | Weight |
| WG | Working Group |
| WHR | Wasted Heat Recovery |

# Appendix 3

# Calculations of EEDI & VENEFI$_{CO}$ & Operation Scenarios Comparison for Passenger / Ro-Ro Cargo Ship “BS1”

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### Calculations of Indices on Existing Passenger Ro-Ro Vessel BS1

### Calculation of EEDI Considering Different Operation Schemes
### Calculation of $VENEFI_{CO}$ and $VENEFI_{OS}$ of BS1 on Existing Route

**EEDI Calculation Results Considering Different Scenarios on EEDI**

| | | | |
|---|---|---|---|
| A | **EEDI With PTO & Speed Reduction** | **23,98** | gCO2/t·nm |
| B | **EEDI No PTO/PTI (Speed Increased)** | **24,51** | gCO2/t·nm |
| C | **EEDI With PTO & Speed Retained** | **25,31** | gCO2/t·nm |
| D | **EEDI Baseline Calculated for spec. Ship** | **26,43** | gCO2/t·nm |
| E | **EEDI Baseline (RO-RO Ships)** | 12,80 | gCO2/t·nm |

**VENEFI Calculations**

| | | | |
|---|---|---|---|
| F1 | **$VENEFI_{OS(D)\ Cruise\ Mode}$** | **39,95** | $gCO_2/t·nm$ |
| F2 | **$VENEFI_{OS(D)\ Reduced\ Speed}$** | **N/A** | $gCO_2/t·nm$ |
| G1 | **$VENEFI_{OS(S)\ Man.\ 3a}$** | **13,22** | $tCO_2/h$ |
| G2 | **$VENEFI_{OS(S)\ Man.\ 3b}$** | **5,97** | $tCO_2/h$ |
| G3 | **$VENEFI_{OS(S)\ Port\ Time\ Mode}$** | **0,55** | $tCO_2/h$ |
| H | **$VENEFI_{CO}$** | **44,85** | gCO2/t·nm |

**Calculated for one typical round trip 48h and considering real transport work. Is not comparable with EEDI as we know it.**

**$VENEFI_{OS}$ is more accurate in representing $CO_2$ emissions:**
- **Takes into consideration the total Auxiliary Energy Demand of the vessel and not only the required for propulsion as EEDI does.**
- **When renewables are used is recalculated considering power decrease to fossil fuel engines.**

**$VENEFI_{CO}$**
- **Is includes all operation modes of the ship.**
- **Is suitable to compare different operational modes at examining a certain voyage or multi-leg voyage.**
- **Considers the real transport work of the vessel.**

**However real statistical loading data (passengers and cars per trip) are needed in order to have useful comparisons**

| **$P_{ME}$ Calculation** | | |
|---|---|---|
| $MCR_{ME(i)}$ | kW | 11200 |
| i | -- | 4 |
| $MCR_{ME}$ | kW | 44800 |
| $P_{Shaft(i)}$ | kW | 1200 |
| i | -- | 2 |
| $P_{shaft}$ | kW | 2400 |
| Shaft $_{eff.}$ | -- | 0,85 |
| $P_{PTO}$ | kW | 1530 |
| $P_{PTI(i)}$ | kW | 0 |
| $P_{ME}$ | kW | 32452,5 |
| | | |
| **$P_{AE}$ Calculation** | | |
| $MCR_{ME}$ >10000 | kW | 44800 |
| $P_{AE}$ | kW | 1370 |
| | | |
| **$V_{ref}$ Calculation** | | |
| P | kW | 44800 |
| $V_{SERVICE}$ | kn | 28 |
| $c=P/V^3$ | -- | 1,734693878 |

|  |  |  |  |
|---|---|---|---|
| A | **EEDI Calculation [MEPC.1 Circ.681]** |  |  |
|  | **Parameters** |  |  |
|  | $f_j$ | -- | 1 |
|  | $f_i$ | -- | 1 |
|  | $f_w$ | -- | 1 |
|  | Capacity = GT | tCO2/tF | 29415 |
|  | $V_{ref}$ | kn | 26,55 |
|  | $SFC_{ME}$ | g/kWh | 177 |
|  | $SFC_{AE}$ | g/kWh | 196 |
|  | $C_{FME}$ | $tCO_2/tF$ | 3,1144 |
|  | $C_{FAE}$ | $tCO_2/tF$ | 3,1144 |
|  | $P_{ME}$ | kW | 32452,5 |
|  | $P_{ME}$ = %MCR | % | 0,72 |
|  | $P_{AE}$ | kW | 1370 |
|  | **Calculation** |  |  |
|  | $f_j$ | -- | 1 |
|  | $P_{ME}$ | kW | 32452,5 |
|  | $C_{FME(i)}$ | $tCO_2/tF$ | 3,1144 |
|  | $SFC_{ME(i)}$ | g/kWh | 177 |
|  | ***Element 1*** |  | 17889401,68 |
|  | $P_{AE}$ | kW | 1370 |
|  | $C_{FAE(i)}$ | $tCO_2/tF$ | 3,1144 |
|  | $SFC_{AE}$ | g/kWh | 196 |
|  | ***Element 2*** | g/h | 836278,688 |
|  | ***Element 3*** |  | 0 |
|  | ***Element 4*** |  | 0 |
|  | $f_i$ | -- | 1 |
|  | Capacity GT | t | 29415 |
|  | $V_{ref}$ | kn | 26,55 |
|  | $f_w$ | -- | 1 |
|  | ***Denominator*** | t·nm/h | 780867,3969 |
| A | **EEDI** | $gCO_2/t·nm$ | **23,98** |

|  |  |  |  |
|---|---|---|---|
| B | **EEDI Calculation [MEPC.1 Circ.681] - NO PTO/PTI** |  |  |
|  | **Parameters** |  |  |
|  | $f_j$ | -- | 1 |
|  | $f_i$ | -- | 1 |
|  | $f_w$ | -- | 1 |
|  | Capacity = GT | m.tn | 29415 |
|  | $V_{ref}$ | kn | 26,86 |
|  | $SFC_{ME}$ | g/kWh | 177 |
|  | $SFC_{AE}$ | g/kWh | 196 |
|  | $C_{FME}$ | $tCO_2/tF$ | 3,1144 |
|  | $C_{FAE}$ | $tCO_2/tF$ | 3,1144 |
|  | $P_{ME}$ | kW | 33600 |
|  | $P_{ME}$ = %MCR | % | 0,75 |
|  | $P_{AE}$ | kW | 1370 |
|  | **Calculation** |  |  |
|  | $f_j$ | -- | 1 |
|  | $P_{ME}$ | kW | 33600 |
|  | $C_{FME(i)}$ | $tCO_2/tF$ | 3,1144 |
|  | $SFC_{ME(i)}$ | g/kWh | 177 |
|  | ***Element 1*** |  | 18521959,68 |
|  | $P_{AE}$ | kW | 1370 |
|  | $C_{FAE(i)}$ | $tCO_2/tF$ | 3,1144 |
|  | $SFC_{AE}$ | g/kWh | 196 |
|  | ***Element 2*** |  | 836278,688 |
|  | ***Element 3*** |  | 0 |
|  | ***Element 4*** |  | 0 |
|  | $f_i$ | -- | 1 |
|  | Capacity | t | 29415 |
|  | $V_{ref}$ | kn | 26,86 |
|  | $f_w$ | -- | 1 |
|  | ***Denominator*** | t·kn | 789964,6604 |
| B | **EEDI** | $gCO_2/t·kn$ | 24,51 |

C

| EEDI Calculation [MEPC.1 Circ.681] - PTO Speed Retained | | |
|---|---|---|
| **Parameters** | | |
| $f_j$ | -- | 1 |
| $f_i$ | -- | 1 |
| $f_w$ | -- | 1 |
| Capacity = GT | t | 29415 |
| $V_{ref}$ | kn | 26,86 |
| $SFC_{ME}$ | g/kWh | 177 |
| $SFC_{AE}$ | g/kWh | 196 |
| $C_{FME}$ | $tCO_2/tF$ | 3,1144 |
| $C_{FAE}$ | $tCO_2/tF$ | 3,1144 |
| $P_{ME}$ | kW | 34747,5 |
| $P_{ME}$ = %MCR | % | 0,78 |
| $P_{AE}$ | kW | 1370 |
| **Calculation** | | |
| $f_j$ | -- | 1 |
| $P_{ME}$ | kW | 34747,5 |
| $C_{FME(i)}$ | $tCO_2/tF$ | 3,1144 |
| $SFC_{ME(i)}$ | g/kWh | 177 |
| ***Element 1*** | | 19154517,68 |
| $P_{AE}$ | kW | 1370 |
| $C_{FAE(i)}$ | $tCO_2/tF$ | 3,1144 |
| $SFC_{AE}$ | g/kWh | 196 |
| ***Element 2*** | | 836278,688 |
| ***Element 3*** | | 0 |
| ***Element 4*** | | 0 |
| $f_i$ | -- | 1 |
| Capacity | m.tn | 29415 |
| $V_{ref}$ | kn | 26,86 |
| $f_w$ | -- | 1 |
| ***Denominator*** | t·kn | 789964,6604 |
| **EEDI** | $gCO_2/t·kn$ | 25,31 |

C (EEDI row)

D

| EEDI Calculation [Baseline GHG-WG 2/2/7] | | |
|---|---|---|
| **Parameters** | | |
| $f_j$ | -- | 1 |
| $f_i$ | -- | 1 |
| $f_w$ | -- | 1 |
| Capacity = GT | t | 29415 |
| $V_{ref}$ | kn | 26,86 |
| $SFC_{ME}$ | g/kWh | 190 |
| $SFC_{AE}$ | g/kWh | 210 |
| $C_{FME}$ | $tCO_2/tF$ | 3,13 |
| $C_{FAE}$ | $tCO_2/tF$ | 3,13 |
| $P_{ME}$ | kW | 33600 |
| $P_{AE}$ | kW | 1370 |
| **Calculation** | | |
| $f_j$ | -- | 1 |
| $P_{ME}$ | kW | 33600 |
| $C_{FME}$ | $tCO_2/tF$ | 3,13 |
| $SFC_{ME}$ | g/kWh | 190 |
| ***Element 1*** | | 19981920 |
| $P_{AE}$ | kW | 1370 |
| $C_{FAE(i)}$ | $tCO_2/tF$ | 3,13 |
| $SFC_{AE}$ | g/kWh | 210 |
| ***Element 2*** | | 900501 |
| ***Element 3*** | | 0 |
| ***Element 4*** | | 0 |
| $f_i$ | -- | 1 |
| Capacity | t | 29415 |
| $V_{ref}$ | kn | 26,86 |
| $f_w$ | -- | 1 |
| ***Denominator*** | t·kn | 789964,6604 |
| D **EEDI Average** | $gCO_2/t·kn$ | 26,43 |
| E **$EEDI_{Baseline}$ DWT** | $gCO_2/t·kn$ | 12,80 |

**Only RO-RO Carriers**

| **$\text{VENEFI}_{CO}$** | gCO$_2$/t·nm | | | | | | **44,85** |
|---|---|---|---|---|---|---|---|
| **Ship's Data** | | | | | | | |
| Capacity GT | m.tn | 29415 | 29415 | 29415 | 29415 | 29415 | 29415 |
| Passengers | | 1802 | 1802 | 1802 | 1802 | 1802 | 1802 |
| Cars | | 640 | 640 | 640 | 640 | 640 | 640 |
| Total Payload | m.tn | 820 | 820 | 820 | 820 | 820 | 820 |
| | | | | | | | |
| **Main Engines** | | | | | | | |
| $MCR_{ME(i)}$ | | 11200 | 11200 | 11200 | 11200 | 11200 | |
| i | | 4 | 4 | 4 | 4 | 4 | |
| $MCR_{ME}$ | | 44800 | 44800 | 44800 | 44800 | 44800 | |
| $C_{FME}$ | tCO$_2$/tF | 3,1144 | 3,1144 | 3,1144 | 3,1144 | 3,1144 | |
| $V_s$ | kn | 28 | 28 | 28 | 28 | 28 | |
| $c=P/V^3$ | -- | 1,734693878 | 1,734693878 | 1,734693878 | 1,734693878 | 1,734693878 | |
| | | | | | | | |
| **Diesel Generators** | | | | | | | |
| $P_{AE\ Diesel(i)}$ | kW | 1260 | 1260 | 1260 | 1260 | 1260 | |
| i | | 3 | 3 | 3 | 3 | 3 | |
| $P_{AE\ Diesel}$ | kW | 3780 | 3780 | 3780 | 3780 | 3780 | |
| $C_{FAE\ Diesel}$ | tCO$_2$/tF | 3,1144 | 3,1144 | 3,1144 | 3,1144 | 3,1144 | |
| | | | | | | | |
| **Shaft Generators** | | | | | | | |
| $P_{AE\ Shaft(i)}$ | kW | 1200 | 1200 | 1200 | 1200 | 1200 | |
| i | | 2 | 2 | 2 | 2 | 2 | |
| $P_{AE\ Shaft}$ | kW | 2400 | 2400 | 2400 | 2400 | 2400 | |
| | | | | | | | |
| | | $t_1$ | $t_2$ | $t_{3a}$ | $t_{3b}$ | $t_4$ | T |
| **t** | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| | | | | | | | |
| **Main Engines** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| Load Factor | % | 0,85 | 0,5 | 0,5 | 0,2 | 0 | |
| $P_{ME}$ | kW | 38080 | 22400 | 22400 | 8960 | 0 | |
| $SFC_{ME}$ | g/kWh | 174,24 | 184,08 | 184,08 | 200,57 | | |
| $\Sigma_{ME}$ | gF | 150615843,8 | 0 | 12370176 | 5840598,4 | 0 | 168826618,2 |
| | | | | | | | |
| **Diesel Generators** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| i | -- | 1 | 1 | 1 | 1 | 1 | |
| Load Factor | % | 0,75 | 0,75 | 0,5 | 0,5 | 0,75 | |
| $P_{AE\ Diesel}$ | kW | 945 | 945 | 630 | 630 | 945 | |
| $SFC_{AE\ Diesel}$ | g/kWh | 188,02 | 188,02 | 191,73 | 191,73 | 188,02 | |
| $\Sigma_{AE\ Diesel}$ | gF | 4033311,03 | 0 | 362369,7 | 392567,175 | 3384783,045 | 8173030,95 |
| | | | | | | | |
| **Shaft Generators (PTO)** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| i | -- | 1 | 1 | 1 | 1 | 0 | |
| Load Factor | % | 0,85 | 0,85 | 0,7 | 0,7 | | |
| $P_{PTO}$ | kW | 1020 | 1020 | 840 | 840 | 0 | |
| $n_{eff.}$ | -- | 0,92 | 0,92 | 0,92 | 0,92 | 0,92 | |
| $P_{PTO}$ | kW | 938,4 | 938,4 | 772,8 | 772,8 | 0 | |
| $SFC_{ME}$ | g/kWh | 174,24 | 184,08 | 184,08 | 200,57 | 0 | |
| $\Sigma_{PTO}$ | gF | 4034352,96 | 0 | 463881,6 | 547556,1 | 0 | 5045790,66 |
| | | | | | | | |
| **Shaft Generators (PTI)** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| i | -- | 0 | 0 | 0 | 0 | 0 | |
| Load Factor | % | 0,85 | 0,85 | 0,85 | 0,85 | | |
| $P_{PTI}$ | kW | 0 | 0 | 0 | 0 | 0 | |
| $n_{eff.}$ | -- | 0,92 | 0,92 | 0,92 | 0,92 | 0,92 | |
| $P_{PTI}$ | kW | 0 | 0 | 0 | 0 | 0 | |
| $SFC_{AE}$ | g/kWh | 188,02 | 188,02 | 191,73 | 191,73 | 188,02 | |
| $\Sigma_{PTI}$ | gF | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| | **Propulsion Energy** | | | | | | | |
| | t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| | $P_{\text{Propulsion}}$ | kW | 37060 | 21380 | 21560 | 8120 | 0 | |
| | $\Sigma_{\text{Propulsion}}$ | gF | 146581490,9 | 0 | 11906294,4 | 5293042,3 | 0 | 163780827,6 |
| | V | kn | 27,75 | 23,10 | 23,16 | 16,73 | | |
| | | | | | | | | |
| | **Auxiliary Energy** | | | | | | | |
| | t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| | $P_{\text{AE Required}}$ | kW | 1850 | 1750 | 1300 | 1300 | 900 | |
| | $P_{\text{Auxiliary}}$ | kW | 1883,4 | 1883,4 | 1402,8 | 1402,8 | 945 | |
| | $\Sigma_{\text{Auxiliary}}$ | gF | 8067663,99 | 0 | 826251,3 | 940123,275 | 3384783,045 | 13218821,61 |
| | | | | | | | | |
| | **Fuel Consumption** | | | | | | | |
| | $\Sigma_{\text{ME}}$ | gF | 150615843,8 | 0 | 12370176 | 5840598,4 | 0 | 168826618,2 |
| | $\Sigma_{\text{AE Diesel}}$ | gF | 4033311,03 | 0 | 362369,7 | 392567,175 | 3384783,045 | 8173030,95 |
| | $\Sigma_{\text{PTO}}$ | gF | 4034352,96 | 0 | 463881,6 | 547556,1 | 0 | 5045790,66 |
| | $\Sigma_{\text{PTI}}$ | gF | 0 | 0 | 0 | 0 | 0 | 0 |
| | $\Sigma_{\text{Propulsion}}$ | gF | 146581490,9 | 0 | 11906294,4 | 5293042,3 | 0 | 163780827,6 |
| | $\Sigma_{\text{Auxiliary}}$ | gF | 8067663,99 | 0 | 826251,3 | 940123,275 | 3384783,045 | 13218821,61 |
| | $\Sigma$ | gF | 154649154,9 | 0 | 12732545,7 | 6233165,575 | 3384783,045 | 176999649,2 |
| | | | | | | | | |
| | **Emissions** | | | | | | | |
| | $\Sigma_{\text{ME}}$ | $gCO_2$ | 469077984,1 | 0 | 38525676,13 | 18189959,66 | 0 | 525793619,8 |
| | $\Sigma_{\text{AE Diesel}}$ | $gCO_2$ | 12561343,87 | 0 | 1128564,194 | 1222611,21 | 10541568,32 | 14912519,28 |
| | $\Sigma_{\text{PTO}}$ | $gCO_2$ | 12564588,86 | 0 | 1444712,855 | 1705308,718 | 0 | 15714610,43 |
| | $\Sigma_{\text{PTI}}$ | $gCO_2$ | 0 | 0 | 0 | 0 | 0 | 0 |
| | $\Sigma_{\text{Propulsion}}$ | $gCO_2$ | 456513395,2 | 0 | 37080963,28 | 16484650,94 | 0 | 510079009,4 |
| | $\Sigma_{\text{Auxiliary}}$ | $gCO_2$ | 25125932,73 | 0 | 2573277,049 | 2927919,928 | 10541568,32 | 30627129,71 |
| | $\Sigma$ | $gCO_2$ | 481639327,9 | 0 | 39654240,33 | 19412570,87 | 10541568,32 | 540706139,1 |
| | | | | | | | | |
| | Denominator | m.tn | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 |
| | $V_{\text{ref}}$ | kn | 27,75 | 23,10 | 23,16 | 16,73 | | |
| | ***Denominator*** | t·nm | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 |
| **F** | **$\text{VENEFI}_{\text{OS(D)}}$** | $gCO_2$/t·nm | **39,95** | **N/A** | -- | -- | -- | -- |
| **G** | **$\text{VENEFI}_{\text{OS(S)}}$** | $tCO_2$/h | -- | -- | **13,22** | **5,97** | **0,55** | -- |
| **H** | **$\text{VENEFI}_{\text{CO}}$** | $gCO_2$/t·nm | | | | | | **44,85** |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | **Transport Work Calculation** | | | | | | | |
| | PIRAEUS - THIRA | 1 | | | | | | |
| | Passengers | -- | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| | LF | -- | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 |
| | Cars | -- | 600 | 600 | 600 | 600 | 600 | 600 |
| | LF | -- | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 |
| | $DWT_{\text{Ref}}$ | t | 25553 | 25553 | 25553 | 25553 | 25553 | 25553 |
| | Distance | nm | 130 | 130 | 130 | 130 | 130 | 130 |
| | $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| | Denominator | t·nm | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 |
| | THIRA - KOS | 2 | | | | | | |
| | Passengers | -- | 1118 | 1118 | 1118 | 1118 | 1118 | 1118 |
| | LF | -- | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 |
| | Cars | -- | 401 | 401 | 401 | 401 | 401 | 401 |
| | LF | -- | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 |
| | $DWT_{\text{Ref}}$ | t | 17388 | 17388 | 17388 | 17388 | 17388 | 17388 |
| | Distance | nm | 108 | 108 | 108 | 108 | 108 | 108 |
| | $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| | Denominator | t·nm | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| KOS - RHODES | 3 | | | | | | |
| Passengers | -- | 952 | 952 | 952 | 952 | 952 | 952 |
| LF | -- | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 |
| Cars | -- | 284 | 284 | 284 | 284 | 284 | 284 |
| LF | -- | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 |
| $DWT_{Ref}$ | t | 12746 | 12746 | 12746 | 12746 | 12746 | 12746 |
| Distance | nm | 65 | 65 | 65 | 65 | 65 | 65 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 828476 | 828476 | 828476 | 828476 | 828476 | 828476 |
| RHODES - KOS | 4 | | | | | | |
| Passengers | -- | 952 | 952 | 952 | 952 | 952 | 952 |
| LF | -- | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 |
| Cars | -- | 284 | 284 | 284 | 284 | 284 | 284 |
| LF | -- | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 |
| $DWT_{Ref}$ | t | 12746 | 12746 | 12746 | 12746 | 12746 | 12746 |
| Distance | nm | 65 | 65 | 65 | 65 | 65 | 65 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 828476 | 828476 | 828476 | 828476 | 828476 | 828476 |
| KOS - THIRA | 5 | | | | | | |
| Passengers | -- | 1118 | 1118 | 1118 | 1118 | 1118 | 1118 |
| LF | -- | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 |
| Cars | -- | 401 | 401 | 401 | 401 | 401 | 401 |
| LF | -- | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 |
| $DWT_{Ref}$ | t | 17388 | 17388 | 17388 | 17388 | 17388 | 17388 |
| Distance | nm | 108 | 108 | 108 | 108 | 108 | 108 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 |
| THIRA - PIRAEUS | 6 | | | | | | |
| Passengers | -- | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| LF | -- | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 |
| Cars | -- | 600 | 600 | 600 | 600 | 600 | 600 |
| LF | -- | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 |
| $DWT_{Ref}$ | t | 25553 | 25553 | 25553 | 25553 | 25553 | 25553 |
| Distance | nm | 130 | 130 | 130 | 130 | 130 | 130 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 |
| | | | | | | | |
| **Total Distance** | nm | 606 | 606 | 606 | 606 | 606 | 606 |
| **Transport Work** | t·nm | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 |

