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AN INVESTIGATION INTO LCA AS A COMPLEMENTARY UTILITY TO REGULATORY MEASURES OF SHIPPING ENERGY EFFICIENCY

By

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This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: E. Blanco-Davis Date: 27 October 2014

Abstract

The IMO has recently developed technical and operational measures aimed at enhancing shipping environmental efficiency, i.e. the EEDI and the EEOI, respectively. The purpose of this exploratory research work is to investigate the Life Cycle Assessment (LCA) methodology as a complementary tool to these metrics, capable of not only serving as a widespread accepted environmental performance indicator, but also able to competently highlight energy efficiency.

The EEDI and EEOI methodology is reviewed, while also using two case vessels as sample implementation case studies. An LCA model formulation is developed and also applied on the two case studies, utilising them for validation, and additionally for comparing the LCA approach to the IMO regulatory metrics. One of the case vessels comprises the evaluation of a proposed retrofit, in order to emphasise on the different metrics' potential to assess changes in the results, with regards to the retrofit's before and after phases.

Results show that aside from the environmental score of CO_2 emissions per unit of work –documented by the current regulatory metrics–, LCA can also offer NO_x and SO_x scores, along with other hazardous releases. Moreover, LCA –aside from showing compliance to the formulation of both IMO regulatory metrics– is able to present material and energy utilisation throughout different stages within the vessel's lifetime. Lastly, it is demonstrated that LCA can be used in parallel to the regulatory metrics, in order to efficiently emphasise detailed environmental information, pertaining to specific substance release or phase improvement/redesign as required.

It is concluded that LCA could serve in aiding to monitor and report maritime transport emissions with an already widely accepted methodology. Furthermore, LCA could be recognised between industry and international stakeholders –including shipping and shipbuilding and repair–, as a common performance marker capable of consistent implementation not only across shipping divisions, but also across different industry sectors.

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This work is dedicated to my mother, Dr Enriqueta Davis, Professor of Sociology and lifelong academic and researcher, with over 25-authored books and countless journal and newspaper publications, for serving as a constant role model and encouragement towards academic and research excellence.

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Nomenclature

A/F	Antifouling paint
AIS	Automatic identification system
ASTANDER	Shipyard, Astilleros de Santander S.A.
BAU	Business As Usual
BWTS	Ballast water treatment system(s)
CDM	Clean Development Mechanism
CER	Certified Emission Reductions
CFC	Chlorofluorocarbon
CFC-11 / R-11	Trichlorofluoromethane
CH_4	Methane
CML	Centre of Environmental Science, University of Leiden, The Netherlands
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	CO_2 Equivalent
CONSAR	Italian Shipowner’s Association, Consorzio Armatori per la Ricerca
COP	Conferences of the Parties
DCB	Dichlorobenzene
DWT	Deadweight, difference between displacement and lightship weight at summer load
EC	European Commission
ECA	Emission Control Areas
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EIO-LCA	Economic Input-output assessment approach
EMS	Environmental Management System
EPA	U.S. Environmental Protection Agency
EPD	Environmental Product Declaration
EPI	Environmental Performance Indicator(s)
ERU	Emission Reduction Units
EU	European Union
EU ETS	European Union Emissions Trading System
EVDI	Existing Vessel Design Index
FRC	Fouling Release Coating
GHG	Greenhouse gas
GT	Gross tonnes
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
ICS	International Chamber of Shipping
IEEC	International Energy Efficiency Certificate
IMO	International Maritime Organization
IOA	Input-Output Analysis
IOT	Input-Output Tables

IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JI	Joint Implementation Mechanism
LBP	Length between perpendiculars
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life cycle inventory analysis phase
LCIA	Life cycle impact assessment phase
LCSA	Life Cycle Sustainability Analysis
LFO	Light Fuel Oil
LNG	Liquefied natural gas, sometimes referred to in context of the ships which transport this cargo (i.e. LNG carriers)
LOA	Length overall
MARPOL	International Convention for the Prevention of Pollution from Ships
MBM	Market-based Measures
MCR	Maximum Continuous Rating
MEPC	Marine Environment Protection Committee
MRV	EU system for monitoring, reporting and verification of carbon dioxide emissions from maritime transport
NGO	Non-Governmental Organization
nm	Nautical mile
NO_x	Nitrogen Oxides
PI	Performance Indicator(s)
PM	Particulate Matter
REPA	Resource and Environmental Profile Analysis
Ro-Ro	Roll-on/Roll-off vessel
Sb	Antimony
SEEMP	Ship Energy Efficiency Management Plan
SETAC	The Society of Environmental Toxicology and Chemistry
SFC	Specific fuel consumption
SLCA	Social Life Cycle Assessment
SMS	Safety Management System
SO_2	Sulphur Dioxide
SO_x	Sulphur Oxides
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
UN	United Nations
UNEP	United Nations Environment Programme
VOC	Volatile organic compounds
WCC	World Climate Conference
WMO	World Meteorological Organization

1 Introduction

1.1 Introductory remarks

The chapter presented herein strives to serve as an outline, aimed at offering the reader a concise context into the research work carried out for the completion of this document. The following section, *Background*, will include a succinct review of the methodology used to carry out the main work, Life Cycle Assessment –or LCA, as commonly known–; and additionally a brief description of how it has been put to practice relative to this work. The actual problematic that this thesis aims to tackle is described subsequently; and lastly, a description as to the physical arrangement of this document is offered.

1.2 Background

LCA is a methodology which has been constantly evolving for the past three decades (Guinée et al., 2011). What started out as a theoretical approach into the assessment of the potential environmental impacts of a chosen and predefined system, has developed into a highly pragmatic application, which could, additionally from the environmental standpoint, produce relevant impacts encompassing economic and social angles (Guinée et al., 2011; Weidema, 2006).

Aside from the economic and social additions into the methodology, its application has grown into a widespread practice among different industries, and consequently has become internationally accepted within renowned environmental organisations, governmental departments, and research groups. The metalworking industry, for example, has since put to practice the use of the methodology often, analysing its manufacturing processes, but additionally utilising its environmental scores as a form of positive advertising (see Figure 1.1).

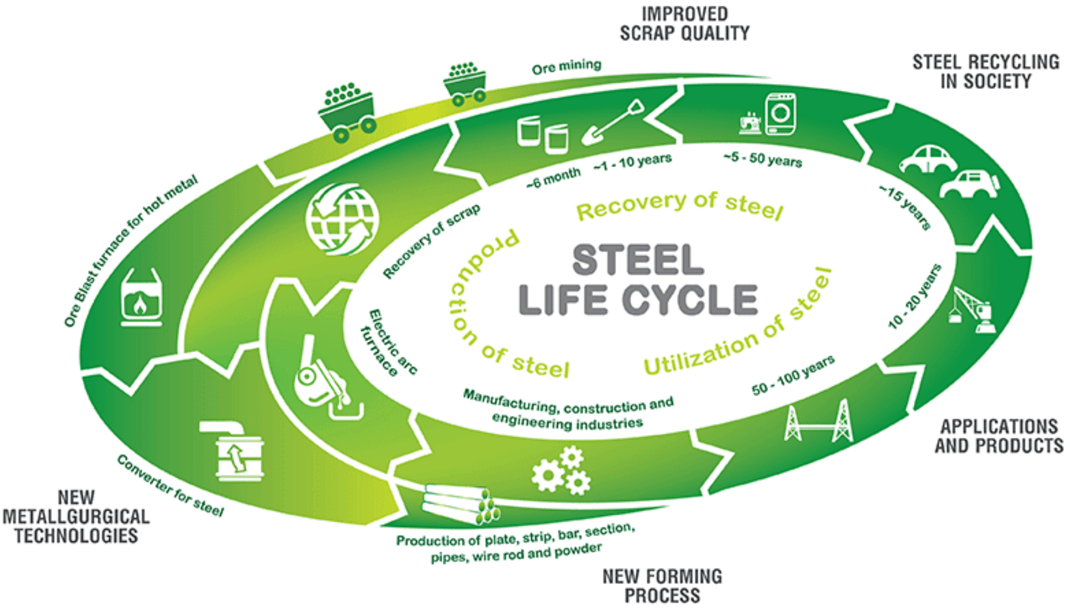

Figure 1.1: Graphical depiction of the life cycle of steel (BLUESCOPE, 2012)