| | | $t_1$ | $t_2$ | $t_{3a}$ | $t_{3b}$ | $t_4$ |
|---|---|---|---|---|---|---|
| $P_{AE\ Required}$ | kW | 1850 | 1750 | 1300 | 1300 | 900 |
| $P_{AE\ Produced}$ | kW | 1883,4 | 1883,4 | 1402,8 | 1402,8 | 945 |
| n (surplus energ.) | -- | 0,018054054 | 0,076228571 | 0,079076923 | 0,079076923 | 0,05 |
| $P_{AE\ Green}$ | kW | 0 | 0 | 0 | 0 | 0 |
| $P_{AE\ Emissions}$ | kW | 1883 | 1883 | 1403 | 1403 | 945 |
| $P_{AE\ Diesel\ Gens}$ | kW | 863 | 863 | 563 | 563 | 945 |
| $P_{AE\ Shaft\ Gens}$ | kW | 1020 | 1020 | 840 | 840 | 0 |

| **Ship's Data** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Name | | BLUE STAR 1 | BLUE STAR 1 | BLUE STAR 1 | BLUE STAR 1 | BLUE STAR 1 | BLUE STAR 1 |
| IMO No. | | 9197105 | 9197105 | 9197105 | 9197105 | 9197105 | 9197105 |
| Type | | Pas/RoRo | Pas/RoRo | Pas/RoRo | Pas/RoRo | Pas/RoRo | Pas/RoRo |
| Ice Class | | No | No | No | No | No | No |
| DOB | Y-M | 200005 | 200005 | 200005 | 200005 | 200005 | 200005 |
| $L_{BP}$ | m | 160,575 | 160,575 | 160,575 | 160,575 | 160,575 | 160,575 |
| B | m | 25,7 | 25,7 | 25,7 | 25,7 | 25,7 | 25,7 |
| $T_{design}$ | m | N/A | N/A | N/A | N/A | N/A | N/A |
| $T_{summer}$ | m | 6,45 | 6,45 | 6,45 | 6,45 | 6,45 | 6,45 |
| DWT | m.tn | 4500 | 4500 | 4500 | 4500 | 4500 | 4500 |
| GT | m.tn | 29415 | 29415 | 29415 | 29415 | 29415 | 29415 |
| Max. Passengers | -- | 1802 | 1802 | 1802 | 1802 | 1802 | 1802 |
| Max. Cars | -- | 640 | 640 | 640 | 640 | 640 | 640 |
| $V_{SERVICE}$ | kn | 28 | 28 | 28 | 28 | 28 | 28 |
| $V_{AVERAGE\ (AIS)}$ | kn | | | | | | |
| $V_{MAX\ (AIS)}$ | kn | | | | | | |
| | | | | | | | |
| **Main Engines** | | 4 | 4 | 4 | 4 | 4 | 4 |
| Propulsion | | Diesel Oil Eng. | Diesel Oil Eng. | Diesel Oil Eng. | Diesel Oil Eng. | Diesel Oil Eng. | Diesel Oil Eng. |
| Drive | | Geared Drive | Geared Drive | Geared Drive | Geared Drive | Geared Drive | Geared Drive |
| Manufacturer | | MAN B&W | MAN B&W | MAN B&W | MAN B&W | MAN B&W | MAN B&W |
| Stroke Type | | 4 | 4 | 4 | 4 | 4 | 4 |
| ME Type | | 8L58/64 | 8L58/64 | 8L58/64 | 8L58/64 | 8L58/64 | 8L58/64 |
| Power | kW | 11200 | 11200 | 11200 | 11200 | 11200 | 11200 |
| RPM | rpm | 428 | 428 | 428 | 428 | 428 | 428 |
| $SFC_{100\%\ Load}$ | g/kWh | 174 | 174 | 174 | 174 | 174 | 174 |
| $SFC_{85\%\ Load}$ | g/kWh | 173 | 173 | 173 | 173 | 173 | 173 |
| $SFC_{75\%\ Load}$ | g/kWh | 177 | 177 | 177 | 177 | 177 | 177 |
| $SFC_{50\%\ Load}$ | g/kWh | 186 | 186 | 186 | 186 | 186 | 186 |
| $SFC_{25\%\ Load}$ | g/kWh | 199 | 199 | 199 | 199 | 199 | 199 |
| Fuel Type | cSt | HFO380 | HFO380 | HFO380 | HFO380 | HFO380 | HFO380 |
| **Total Power** | **kW** | **44800** | **44800** | **44800** | **44800** | **44800** | **44800** |
| | | | | | | | |
| **Aux. Engines** | | 1 | 1 | 1 | 1 | 1 | 1 |
| **Type 1** | | | | | | | |
| Manufacturer | | | | | | | |
| Stroke Type | | | | | | | |
| Type | | | | | | | |
| Max Power | kW | | | | | | |
| RPM | rpm | | | | | | |
| Cylinders | | | | | | | |
| $SFC_{100\%\ Load}$ | g/kWh | | | | | | |
| $SFC_{85\%\ Load}$ | g/kWh | | | | | | |
| $SFC_{75\%\ Load}$ | g/kWh | | | | | | |
| $SFC_{50\%\ Load}$ | g/kWh | | | | | | |
| $SFC_{25\%\ Load}$ | g/kWh | | | | | | |
| Fuel Type | cSt | | | | | | |
| **Type 2** | | 1 | 1 | 1 | 1 | 1 | 1 |
| Manufacturer | | CATERPILLAR | CATERPILLAR | CATERPILLAR | CATERPILLAR | CATERPILLAR | CATERPILLAR |
| Stroke Type | | 4 | 4 | 4 | 4 | 4 | 4 |
| Type | | 3408DITA | 3408DITA | 3408DITA | 3408DITA | 3408DITA | 3408DITA |
| Max Power | kW | 400 | 400 | 400 | 400 | 400 | 400 |
| RPM | rpm | | | | | | |
| Cylinders | | 8 | 8 | 8 | 8 | 8 | 8 |
| **Total Power** | **kW** | **400** | **400** | **400** | **400** | **400** | **400** |
| | | | | | | | |
| **Main Generat.** | | | | | | | |
| Manufacturer | | | | | | | |
| Type | kVA | | | | | | |
| PF | -- | | | | | | |
| Power | kW | | | | | | |
| RPM | rpm | | | | | | |
| SFC | g/kWh | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Fuel Type | cSt | | | | | | |
| Frequency | Hz | | | | | | |
| Voltage 1 | V | | | | | | |
| **Total Power** | **kW** | | | | | | |
| | | | | | | | |
| **Aux. Generat.** | | 5 | 5 | 5 | 5 | 5 | 5 |
| **Diesel Gens** | | 3 | 3 | 3 | 3 | 3 | 3 |
| Manufacturer | | MAN B&W | MAN B&W | MAN B&W | MAN B&W | MAN B&W | MAN B&W |
| Type | | 6L28/32H | 6L28/32H | 6L28/32H | 6L28/32H | 6L28/32H | 6L28/32H |
| Power | kW | 1260 | 1260 | 1260 | 1260 | 1260 | 1260 |
| RPM | rpm | 720 | 720 | 720 | 720 | 720 | 720 |
| $SFC_{100\%\ Load}$ | g/kWh | 196 | 196 | 196 | 196 | 196 | 196 |
| $SFC_{85\%\ Load}$ | g/kWh | 196 | 196 | 196 | 196 | 196 | 196 |
| $SFC_{75\%\ Load}$ | g/kWh | 197 | 197 | 197 | 197 | 197 | 197 |
| $SFC_{50\%\ Load}$ | g/kWh | 201 | 201 | 201 | 201 | 201 | 201 |
| $SFC_{25\%\ Load}$ | g/kWh | | | | | | |
| Fuel Type | cSt | HFO380 | HFO380 | HFO380 | HFO380 | HFO380 | HFO380 |
| Frequency | Hz | 60 | 60 | 60 | 60 | 60 | 60 |
| Voltage 1 | V | 440 | 440 | 440 | 440 | 440 | 440 |
| Voltage 2 | V | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total Diesel P** | **kW** | **3780** | **3780** | **3780** | **3780** | **3780** | **3780** |
| **Shaft Gens** | | 2 | 2 | 2 | 2 | 2 | 2 |
| Manufacturer | | LEROY | LEROY | LEROY | LEROY | LEROY | LEROY |
| Type | | LSA | LSA | LSA | LSA | LSA | LSA |
| Power | kW | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 |
| Frequency | Hz | 60 | 60 | 60 | 60 | 60 | 60 |
| Voltage 1 | V | 440 | 440 | 440 | 440 | 440 | 440 |
| Voltage 2 | V | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total Shaft P** | **kW** | **2400** | **2400** | **2400** | **2400** | **2400** | **2400** |
| **Total Power** | **kW** | **6180** | **6180** | **6180** | **6180** | **6180** | **6180** |
| | | | | | | | |
| **Propellers** | | 2 | 2 | 2 | 2 | 2 | 2 |
| Manufacturer | | KAMEWA | KAMEWA | KAMEWA | KAMEWA | KAMEWA | KAMEWA |
| Type | | CPP | CPP | CPP | CPP | CPP | CPP |
| RPM | rpm | 149 | 149 | 149 | 149 | 149 | 149 |
| Electric Motor | kW | | | | | | |
| D | m | 5,4 | 5,4 | 5,4 | 5,4 | 5,4 | 5,4 |
| **Total Power** | **kW** | **0** | **0** | **0** | **0** | **0** | **0** |
| | | | | | | | |
| **Thrusters** | | 2 | 2 | 2 | 2 | 2 | 2 |
| **Foreward** | | 2 | 2 | 2 | 2 | 2 | 2 |
| Manufacturer | | KAMEWA | KAMEWA | KAMEWA | KAMEWA | KAMEWA | KAMEWA |
| Type | | CPT | CPT | CPT | CPT | CPT | CPT |
| Power kW | kW | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 |
| **Aftward** | | 0 | 0 | 0 | 0 | 0 | 0 |
| Manufacturer | | | | | | | |
| Type | | | | | | | |
| Power | kW | | | | | | |
| **Total Power** | | **2400** | **2400** | **2400** | **2400** | **2400** | **2400** |

**BS1 Calculation Assuming No PTO**

| **$\text{VENEFI}_{CO}$** | $gCO_2/t\cdot nm$ | | | | | | **40,98** |
|---|---|---|---|---|---|---|---|
| **Ship's Data** | | | | | | | |
| Capacity GT | m.tn | 29415 | 29415 | 29415 | 29415 | 29415 | 29415 |
| Passengers | | 1802 | 1802 | 1802 | 1802 | 1802 | 1802 |
| Cars | | 640 | 640 | 640 | 640 | 640 | 640 |
| Total Payload | m.tn | 820 | 820 | 820 | 820 | 820 | 820 |
| | | | | | | | |
| **Main Engines** | | | | | | | |
| $MCR_{ME(i)}$ | | 11200 | 11200 | 11200 | 11200 | 11200 | |
| i | | 4 | 4 | 4 | 4 | 4 | |
| $MCR_{ME}$ | | 44800 | 44800 | 44800 | 44800 | 44800 | |
| $C_{FME}$ | $tCO_2/tF$ | 3,1144 | 3,1144 | 3,1144 | 3,1144 | 3,1144 | |
| $V_s$ | kn | 28 | 28 | 28 | 28 | 28 | |
| $c=P/V^3$ | -- | 1,734693878 | 1,734693878 | 1,734693878 | 1,734693878 | 1,734693878 | |
| | | | | | | | |
| **Diesel Generators** | | | | | | | |
| $P_{AE\ Diesel(i)}$ | kW | 1260 | 1260 | 1260 | 1260 | 1260 | |
| i | | 3 | 3 | 3 | 3 | 3 | |
| $P_{AE\ Diesel}$ | kW | 3780 | 3780 | 3780 | 3780 | 3780 | |
| $C_{FAE\ Diesel}$ | $tCO_2/tF$ | 3,1144 | 3,1144 | 3,1144 | 3,1144 | 3,1144 | |
| | | | | | | | |
| **Shaft Generators** | | | | | | | |
| $P_{AE\ Shaft(i)}$ | kW | 1200 | 1200 | 1200 | 1200 | 1200 | |
| i | | 2 | 2 | 2 | 2 | 2 | |
| $P_{AE\ Shaft}$ | kW | 2400 | 2400 | 2400 | 2400 | 2400 | |
| | | | | | | | |
| | | $t_1$ | $t_2$ | $t_{3a}$ | $t_{3b}$ | $t_4$ | T |
| **t** | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| | | | | | | | |
| **Main Engines** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| Load Factor | % | 0,73 | 0,5 | 0,5 | 0,2 | 0 | |
| $P_{ME}$ | kW | 32704 | 22400 | 22400 | 8960 | 0 | |
| $SFC_{ME}$ | g/kWh | 176,09 | 184,08 | 184,08 | 200,57 | | |
| $\Sigma_{ME}$ | gF | 130725835,1 | 0 | 12370176 | 5840598,4 | 0 | 148936609,5 |
| | | | | | | | |
| **Diesel Generators** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| i | -- | 2 | 2 | 2 | 2 | 1 | |
| Load Factor | % | 0,75 | 0,75 | 0,55 | 0,55 | 0,75 | |
| $P_{AE\ Diesel}$ | kW | 1890 | 1890 | 1386 | 1386 | 945 | |
| $SFC_{AE\ Diesel}$ | g/kWh | 188,02 | 188,02 | 190,85 | 190,85 | 188,02 | |
| $\Sigma_{AE\ Diesel}$ | gF | 8066622,06 | 0 | 793554,3 | 859683,825 | 3384783,045 | 13104643,23 |
| | | | | | | | |
| **Shaft Generators (PTO)** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| i | -- | 0 | 0 | 0 | 0 | 0 | |
| Load Factor | % | 0,85 | 0,5 | 0,5 | 0,2 | 0 | |
| $P_{PTO}$ | kW | 0 | 0 | 0 | 0 | 0 | |
| $n_{eff.}$ | -- | 0,92 | 0,92 | 0,92 | 0,92 | 0,92 | |
| $P_{PTO}$ | kW | 0 | 0 | 0 | 0 | 0 | |
| $SFC_{ME}$ | g/kWh | 176,09 | 184,08 | 184,08 | 200,57 | 0 | |
| $\Sigma_{PTO}$ | gF | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | |
| **Shaft Generators (PTI)** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| i | -- | 0 | 0 | 0 | 0 | 0 | |
| Load Factor | % | 0,85 | 0,5 | 0,5 | 0,2 | 0 | |
| $P_{PTI}$ | kW | 0 | 0 | 0 | 0 | 0 | |
| $n_{eff.}$ | -- | 0,92 | 0,92 | 0,92 | 0,92 | 0,92 | |
| $P_{PTI}$ | kW | 0 | 0 | 0 | 0 | 0 | |
| $SFC_{AE}$ | g/kWh | 188,02 | 188,02 | 190,85 | 190,85 | 188,02 | |
| $\Sigma_{PTI}$ | gF | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | |
| **Propulsion Energy** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| $P_{Propulsion}$ | kW | 32704 | 22400 | 22400 | 8960 | 0 | |
| $\Sigma_{Propulsion}$ | gF | 130725835,1 | 0 | 12370176 | 5840598,4 | 0 | 148936609,5 |
| V | kn | 26,61 | 23,46 | 23,46 | 17,29 | | |
| | | | | | | | |
| **Auxiliary Energy** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| $P_{AE\ Required}$ | kW | 1850 | 1750 | 1300 | 1300 | 900 | |
| $P_{Auxiliary}$ | kW | 1890 | 1890 | 1386 | 1386 | 945 | |
| $\Sigma_{Auxiliary}$ | gF | 8066622,06 | 0 | 793554,3 | 859683,825 | 3384783,045 | 13104643,23 |
| | | | | | | | |
| **Fuel Consumption** | | | | | | | |
| $\Sigma_{ME}$ | gF | 130725835,1 | 0 | 12370176 | 5840598,4 | 0 | 148936609,5 |
| $\Sigma_{AE\ Diesel}$ | gF | 8066622,06 | 0 | 793554,3 | 859683,825 | 3384783,045 | 13104643,23 |
| $\Sigma_{PTO}$ | gF | 0 | 0 | 0 | 0 | 0 | 0 |
| $\Sigma_{PTI}$ | gF | 0 | 0 | 0 | 0 | 0 | 0 |
| $\Sigma_{Propulsion}$ | gF | 130725835,1 | 0 | 12370176 | 5840598,4 | 0 | 148936609,5 |
| $\Sigma_{Auxiliary}$ | gF | 8066622,06 | 0 | 793554,3 | 859683,825 | 3384783,045 | 13104643,23 |
| $\Sigma$ | gF | 138792457,1 | 0 | 13163730,3 | 6700282,225 | 3384783,045 | 162041252,7 |
| | | | | | | | |
| **Emissions** | | | | | | | |
| $\Sigma_{ME}$ | $gCO_2$ | 407132540,7 | 0 | 38525676,13 | 18189959,66 | 0 | 463848176,5 |
| $\Sigma_{AE\ Diesel}$ | $gCO_2$ | 25122687,74 | 0 | 2471445,512 | 2677399,305 | 10541568,32 | 30271532,56 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\Sigma_{PTO}$ | $gCO_2$ | 0 | 0 | 0 | 0 | 0 | 0 |
| $\Sigma_{PTI}$ | $gCO_2$ | 0 | 0 | 0 | 0 | 0 | 0 |
| $\Sigma_{Propulsion}$ | $gCO_2$ | 407132540,7 | 0 | 38525676,13 | 18189959,66 | 0 | 463848176,5 |
| $\Sigma_{Auxiliary}$ | $gCO_2$ | 25122687,74 | 0 | 2471445,512 | 2677399,305 | 10541568,32 | 30271532,56 |
| $\Sigma$ | $gCO_2$ | 432255228,5 | 0 | 40997121,65 | 20867358,96 | 10541568,32 | 494119709,1 |
| | | | | | | | |
| Denominator | m.tn | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 |
| $V_{ref}$ | kn | 26,61 | 23,46 | 23,46 | 17,29 | | |
| ***Denominator*** | t·nm | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 |
| | | | | | | | |
| **$VENEFI_{OS(D)}$** | $gCO_2/t·nm$ | **35,85** | **N/A** | -- | -- | -- | -- |
| **$VENEFI_{OS(S)}$** | $tCO_2/h$ | **19,04** | -- | **13,67** | **6,42** | **0,55** | -- |
| **$VENEFI_{CO}$** | $gCO_2/t·nm$ | -- | -- | -- | -- | -- | **40,98** |
| | | | | | | | |
| **$VENEFI_{OS(D)\,(PE)}$** | $gCO_2/t·nm$ | **33,77** | **N/A** | -- | -- | -- | |
| **$VENEFI_{OS(S)\,(PE)}$** | $tCO_2/h$ | **17,94** | **N/A** | **12,84** | **5,60** | **0,00** | |
| **$VENEFI_{CO\,(PE)}$** | $gCO_2/t·nm$ | -- | -- | -- | -- | -- | **38,47** |
| | | | | | | | |
| **$VENEFI_{OS(D)\,(AE)}$** | $gCO_2/t·nm$ | **2,08** | **N/A** | -- | -- | -- | -- |
| **$VENEFI_{OS(S)\,(AE)}$** | $tCO_2/h$ | **1,11** | **N/A** | **0,82** | **0,82** | **0,55** | -- |
| **$VENEFI_{CO\,(AE)}$** | $gCO_2/t·nm$ | -- | -- | -- | -- | -- | **2,51** |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| **Transport Work Calculation** | | | | | | | |
| PIRAEUS - THIRA | 1 | | | | | | |
| Passengers | -- | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| LF | -- | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 |
| Cars | -- | 600 | 600 | 600 | 600 | 600 | 600 |
| LF | -- | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 |
| $DWT_{Ref}$ | t | 25553 | 25553 | 25553 | 25553 | 25553 | 25553 |
| Distance | nm | 130 | 130 | 130 | 130 | 130 | 130 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 |
| THIRA - KOS | 2 | | | | | | |
| Passengers | -- | 1118 | 1118 | 1118 | 1118 | 1118 | 1118 |
| LF | -- | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 |
| Cars | -- | 401 | 401 | 401 | 401 | 401 | 401 |
| LF | -- | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 |
| $DWT_{Ref}$ | t | 17388 | 17388 | 17388 | 17388 | 17388 | 17388 |
| Distance | nm | 108 | 108 | 108 | 108 | 108 | 108 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 |
| KOS - RHODES | 3 | | | | | | |
| Passengers | -- | 952 | 952 | 952 | 952 | 952 | 952 |
| LF | -- | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 |
| Cars | -- | 284 | 284 | 284 | 284 | 284 | 284 |
| LF | -- | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 |
| $DWT_{Ref}$ | t | 12746 | 12746 | 12746 | 12746 | 12746 | 12746 |
| Distance | nm | 65 | 65 | 65 | 65 | 65 | 65 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 828476 | 828476 | 828476 | 828476 | 828476 | 828476 |
| RHODES - KOS | 4 | | | | | | |
| Passengers | -- | 952 | 952 | 952 | 952 | 952 | 952 |
| LF | -- | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 |
| Cars | -- | 284 | 284 | 284 | 284 | 284 | 284 |
| LF | -- | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 |
| $DWT_{Ref}$ | t | 12746 | 12746 | 12746 | 12746 | 12746 | 12746 |
| Distance | nm | 65 | 65 | 65 | 65 | 65 | 65 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 828476 | 828476 | 828476 | 828476 | 828476 | 828476 |
| KOS - THIRA | 5 | | | | | | |
| Passengers | -- | 1118 | 1118 | 1118 | 1118 | 1118 | 1118 |
| LF | -- | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 |
| Cars | -- | 401 | 401 | 401 | 401 | 401 | 401 |
| LF | -- | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 |
| $DWT_{Ref}$ | t | 17388 | 17388 | 17388 | 17388 | 17388 | 17388 |
| Distance | nm | 108 | 108 | 108 | 108 | 108 | 108 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 |
| THIRA - PIRAEUS | 6 | | | | | | |
| Passengers | -- | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| LF | -- | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 |
| Cars | -- | 600 | 600 | 600 | 600 | 600 | 600 |
| LF | -- | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 |
| $DWT_{Ref}$ | t | 25553 | 25553 | 25553 | 25553 | 25553 | 25553 |
| Distance | nm | 130 | 130 | 130 | 130 | 130 | 130 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 |
| | | | | | | | |
| **Total Distance** | nm | 606 | 606 | 606 | 606 | 606 | 606 |
| **Transport Work** | t·nm | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 |

| | | $t_1$ | $t_2$ | $t_{3a}$ | $t_{3b}$ | $t_4$ |
|---|---|---|---|---|---|---|
| $P_{AE\ Required}$ | kW | 1850 | 1750 | 1300 | 1300 | 900 |
| $P_{AE\ Produced}$ | kW | 1890 | 1890 | 1386 | 1386 | 945 |
| n (surplus energ.) | -- | 0,021621622 | 0,08 | 0,066153846 | 0,066153846 | 0,05 |
| $P_{AE\ Green}$ | kW | 0 | 0 | 0 | 0 | 0 |
| $P_{AE\ Emissions}$ | kW | 1890 | 1890 | 1386 | 1386 | 945 |
| $P_{AE\ Diesel\ Gens}$ | kW | 1890 | 1890 | 1386 | 1386 | 945 |
| $P_{AE\ Shaft\ Gens}$ | kW | 0 | 0 | 0 | 0 | 0 |