Apart from marketing purposes, the methodology can also serve to identify environmental improvement opportunities within the different phases of the life cycle of a product or system, in turn providing prospects for product and process design or re-design. Most importantly, however, is the recognised potential of the tool to allow for the proper selection of a relevant indicator of environmental performance, including measurement techniques and indicator appraisal (ISO, 2006a, b; PE-International, 2011).

Furthermore, innovative management practices are also included within the methodology (Rebitzer, 2005; Rebitzer and Hunkeler, 2003), giving specific relevance to environmental improvement and sustainability (Klöpffer, 2008), and even corporate social responsibility and social life cycle assessments (Benoît and Mazijn, 2010; Brent and Labuschagne, 2006).

Nevertheless, while other industries such as the car manufacturing industry, for example, exemplify various LCA case studies and implement the methodology frequently along their supply networks, the shipping and shipbuilding and repair industry offers great potential for further tool implementation, given the fact that in comparison to other industries, less concrete LCA applications have been exercised (Blanco-Davis, 2013a).

As far as the shipping and shipbuilding and repair industry goes, LCA application extends from process or product design (Ellingsen et al., 2002; Koch et al., 2013), construction and repair or retrofitting (Blanco-Davis, 2013b; Fet, 1998), transportation and fishing (Fet and Michelsen, 2000; Utne, 2009), alternative power sources and fuels (Alkaner and Zhou, 2006; Bengtsson et al., 2012), onboard system assessment (Blanco-Davis and Zhou, 2014; Cabezas-Basurko and Mesbahi, 2012), and systems engineering and management (Fet et al., 2013).

The application of the methodology within this work, however, is aimed specifically at implementing LCA as an environmental performance indicator (EPI) for ships, which could additionally highlight and report energy efficiency. This has been briefly mentioned by Blanco-Davis (2014), and while in a different context than presented herein, also endorsed by Fet et al. (2013), relative to implementing EPIs on ships' life cycle designs. More information with regards to LCA, and the state-of-the-art and application within the industry and the work presented here will be included further, in the *Literature Review* chapter.

Lastly, the reader should note that the definitions for data, indicator, and index provided in Figure 1.2, will be valid throughout the work herein.

Data: information, especially facts or numbers, collected to be examined and considered and used to help with making decisions.

E.g. The data shows that more than 80% of the agricultural workforce is Hispanic; financial/personal/sales data.

Indicator: something that shows what a situation is like.

E.g. Commodity prices can be useful indicator of inflation, he claimed; an economic indicator.

Index: a system of numbers used for comparing values of things that change according to each other or a fixed standard.

E.g. the FTSE 100 Index; the Dow Jones Index; a wage/price index.

Figure 1.2: Definitions of data, indicator, and index, according to Cambridge-Dictionary (2014)

1.3 Formulation of the problem

The aim to measure and improve energy efficiency within a ship, relative to an environmental context, is not novel. The discussion, however, has been intensified during the past decade; probably due to the harmonised advertisement from intergovernmental and global environmental organisations, with regards to the potentially irreversible downsides brought about by climate change. In 2013, for example, the Intergovernmental Panel on Climate Change remarkably underlined, in their IPCC's Fifth Assessment Report, that the current climate warming trends are highly likely to be induced by human activities (BBC, 2014; IPCC, 2013).

This and other initiatives, such as the European Commission's Europe 2020, which among other goals aims to set rigid climate and energy targets by the year 2020 (EC, 2010), exert pressure on the public and the industry, not only aiming at creating a general awareness towards environmental wellbeing, but setting strict regulatory framework awaiting proper compliance.

Following this trend, the shipping industry has acted accordingly in order to strive to regulate shipping energy efficiency, and consequently improve the reduction of greenhouse gas (GHG) emissions. The International Maritime Organization (IMO), shipping's main regulatory body, has dedicated relevant efforts to develop technical and operational measures aimed at enhancing onboard environmental efficiency. These measures include the following:

- The Energy Efficiency Design Index (EEDI),
- The Energy Efficiency Operational Indicator (EEOI), and
- The Ship Energy Efficiency Management Plan (SEEMP).

The IMO's Marine Environment Protection Committee (MEPC) met as early as 1997 to address CO_2 emissions from ships, introducing Resolution 8, which requested the assessment of practical CO_2 reduction measures, in the light of the emission's likely environmental impact (IMO, 2014f). The resolution is considered a steppingstone into the study, and ultimately the introduction of guidelines and regulations encompassing the above-mentioned measures (see Figure 1.3).

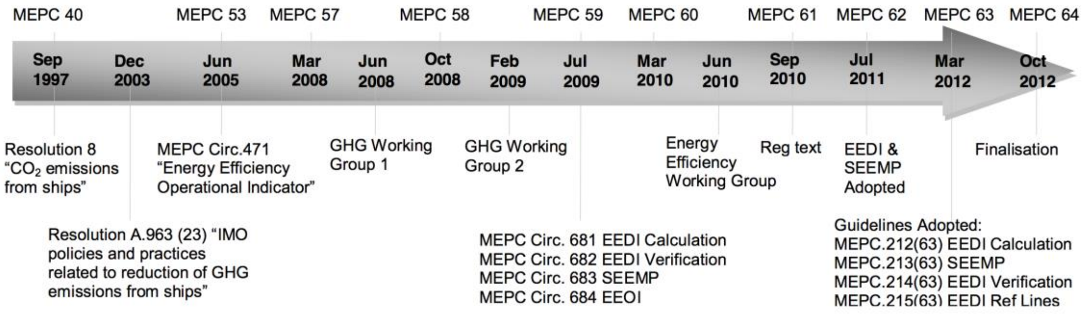

Figure 1.3: IMO's greenhouse gas regulatory background (Lloyd's-Register, 2012b)

The prescriptive measures above, otherwise also categorised as energy efficiency metrics, while originally good in nature, have not been welcomed completely by all industry stakeholders. The last may be a reaction to some of the measures' shortcomings, such as their direct applicability to different sections of the fleet, e.g. newbuilds and existing vessels.

Aside from these regulatory measures, other metrics have also been developed, voluntary in nature, and allegedly offering to cover the gaps of the previous. Examples of such metrics are the Existing Vessel Design Index (EVDI), developed by Rightship (2014), and the AIS-based performance metric proposed by Smith et al. (2013); the former offers an attempt to develop a single efficiency metric capable of being applied to new ship designs as well as to existing vessels, while the latter proposes separate formulations, not specifically in favour of a single or simplified energy efficiency indicator.