## BS1 Calculation Assuming PTO

| **$VENEFI_{CO}$** | $gCO_2/t\cdot nm$ | | | | | | **40,73** |
|---|---|---|---|---|---|---|---|
| **Ship's Data** | | | | | | | |
| Capacity GT | m.tn | 29415 | 29415 | 29415 | 29415 | 29415 | 29415 |
| Passengers | | 1802 | 1802 | 1802 | 1802 | 1802 | 1802 |
| Cars | | 640 | 640 | 640 | 640 | 640 | 640 |
| Total Payload | m.tn | 820 | 820 | 820 | 820 | 820 | 820 |
| | | | | | | | |
| **Main Engines** | | | | | | | |
| $MCR_{ME(i)}$ | | 11200 | 11200 | 11200 | 11200 | 11200 | |
| i | | 4 | 4 | 4 | 4 | 4 | |
| $MCR_{ME}$ | | 44800 | 44800 | 44800 | 44800 | 44800 | |
| $C_{FME}$ | $tCO_2/tF$ | 3,1144 | 3,1144 | 3,1144 | 3,1144 | 3,1144 | |
| $V_s$ | kn | 28 | 28 | 28 | 28 | 28 | |
| $c=P/V^3$ | -- | 1,734693878 | 1,734693878 | 1,734693878 | 1,734693878 | 1,734693878 | |
| | | | | | | | |
| **Diesel Generators** | | | | | | | |
| $P_{AE\ Diesel(i)}$ | kW | 1260 | 1260 | 1260 | 1260 | 1260 | |
| i | | 3 | 3 | 3 | 3 | 3 | |
| $P_{AE\ Diesel}$ | kW | 3780 | 3780 | 3780 | 3780 | 3780 | |
| $C_{FAE\ Diesel}$ | $tCO_2/tF$ | 3,1144 | 3,1144 | 3,1144 | 3,1144 | 3,1144 | |
| | | | | | | | |
| **Shaft Generators** | | | | | | | |
| $P_{AE\ Shaft(i)}$ | kW | 1200 | 1200 | 1200 | 1200 | 1200 | |
| i | | 2 | 2 | 2 | 2 | 2 | |
| $P_{AE\ Shaft}$ | kW | 2400 | 2400 | 2400 | 2400 | 2400 | |
| | | | | | | | |
| | | $t_1$ | $t_2$ | $t_{3a}$ | $t_{3b}$ | $t_4$ | T |
| **t** | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| | | | | | | | |
| **Main Engines** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| Load Factor | % | 0,75 | 0,5 | 0,5 | 0,2 | 0 | |
| $P_{ME}$ | kW | 33600 | 22400 | 22400 | 8960 | 0 | |
| $SFC_{ME}$ | g/kWh | 175,66 | 184,08 | 184,08 | 200,57 | | |
| $\Sigma_{ME}$ | gF | 133979395,2 | 0 | 12370176 | 5840598,4 | 0 | 152190169,6 |
| | | | | | | | |
| **Diesel Generators** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| i | -- | 1 | 1 | 1 | 1 | 1 | |
| Load Factor | % | 0,82 | 0,97 | 0,6 | 0,88 | 0,75 | |
| $P_{AE\ Diesel}$ | kW | 1033,2 | 1222,2 | 756 | 1108,8 | 945 | |
| $SFC_{AE\ Diesel}$ | g/kWh | 187,5 | 188,02 | 187,6 | 187,39 | 188,02 | |
| $\Sigma_{AE\ Diesel}$ | gF | 4397557,5 | 0 | 425476,8 | 675278,604 | 3384783,045 | 8883095,949 |
| | | | | | | | |
| **Shaft Generators (PTO)** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| i | -- | 1 | 1 | 1 | 1 | 0 | |
| Load Factor | % | 0,75 | 0,5 | 0,5 | 0,2 | | |
| $P_{PTO}$ | kW | 900 | 600 | 600 | 240 | 0 | |
| $n_{eff.}$ | -- | 0,92 | 0,92 | 0,92 | 0,92 | 0,92 | |
| $P_{PTO}$ | kW | 828 | 552 | 552 | 220,8 | 0 | |
| $SFC_{ME}$ | g/kWh | 175,66 | 184,08 | 184,08 | 200,57 | 0 | |
| $\Sigma_{PTO}$ | gF | 3588733,8 | 0 | 331344 | 156444,6 | 0 | 4076522,4 |
| | | | | | | | |
| **Shaft Generators (PTI)** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| i | -- | 0 | 0 | 0 | 0 | 0 | |
| Load Factor | % | 0,85 | 0,85 | 0,85 | 0,85 | | |
| $P_{PTI}$ | kW | 0 | 0 | 0 | 0 | 0 | |
| $n_{eff.}$ | -- | 0,92 | 0,92 | 0,92 | 0,92 | 0,92 | |
| $P_{PTI}$ | kW | 0 | 0 | 0 | 0 | 0 | |
| $SFC_{AE}$ | g/kWh | 187,5 | 188,02 | 187,6 | 187,39 | 188,02 | |
| $\Sigma_{PTI}$ | gF | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | |
| **Propulsion Energy** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| $P_{Propulsion}$ | kW | 32700 | 21800 | 21800 | 8720 | 0 | |
| $\Sigma_{Propulsion}$ | gF | 130390661,4 | 0 | 12038832 | 5684153,8 | 0 | 148113647,2 |
| V | kn | 26,61 | 23,25 | 23,25 | 17,13 | | |
| | | | | | | | |
| **Auxiliary Energy** | | | | | | | |
| t | h | 22,7 | 0 | 3 | 3,25 | 19,05 | 48 |
| $P_{AE\ Required}$ | kW | 1850 | 1750 | 1300 | 1300 | 900 | |
| $P_{Auxiliary}$ | kW | 1861,2 | 1774,2 | 1308 | 1329,6 | 945 | |
| $\Sigma_{Auxiliary}$ | gF | 7986291,3 | 0 | 756820,8 | 831723,204 | 3384783,045 | 12959618,35 |
| | | | | | | | |
| **Fuel Consumption** | | | | | | | |
| $\Sigma_{ME}$ | gF | 133979395,2 | 0 | 12370176 | 5840598,4 | 0 | 152190169,6 |
| $\Sigma_{AE\ Diesel}$ | gF | 4397557,5 | 0 | 425476,8 | 675278,604 | 3384783,045 | 8883095,949 |
| $\Sigma_{PTO}$ | gF | 3588733,8 | 0 | 331344 | 156444,6 | 0 | 4076522,4 |
| $\Sigma_{PTI}$ | gF | 0 | 0 | 0 | 0 | 0 | 0 |
| $\Sigma_{Propulsion}$ | gF | 130390661,4 | 0 | 12038832 | 5684153,8 | 0 | 148113647,2 |
| $\Sigma_{Auxiliary}$ | gF | 7986291,3 | 0 | 756820,8 | 831723,204 | 3384783,045 | 12959618,35 |
| $\Sigma$ | gF | 138376952,7 | 0 | 12795652,8 | 6515877,004 | 3384783,045 | 161073265,5 |
| | | | | | | | |
| **Emissions** | | | | | | | |
| $\Sigma_{ME}$ | $gCO_2$ | 417265428,4 | 0 | 38525676,13 | 18189959,66 | 0 | 473981064,2 |
| $\Sigma_{AE\ Diesel}$ | $gCO_2$ | 13695753,08 | 0 | 1325104,946 | 2103087,684 | 10541568,32 | 17123945,71 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\Sigma_{PTO}$ | $gCO_2$ | 11176752,55 | 0 | 1031937,754 | 487231,0622 | 0 | 12695921,36 |
| $\Sigma_{PTI}$ | $gCO_2$ | 0 | 0 | 0 | 0 | 0 | 0 |
| $\Sigma_{Propulsion}$ | $gCO_2$ | 406088675,9 | 0 | 37493738,38 | 17702728,59 | 0 | 461285142,8 |
| $\Sigma_{Auxiliary}$ | $gCO_2$ | 24872505,62 | 0 | 2357042,7 | 2590318,747 | 10541568,32 | 29819867,07 |
| $\Sigma$ | $gCO_2$ | 430961181,5 | 0 | 39850781,08 | 20293047,34 | 10541568,32 | 491105009,9 |
| | | | | | | | |
| Denominator | m.tn | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 |
| $V_{ref}$ | kn | 26,61 | 23,25 | 23,25 | 17,13 | | |
| ***Denominator*** | t·nm | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 |
| | | | | | | | |
| **VENEFI$_{OS(D)}$** | $gCO_2/t·nm$ | **35,75** | **N/A** | **--** | **--** | **--** | **--** |
| **VENEFI$_{OS(S)}$** | $tCO_2/h$ | **18,99** | **--** | **13,28** | **6,24** | **0,55** | **--** |
| **VENEFI$_{CO}$** | $gCO_2/t·nm$ | **--** | **--** | **--** | **--** | **--** | **40,73** |
| | | | | | | | |
| **VENEFI$_{OS(D)\ (PE)}$** | $gCO_2/t·nm$ | **33,68** | **N/A** | **--** | **--** | **--** | |
| **VENEFI$_{OS(S)\ (PE)}$** | $tCO_2/h$ | **17,89** | **N/A** | **12,50** | **5,45** | **0,00** | |
| **VENEFI$_{CO\ (PE)}$** | $gCO_2/t·nm$ | **--** | **--** | **--** | **--** | **--** | **38,26** |
| | | | | | | | |
| **VENEFI$_{OS(D)\ (AE)}$** | $gCO_2/t·nm$ | **2,06** | **N/A** | **--** | **--** | **--** | **--** |
| **VENEFI$_{OS(S)\ (AE)}$** | $tCO_2/h$ | **1,10** | **N/A** | **0,79** | **0,80** | **0,55** | **--** |
| **VENEFI$_{CO\ (AE)}$** | $gCO_2/t·nm$ | **--** | **--** | **--** | **--** | **--** | **2,47** |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| **Transport Work Calculation** | | | | | | | |
| PIRAEUS - THIRA | 1 | | | | | | |
| Passengers | -- | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| LF | -- | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 |
| Cars | -- | 600 | 600 | 600 | 600 | 600 | 600 |
| LF | -- | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 |
| $DWT_{Ref}$ | t | 25553 | 25553 | 25553 | 25553 | 25553 | 25553 |
| Distance | nm | 130 | 130 | 130 | 130 | 130 | 130 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 |
| THIRA - KOS | 2 | | | | | | |
| Passengers | -- | 1118 | 1118 | 1118 | 1118 | 1118 | 1118 |
| LF | -- | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 |
| Cars | -- | 401 | 401 | 401 | 401 | 401 | 401 |
| LF | -- | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 |
| $DWT_{Ref}$ | t | 17388 | 17388 | 17388 | 17388 | 17388 | 17388 |
| Distance | nm | 108 | 108 | 108 | 108 | 108 | 108 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 |
| KOS - RHODES | 3 | | | | | | |
| Passengers | -- | 952 | 952 | 952 | 952 | 952 | 952 |
| LF | -- | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 |
| Cars | -- | 284 | 284 | 284 | 284 | 284 | 284 |
| LF | -- | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 |
| $DWT_{Ref}$ | t | 12746 | 12746 | 12746 | 12746 | 12746 | 12746 |
| Distance | nm | 65 | 65 | 65 | 65 | 65 | 65 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 828476 | 828476 | 828476 | 828476 | 828476 | 828476 |
| RHODES - KOS | 4 | | | | | | |
| Passengers | -- | 952 | 952 | 952 | 952 | 952 | 952 |
| LF | -- | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 | 0,528 |
| Cars | -- | 284 | 284 | 284 | 284 | 284 | 284 |
| LF | -- | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 | 0,444 |
| $DWT_{Ref}$ | t | 12746 | 12746 | 12746 | 12746 | 12746 | 12746 |
| Distance | nm | 65 | 65 | 65 | 65 | 65 | 65 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 828476 | 828476 | 828476 | 828476 | 828476 | 828476 |
| KOS - THIRA | 5 | | | | | | |
| Passengers | -- | 1118 | 1118 | 1118 | 1118 | 1118 | 1118 |
| LF | -- | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 | 0,620 |
| Cars | -- | 401 | 401 | 401 | 401 | 401 | 401 |
| LF | -- | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 | 0,627 |
| $DWT_{Ref}$ | t | 17388 | 17388 | 17388 | 17388 | 17388 | 17388 |
| Distance | nm | 108 | 108 | 108 | 108 | 108 | 108 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 | 1877934 |
| THIRA - PIRAEUS | 6 | | | | | | |
| Passengers | -- | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| LF | -- | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 | 0,832 |
| Cars | -- | 600 | 600 | 600 | 600 | 600 | 600 |
| LF | -- | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 | 0,938 |
| $DWT_{Ref}$ | t | 25553 | 25553 | 25553 | 25553 | 25553 | 25553 |
| Distance | nm | 130 | 130 | 130 | 130 | 130 | 130 |
| $f_w$ | -- | 1 | 1 | 1 | 1 | 1 | 1 |
| Denominator | t·nm | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 | 3321829 |
| | | | | | | | |
| **Total Distance** | nm | 606 | 606 | 606 | 606 | 606 | 606 |
| **Transport Work** | t·nm | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 | 12056478 |

| | | $t_1$ | $t_2$ | $t_{3a}$ | $t_{3b}$ | $t_4$ |
|---|---|---|---|---|---|---|
| $P_{AE\ Required}$ | kW | 1850 | 1750 | 1300 | 1300 | 900 |
| $P_{AE\ Produced}$ | kW | 1861,2 | 1774,2 | 1308 | 1329,6 | 945 |
| n (surplus energ.) | -- | 0,006054054 | 0,013828571 | 0,006153846 | 0,022769231 | 0,05 |
| $P_{AE\ Green}$ | kW | 0 | 0 | 0 | 0 | 0 |
| $P_{AE\ Emissions}$ | kW | 1861 | 1774 | 1308 | 1330 | 945 |
| $P_{AE\ Diesel\ Gens}$ | kW | 961 | 1174 | 708 | 1090 | 945 |
| $P_{AE\ Shaft\ Gens}$ | kW | 900 | 600 | 600 | 240 | 0 |

# Appendix 4

# SFC Curves of Main Engines & Diesel Generators of "BS1"

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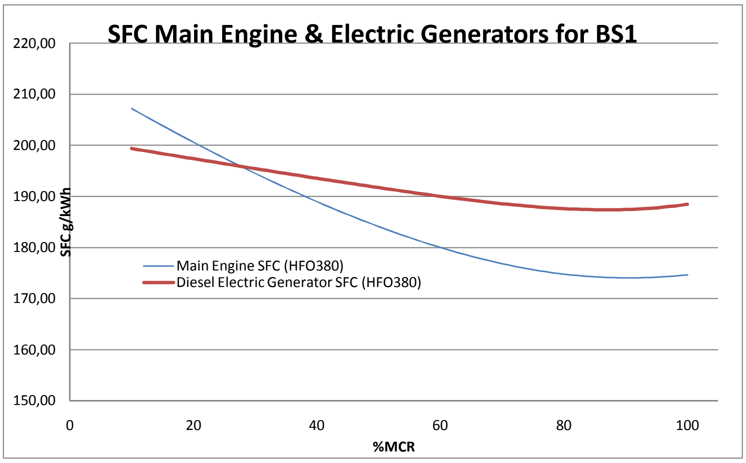
## "BS1" SFC - %MCR Tables Of Main Engines and Diesel Generators



Main Engine Type: MAN B&W -6L28/32H
Fuel: HFO380

| | |
|---|---|
| $SFC_{100\%\ Load}$ | 174 |
| $SFC_{85\%\ Load}$ | 173 |
| $SFC_{75\%\ Load}$ | 177 |
| $SFC_{50\%\ Load}$ | 186 |

| Load Factor | SFC | Load Factor | SFC |
|---|---|---|---|
| [% MCR] | [g/kWh] | [% MCR] | [g/kWh] |
| 1 | 213,42 | 51 | 183,64 |
| 2 | 212,70 | 52 | 183,20 |
| 3 | 212,00 | 53 | 182,76 |
| 4 | 211,29 | 54 | 182,34 |
| 5 | 210,59 | 55 | 181,93 |
| 6 | 209,89 | 56 | 181,52 |
| 7 | 209,20 | 57 | 181,12 |
| 8 | 208,51 | 58 | 180,73 |
| 9 | 207,83 | 59 | 180,35 |
| 10 | 207,15 | 60 | 179,98 |
| 11 | 206,47 | 61 | 179,62 |
| 12 | 205,80 | 62 | 179,26 |
| 13 | 205,13 | 63 | 178,92 |
| 14 | 204,46 | 64 | 178,59 |
| 15 | 203,80 | 65 | 178,27 |
| 16 | 203,15 | 66 | 177,96 |
| 17 | 202,50 | 67 | 177,66 |
| 18 | 201,85 | 68 | 177,37 |
| 19 | 201,21 | 69 | 177,09 |
| 20 | 200,57 | 70 | 176,82 |
| 21 | 199,94 | 71 | 176,57 |
| 22 | 199,31 | 72 | 176,32 |
| 23 | 198,69 | 73 | 176,09 |
| 24 | 198,07 | 74 | 175,87 |
| 25 | 197,46 | 75 | 175,66 |
| 26 | 196,86 | 76 | 175,46 |
| 27 | 196,25 | 77 | 175,27 |
| 28 | 195,66 | 78 | 175,09 |
| 29 | 195,07 | 79 | 174,93 |
| 30 | 194,48 | 80 | 174,78 |
| 31 | 193,90 | 81 | 174,65 |
| 32 | 193,33 | 82 | 174,52 |
| 33 | 192,76 | 83 | 174,42 |
| 34 | 192,20 | 84 | 174,32 |
| 35 | 191,64 | 85 | 174,24 |
| 36 | 191,09 | 86 | 174,17 |
| 37 | 190,55 | 87 | 174,12 |
| 38 | 190,01 | 88 | 174,08 |
| 39 | 189,48 | 89 | 174,06 |
| 40 | 188,95 | 90 | 174,05 |
| 41 | 188,43 | 91 | 174,05 |
| 42 | 187,92 | 92 | 174,07 |
| 43 | 187,42 | 93 | 174,10 |
| 44 | 186,92 | 94 | 174,14 |
| 45 | 186,43 | 95 | 174,19 |
| 46 | 185,95 | 96 | 174,26 |
| 47 | 185,47 | 97 | 174,34 |
| 48 | 185,00 | 98 | 174,43 |
| 49 | 184,54 | 99 | 174,53 |
| 50 | 184,08 | 100 | 174,64 |

Diesel Generator Type: MAN B&W 8L58/64
Fuel: HFO380

| | |
|---|---|
| $SFC_{100\%\ Load}$ | 196 |
| $SFC_{85\%\ Load}$ | 196 |
| $SFC_{75\%\ Load}$ | 197 |
| $SFC_{50\%\ Load}$ | 201 |

| Load Factor | SFC | Load Factor | SFC |
|---|---|---|---|
| [% MCR] | [g/kWh] | [% MCR] | [g/kWh] |
| 1 | 201,17 | 51 | 191,55 |
| 2 | 200,97 | 52 | 191,37 |
| 3 | 200,77 | 53 | 191,20 |
| 4 | 200,57 | 54 | 191,03 |
| 5 | 200,37 | 55 | 190,85 |
| 6 | 200,17 | 56 | 190,68 |
| 7 | 199,97 | 57 | 190,51 |
| 8 | 199,77 | 58 | 190,35 |
| 9 | 199,57 | 59 | 190,18 |
| 10 | 199,37 | 60 | 190,02 |
| 11 | 199,17 | 61 | 189,86 |
| 12 | 198,97 | 62 | 189,70 |
| 13 | 198,77 | 63 | 189,55 |
| 14 | 198,57 | 64 | 189,40 |
| 15 | 198,37 | 65 | 189,25 |
| 16 | 198,17 | 66 | 189,11 |
| 17 | 197,97 | 67 | 188,97 |
| 18 | 197,78 | 68 | 188,83 |
| 19 | 197,58 | 69 | 188,70 |
| 20 | 197,38 | 70 | 188,58 |
| 21 | 197,19 | 71 | 188,45 |
| 22 | 196,99 | 72 | 188,34 |
| 23 | 196,79 | 73 | 188,23 |
| 24 | 196,60 | 74 | 188,12 |
| 25 | 196,40 | 75 | 188,02 |
| 26 | 196,21 | 76 | 187,93 |
| 27 | 196,02 | 77 | 187,84 |
| 28 | 195,82 | 78 | 187,76 |
| 29 | 195,63 | 79 | 187,68 |
| 30 | 195,44 | 80 | 187,61 |
| 31 | 195,25 | 81 | 187,56 |
| 32 | 195,05 | 82 | 187,50 |
| 33 | 194,86 | 83 | 187,46 |
| 34 | 194,67 | 84 | 187,43 |
| 35 | 194,48 | 85 | 187,40 |
| 36 | 194,30 | 86 | 187,39 |
| 37 | 194,11 | 87 | 187,38 |
| 38 | 193,92 | 88 | 187,39 |
| 39 | 193,73 | 89 | 187,41 |
| 40 | 193,55 | 90 | 187,44 |
| 41 | 193,36 | 91 | 187,48 |
| 42 | 193,18 | 92 | 187,53 |
| 43 | 192,99 | 93 | 187,60 |
| 44 | 192,81 | 94 | 187,68 |
| 45 | 192,63 | 95 | 187,77 |
| 46 | 192,45 | 96 | 187,88 |
| 47 | 192,26 | 97 | 188,00 |
| 48 | 192,08 | 98 | 188,14 |
| 49 | 191,91 | 99 | 188,29 |
| 50 | 191,73 | 100 | 188,46 |

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# Appendix 5

# Abstract from Second IMO GHG Report

## Technological and Operational Potential for Reduction of Emissions & Policy Options for Reductions of GHG & Other Relevant Substances

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# 5

# Technological and operational potential for reduction of emissions

**5.1** As shown in Chapter 3, ships are a significant source of air pollution and emissions of greenhouse gases. Chapter 4 clearly demonstrates that it is possible to achieve reduction of emissions through international regulations. This chapter reviews potentials for reduction of emission of GHG and other relevant substances from a technological perspective.

**5.2** In principle, there are four fundamental categories of options for reducing emissions from shipping.

1. Improving energy efficiency, i.e. doing more useful work with the same energy consumption. This applies to both the design and the operation of ships.
2. Using renewable energy sources, such as the wind and the sun.
3. Using fuels with less total fuel-cycle emissions per unit of work done, such as biofuels and natural gas.
4. Using emission-reduction technologies – i.e. achieving reduction of emissions through chemical conversion, capture and storage, and other options.

**5.3** These options are discussed in the following sections. More detailed and complementary information on specific emission-reduction solutions and technologies is provided in Appendix 2 to this report.

## OPTIONS FOR IMPROVING ENERGY EFFICIENCY

**5.4** Improved energy efficiency means that the same amount of useful work is done, but using less energy. This in turn means less fuel burned and reductions in emissions of all exhaust gases. A wide range of options are available for increasing the energy efficiency of ship design and ship operation. Key areas of importance for energy saving are shown in Table 5.1, where options are categorized as “design” and “operation”.

**Table 5.1** *Principal options for improving energy efficiency*

| DESIGN | OPERATION |
|---|---|
| Concept, design speed and capability | Fleet management, logistics and incentives |
| Hull and superstructure | Voyage optimization |
| Power and propulsion systems | Energy management |

## IMPROVING ENERGY EFFICIENCY BY SHIP DESIGN

**5.5** Paragraphs 5.5 to 5.20 deal with options to improve the energy efficiency by changes in design. The development of the energy efficiency design index, EEDI, by MEPC (see Chapter 6) is an effort to exploit this option to increase efficiency. Most modifications of design are primarily suitable for newbuildings. This means that the phase-in and the reductions achieved by design-based improvements in energy efficiency will be slow, due to the long service life expected for ships (Chapter 2). Certain options may, however, be retrofitted to existing ships.

## Concept, design speed and capability

**5.6** The energy efficiency of a ship is closely linked to the specification of the original design. Speed, size, and key parameters such as beam, draught, and length have significant influence on the potential energy efficiency of the design. Restrictions on draught, beam, length, etc., imposed by requirements to access harbours and canals, constrain the design, with possible adverse effects on efficiency. Geared ships (i.e. ships with cranes to unload cargo) or ice-class ships and ships with redundant propulsion systems may be less energy-efficient; however, such ships also have extra capabilities [1].

**5.7** Ships' lifetimes may exceed thirty years, and the operating and business environment may change significantly in the course of this time. Flexibility to allow upgrades and efficient operation in different scenarios should be considered at the design stage. It is thus critical to build the right ship for the job, which provides sufficient flexibility in operation. Specifying a ship and subsequently designing to that specification is a highly complex task. Estimating the potential for saving energy at this stage is equally complex; however, the influence of choices that are made at this stage of the design process is very significant and should not be under-estimated [2, 3]. For instance, while larger ships tend to be more efficient per tonne-mile than smaller ships when loaded, smaller or better-adapted ships may achieve a higher utilization factor, which may result in higher overall efficiency. The design speed also has a significant impact on transport efficiency.

**5.8** The emission-reduction potential of concept, speed and capability is closely linked to the ship's operations. Better planning at the design stage may lead to a higher potential for reduction at the operational stage.

## Hull and superstructure

**5.9** Optimization of the underwater hull form is regularly applied to new ship designs. It is likely that most new designs today are going through some systematic form of hull optimization process, focusing on reduced resistance and improved propulsive efficiency. The actual proportion of the world fleet that has undergone this process is not known. Such optimization is challenging, and it is difficult to ensure that the final result from the "optimization" procedures performed really does provide an optimum design as the end result. Ensuring optimal working conditions for the propeller is a key issue in hull optimization, and hull and propeller optimization is done as a single process.

**5.10** A key issue is that the design point for optimization should be as relevant as possible to the operation of the ship. In particular, full optimization for weather and waves is not always achieved. This may be linked, in part, to the fact that the trial runs, on which the performance of the ship is measured with respect to the contracted performance, are performed under still-water conditions.

**5.11** The superstructure of the hull represents a small fraction of the resistance; however, it is still possible to save energy by optimizing the design so as to minimize air resistance and the adverse effects of side winds, such as drifting. This is particularly important for ships with large superstructures.

**5.12** Reducing the weight of the hull reduces the wetted surface area and the drag at any given payload, thus saving energy. The potential for reducing weight is linked to strength and safety requirements and how they are specified in design codes. To reduce weight, it will generally be necessary to use high-grade steels and lighter materials. At present, lightweight materials such as aluminium, carbon fibre or glass-fibre sandwich constructions are mainly used on planning high-speed craft.

**5.13** The first greenhouse gas study [4] analysed model tests from MARINTEK's database in order to estimate the potential for optimization. This analysis indicated a potential for savings in the range 5–20% for optimization of the behaviour of the hull in still water. The potential for savings may be greater for smaller ships, where there are less resources for optimization and ships are built in smaller series. Optimization of the hull must also consider its performance in waves, which has also been shown to differ significantly between ships [5].

## Power and propulsion systems

**5.14** Power on board is generated either by low-speed or medium-speed diesel engines, except in very special cases. Energy efficiency in the power-generation system can be increased in many ways.

**5.15** The efficiency of older engines can be improved through upgrading (modernizing) engines and replacing old turbochargers or by de-rating engines, if lower power can be accepted. This type of upgrade is not very common at present, probably due to the cost and complexity. The upgrade of the engine may also be considered to be a major modification, in which case it will be necessary to obtain and maintain a new certificate with respect to IMO $NO_x$ regulations.

**5.16** Energy can be recovered from exhaust gases by using power turbines, driven either directly by an exhaust side-stream, by steam generated from the waste heat from the engine, or by both methods. The power that is recovered can then be used to drive a shaft generator/motor to generate electricity or to assist the main engine. Energy may also be recovered from the exhaust gases from auxiliary engines. Future systems may see the use of fluids other than steam, since these may permit smaller systems with higher efficiencies. Recovery of energy from exhausts can generate additional power corresponding to about 10% of the total, and shaft efficiencies can be increased from 50% to about 55% for large two-stroke engines. Recovery of energy from exhausts can also be used on smaller engines. Two-stage turbocharging can be considered as another means of capturing exhaust energy to increase energy efficiency [5].

**5.17** In cases where the operating profile is variable, special arrangements may be installed to optimize utilization and efficiency, e.g., “father and son” propulsion engine arrangements, variations in number and size of auxiliary engines, shaft generator systems, etc. Diesel-electric propulsion systems may also be considered for energy-saving purposes in these cases; however, electric propulsion introduces additional transmission losses that must first be recovered before any saving can be made. Diesel-electric propulsion provides other benefits, such as increased design flexibility, which may indirectly translate to energy saving.

**5.18** Thrust is generated in the propeller where high propeller efficiency is obtained with a large propeller rotating at low speed. Ideally, the number of blades should be minimized, to reduce blade area and frictional resistance. Typical design restrictions are limitations on diameter, cavitation and loading. The size of the propeller may be limited by the design of the ship, by restrictions on draught in expected areas of operation or by engine torque [1].

**5.19** In certain cases, energy efficiency can be gained through various enhancements such as vanes, fins, ducts, high-efficiency rudders, vane wheels, asymmetric rudders, contra-rotating propellers, etc. A number of such devices are described in Appendix 2. Many of these devices can be considered generically as alternative ways of recovering rotational energy of the propeller. The typical potential savings of such systems are assessed to be in the order of 5–10% of the ship propulsion power, although higher figures may be presented by industry for specific cases.

**5.20** Not all of these propulsive devices are suitable for all kinds of ships. Special propulsion-enhancing devices are not widely used, due to cost, reliability issues, etc. The mechanical loading on the propeller is very high and the ability to withstand heavy seas is critical. Moreover, it is difficult to measure the benefits of such devices in full scale, and the benefits that are achieved in one ship may not be transferable to another. Therefore, investing in such advanced propulsion devices may be regarded as being rather risky.

## ENERGY SAVING BY OPERATIONS

**5.21** Saving energy at the operational stage can be achieved by all ships. However, as discussed in paragraphs 5.6 to 5.8, new ships may have more flexibility to exploit potential operational improvements, e.g., such as better cargo-handling gear, ability to cruise efficiently at different speeds, etc. Saving energy at the operational stage is presently addressed by the MEPC with the development of the Energy Efficiency Operational Indicator (EEOI) and the Ship Efficiency Management Plan (SEMP).

### Fleet management, logistics and incentives

**5.22** Energy efficiency can be improved by using the right ships in a transport system. Generally speaking, efficiency will increase if we concentrate cargoes in larger ships wherever possible, as demonstrated in paragraphs 5.6 to 5.8. While using large ships tends to reduce energy consumption in the shipping leg itself, the total impact on overall door-to-door logistics performance may be negative unless such a move is complemented by smaller ships that can assist in the onward distribution of cargoes. Naturally, larger ships are not efficient if not enough cargo is available and they have to sail only partly loaded. Net energy efficiency may be better for a small ship, with access to more ports and cargo types, being able to fill its cargo hold to capacity [7].

**5.23** Reductions in scheduled speed (i.e. accepting longer voyage times) will increase efficiency, but result in more ships being needed. Reductions in scheduled speed can be expensive, since they directly affect the amount of freight carried and hence the income of a ship. However, there is a trade-off between freight rates and fuel cost: when freight rates are low and fuel prices are high, it may be profitable to reduce speed.

**5.24** Traffic management and control systems, including queue prioritization on criteria other than “first in”, may also play a role. Reducing time in port through more efficient cargo handling, berthing and mooring can also help to reduce emissions.

**5.25** While there may be many opportunities to optimize and improve operational efficiency at some level (e.g., as discussed in paragraphs above and in paragraphs 5.29 to 5.38 as well as the description of the SEMP [30]), doing so requires the cooperation of several parties. It is essential that each of these has the incentives and flexibility to join the energy-saving effort, and it is particularly important that they do not have incentives to contribute to inefficient behaviour. As an example of the latter, ship upgrades and major maintenance activities depend on the high-level strategies of the operating companies. In cases where ships are operated by a different company than the commercial operator, the technical operator may tend to minimize time in dry dock (to minimize off-hire cost) and other maintenance costs (e.g., painting costs) while at the same time handing the fuel bill to the commercial operator. In another example, a ship operator may arrive in a busy harbour, only to wait for days or weeks to unload, while receiving compensation (demurrage) for each day of waiting. It is evident that contractual arrangements and incentives have a significant influence on operations and hence on efficiency.

**5.26** Typically, contracts are agreed between two parties only, and aim to safeguard the (economic) interest of the parties under various conditions. In the typical time charterparty the charterer both controls the speed and the fuel bill, as well as the consequences of delay. Under a typical voyage charterparty the ship operator sets the speed, but is also entitled to an economic compensation – demurrage – in case of a delay in port due to congestion. If the port is able to handle the ship, the ship operator can take on a new cargo; if not, the ship operator is compensated by the demurrage. Often the demurrage rate is higher than the extra fuel cost and then, in both cases, the incentive for the ship operator is to sail at high speed to arrive as early as possible.

**5.27** The net result may be low flexibility for efficient operation and, in the worst cases, incentives for inefficient operation. While it is easy to point to areas where the present system falls short, it is more difficult to find solutions that would resolve these issues to the satisfaction of all parties. Indeed, there are many parties involved in shipping that directly or indirectly affect transport efficiency. The relationship between these actors is regulated by a number of contracts. Depending on the type of shipping, the list of involved parties may include:

- owner (including bareboat charterer/operator);
- charterer;
- multi-modal transport operators (MTOs);
- shipper and receiver of the goods;
- cargo buyer/seller (the original source of the transport demand);
- transport agents/brokers;
- port authorities; and
- terminal operators.

**5.28** Transport efficiency is affected by time spent in port: additional to the parties listed above, other parties (including shipping agents, stevedores, tug operators, pilots, bunker suppliers and other service providers) may have a role to play in minimizing port time.

## Voyage optimization

**5.29** Voyage optimization is the optimization of ship operation that the master can achieve within the constraints that are imposed by logistics, scheduling, contractual arrangements and other constraints. These include issues such as:

- Selection of optimal routes with respect to weather and currents in order to minimize energy consumption (weather routeing);
- Just-in-time arrival, considering tides, queues, and arrival windows. As discussed above, incentives and contractual arrangements are very important in this respect. For instance, severe penalties for late arrival encourage safety margins on the ship side. Extra payment for time spent waiting (demurrage) discourages just-in-time arrival;
- Ballast optimization – avoiding unnecessary ballast. Determining optimal ballast is sometimes a difficult consideration, as it also affects the comfort and safety of the crew; and
- Trim optimization – finding and operating at the correct trim.

**5.30** The potential improvements in efficiency that can be gained by voyage optimization are highly variable and difficult to assess on a general basis, since this depends on how ships are presently operated. In the 2000 study of greenhouse gas emissions from ships, the fleet average potential saving by optimization of trim and ballast in operation was estimated as small (0–1% of total fuel consumption) [4]. In a recent specific case study of tanker operations done by DNV, savings of 0.6% were estimated for trim and ballast optimization. Higher figures may be relevant for specific ship types that carry significant ballast during much of the operation.

**5.31** Weather routeing can result in substantial savings for ships on certain routes. However, weather routeing systems are not uncommon, and the incremental saving that can be expected from improvements in such systems and from their more widespread use has not been assessed. The potential for just-in-time arrival was assessed at 1–5% in the 2000 study [4]. The highest potential saving would be expected where economic considerations (incentives from contractual arrangement) presently favour inefficient operational arrival. More recently, the potential for energy saving by just-in-time arrival has been estimated to be 1% [32], based on the Japanese domestic fleet.

**5.32** Several types of weather routeing systems, technical support systems, performance monitoring systems and other systems can be used to help achieve optimal voyage performance. These systems must be used and understood, and the skills and motivation of the crew are critical. Incentive schemes, whereby crew members profit from efficient operation, are one approach to improving motivation.

### Energy management

**5.33** Besides the power needed for propulsion, electric power is needed to sustain the crew (the hotel load) as well as various ancillary systems, such as cooling-water pumps, ventilation fans, control and navigational systems, etc. Most merchant ships have transverse thrusters, for manoeuvring at low speed, which need significant power but are used only for short periods. Some ships also carry cargo gear that requires high power when loading and unloading. Passenger ferries and cruise ships will have significant power demands for passenger accommodation, ventilation and air-conditioning. Significant heat demands may also be required for passenger comfort and for production of fresh water.

**5.34** In certain cases, the cargo requires cooling to maintain quality; e.g., refrigerated or frozen cargo. Certain cargoes, such as special crude oils, heavy fuel oils, bitumen, etc., require heating. Some of this heat can be supplied by generating steam, using heat from the exhaust. However, in many cases an additional steam boiler is needed to supply sufficient steam. Steam from exhaust gas is generally sufficient to heat the heavy fuel oil that is used on most ships; in port, however, steam from an auxiliary boiler may be needed.

**5.35** It is often possible to reduce energy consumption on board by working towards more conscious and optimal operation of ship systems. Examples of measures that can be taken include:

- avoidance of unnecessary consumption of energy;
- avoidance of parallel operation of electrical generators;
- optimization of steam plant (tankers);
- optimization of the fuel clarifier/separator;
- optimized HVAC operation on board;
- cleaning the economiser and other heat exchangers; and
- detection and repair of leaking steam and compressed-air systems, etc.

**5.36** This may require investments in training and motivating the crew, and in monitoring/benchmarking consumption. In parallel, upgrades of automation and process control, such as automatic temperature control, flow control (automatic speed control of pumps and fans), automatic lights, etc., may help to save energy. The energy-saving potential of energy-management measures is difficult to assess, as this depends on how efficiently the vessel was already being operated and on the share of auxiliary power consumption in the total energy picture. A saving of 10% on auxiliary power may be realistic for many vessels. This corresponds to ~1–2% of total fuel consumption, depending on circumstances.

**5.37** Optimal maintenance of main engines and ensuring that these are operating at the most effective (highest) pressures is also important. Savings of 1–2% of the fuel consumption of the main engine through "tuning" have been observed, with even more in extreme cases, although the average potential may be around 1%.

**5.38** Maintaining a clean hull and propeller is important for fuel efficiency. Many shipowners have made substantial savings by increasing the frequency of cleaning operations on the hull and propellers or by implementing condition-based cleaning. Selection of more effective hull coatings may reduce resistance and result in longer intervals between dry-dockings. Surface finishing, hull coating and friction reduction are all very important in determining resistance. As discussed in appendix 1, the appropriate choice of hull coating and hull maintenance alone can amount to a 5% difference in energy requirements.

## RENEWABLE ENERGY SOURCES

**5.39** Renewable energy can be used either directly on board ships (by utilizing wind, solar and wave energy) or energy can be generated on-shore and converted into an energy carrier such as hydrogen or electricity.

## WIND POWER, ON BOARD USE

**5.40** Wind power can be exploited in various ways as the motive power for ships, for example by:

- traditional sails;
- solid wing sails;
- kites; and
- Flettner-type rotors.

**5.41** These systems have different characteristics. Wind conditions differ between regions, so that wind power is more attractive in certain regions and routes than in others. In a study carried out at the Technical University of Berlin [8], three different types of sail were modelled on two types of ships on three different routes. The objective of the study was to assess the potential savings of energy and of fuel obtainable over a five-year period, using actual weather data. This study indicated that the potential for sail energy was better in the North Atlantic and North Pacific than in the South Pacific. Fuel savings were slightly greater at higher speeds. However, in terms of percentages, the fuel savings were greater at low speed, due to the low total demand for propulsion power. In percentage terms, savings were typically about 5% at 15 knots, rising to about 20% at 10 knots.

**5.42** Present-day experience of all of these technologies on board large vessels is limited, and modelling results are therefore difficult to verify. Nevertheless, wind-assisted power appears to have potential for fuel-saving in the medium and long term.

## SOLAR POWER, ON BOARD USE

**5.43** Current solar-cell technology is sufficient to meet only a fraction of the auxiliary power requirements of a tanker, even if the entire deck area were to be covered with photovoltaic cells. Naturally, at certain times and in certain areas, solar radiation will be above average and the auxiliary demands for power could be met. Moreover, since solar power is not always available (e.g., at night), backup power would be needed. Therefore, solar power appears to be of interest primarily as a complementary source of energy. With present technology it could be possible to save only a few percent of total energy requirements, even with extensive use of solar power. However, present-day cost levels and efficiency place solar power towards the lower end of the cost-effectiveness list [9].