To add to the above mix of energy efficiency metrics, the European Commission has also decided to contribute with a proposal applicable to regulate CO_2 emissions within Europe –aimed at being applicable globally, however, if ultimately acknowledged–, establishing a regulation "on the monitoring, reporting and verification [MRV] of carbon dioxide emissions from maritime transport" (EC, 2013g).

The problematic carried forward by the available performance measures underlines the issues of applicability within the different metrics (e.g. newbuilds and existing vessels), the incomparability or non-equivalency of the scores between them, the on-going discussion of a single metric approach, and their partial coverage and application, among other concerns that will be described further at a later stage. The last emphasises an evident prospect for a standardised alternative performance method –utilised as supplementary to the current regulatory measures–, and capable of not only highlighting energy efficiency but also serving as a widespread accepted environmental performance indicator, in order to strive to cover the inherited gaps of the regulatory metrics.

1.4 Research methodology

The primary aim of this exploratory research is to propose and test LCA as a proficient ship energy efficiency and environmental performance tool, capable of consistent implementation across shipping divisions (i.e. newbuilds versus existing ships). The last would serve to identify LCA as an efficient complementary utility to the current shipping energy efficiency metrics.

To meet the above scope, the following objectives should be fulfilled:

- To understand the actual methodology of the current available ship energy efficiency metrics and their inherited limitations. This is pursued through the revision of the available literature and existing samples, if any. The last will define the regulatory metrics' gaps and also allow developing a context in which the LCA methodology can be later compared to the metrics; in turn, this will allow the appraisal of the proposed tool in parallel to the metrics, with the aim of covering such gaps.

- To understand the LCA methodology, specifically with regards to its direct application on the shipping and shipbuilding and repair industry, also pursued through the revision of the available literature and existing samples, if any; the last should focus on highlighting advantages, which should be of aid to covering the previously mentioned gaps.

- To develop an LCA ship's life cycle model; this last in order to apply the model to the selected case studies, as an approach to experiment on the proposed tool and the chosen test metrics. The reader should know that the extension of the test metrics comprises solely IMO's EEDI and EEOI, as explained in further sections.

- Lastly, the proposed tool should offer significant results while covering the gaps of the chosen available test metrics, in order to ultimately advise or not, about its potential contributions to the field.

1.5 Thesis layout

The work herein presented is composed of 8 main chapters. The following is a brief description of the contents of each chapter:

- Chapter 1 Introduction: this chapter offers an outline of the thesis, including a summary of the approach adopted, and the problematic to be tackled. It also sets specific aims and objectives for the remainder of the thesis, underlining expected outcomes.

- Chapter 2 Literature review: this chapter undertakes a close revision of the available literature, both with regards to the problematic presented, as well as to the state-of-the-art of the approach to be used as a complementary solution. Additionally, the methodology of the energy efficiency metrics is described, including the shortcomings and impracticalities of the relevant measures.

- Chapter 3 Approach adopted: the previous chapter sets out a context in which the adopted approach can be compared to; therefore this chapter highlights the basics of the LCA methodology, and explains how it is applied within the scope of this work. Additionally, the development of the ship's LCA model is discussed; this model is in turn applied in the following chapter.

- Chapter 4 Case studies: two distinctive case studies are presented, in order to validate the LCA methodology and model presented previously, assessing the proposed tool's potential to offer a solution to the problematic described.

- Chapter 5 Discussion: this chapter lists the findings of the validation stage, and ultimately underlines the contributions to the field. It additionally encompasses the difficulties encountered, as well as recommendations for further research and improvement.

- Chapter 6 Conclusion: the main conclusions of this research work are summarised in this chapter.

- Chapter 7 References: this chapter inventories all the references used throughout the thesis.

- Chapter 8 Publications: lastly, this chapter lists some of the author's publications, which are related to the work presented herein.

1.6 Concluding remarks

The following are the most significant remarks comprised in the chapter, and underscored in the form of bullet points for the reader’s ease:

- LCA, which is a standardised methodology supported by publicly available guidelines and implementation literature –with additionally widespread practice–, is being put forward as an environmental performance tool for ships, capable of also reporting energy efficiency.

- LCA could then serve as a supplementary utility to the available compulsory shipping energy efficiency measures –or metrics–, which have shown limitations such as partial coverage and application, due to relevant shortcomings that will be further underlined.

2 Literature Review

2.1 Introductory remarks

The following chapter will comprise four main sections. The first section includes a summary of the historic background that gave way to the development of the available energy performance metrics, followed by a discussion into the problematic of shipping emissions. The subsequent section contains an explanation of the actual methodology of the performance metrics, including regulatory shortcomings, or additional issues and/or impracticalities relative to the metrics. Lastly, a brief timeline account of the LCA methodology is presented, while additionally offering a review into its current direct application, as far as the shipping and shipbuilding and repair industry goes.

2.2 Historical background on GHG-relative performance metrics

2.2.1 Global climate change discussions

As previously inferred by in the *Introduction*, currently there is a strong campaign towards making a shift for a more environment-friendly and sustainable development (BBC, 2014). This was not always the case, however, and it took a number of years after consistent evidence during the 1960's and 70's alerted of higher concentrations of CO_2 in the atmosphere –and consequently higher global warming potential–, before the international community decided to act (IMO, 2014f).

In 1988, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change, as a way to offer the global public a credible scientific context of the available knowledge on climate change, and any potential environmental and socioeconomic impacts derived by it (IPCC, 2014a). In 1990, the IPCC's first assessment report, based on the views of 400 scientists, underlined the reality of global warming, and the necessity of urgent action (IMO, 2014f).

The IPCC's findings triggered the acceptance of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, during the popularly known 'Earth Summit', in Rio de Janeiro (IMO, 2014f). The Convention is acknowledged as an international treaty, which exhorts the signing countries to cooperatively deliberate on measures to cap average global temperature increases, and to strive to manage whichever impacts come as a result of climate change (UNFCCC, 2014a). In addition, signing parties gather and share data, and launch national strategic emissions plans (Buhaug et al., 2009).

Worthy of mention is that by 1995, many signing countries realised that the limits agreed within the original Convention were impractical (UNFCCC, 2014a). Two years later in 1997, and after various negotiations, the Kyoto summit takes place in Japan; its main result is the recognition that developed countries are principally responsible for the higher concentrations of GHG emissions, after more than 150 years of industrial progress (UNFCCC, 2014c).

The summit resulted in the Kyoto Protocol, an international agreement that sets binding targets for 37 industrialised countries and the European Union, in order to proactively reduce GHG emissions (IMO, 2014f). For the first commitment period, originally from 2008 to 2012 (UNFCCC, 1998), the parties pledge to reduce GHG emissions to an average of 5 per cent against 1990 levels; while during the second commitment period, from 2013 to 2020, the parties agree to reduce GHG emissions by at least 18 per cent below 1990 levels (UNFCCC, 2014c).

Worthy of remark is that the Kyoto Protocol also presented numerous measures aimed at reducing emissions; these are known as emissions trading, the clean development mechanism (CDM), and the joint implementation mechanism (JI).