## WAVE POWER, ON BOARD USE

**5.44** This includes concepts for utilizing wave energy and/or ship motion. Examples include internal systems (gyro-based) and external systems such as wavefoils, stern flaps or relative movement between multiple hulls (trimarans). These systems have high technical complexity, limited potential energy efficiency and are not regarded as being very promising.

## RENEWABLE ENERGY FROM SHORE

**5.45** Renewable energy is generated onshore from wind turbines, hydroelectric schemes, geothermal plants, solar energy plants, etc. Potentially, energy from such sources could be used to power ships if a suitable energy carrier was available. However, as long as there is a shortage of renewable energy onshore, there is little to be gained by directing shore-based renewable energy to ship propulsion. A notable exception is the use of shore power when a ship is berthed.

## FUELS WITH LOWER FUEL-CYCLE $CO_2$ EMISSIONS

**5.46** Emissions of $CO_2$ can be cut by switching to fuels with lower total emissions through the full fuel cycle (i.e. production, refining, distribution and consumption). The switch from using residual fuels to distillate fuels that is implied by the sulphur regulation in the revised MARPOL Annex VI has already been agreed; hence, there is no reason to discuss the potential merits and demerits of this move on the emission of $CO_2$ here. Other fuel options with potential benefits for reducing the production of $CO_2$ include biofuels and natural gas.

## BIOFUELS

**5.47** Present-day biofuels (often referred to as “first-generation” biofuels) are produced from sugar, starch, vegetable oil, or animal fats. Many of these fuels can readily be used for ship diesels with no (or minor) adaptation of the engine. Depending on source, there are certain technical issues, such as stability during storage, acidity, lack of water-shedding (potentially resulting in increased biological growth in the fuel tank), plugging of filters, formation of waxes, increased engine deposits, etc., which suggest that care must be exercised in selecting the fuel and adapting the engine. Care must be exercised to avoid contamination with water, since biofuels are particularly susceptible to biofouling. Blending bio-derived fuel fractions into diesel fuel or heavy fuel oil is also feasible from the technical perspective; however, compatibility must be checked, as with bunker fuels [25, 26, 27]. It should be noted that, although many of the technical challenges related to biofuels may look trivial, the consequence may be engine shutdown, which may be more critical with respect to the safety of a ship than, for instance, in the case of a car or a stationary combustion source on land. First-generation biofuels can be upgraded (hydrogenated) in a refinery. In this case, the resulting fuel is of high quality and the aforementioned practical problems do not apply. This upgrading costs energy, and hence results in additional emissions.

**5.48** The net benefits on emissions of $CO_2$ differ among different types of biofuels. Not all biofuels have a $CO_2$ benefit [25, 28]. The benefit is related to how the fuel is produced; hence the $CO_2$ benefit is not necessarily a function of the type of fuel alone. Biofuels have different combustion characteristics than traditional diesel. Use of biofuels has in certain cases resulted in a 7% to 10% increase in the $NO_x$ emissions; however, the effect of $NO_x$ could be different if the engine was optimized (e.g., fuel injection rate and timing) for biofuel in these cases.

**5.49** First-generation biofuels have been criticized for diverting food away from the human food chain, leading to food shortages and higher prices. Additional issues relate to deforestation, soil erosion, impact on water resources and more. Sustainability issues related to biofuels are discussed in the UN-Energy paper “Sustainable Biofuels: a framework for decision makers” [29].

**5.50** Biofuel produced from residual non-food crops, non-food parts of current crops (leaves, stems), and also industry waste such as wood chips, skins and pulp from fruit pressing is sometimes referred to as “second-generation” biofuels. These fuels are considered more sustainable. The conversion process that is needed to facilitate production of second-generation biofuel on an industrial scale and economically viable is still in development. Biofuels based on using algae are sometimes referred to as “third-generation” biofuels. This technology is presently at an early stage of development.

**5.51** In summary, the present potential for reducing emissions of $CO_2$ from shipping through the use of biofuels is limited. This is caused not only by technology issues but by cost, by lack of availability and by other factors related to the production of biofuels and their use. Additionally, the biofuels are, at present, significantly more expensive than petroleum fuels. Possible future use of biofuels towards 2050 is discussed in Chapter 7 within the context of IPCC scenarios.

## LIQUEFIED NATURAL GAS (LNG)

**5.52** Liquefied natural gas can be used as an alternative fuel in the shipping industry. The fuel has a higher hydrogen-to-carbon ratio compared with oil-based fuels, which results in lower specific $CO_2$ emissions (kg of $CO_2$/kg of fuel). In addition, LNG is a clean fuel, containing no sulphur; this eliminates the $SO_x$ emissions and almost eliminates the emissions of particulate matter. Additionally, the $NO_x$ emissions are reduced by up to 90% due to reduced peak temperatures in the combustion process. Unfortunately, the use of LNG will increase the emissions of methane ($CH_4$), hence reducing the net global warming benefit from 25% to about 15% [24].

**5.53** LNG-propelled ships will be particularly attractive in future emission control areas since they can meet Tier III emission levels and the $SO_x$ requirements without any treatment of the exhaust gas.

**5.54** One of the main challenges for the use of LNG as a fuel for ships is to find sufficient space for the on board storage of the fuel. At the same energy content, LNG has a volume 1.8-times larger than diesel oil. However, the bulky pressure storage tank requires a large space, and the actual volume requirement is in the range of three times that of diesel oil. In addition, the availability of LNG fuels in bunkering ports is a challenge which needs to be solved before LNG becomes a practical alternative. Conversion from diesel propulsion to LNG propulsion is possible, but the LNG is mainly relevant for newbuildings since substantial modification of engines and allocation of extra storage capacity is required.

**5.55** At present, the LNG technology is only available for four-stroke engines. For two-stroke engines, a different gas-engine concept, based on direct injection, may be more attractive. The $NO_x$ benefit of this technology is less than the premixed lean-burn concept that is used in four-stroke engines.

**5.56** In summary, the present potential for reduction of emissions of $CO_2$ from ships through the use of LNG is somewhat limited, since it is mainly relevant for newbuildings and because, at present, LNG bunkering options are limited. The forthcoming $NO_x$ and $SO_x$ ECAs will provide significant additional incentives for the use of LNG propulsion in short sea operations, since ECA requirements can easily be met by LNG-propelled ships. The price of LNG is presently significantly lower than that of distillate fuels, making an economic incentive for a move to LNG.

## EMISSION-REDUCTION TECHNOLOGIES

**5.57** Various emission-reduction technologies are available. Although it is possible to remove $CO_2$ from exhaust gases, e.g., by chemical conversion, this is not considered feasible. Indeed, considering the list of pollutants in the scope of this report, emission-reduction technologies are mainly relevant to pollutants within exhaust gases, i.e. $NO_x$, $SO_x$, PM, $CH_4$, NMVOC. Technological options for reducing these emissions are discussed in Appendix 2, and only a brief introduction is given here.

## EMISSION-REDUCTION OPTIONS FOR $NO_X$

**5.58** Emissions of $NO_x$ from diesel engines can be reduced by a number of measures, including:

- fuel modification, e.g., water emulsion;
- modification of the charge air, e.g., humidification and exhaust gas recirculation (EGR);
- modification of the combustion process, e.g., miller timing; and
- treatment of the exhaust gas, e.g., selective catalytic reduction (SCR).

**5.59** The sulphur content and the deposit-forming tendency of a fuel influence the possibilities for other emission-reduction technologies, such as exhaust gas recirculation (EGR) or selective catalytic reduction (SCR). Consumption and purity of water are issues with all options that use water.

**5.60** A certain trade-off exists, as the emissions of $CO_2$ and of PM increase when those of $NO_x$ are reduced. This does not mean that future engines, with lower $NO_x$ levels, must have higher levels of $CO_2$, HC, CO and PM emissions than current models. Simultaneous improvement in several areas is possible, as demonstrated in [5]. What remains is that, if the improved engine was re-optimized, $NO_x$ could still be traded against other pollutants. Miller cycling, in combination with two-stage turbocharging, has resulted in reductions in $NO_x$ emissions of >40% and improved fuel consumption in four-stroke engines [5].

**5.61** The use of LNG as a fuel is both a switch of fuel and a change in the combustion process. LNG operation can bring about very large reductions in $NO_x$ emissions (~90%) in four-stroke engines [10]. The potential for reduction of $NO_x$ emissions for large two-stroke engines has not been demonstrated. Use of LNG as a fuel is discussed in paragraphs 5.52 to 5.56.

**5.62** Tier II $NO_x$ limits, i.e. 15–20% reduction from the current levels, can be achieved with modifications of the internal-combustion process. At present, reduction of emissions of $NO_x$ to Tier III limits (~80% reduction from Tier I) can only be achieved by selective catalytic reduction (SCR) post-treatment or by using LNG and lean premixed combustion. These technologies are proven for four-stroke engines; however, experience with large two-stroke engines is limited.

**5.63** By using SCR and LNG technology, it is possible to achieve reductions of emissions even beyond Tier III limits on some load points. However, achieving further reductions at low load is problematic with SCR, principally because the temperature of exhaust gases from marine engines is not sufficiently high for effective operation of the catalyst. Achieving reduction of emissions to a very low level consistently, for extended time periods, may prove problematic with a catalyst, due to its possible deactivation. Technology for reduction of $NO_x$ emissions at low load in marine engines is presently being forced by IMO through the modified Tier III test-cycle requirements in the revised $NO_x$ Technical Code.

## EMISSION-REDUCTION OPTIONS FOR $SO_X$

**5.64** Emissions of $SO_x$ originate in sulphur that is chemically bound to the fuel hydrocarbon. When the fuel is burned, the sulphur is oxidized to $SO_x$ (mainly $SO_2$). In order to reduce $SO_x$ emissions, it is necessary to use a fuel with lower sulphur content or to remove the $SO_x$ that is formed in the combustion process.

**5.65** The revised MARPOL ensures that significant reductions of $SO_x$ emissions will be achieved through limitations on the sulphur content of fuel. As an alternative to using low-sulphur fuels, an exhaust-gas scrubbing system can be employed to reduce the level of sulphur dioxide ($SO_2$). Two main principles exist: open-loop seawater scrubbers and closed-loop scrubbers. Both scrubber concepts may also remove PM and limited amounts of $NO_x$ [16, 17]. Scrubbing of exhaust gases requires energy, which is estimated to be in the range of 1–2% of the MCR [18].

**5.66** Scrubbing to remove $SO_x$ reduces the temperature of exhaust gas. On the other hand, SCR technology requires high temperatures of exhaust gas and at the same time creates low sulphur and PM content in the exhaust gas. Combining SCR with scrubbing to remove $SO_x$ is thus not considered feasible.

**5.67** Pollutant material that is removed from the exhaust is carried in the wash water. Sulphur oxides react with the seawater to form stable compounds that are normally abundant in seawater and not believed to pose a danger to the environment in most areas. On the other hand, particulate matter in the exhaust that is trapped in the seawater may be harmful to the environment. The revised IMO Scrubber Guidelines [31] provide limits for the effluent, including limits for Polycyclic Aromatic Hydrocarbons (PAH), turbidity, pH, nitrates and other substances. Port State requirements for effluent discharges will have a significant impact on the possible use of seawater scrubbers. To fulfil these requirements, it will be necessary to install a treatment system to clean the effluent. Generally, the more $SO_x$ and PM that is removed from the exhaust by the scrubber, the more pollutant will have to be removed from the effluent.

## EMISSION-REDUCTION OPTIONS FOR PM

**5.68** Unlike other emissions, which are chemically defined, particulate matter (PM) is defined in international standards (ISO 8178) as the mass that is collected on a filter under specified conditions. However, the mass of PM does not define the chemical composition and the size distribution of the PM; these are important to health and in causing environmental effects.

**5.69** The extent of generation of Particulate Organic Matter (POM) is related to the consumption of engine lubricating oil, which may potentially be reduced. Changes in the base stocks and the additives of lube oil may also reduce PM mass. Emissions of elemental carbon are related to the amount of soot that is formed during combustion, some of which may be removed. Amounts of organic material and of elemental carbon that are generated may therefore be considered to be fuel-independent. Amounts of sulphate, associated water and ash are mainly determined by the fuel. When the sulphur content of a fuel is high, the PM emissions are mainly fuel-dependent, while other PM fractions are comparatively insignificant. When the sulphur content of a fuel is reduced, fuel-independent PM is less prominent.

**5.70** Some emissions of PM from high-sulphur fuels can be reduced by scrubbing with seawater. Claims for the potential reduction of PM levels range from 90% to 20%, depending on source [16, 17]. With low-sulphur fuels, emissions of PM can be further reduced by optimizing combustion to achieve increased oxidation of soot and of PM, minimizing consumption of lube oil and minimizing the use of additives in lube oil. The burning of fuel–water emulsions can also reduce emissions of PM to a certain extent.

**5.71** Post-treatment technologies that have been considered or are used in the automotive sector, such as particulate traps, are not regarded as being suitable for marine fuels due to the high sulphur content in these fuels [18]. Even future levels of 0.1% of sulphur in the fuels that are used in a SECA are 100-times the current sulphur limit for automotive diesel that is used in the European Union.

## EMISSION-REDUCTION OPTIONS FOR $CH_4$ AND NMVOC

**5.72** Engine exhaust emissions of methane ($CH_4$) and NMVOC are comparatively low. Some reductions may be achieved by optimizing the combustion process. NMVOC may also be oxidized with a catalyst. Oxidation catalysts are not uncommon in conjunction with SCR installations, where they oxidize unused ammonia, thus eliminating emissions of ammonia. Levels of $CH_4$ in exhaust are more difficult to reduce by using a catalyst.

**5.73** Emissions of $CH_4$ from gas engines are due to unburned methane arising from the process of premixed combustion. The level of $CH_4$ emissions depends on the layout of the combustion chamber. By careful design to avoid crevices, emissions can be significantly reduced. However, there will be a remaining level of $CH_4$ emissions. This $CH_4$ can be oxidized by using a catalyst, although this is not as simple as reducing the levels of NMVOC, and this is an area for research and development.

**5.74** Emissions of $CH_4$ from gas engines can be virtually eliminated by replacing the concept of lean premixed combustion with high-pressure gas injection. This latter concept is believed to be beneficial for large two-stroke engines. The disadvantage of this option is that the reduction of $NO_x$ emissions that is achieved through direct injection is less than can be achieved with lean premixed combustion.

## OPTIONS FOR REDUCING EMISSIONS OF HFC AND OTHER REFRIGERANTS

**5.75** Emissions of HFC are related to leaks during the operation and maintenance of refrigeration plants. Technical measures to reduce leaks include designs that are more resistant to corrosion, vibration and other stresses, reducing the impact of leaks by reducing the refrigerant charge (i.e. by indirect cooling), and compartmentalizing the piping system, so that a leakage may be isolated. It is also important that facilities are available to allow safe and not unreasonably burdensome recovery of refrigerants during maintenance. Operational measures include planned maintenance and monitoring of the consumption of refrigerant in order to prevent and detect leaks [19, 20].

## ASSESSMENT OF POTENTIAL REDUCTION OF EMISSIONS

## POTENTIAL FOR REDUCTION OF $CO_2$ EMISSIONS

**5.76** A number of options for improvements in efficiency have been discussed in previous paragraphs and the potential for saving energy by combining these options is very significant. On the other hand, costs, lack of incentives and other barriers prevent many of them from being adopted. Therefore, when making an assessment of the potential saving, we also make implicit assumptions regarding the degree of compromise, effort and extra costs that would be required. An assessment of energy-saving potentials, using known technology and practices, is shown in Table 5.2. The ranges in the figures in this table express the variation in potential for different ship types and the degree of commitment to making savings.

**5.77** Assumptions of future improvements in efficiency are used in the future emissions scenarios presented in Chapter 7. The high figures shown in Table 5.2 correspond fairly well to the scenario with the highest improvement in energy consumption, in which net improvements, excluding the use of low-carbon fuels, range from 58% to 75% in 2050 depending on the ship type. This assumption, as well as indicators of historic transport efficiency for different ship types, is illustrated in Figure 5.1. The background of the generation of historical efficiency data is presented in Chapter 9.

**Table 5.2** *Assessment of potential reduction of $CO_2$ emissions from shipping by using known technology and practices*

| **DESIGN (New ships)** | **Saving (%) of $CO_2$/tonne-mile** | **Combined** | **Combined** |
|---|---|---|---|
| Concept, speed and capability | 2–50$^{\dagger}$ | 10–50%$^{\dagger}$ | 25–75%$^{\dagger}$ |
| Hull and superstructure | 2–20 | | |
| Power and propulsion systems | 5–15 | | |
| Low-carbon fuels | 5–15* | | |
| Renewable energy | 1–10 | | |
| Exhaust gas $CO_2$ reduction | 0 | | |
| **OPERATION (All ships)** | | | |
| Fleet management, logistics and incentives | 5–50$^{\dagger}$ | 10–50%$^{+}$ | |
| Voyage optimization | 1–10 | | |
| Energy management | 1–10 | | |

* $CO_2$ equivalent based on the use of LNG.

$^{\dagger}$ Reductions at this level would require reductions of speed.