The emissions trading scheme allows countries that have emission units to spare, to sell this excess to countries that are over their targets (UNFCCC, 2014d). The CDM allows a developed country to earn vendible certified emissions reductions (CER) for emission-reduction projects in developing countries, while the JI allows a country to earn emission reduction units (ERUs) from either an emission-reduction or an emission-removal project (Buhaug et al., 2009). In doing so, the Protocol introduced the first international market-based measures (MBMs) aimed at reducing GHG emissions, and additionally created what is now known as the ‘carbon market’ (UNFCCC, 2014d).

The detailed rules that implement the Kyoto Protocol were ultimately agreed at COP7, which is the denomination for the 7th annual Conference(s) of the [UNFCCC] Parties, namely known as the Marrakesh Accords, due to having the gathering take place at Marrakesh, Morocco, in 2001 (UNFCCC, 2014c). The Kyoto Protocol entered into force on 15 February 2005 (IMO, 2014f), and it is of relevance to underline that it contains direct reference to urge measures against GHG emissions resulting from international aviation and shipping.

The following quote from the original text of the Protocol highlights the above: "The Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol[1] from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively" (UNFCCC, 1998).

The IMO reports that these sectors, aviation and shipping, are treated in a different way in comparison to other emission sources, mostly given their global operations (i.e. emissions from international shipping cannot be attributed to any particular national economy, due to its complex and globalised operations) (IMO, 2014d); additionally, the IMO is compelled to report progress within this field to the UNFCCC regularly (IMO, 2014f).

Table 2.1: Chronological development of the most relevant climate change discussions as adapted from UNFCCC (2014a) and IPCC (2014b)

Year	Event
1979	First World Climate Conference (WCC) takes place
1988	The Intergovernmental Panel on Climate Change is established by the UNEP and the WMO
1990	IPCC's 1st Assessment Report released; IPCC and 2nd WCC call for treaty on climate change
1992	At the Earth Summit in Rio de Janeiro, the UNFCCC is adopted
1994	The UNFCCC enters into force
1995	The first Conference of the Parties (COP1) takes place in Berlin; IPCC's 2nd Assessment Report released
1997	Kyoto Protocol adopted in December at the COP3
2001	Release of IPCC's 3rd Assessment Report; Marrakech Accords adopted at COP7
2005	Entry into force of Kyoto Protocol; negotiations begin for the next phase of the KP
2007	IPCC's 4th Assessment Report released; climate science entered into popular consciousness
2009	Copenhagen Accord drafted at COP15 in Copenhagen
2010	Cancun agreements drafted and largely accepted at COP16
2011	The Durban Platform for Enhanced Action is drafted and accepted at COP17
2013	Decisions adopted at COP19 advancing with the Durban Platform, the Green Climate Fund, and the Long-Term Finance; IPCC's 5th Assessment Report released

While of rational widespread relevance, global discussions and breakthroughs on climate change and its subsequent policy development continue to take place, the discussion herein must now focus on the impact these global debates have caused on the shipping and shipbuilding and repair industry, and consequently on its regulatory framework. The table above, nevertheless, lists major chronological events among

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[1] As described by UNFCCC (1998): "Montreal Protocol means the Montreal Protocol on Substances that Deplete the Ozone Layer, adopted in Montreal on 16 September 1987 and as subsequently adjusted and amended." The protocol is an international environmental treaty, under the auspices of the United Nations (IMO, 2014b).

these debates, before singling out specific events worth of mention along IMO's account of its own interaction and efforts in the next section, with regards to proposed measures and regulation development (see Table 2.1).

2.2.2 IMO's work on marine environment protection: air pollution control

While the issue of controlling air pollution from ships was raised in the lead up to the adoption of the 1973 MARPOL Convention (IMO, 2014e), IMO's discussion with regards to the regulation of air pollution and control of greenhouse gas emissions from ships started in the late 1980s; these were specifically related to the out-phasing of ozone depleting substances from refrigerant gases and fire-fighting equipment, and additionally related to the adoption of firmer limits for nitrogen and sulphur oxides from ship exhaust gases (IMO, 2014g).

IMO acknowledges that the above efforts were actually, at the time, a departure from the most commonly known form of ship-produced pollution prevention: oil spills caused by shipping accidents. These last showed immediate impacts, while the GHG effects on human health and ecosystems were not so immediately recognised (IMO, 2011b, 2014m).

Given the emerging scientific reports on the adverse effects of GHG emissions, most relevantly IPCC's first assessment report in 1990, it was not a surprise when the IMO Assembly, November 1991, decided to establish international policy in favour of the prevention of air pollution from ships. This decision derived in the aim of developing a new annex (Annex VI), specifically underlining air pollution control and designated in Resolution A.719(17) (IMO, 2014a); this annex would supplement the International Convention for the Prevention of Pollution from Ships, most commonly known as the above-mentioned MARPOL Convention (IMO, 2011b, 2014h).

In 1992, the ‘Earth Summit’ in Rio de Janeiro, as previously mentioned, witnessed the acceptance of the United Nations Framework Convention on Climate Change. IMO (2011b) emphasises that since, the IMO Secretariat has participated on all climate change conferences, and a resulting –and currently on-going– collaboration with the UNFCCC was developed. Significantly, this cooperation between IMO and UNFCCC comprises –among other matters–, the reporting on the use of bunker fuel oils specific to international shipping, since the UNFCCC came into force in 1994.

An important milestone took place in September 1997, when during the International Conference of the Parties to the MARPOL Convention, the participants agreed to adopt the Protocol of 1997; this protocol added Annex VI titled ‘Regulations for the Prevention of Air Pollution from Ships’, to the aforementioned Convention (IMO, 2014f). This annex originally included limits on sulphur and nitrogen oxides from ship exhaust (IMO, 1998), and ultimately designated emission control areas for more strict compliance, among other relevant issues (IMO, 2014h, m, n).

Furthermore, Resolution 8 on ‘CO_2 emissions from ships’ was adopted at the aforesaid conference, underlining once again the importance of the collaboration between the IMO Secretary-General and the Executive Secretary of the UNFCCC, with regards to the data exchange on the issues of GHG emissions; this last resulted in the undertaking of a study of CO_2 emissions from ships, with the purpose of analysing the amount relative to international shipping, versus a global inventory of CO_2 emissions. Lastly, this resolution also encouraged the MEPC to investigate further feasible CO_2 reduction measures, with the aim of future potential application (IMO, 2011b, 2014f).

The above stated study was published as the first ‘IMO Study of Greenhouse Gas Emissions from Ships’, and was presented to the MEPC’s 45th session meeting in October 2000. The study was performed by a consortium of internationally renowned research institutions, and mainly examined GHG emission reduction possibilities through technical, operational, and market-based measures (IMO, 2011b).

The study concluded, while using data from 1996, that international shipping amounted to 1.8% of the world's total CO_2 emissions (Skjølsvik et al., 2000). Worthy of mention is that Skjølsvik et al. (2000), additionally indicated that technical measures alone would not be able to prevent a total growth in emissions from ships, given the increasing demand for shipping services.

In an effort to address some of the conclusions put forward by the first GHG study, and additionally underscoring the Kyoto Protocol aims, the IMO Assembly, December 2003, adopted Resolution A.963(23) titled 'IMO Policies and Practices related to the Reduction of GHG Emissions from Ships' (IMO, 2011b, 2014f). In summary, the resolution urges the MEPC to identify and develop feasible measures to reduce GHG emissions from ships, by giving priority to the elaboration of a GHG emissions baseline, and more importantly, to the development of a methodology to depict a ship's GHG efficiency in terms of a GHG emission index for that specific ship (IMO, 2003).

Although the last is not properly expanded on the resolution, this may possibly be the first time a regulatory requirement to state shipping efficiency in terms of an environmental context was expressed. Lastly, the resolution also states that CO_2 is to be regarded as the main GHG emitted by ships under the soon-to-be featured GHG emission indexing, and that considerations should be regarded as to the proper reporting of GHG emissions from ships, when these are engaged in international transport (IMO, 2003).

The year 2005 observed the Kyoto Protocol enter into force in February, while in May, MARPOL's Annex VI went similarly into validity, with novel NO_x and SO_x emission limits (IMO, 2011b). Shortly after in July, during the MEPC's 53rd session meeting, it was agreed to revise the Annex in order to further reinforce the then current emission restrictions (IMO, 2014m). Of relevance, however, is that this particular session meeting also observed Resolution A.963(23)'s conclusions and in turn approved IMO's 'Interim Guidelines for Voluntary Ship CO_2 Emission Indexing for use in Trials', known as MEPC/Circ.471 (IMO, 2011b).

The Interim Guidelines offered a methodology for evaluating a ship's transport-work performance relative to its CO_2 emissions, and furthermore, advertised the approach as a useful way for shipowners to gauge their fleet's performance under the emission indexing. Additionally highlighted was the ability to analyse the ship's performance with regards to fuel efficiency, while underscoring that the CO_2 emissions were directly related to the ship's consumption of bunker fuel oil (IMO, 2005). Although voluntary in nature, this document offered the first IMO-sourced ship energy efficiency and environmental performance metric.

The aforesaid Guidelines termed the index as the 'Carbon Dioxide Transport Efficiency Index', and was defined simply as the ratio of mass of CO_2 per unit of transport work. The document went as far as including a stoichiometric explanation of the characterisation of the content of CO_2 per quantity of fuel, for commonly used shipping fuels. Moreover, steps are included for calculating the index, additionally nicknamed the 'CO_2 Operational Index', in which it is suggested that for existing vessels the index should represent an average value of the energy efficiency of the ship operation for a period of one year (IMO, 2005). Design considerations are not included within this document, nevertheless.

The Guidelines are understood to have offered assistance in the process of developing a widespread mechanism to achieve the limitation or reduction of GHG emissions from shipping, by establishing a common approach for trials on a voluntary basis (IMO, 2011b). The CO_2 Operational Index was since used by flag states and industry organisations to determine their ships operation's fuel efficiency, while in turn providing IMO with the outcome of numerous trials and vast amounts of data. This last, consequently, assisted in identifying a range of operational measures which offered proficient emissions reduction potential, while seemingly of reasonable investment cost (IMO, 2014f).

The MEPC 55th session in October 2006 not only agreed to revise the first IMO Study on GHG Emissions from 2000 with more current data (Buhaug et al., 2009), but significantly –as a follow-up to Resolution A.963(23)–, agreed on a 'Work plan to identify and develop the mechanisms needed to achieve the limitation or reduction of CO_2 emissions from international shipping' (IMO, 2011b).

The work plan was comprised of a defined timetable, which underlined efforts required by the MEPC in the areas of the improvement of the CO_2 indexing methodology, the establishment of a CO_2 emission baseline(s), and additionally the consideration of other measures to engage GHG emissions from international shipping. These other distinctive measures were described as technical measures particularly applied to new ship designs, operational measures available for all ships (new and existing), and lastly market-based measures, which were meant to provide further enticements for the shipping industry, by setting a price on its emissions (IMO, 2011b).

As stated previously, and referenced to some of Skjølsvik et al. (2000)'s conclusions (which will be somewhat similar to other authors' conclusions explained further ahead), technical measures alone are unlikely to offer proper emissions reduction potential, given the increasing shipping trade demand. This last emphasises the importance of MBMs as a complementary platform for regulating international shipping emissions. Nevertheless, the development and current state of MBMs will not be further broaden within this document, as doing so falls away from the defined scope of this work. The reader should refer to UNFCCC (2014d) for generic information, and to Buhaug et al. (2009), IMO (2011b) and IMO (2014j) for a shipping-related account.

The 1st Inter-sessional Meeting of IMO's newly formed Working Group on Greenhouse Gas Emissions from Ships took place in Norway, June 2008. Worthy of indication is that the group made considerable technical progress on establishing draft calculations –and a concrete formula–, for a CO_2 Design Index (BIMCO, 2009). The Index, the first IMO-based environmental performance metric aimed at improving ship design, did so by striving to improve the fuel efficiency of different ship types, by enhancing certain design inputs, such as design speed, propeller design, use of waste heat recovery systems, and etcetera. The Index was required to be assessed against a developed baseline of fuel efficiency data for ships delivered between 1995 and 2005 (IMO, 2014f).

During October 2008, the MEPC's 58th session meeting took place, and while using preliminary information received from the consortium in charge of updating the first GHG study, the Committee endorsed the application of the draft CO_2 Design Index guidelines for new ships, for calculation and trial purposes, and with a view for further refinement and improvement (IMO, 2014f). Furthermore, it was recommended that the aforesaid CO_2 Operational Index should not be compulsory in nature, but left the open possibility of making it mandatory in the future (Buhaug et al., 2009).

The MEPC 58th session meeting also witnessed the previously mentioned tightening of the limits of NO_x and SO_x exhaust emissions, by ultimately adopting them under the revised MARPOL Annex VI, along with the supplementary NO_x Technical Code (IMO, 2014m) under Resolutions MEPC.176(58) and MEPC.177(58), respectively.

The revised Annex includes a gradual global cap in NO_x and SO_x emissions and particulate matter, and additionally the introduction of emission control areas (ECAs), where stricter limits are observed (IMO, 2008a). The NO_x Technical Code in turn, offers guidance as to the measurement and monitoring of marine diesel engines, with regards to the gradual tier-system tightening of mandatory NO_x emission reductions (IMO, 2008b). Additional information is available in IMO (2014l) and IMO (2014p).

During the 2nd Inter-sessional meeting of IMO's Working Group on GHG Emissions from Ships, in March 2009, a considerable advancement with regards to technical and operational measures for GHG reduction was witnessed. Within this meeting, and also included in the then soon-to-be published 2nd IMO Study, the CO_2 Design Index and the CO_2 Operational Index were officially termed EEDI and EEOI, respectively (BIMCO, 2009; Buhaug et al., 2009; IMO, 2014f). The first meaning the Energy Efficiency Design Index, while the latter stood for the Energy Efficiency Operational Indicator, as mentioned previously in the *Introduction*.

The EEDI was understood to be applied solely to newbuilds, while encouraging innovation and technical development of elements forming part of the overall energy efficiency of a ship; whereas the EEOI was meant to be applied to existing vessels to offer a measure of the fuel efficiency of a ship, and also capable of showing the effectiveness of energy reduction measures applied onboard (Buhaug et al., 2009). Both the EEDI and EEOI were considered by the Group for further refinement, on the basis of experience gained through several trials and applications (IMO, 2014f).