**5.78** Another perspective on the potential for reduction is that of marginal abatement cost curves (MACC). These add information to the reduction potential, as given in Table 5.2, by also assessing the costs of measures. A MACC plots the maximum achievable reductions against estimated cost-effectiveness. Assuming that the most cost-effective measures for reduction of emissions are implemented first, the subsequent options will be more expensive and less effective. For example, if an improved design of hull reduces the energy requirement by 5% and a better propeller achieves a reduction of 3%, implementing both will not necessarily yield a reduction of 8%. A MACC always considers the cost of reducing the emissions by the next tonne of $CO_2$, given the reduction that has been achieved by the options that have already been implemented [22].

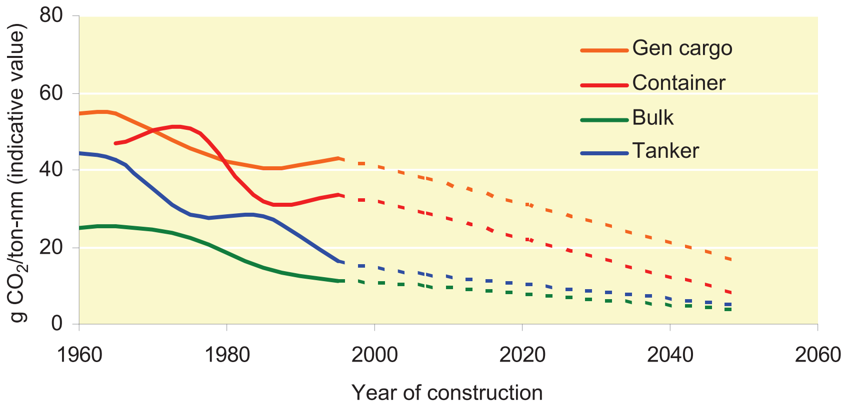

**Figure 5.1** *Indicated historical efficiency and "high-efficiency" scenarios*

**5.79** A MACC can inform policymakers about the costs of meeting certain reductions in emissions or the environmental effect of a tax or levy. It has to be noted, however, that the MACC does not capture all of the possible reactions to a certain policy. The effects of change of demand are absent, for example, so a thorough analysis of the costs of a policy should also use economic models.

**5.80** The generation of MACC curves is very demanding in terms of data. This is especially true for the MACC that is presented here, as little data on the cost-effectiveness of emission-reduction measures in shipping was available hitherto. In this study, only a subset of measures (a total of 25 individual measures) was available for inclusion. In certain cases, the criterion for exclusion has been the availability of data rather than the relevance of those data. Nevertheless, sufficient options are included to provide a meaningful indication of costs and the reduction potential for the world fleet. A better coverage of measures would show that the potential to reduce emissions is larger. As some of the measures that have not been considered here are currently implemented, it seems reasonable to assume that the cost-effective potential to reduce emissions would also be larger.

**5.81** Since, for most options, it is not possible to estimate a single value for costs and the potential for abatement, we decided to present ranges rather than single values. Assumptions, data and further information on the cost-effectiveness of specific measures are provided in Appendix 4. The marginal abatement cost curve for $CO_2$ is shown in Figure 5.2. In considering this curve, the following should be noted.

1. The curve adopts a social perspective. In other words, it answers the question of what it would cost the world economy to reduce emissions. It does not represent the expenditures that ship operators would have to make to do this.

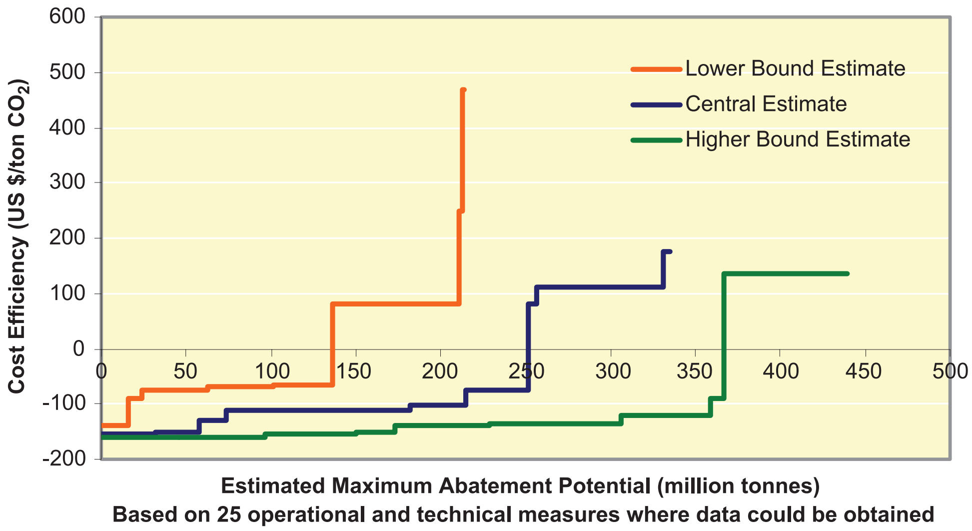

**Figure 5.2** *Indicative marginal $CO_2$ abatement costs for 2020 (fuel price 500 \$/tonne)*

2. The model assesses the fleet-average potential for abatement and the cost-effectiveness of measures. Some measures may be very cost-effective for some ship types, but would have high costs if applied to the world fleet. In that case, they would not seem to be cost-effective in this graph.
3. The model uses a subset of improvement options. The inclusion of more options would increase the total potential for reduction.
4. The maximum abatement potential is what can be implemented in the world fleet in 2020. It is not directly comparable to Table 5.2. Moreover, market constraints, such as limited availability of certain measures, have not been taken into account.
5. Some options have negative cost and would be profitable to use. There may be non-financial barriers that prevent their use, or they might be cost-effective from a social perspective but not from the perspective of a ship operator.
6. In general, higher discount rates will increase the investment annuity costs and shift the curve upwards (measures become less cost-effective).
7. In general, higher fuel prices increase the benefits of measures in terms of the fuel that is saved, and this shifts the curve downwards (measures become more cost-effective).
8. In 2020 the maximum abatement potential ranges from about 210 to 440 Mt of $CO_2$, i.e. about 15–30% of projected emissions in the A1 scenario family.

## POTENTIAL FOR REDUCTION OF OTHER GHG EMISSIONS

**5.82** A detailed analysis of impacts of emissions from shipping on climate is provided in Chapter 8. Somewhat simplified, the relative importance of the individual greenhouse gases that are emitted from ships can be indicated in terms of their global warming potential (GWP) [21]. A comparison of the GWP on a 100-year horizon, based on 2007, is shown in Table 5.3. This table shows that $CO_2$ is the primary GHG emitted by shipping, and that the potential for reduction of emissions from other sources is comparatively small.

**Table 5.3** *Relative importance of GHG emissions from ships in 2007*

| | million tonnes | GWP | $CO_2$ equivalent | GWP % |
|---|---|---|---|---|
| $CO_2$ | 1,050 | 1 | 1,050 | 98% |
| $CH_4$ | 0.24 | 25 | 6 | 0.6% |
| $N_2O$ | 0.03 | 298 | 8 | 0.7% |
| HFC* | 0.0004 | 1,300 | 0.5 | 0.6% |
| $SF_6$ | 0 | 23,900 | 0 | 0 |
| PFCs | Negligible | 6,500–9,200 | Negligible | Negligible |

* The GWP values vary greatly between the different HFCs. The refrigerant HCFC-22 is the most commonly used refrigerant on board ships; hence the corresponding value of GWP is used in the above calculations.

**5.83** The $N_2O$ and the $CH_4$ fraction of the exhaust gas can be reduced in proportion to energy consumption. The reduction potentials indicated in Table 5.2 can thus be applied also to these emissions. Note that some emissions of $CH_4$ also originate in the transport and handling of crude oil, and that these emissions are not reduced by increasing ship efficiency. With respect to HFC, these emissions are leaks. The theoretical potential to reduce their emissions is thus very high, although it may be very difficult to achieve.

## POTENTIAL FOR REDUCTION OF OTHER RELEVANT SUBSTANCES

**5.84** Emissions of other relevant substances ($NO_x$, $SO_x$, PM, CO and NMVOC) in exhaust gases will be reduced as the energy efficiency of shipping increases. Therefore, the potentials that are indicated in Table 5.2 can be applied for these emissions also, although the fraction of emissions of NMVOC that originates in the transport and handling of crude oil is not affected. Paragraphs 5.84 to 5.90 discuss the potential for additional reductions.

**5.85** The reductions in emissions that are mandated or expected from the revised Annex VI are shown in Table 5.4. The potentials for reduction are based on a sulphur content of 2.7% in fuel and PM compositions as shown in paragraphs 7.53 and 7.54.

**Table 5.4** *Maximum reductions in emissions in the revised Annex VI*

| | **Global** | **ECA** |
|---|---|---|
| $NO_x$ (g/kW·h) | 15–20% | 80% |
| $SO_x$* (g/kW·h) | 80% | 96% |
| PM (mass)[†](g/kW·h) | 73% | 83% |

* Reduction relative to 2.7% sulphur content in fuel.
[†] Expected reduction of PM from fuel change.

## $NO_x$

**5.86** Reduction of $NO_x$ emissions to Tier III limits (~80% reduction from Tier I) can only be achieved at present by SCR after-treatment or by using LNG as the fuel and lean premixed combustion. These technologies are proven for four-stroke engines; however, experience with large two-stroke engines is limited. A reduction of around 40–50% from Tier I has been demonstrated for four-stroke engines, with a simultaneous improvement in energy efficiency and reduction of emissions of $CO_2$ compared to current engines [5].

**5.87** Using SCR and LNG technology, it is possible to achieve reductions of emissions even beyond Tier III limits at high loads. However, achieving further reductions at low loads and achieving the reduction consistently for extended time periods may be more difficult. Furthermore, the potential for reductions for two-stroke engines is less well documented. Therefore, a primary gateway to reduce emissions of $NO_x$ could be to extend or introduce new ECAs and/or reduce the global $NO_x$ limit. The potential for extending the coverage of ECAs has not been analysed.

## $SO_x$ and PM

**5.88** The revised MARPOL Annex VI requires significant reductions in emissions of $SO_x$ and of PM, as shown in Table 5.4. While there have been few discussions as to the possibility of reducing emissions of $SO_x$ from individual vessels, there has been debate among experts on the total impact on emissions of $CO_2$ when these reductions are applied to the world fleet. This is also the case when considering the potential for further reductions. Technically, from the perspective of the ship, further reductions in sulphur are clearly feasible. Indeed, a lower sulphur content in the fuel is purely an advantage for the engine. However, other aspects of the fuel (such as, e.g., lubricity, ignition and combustion properties) are critical to the performance of the engine. Reductions in the sulphur limits of marine fuel may cause marine fuels to be blended in new ways, using different components, which could positively or negatively influence other parameters of the fuel. Therefore, more comprehensive and narrower specifications of marine fuels may be needed in the future.

**5.89** A potential for reducing emissions of $SO_x$ and of PM below the levels that are indicated in Table 5.4 by using scrubbing technology has been claimed. Alternative fuels, such as LNG, will also enable emissions of $SO_x$ to be reduced, although such fuels must be expected to be relevant for only part of the fleet. Possible future application of LNG as a fuel for ships is discussed in Chapter 7. The potential for reducing emissions of $SO_x$ through increasing ECA coverage has not been analysed.

## CO and NMVOC

**5.90** Carbon monoxide and NMVOC are by-products of incomplete combustion. These emissions show a certain trade-off with $NO_x$, as technologies aimed at reducing $NO_x$, other than SCR, tend to increase these emissions. Typical levels of these emissions are very low, in the range of 0.1–0.3 g/kW·h, and little effort has been made to reduce them further.

## SUMMARY

**5.91** Paragraphs 5.91 to 5.94 discuss the potential options for reduction of emissions of greenhouse gases and other relevant substances from the shipping sector, from a technological perspective. In principle, there are four fundamental categories of options for reducing emissions from shipping.

1. Improving energy efficiency, i.e. doing more useful work with the same energy consumption. This applies to both the design and the operation of ships.
2. Using renewable energy sources, such as the wind and the sun.
3. Using fuels with less total fuel-cycle emissions per unit of work done, such as biofuels and natural gas.
4. Using emission-reduction technologies – i.e. achieving reduction of emissions through chemical conversion, capture and storage, and other options.

**5.92** The potential for saving energy by combining these options is very significant, as shown in Table 5.2. It has been assessed that, by application of known technology and practices, shipping could be 25–75% more energy-efficient, depending on the ship type and the degree of compromise.

**5.93** Renewable energy, in the form of wind and solar energy, can be used on board ships as additional power; however, the total share of energy that can be covered in this way is limited both by the availability and variable intensity of wind and solar energy and the present-day ability to make use of it.

**5.94** LNG is a marine fuel that delivers very significant reduction of $NO_x$, $SO_x$ and PM emissions and also at the same time a reduction in $CO_2$ equivalents. Where available, LNG is expected to remain a less expensive fuel than distillate fuels. This combination makes it particularly interesting for use within future ECAs. Emission-reduction technologies can be applied to reduce $SO_x$, $NO_x$ and PM emissions.

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# 6

# Policy options for reductions of GHG and other relevant substances

## INTRODUCTION

**6.1** Scenarios for future emissions from ships are presented in Chapter 7 of this report. These scenarios show that emissions of GHG from shipping are likely to increase in the future, principally due to an anticipated increased demand for transport. Chapter 3 has identified $CO_2$ as the most important GHG emission from shipping. Therefore, this chapter emphasizes reduction of emissions of $CO_2$. Chapter 8, which addresses climate impacts, puts the future emission from shipping in a global context. This is done by comparing scenarios for future emissions of $CO_2$ from ships with the total global emission of $CO_2$ that is believed to result in an increase in temperature of 2°C. It is clear from this comparison that reductions in emissions of $CO_2$ from the shipping sector are needed beyond what is anticipated in the scenarios. Chapter 5 provides examples of technical and operational measures that can be taken to reduce emissions. As some of these measures are costly, policies will be needed to support their implementation. This chapter analyses the policy options that may be applied to achieve reductions of emissions.

**6.2** The chapter is structured as follows. Paragraphs 6.4 to 6.33 discuss progress and current work within IMO on this topic. Paragraphs 6.34 to 6.47 provide an analytical overview of policy options, while paragraphs 6.48 to 6.71 describe the design of the policy options to be analysed. Paragraphs 6.72 to 6.130 discuss criteria for analysis of policy options and present a qualitative analysis of these options. Conclusions are provided in paragraph 6.131.

**6.3** General background information that is relevant to the discussion is provided in Chapter 2 of this report. This background includes, *inter alia*, introduction to the United Nations Framework Convention on Climate Change (UNFCCC), differences in interpretation of the wording of Article 2.2 of the Kyoto Protocol, and a general overview of regulation and the legislative framework for shipping.

## PROGRESS AND CURRENT DISCUSSIONS IN IMO

**6.4** In 1997, the MARPOL Conference adopted a resolution on "$CO_2$ emissions from ships", inviting the IMO to undertake a study on the quantity of GHG emissions from ships and to consider "feasible GHG emission reduction strategies". The MEPC commissioned a study which was completed in 2000 and provided an examination of emissions of greenhouse gases from ships as well as possibilities for the reduction of these emissions through different technical, operational and market-based approaches.

**6.5** To further address the issue of GHG emissions from ships, the IMO Assembly adopted (December 2003) resolution A.963(23) on "IMO Policies and practices related to the reduction of greenhouse gas emissions from ships", which, *inter alia*:

1. Urges the MEPC to identify and develop the mechanism or mechanisms needed to achieve the limitation or reduction of GHG emissions from international shipping and, in doing so, to give priority to:
   - the establishment of a GHG emission baseline;
   - the development of a methodology to describe the GHG efficiency of a ship in terms of a GHG emission index for that ship. In developing the methodology for the GHG emission indexing scheme, the MEPC should recognize that $CO_2$ is the main greenhouse gas emitted by ships;

- the development of Guidelines by which the GHG emission indexing scheme may be applied in practice. The Guidelines are to address issues such as verification; and
- the evaluation of technical, operational and market-based solutions.

**6.6** Results from the extensive work within the MEPC in response to this challenge are briefly summarized in the following sections. Paragraphs 6.7 to 6.12 discuss progress towards the establishment of a GHG emission baseline. Paragraphs 6.13 to 6.28 focus on methodologies to describe the GHG efficiency of a ship. Paragraphs 6.29 and 6.30 address the development of guidelines by which the GHG emission indexing scheme may be applied in practice. Paragraph 6.31 briefly describes the evaluation of technical, operational and market-based solutions, although this is also captured by paragraphs 6.48 to 6.71.

## The establishment of a GHG emission baseline

**6.7** When referring to a baseline for GHG emissions, resolution A.963(23) calls for an overall baseline for total emissions of $CO_2$ from ships for a given year, with the purpose of illustrating the trends in total emissions. The same resolution also requests that the MEPC consider the methodological aspects related to the reporting of emissions of GHG from ships that are engaged in international trade.

**6.8** Establishing a baseline for shipping is a challenging discussion for the MEPC, since the scope of the baseline may or may not be subject to flag, i.e. the still-to-be-resolved question of whether "common but differentiated responsibility" should apply to a GHG regime for international shipping rather than IMO's basic principle of "no more favourable treatment".

**6.9** Moreover, there are methodological difficulties in establishing such baselines. This can be appreciated by the discussions in Chapter 3 and Appendix 1 of this report, in which, *inter alia*, it is concluded that statistical data presently available are likely to under-report the consumption of marine fuel. The emissions inventory for this study relies on an activity-based estimate for 2007. As can be seen in Chapter 3, there is a considerable uncertainty in the estimate. In this study, the estimated annual changes in emissions in years prior to 2007 are based on trending with seaborne trade estimates from Fearnleys. While this was found to be the best possible approach for this study, it is inappropriate to rely on data from Fearnleys to calculate future emissions in a framework where direct activity data are instrumental in determining whether or not goals have been achieved.