Furthermore, the Group debated over a draft SEEMP, also explained in the upcoming 2nd IMO Study and then termed the SEMP, which stood for Ship Efficiency Management Plan (Buhaug et al., 2009). The plan, developed by a consortium of industry organisations, was meant to offer guidance on shipping industry's best practices; these included methods such as voyage planning, speed and power optimisation, and enhanced fleet management, among others (IMO, 2014f), ultimately aimed at improving fleet energy efficiency and consequently reduce emissions.

Much like the first Study, the 2nd IMO GHG Study was carried out by an international consortium of renowned research institutions, and was ultimately presented at the MEPC's 59th session meeting in July 2009 (IMO, 2011b). The Study encompasses a vast review of the kind of emissions –and the potential quantities–, international shipping entails, while also offering proactive emission control and abatement methods, applicable to new designs as well as existing vessels (Buhaug et al., 2009).

One of the most significant conclusions found in Buhaug et al. (2009) is that international shipping corresponded to 2.7% of the global emissions during 2007, a visible increase from the previous 1.8% during 1996 and underlined by Skjølsvik et al. (2000). Also, similarly as Skjølsvik et al. (2000), Buhaug et al. (2009) predict that

GHG emissions from shipping are likely to keep increasing in the future, underscoring the anticipated demand for transport. Therefore, aside from technical and operational measures (which include the EEDI, the EEOI, and the SEMP, among other more readily available and applicable measures), they also present and explain various policy options aimed at the reduction of GHG and other relevant substances.

Other conclusion worthy of mention is that without the implementation of policies, –including technical and operational measures–, and again underlining the exponential growth in shipping demand, model emission scenarios anticipate that by 2050, CO_2 emissions from ships could double or triple, compared to the totals in 2007. Nevertheless, Buhaug et al. (2009) also conclude that there is a relevant potential for GHG reduction, found through the technical and operational measures identified; they state that if implemented together, the measures could increase efficiency and reduce emissions by a rate of between 25% to 75% below the 2007 levels (IMO, 2014d).

Lastly, Buhaug et al. (2009) reaffirm IMO's focus on CO_2 as the most relevant GHG emitted by ships, cataloguing other GHG emissions from ships as less important, in terms of quantity and global warming potential. Additionally, while they underline the benefits of a mandatory EEDI, they also agree that its true environmental effect is limited, given its exclusive application to new ships. With regards to the EEOI, they suggest a compulsory application could be a cost-effective solution for ships engaged in transport work; nevertheless, they underline the option technically challenging, given the difficulties in the establishment of operational efficiency baselines.

The work plan proposed by the MEPC 55th session culminated at the MEPC 59th session meeting, and presented a relevant amount of work with regards to technical and operational options, and included the work and conclusions found in the 2nd IMO GHG Study. Most relevantly, however, the Committee agreed to disseminate a package of interim and voluntary GHG reduction measures for further trial purposes, with the intention of consideration for refinement and possible application (IMO, 2014f). The package included the following measures:

1. Interim guidelines on the method of calculation of the Energy Efficiency Design Index for new ships (EEDI), namely MEPC.1/Circ.681 (IMO, 2009a),
2. Interim guidelines for voluntary verification of Energy Efficiency Design Index, namely MEPC.1/Circ.682 (IMO, 2009b),
3. Guidance for the development of a Ship Energy Efficiency Management Plan (SEEMP), namely MEPC.1/Circ.683 (IMO, 2009c), and
4. Guidelines for voluntary use of the Energy Efficiency Operational Indicator (EEOI), namely MEPC.1/Circ.684 (IMO, 2009d).

The above measures were intended to facilitate implementation decisions at the following MEPC session meeting (60th), in March 2010; nevertheless, the Committee concluded that supplementary work was needed before considering the proposal for the application of these measures (IMO, 2010a, 2014d). An Inter-sessional Working Group was established in order to carry out efforts to improve the above mentioned, and was due to report back to the MEPC's 61st session meeting (IMO, 2014f).

The MEPC's 61st session meeting, during September 27th to October 1st, 2010, took place in London. Of significance is that the Committee considered implementing further amendments to MARPOL's Annex VI, as a way to introduce non-mandatory EEDI and SEEMP measures into the IMO's regulatory framework (IMO, 2011b). However, a number of States party to the MARPOL Convention, suggested the proposed amendments to be obligatory, instead of voluntary. The circulated draft amendments would then be considered at MEPC's next session. Also noted is that various States did not support the circulation of the suggested amendments (IMO, 2010b, 2014f).

Worthy of indication is that previous to the next session, MEPC's 62nd meeting, the 3rd Inter-sessional Meeting of IMO's Working Group on GHG Emissions from Ships took place, in March 2011 (IMO, 2011b). Although not further expanded within this document, the meeting held significant efforts on the discussion of feasible MBMs. The Group catalogued a number of MBMs, and included strengths and weaknesses, in order to present this assessment at the next MEPC meeting. Furthermore, additional studies were agreed (IMO, 2014f). IMO (2014d) underlines the importance of MBMs as two-fold: they provide a fiscal incentive for the marine industry to invest in more energy efficient ways, and serve as a tool for the offset of increasing ship emissions.

The 62nd Marine Environment Protection Committee session, July 2011, is acknowledged proudly as a ‘breakthrough’ by IMO (IMO, 2012f, 2014c). The Committee considered and adopted the proposed amendments to MARPOL’s Annex VI, under Resolution MEPC.203(62) (IMO, 2011a). The amendments add a new chapter (Chapter 4) to Annex VI, titled ‘Regulations on energy efficiency for ships’, and underline both as mandatory, the EEDI for new ships, and the SEEMP for new and existing vessels (IMO, 2011c). These regulations are applicable to all ships above 400 gross tonnes and above, regardless of their national flag or the nationality of the owner, and are underlined to enter into force after January 1st, 2013 (IMO, 2014f).

The above session additionally agreed on having an Inter-sessional Working Group continue with the efforts to develop the EEDI framework for different ship types, sizes, and propulsion systems, and also identify the requirements of additional guidelines or supporting documents for these measures; the Group was understood to report any progress to the succeeding MEPC session (IMO, 2011d).

The amendments to MARPOL’s Annex VI, and consequently its regulatory framework, are considered the first international climate change treaty formally adopted since the Kyoto Protocol in 1997, and additionally the first ever global and legally binding instrument, underscoring energy efficiency regulations for any industrial sector (IMO, 2011b). This action has received high commendation from relevant international environment protection organisations, including praiseful remarks by Mr Ban Ki-moon, UN Secretary-General, and by Mrs Christiana Figueres, UNFCCC Executive Secretary (IMO, 2011b, 2012f).

Taking place at the end of February and the beginning of March 2012, the MEPC's 63rd session is significant because it finalised and adopted complementary guidelines, aimed at assisting state and port administrations and industry alike, at the homogeneous implementation of the recent Annex VI's emission reduction amendments (IMO, 2012g). The Committee also acknowledged the need to establish additional guidelines for those ships not yet covered by the then current EEDI regulations, by the development of a work plan (IMO, 2014q). The aforementioned supporting guidelines are the following:

1. 2012 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships, namely MEPC.212(63) (IMO, 2012a),
2. 2012 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP), namely MEPC.213(63) (IMO, 2012c),
3. 2012 Guidelines on survey and certification of the Energy Efficiency Design Index (EEDI), namely MEPC.214(63) (IMO, 2012d), and
4. Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI), namely MEPC.215(63) (IMO, 2012e).