**6.10** Chapter 3 and Appendix 1 of this study exemplify the use of shipping activity input to establish current-year emissions, and demonstrate how to use explicit scenario drivers to articulate future estimates under various interventions and economic signals. This discussion is relevant, since establishing baselines is an important element of some policy options that will be discussed in forthcoming sections.

**6.11** The number of days at sea for the various ship types is the parameter in the activity-based inventory that contributes the largest uncertainty. Long Range Identification and Tracking (LRIT) systems may provide data that could provide trends in ship activity that are suitable for an activity-based baseline. The related provisions of the 1974 SOLAS Convention have entered into force on 1 January 2008; the phased-in implementation started on 31 December 2008 and will be completed for passenger ships (including high-speed craft), cargo ships of 500 gross tonnage and above (including high-speed craft), and mobile offshore drilling units (when they are not on location), when engaged on international voyages, by 30 December 2009 (for the SOLAS Contracting Governments which are also Parties to the 1988 SOLAS Protocol, this will be completed by 30 March 2010).

**6.12** The cost of LRIT information has to be paid for by those requesting such information, and in essence the total cost of the LRIT system is paid by SOLAS Contracting Governments as flag States. As a result, there are certain caveats in relation to the use and sharing of LRIT information, and thus it will be necessary to discuss certain issues within the Maritime Safety Committee, including amending the current decision so as to allow the use of LRIT information for purposes of protection of the environment. Nevertheless, while some uncertainty is inevitable, it is considered to be technically feasible to generate rigorous baselines, using activity-based data, in the near future.

## Methodologies to describe the GHG efficiency of a ship

**6.13** Resolution A.963(23) calls for the development of a methodology to describe the GHG efficiency of a ship in terms of a GHG emission index for that ship. Recognizing that $CO_2$ is the most important greenhouse gas that is emitted from ships, the MEPC has mainly emphasized emissions of $CO_2$ in their discussions and has explored three principal pathways to indexing emissions:

1. Indexes expressing the GHG efficiency of the design of the ship;
2. Indexes expressing the GHG efficiency of the operation of the ship; and
3. Combinations of the above.

**6.14** Emission indexes are designed to benchmark design or performance of ships. This information can potentially be used by shipowners and ship operators for self-improvement. Potentially, emission indexing could be used in voluntary incentive systems or in mandatory schemes, as is discussed in paragraphs 6.48 to 6.71. The remainder of this section describes the two indexes that are currently discussed in IMO, viz. the Energy Efficiency Design Index (paragraphs 615 to 6.23) and the Energy Efficiency Operational Indicator (paragraphs 6.24 to 6.28).

## Energy Efficiency Design Index (EEDI)

**6.15** The MEPC has considered indexes expressing the GHG efficiency of the design of a ship in great detail. The fundamental principle that has been agreed is that the emission index expresses the ratio between the cost (i.e. emission) and the benefit that is generated, which is expressed as transport work capacity.

**6.16** MEPC 58 approved the use of the draft Interim Guidelines on the method of calculation of the Energy Efficiency Design Index for new ships, for calculation and trial purposes with a view to further refinement and improvement, as set out in annex 11 of its report [1]. Since the EEDI has not been finalized at the time of writing (March 2009), it is possible that changes could be made compared to what is presented here. It is likely, however, that such changes will apply only to details of the EEDI, which will have little impact on the overall concept that is discussed here.

**6.17** The EEDI expresses the emission of $CO_2$ from a ship under specified conditions (e.g., engine load, draught, wind, waves, etc.) in relation to a nominal transport work rate. The unit for EEDI is grams of $CO_2$ per capacity-mile, where "capacity" is an expression of the cargo-carrying capacity relevant to the cargo that the ship is designed to carry. For most ships, capacity will be expressed as deadweight tonnage.

**6.18** The EEDI formula takes into consideration special design features and needs, including the use of energy recovery, the use of low-carbon fuels, performance of ships in waves and the need for ice strengthening of certain ships. The handling of certain design features, such as electric propulsion, is still subject to evaluation. The EEDI has a constant value that will only be changed if the design is altered.

**6.19** The EEDI provides, for each ship, a figure that expresses its design performance. By collecting data on the EEDI for a number of ships within a category, it will be possible to establish baselines that express typical efficiencies of these ships. Figure 6.1 shows the effect of deadweight of a ship on the $CO_2$ design index for some categories of ship [2]. The formula that was used to calculate the $CO_2$ design index is similar to the EEDI, and the EEDI is expected to show the same behaviour.

**6.20** Based on this type of analysis, EEDI baselines have been proposed for different ship categories that are functions of ship size [3], where size is expressed, e.g., as deadweight tonnage or gross tonnage. EEDI baselines could be part of different policies using the EEDI. It is clear from this figure, however, that, when the ship size gets very small, the curve showing the EEDI trend becomes steep for these small container ships and dry cargo ships shown. Therefore, small variations in ship size may result in very large variation in the EEDI baseline. This could potentially encourage non-optimal design practices where ship size is selected by the EEDI baseline allowance rather than by operational need, which may not be a desirable outcome. Therefore, a size threshold could be considered for the application of an EEDI baseline of this type.

**6.21** Establishing an EEDI baseline, using different datasets, will result in different baselines being calculated. Presently, the EEDI is not finalized and baseline data have been approximated by using data from existing ship databases rather than being obtained through the process of establishing the EEDI for

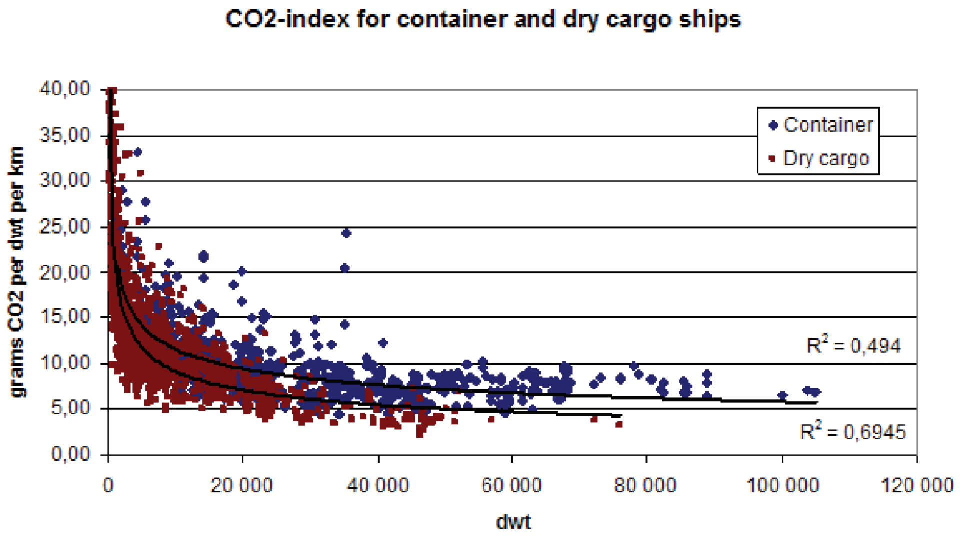

**Figure 6.1** *The effect of ship deadweight on $CO_2$ design index [2]*

individual ships. Also, the introduction of Common Structure Rules (CSR) has increased the steel weight of new ships, which may need to be taken into account. Presently, some work remains within the MEPC to finalize the development of EEDI baselines.

**6.22** Some ships are not primarily designed to transport cargo. Examples include tugs, ice-breakers, dredgers, fishing vessels and cruise ships. In these cases, transport work is not suitable to express the benefit they provide [4]. Therefore, there are some ship types where the EEDI, in units per kilometre, may be considered less meaningful or relevant. This, and the possible need for a minimum size threshold, suggests that the units in which EEDI is measured may need modification to address some ship types and sizes, and that the EEDI may not be practically applicable to all ship types. However, large cargo ships can be covered and, as shown in Chapter 3, these ships account for a significant share of emissions.

**6.23** Potential policies, using the EEDI as a basic parameter, are discussed in forthcoming sections.

### Energy Efficiency Operational Indicator (EEOI)

**6.24** The fundamental principle for the EEOI is the same as agreed for the EEDI, i.e. that the emission index expresses the ratio between the cost (i.e. the emission) and the benefit that is generated.

**6.25** The EEOI was previously referred to as the (operational) “IMO $CO_2$ index”. The Interim Guidelines for voluntary ship $CO_2$ emission indexing for use in trials were adopted by MEPC 53 in July 2005 and published as MEPC/Circ.471. The MEPC urged interested parties to facilitate trials and report results. In the work leading to the adoption of MEPC/Circ.471, alternative formulas, approaches and use of the index were discussed, as presented in MEPC 53/WP.3 and MEPC 49/4. At the time of writing (March 2009), IMO is in the process of finalizing an updated version of the EEOI. The final EEOI could, therefore, be somewhat different if compared to the EEOI as discussed here.

**6.26** The EEOI expresses actual $CO_2$-efficiency in terms of emissions of $CO_2$ per unit of transport work, using the following formula (MEPC/Circ.471):

$$\mathrm{EEOI} = \frac{\sum_i \mathrm{FC}_i \times \mathrm{C}_{\mathrm{carbon}}}{\sum_i \mathrm{m}_{\mathrm{cargo},i} \times \mathrm{D}_i}$$

where:

$\mathrm{FC}_i$ denotes fuel consumption on voyage $i$;
$\mathrm{C}_{\mathrm{carbon}}$ is the carbon content of the fuel used;
$\mathrm{m}_{\mathrm{cargo},i}$ is the mass of cargo transported on voyage $i$; and
$\mathrm{D}_i$ is the distance of voyage $i$.

The unit for the EEOI is grams of $CO_2$ per capacity-mile, where "capacity" is an expression of the actual amount of cargo that the ship is carrying. For most ships, capacity will be expressed as tonnes of cargo moved; however, other units (such as passengers, TEU, cars and more) may also be used. Unlike the EEDI, the EEOI changes with operational conditions. The EEOI may thus be calculated for each leg of a voyage and reported as a rolling average or periodically.

**6.27** MEPC/Circ.471 specifies that "the guidelines are applicable for all ships performing transport work".

**6.28** From the trials conducted to date, it appears that the value of the EEOI will, amongst others, depend on the average utilization of the cargo-carrying capacity that can be achieved in actual operation. The latter is affected by the cyclical "business climate" for the various trades [5]. Hence the average indicator for a ship category may vary from one year to the next, given changes to demand and competition, and among trade routes. Some transport tasks appear to offer the possibility for high average utilization (e.g., return cargo, or trade triangles), while other trade patterns (e.g., distribution of smaller cargo parcels) may result in inherent low efficiency that is related to the nature and geography of the transport demand, not to the operation or choice of ship [6]. All of these issues may make it hard to establish a baseline for the EEOI.

### Applying the GHG emission indexing schemes in practice

**6.29** In order to promote best practices for fuel-efficient operation of ships, the MEPC is considering the introduction of a Ship Efficiency Management Plan (SEMP). The shipping industry has put significant effort into the development of the technical details of how this could be done, as presented in MEPC 58/INF.7 [7].

**6.30** The SEMP presents a framework for a ship to address energy-efficient operation by monitoring performance and considering possible improvements in a structured fashion. A SEMP could be developed by the ship operator or other relevant party, such as a ship charterer. Its successful implementation would include four phases:

1. Planning;
2. Implementation;
3. Performance monitoring; and
4. Self-improvement.

The EEOI could be utilized for performance monitoring within the SEMP – the SEMP should not be seen in isolation. Provisions already exist in the ISM Code for owners and operators to monitor environmental performance and to establish a programme for continuous improvement. The proposed Ship Efficiency Management Plan may be considered an amplification of the requirements of the ISM Code. It provides a possible mechanism for monitoring ship and fleet efficiency performance over time (based on the EEOI) and some options to be considered when seeking to optimize the performance of the ship [7].

### The evaluation of technical, operational and market-based solutions

**6.31** One of the tasks that IMO Assembly resolution A.963(23) urges the MEPC to undertake is "the evaluation of technical, operational and market-based solutions". The MEPC has indeed discussed technical, operational and market-based policy instruments. These discussions have not yet resulted in the adoption of a policy. The proposals that were made during these discussions are the basis for paragraphs 6.48 to 6.71, on the design of GHG policies for shipping.

### Work plan for IMO GHG work

**6.32** As a follow-up to resolution A.963(23), MEPC 55 (October 2006) approved a "Work plan to identify and develop the mechanisms needed to achieve the limitation or reduction of $CO_2$ emissions from international shipping", inviting Member Governments to participate actively in the work. The work plan culminates at MEPC 59 (July 2009) and contains, *inter alia*, improvement of the method of operational efficiency indexing that is described in paragraphs 6.13 to 6.28 above, establishment of $CO_2$ emission baseline(s), and consideration of technical, operational and market-based methods for dealing with emissions of GHG from ships in international trade.

**6.33** Results from this work will be important to the considerations that will take place within the UNFCCC at the fifteenth session of the conference of the parties (COP-15, December 2009). The overall goal for this conference is to establish an ambitious agreement on global climate.

## IDENTIFICATION OF POLICY OPTIONS

**6.34** A large number of policies to reduce ships' GHG emissions are conceivable. This section sets out to identify a comprehensive overview of options, abstracting from concrete proposals that have been made to IMO. The next section will discuss the options that are relevant to the current IMO debate in more detail.

**6.35** There are various ways to classify policies, we list two.

1. Policies can be classified according to the *basic parameter* that the policy uses. In the case of climate policies, the basic parameter can be absolute emissions, an efficiency indicator, life-cycle carbon emissions arising from a fuel, etc.
2. Policies can be classified according to the *type of policy instrument*. In environmental policies, a classification of market-based instruments, command-and-control[1] instruments and voluntary instruments is often used.

This study identifies policy instruments according to the basic parameter.[2] Paragraphs 6.42 to 6.44 present a matrix where policy instruments are categorized according to both the basic parameter and the type of instrument.

### Factors determining maritime emissions of $CO_2$

**6.36** Figure 6.2 presents a stylized overview of the principal factors that influence the magnitude of emissions from seaborne transport. The purpose is to provide a policy-analytical framework to evaluate

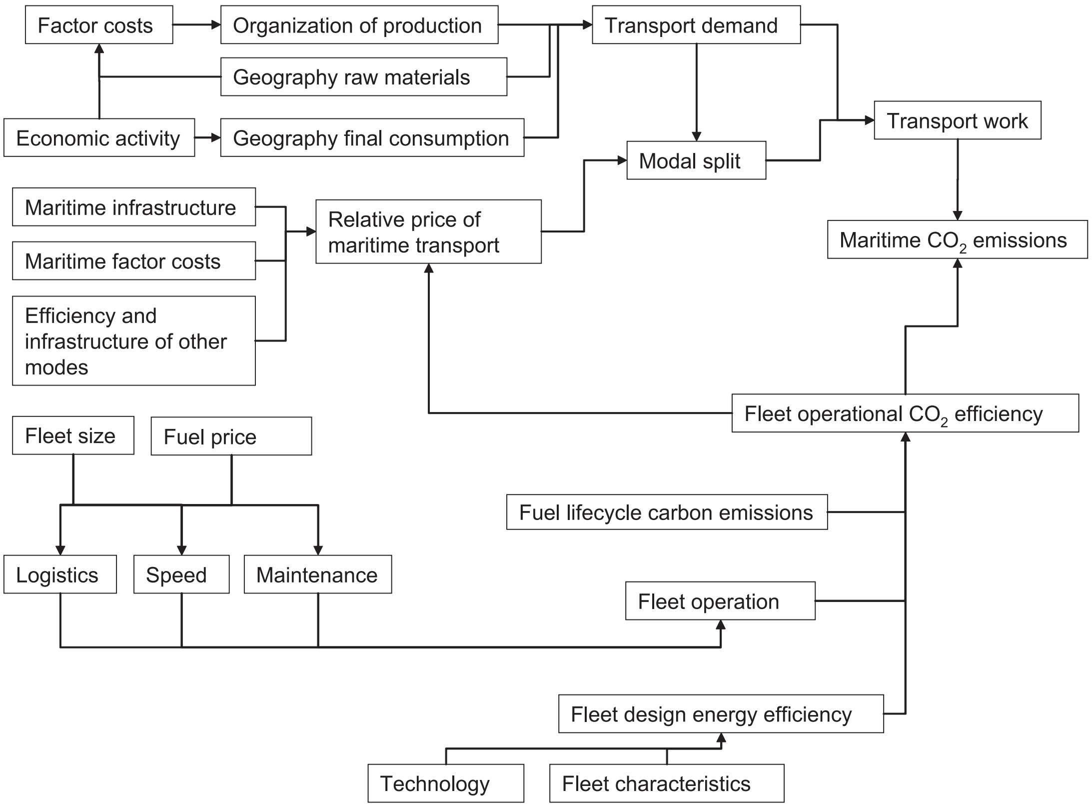

**Figure 6.2** *Stylized representation of factors determining maritime emissions*

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[1] The term "command-and-control" generally comprises all prescriptive regulations, be they prohibitions, technology-based discharge standards, performance standards, etc. (Russell and Powell, 1999 [26]).

[2] For a list of policies classified according to the type of policy, see, e.g., Torvanger *et al.* (2007) [29].