October 2012 gave way to the MEPC's 64th session, where the Committee agreed to adopt amendments to the 2012 Guidelines on the method of calculation of the attained EEDI for new ships, MEPC.212(63), by adjusting the calculation of the shaft-generator power and shaft-motor power (IMO, 2012h). The changes above are summarised in MEPC.224(64) (IMO, 2012b). Shortly after, on January 1st, 2013, the new chapter 4 of MARPOL's Annex VI entered into force, underlining, as mentioned previously, compulsory requirements on the EEDI for new ships and the SEEMP for all ships (IMO, 2013e).

MEPC's 65th session (May 2013), aside from agreeing to undertake a study to update the emissions' estimate found in the most current GHG emission study (2nd GHG Study) (IMO, 2013e), also introduced resolution MEPC.233(65), based on the EEDI calculation for cruise passenger ships with non-conventional propulsion (IMO, 2013b). The Committee additionally decided to amend Resolution MEPC.214(63) and revoke Resolution MEPC.215(63) with the following resolutions, MEPC.234(65) and MEPC.231(65), respectively. The first adds further references to measuring sea conditions (IMO, 2013c), while the latter includes the addition of different types of Ro-Ro ships and LNG Carriers (IMO, 2013a).

Up to the development of the work presented herein, the most recent MEPC session (66th) took place in March/April 2014. Most significantly, the Committee adopted the 2014 Guidelines on the method of calculation of the attained EEDI for new ships (IMO, 2014b), and discussed various proposals to develop a framework for the monitoring and collection of data regarding ship fuel consumption (IMO, 2014i).

The 2014 Guidelines, while adopted, are not yet listed at IMO's Index of Resolutions[2]; nevertheless, the update includes calculation revisions for LNGs, Ro-Ro and passenger ships, and the extension of the application of the ice correction factor for refrigerated cargo ships, among other relevant inclusions. With regards to the framework for fuel consumption data –although not directly mentioned–, may possibly be linked to the European Commission's MRV proposal, which will be discussed in the upcoming sections. Lastly, MEPC's 66th session agreed on the establishment of an EEDI database –related to data provided by ships required to comply with the EEDI–, in order to support the review of technical developments and ultimately EEDI implementation (IMO, 2014k).

As documented within this section, the International Maritime Organization has carried out significant work under the maritime environment protection banner; most specifically on measures to enhance energy efficiency and consequently, reduce ship emissions. While it is foreseeable further technical and regulatory work will be pursued by the IMO, the current mandatory requirements established (i.e. EEDI and SEEMP), are predicted to lead to significant CO_2 emission reductions, and

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[2] Please see IMO, 2013d. Marine Environment Protection Committee (MEPC), Index of IMO Resolutions, http://www.imo.org/KnowledgeCentre/IndexofIMOResolutions/Pages/Marine-Environment-Protection-Committee-(MEPC).aspx.

additionally relevant cost savings for the shipping industry (Buhaug et al., 2009; IMO, 2014q).

Table 2.2: Chronological development of the most relevant air pollution control discussions at IMO as adapted from (IMO, 2011b, 2012f, 2014f, o) and (Lloyd's-Register, 2012a, b)

Year	Event
1985	The MEPC went from a subsidiary body of the IMO Assembly to full constitutional status
Late 1980s	IMO started work on prevention of air pollution and control of greenhouse gas (GHG) emissions from ships
1991	The 17th session of the IMO Assembly agrees to develop a new annex for the MARPOL Convention, underlining prevention of air pollution
1992	At the Earth Summit in Rio de Janeiro, the UNFCCC is adopted
1994	The UNFCCC enters into force; ever since there has been on-going cooperation among the secretariats of IMO and UNFCCC on GHG emissions reporting relative to int'l shipping
1997	The Protocol of 1997 added Annex VI to the MARPOL Convention; Resolution 8 on CO_2 emissions from ships was also adopted
2000	The first IMO Study on GHG Emissions from Ships was presented to MEPC 45 in October
2003	Assembly resolution A.963(23) underlining reduction of GHG emissions from ships was adopted in December
2005	MARPOL's Annex VI comes into force on May; additionally, MEPC 53 approved IMO's "Interim Guidelines for Voluntary Ship CO2 Emission Indexing for use in Trials" (MEPC/Circ.471) in July
2006	At MEPC 55 in October, it was agreed to update the first IMO Study of Greenhouse Gas Emissions from Ships from 2000; the work plan requested by Assembly resolution A.963(23) is also approved
2008	MEPC 57 in April, acknowledged the importance of developing fundamental principles for regulation of GHG from ships; the 1st Inter-sessional Meeting of IMO's GHG Working Group was held in Oslo, Norway (June); lastly, a revised version of MARPOL's Annex VI was also adopted at the 58th session of MEPC, in October
2009	The 2nd Inter-sessional meeting of IMO's GHG Working Group takes place in March; the Second IMO GHG Study 2009 was presented at MEPC 59 in July; the Committee also approved the circulation of Interim Guidelines on the calculation of the EEDI, SEEMP and the EEOI; lastly, the work plan from Resolution A.963(23) culminated at MEPC 59
2010	The revised version of MARPOL's Annex VI from MEPC 58 enters into force on July; MEPC 61 in September/October considers further amendments to MARPOL's Annex VI and it is proposed to make the EEDI and SEEMP mandatory for new ships, and to be considered for adoption at MEPC 62 in July 2011
2011	The 3rd Inter-sessional meeting of IMO's GHG Working Group takes place in March, and discusses the desirability of MBMs application for GHG reduction; MEPC 62 in July considers and adopts draft amendments to MARPOL's Annex VI with regards to the mandatory implementation of the EEDI and SEEMP
2012	MEPC 63 in February/March adopts further revised guidelines MEPC.212(63) on EEDI Calculation, MEPC.213(63) on the SEEMP, MEPC.214(63) on EEDI Verification, and MEPC.215(63) on EEDI Reference Lines
2013	The Regulations on Energy Efficiency relating to the EEDI (new vessels) and SEEMP (new and existing vessels) enter into force from 1st January, within the novel Chapter 4 of MARPOL's Annex VI
2014	MEPC 66 adopted the 2014 Guidelines on the method of calculation of the attained EEDI, namely MEPC.245(66), superseding resolution MEPC.212(63), as amended by resolution MEPC.224(64)

These measures, however, along with the application of the EEOI –which serves as a tool for the SEEMP implementation–, also observe relevant opposition from stakeholders within the industry; this in turn may hamper their positive effect on the environment. The most current version of these measures will be further expanded ahead, including a discussion on their inherited disadvantages.

Lastly, Table 2.2 summarises the most relevant events with regards to IMO's work presented in this section (see also Figure 1.3).

2.3 Global climate change and shipping emissions

2.3.1 Problem definition

The 15th session of the Conference of the Parties to the UNFCCC, and also the 5th session of the Conference of the Parties under the Kyoto Protocol, took place in December 2009 in Copenhagen, Denmark. The COP15 is known as a climate change conference of a high political regard, having been attended by more than 40,000 people in representation of governments, NGOs, and intergovernmental organisations, among others groups of relevant participants. Aside from making significant progress with regards to the negotiations required for implementing a global climate chance cooperation framework, it additionally produced the Copenhagen Accord (UNFCCC, 2014b).

The Accord literally underlines climate change as one of the greatest challenges of our time, and acknowledges the need to stabilise greenhouse gas concentrations in the atmosphere, in order to prevent dangerous anthropogenic interference with the climate system. It additionally recognises needed reductions in global emissions according to science –specifically acknowledging the 4th IPCC Assessment Report– and ultimately agreeing on cooperative efforts –global and national–, to hold the increase in global temperature below 2 degrees Celsius (UNFCCC, 2009). While there is factually no representation on exactly how to achieve the above in the document, it is nevertheless considered as a milestone, representing the strong convergence of views of various participating governments (UNFCCC, 2014b).

Accordingly, the IPCC (2007a) explains that there is increased confidence that a 1 to 2ºC increase in global mean temperature above 1990 levels, poses relevant risks to many unique and threatened ecosystems, including many biodiversity hotspots. Nevertheless, the IPCC (2007a) also states that many impacts can be reduced, delayed or avoided by mitigation, and that mitigation efforts and investments over the next two to three decades, can have a significant impact on the likelihood of succeeding to lower stabilisation levels.

Furthermore, the IPCC (2007a) clarifies that in order to stabilise the current concentration of GHGs in the atmosphere, emissions would have to reach a peak and decline thereafter. Consequently, the lower the stabilisation level, the more quickly that this peak and subsequent decline would occur. Additionally, the IPCC Report advertises that there is strong evidence that all stabilisation levels required could be achieved, by the implementation of the range of technologies currently available, or expected to be commercially available in the upcoming decades, assuming –logically–, that effective enticements are in place for widespread application of these technologies (IPCC, 2007a).

More importantly, the Report agrees that all required stabilisation scenarios indicate that 60 to 80% of the reduction would come from energy supply and use, and additionally industrial processes, with energy efficiency implementation playing a relevant role in various scenarios (IPCC, 2007a). Rehmatulla et al. (2012) utilise the 4th IPCC Report and highlight one of its many important conclusions: global GHG emissions are required to be reduced by 50 to 85% below 1990 levels, in order to stabilise global average temperature, and therefore mitigate or avoid dangerous climate change impacts.

The above is relevant to shipping because ships emit sizeable quantities of CO_2, and additionally, as it will be portrayed shortly in the next section, despite significant energy efficiency measures, emissions from shipping are projected to keep rising. Aside from CO_2, an important GHG which can remain in the atmosphere for long periods of time (millennia), causing significant climate warming –which could become irreversible to future generations, if not acted upon–, ships emit other pollutants, such as NO_x, SO_2, and particulate matter (PM), among others (Faber et al., 2009).

Airborne NO_x and SO_2, can get into the lungs and consequently into the human bloodstream, causing inflammations which could eventually lead to heart and lung failures (T&E, 2014). Furthermore, these pollutants are also known to impact ecosystems and biodiversity by acidification, in the case of SO_x, and eutrophication, in the case of NO_x (RICARDO-AEA, 2013).

2.3.2 GHG emissions from shipping

While shipping is regarded as an energy efficient way of transportation, compared to other modes (Buhaug et al., 2009), it is still observed as a large and growing source of GHG emissions (EC, 2014), estimated to correspond to 2.7% of the global emissions of CO_2 in 2007 (Buhaug et al., 2009), while most recent figures currently catalogue international shipping's CO_2 emissions at 3% of the global total (RAE, 2013).

Moreover, while the energy supply emission reduction requirements mentioned in the previous section by the IPCC Report, probably do not account directly for any source of ship-related emissions, they underline the importance of all sectors of the global economy converging on efforts to lower GHG emissions. The last also significantly underscores IMO's proactive work on energy efficiency regulations, and also its efforts to develop a framework of applicable and proficient incentives.

With regards to IMO's recent work on energy efficiency regulations, Bazari and Longva (2011) inform that relevant CO_2 emission reduction from ships is expected due to the EEDI and SEEMP implementation, with reductions from the SEEMP realised more rapidly in comparison to the EEDI, given that the effect of this last will become clearer as older, less efficient ships are replaced by new vessels under the EEDI designation.

Furthermore, Bazari and Longva (2011) present different emission forecast scenarios; of relevance, a forecast scenario underlining low fleet growth combined with low SEEMP application and reference fuel price, displaying a total annual CO_2 emissions of around 2014 million tonnes for business as usual (BAU, meaning no EEDI or SEEMP implementation) in 2050. Even with low SEEMP uptake, this scenario also shows a forecasted reduction of 706 million tonnes of CO_2 in 2050, between both the EEDI and the SEEMP (see Figure 2.1). Consequently, other scenarios with larger fleet growth, aside from displaying larger emission reductions, also indicate increased overall emissions.

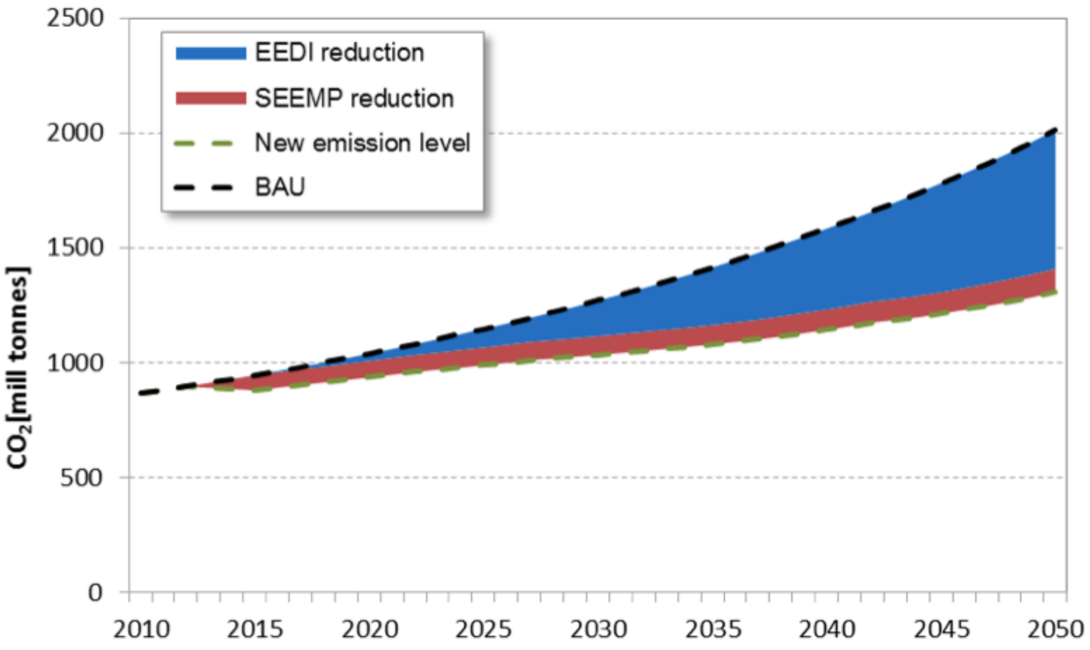

Figure 2.1: Estimated EEDI and SEEMP world fleet CO_2 reduction potential (Bazari and Longva, 2011)

This forecast scenario also shows that, despite the significant reductions in CO_2 emissions due to the application of the SEEMP and EEDI measures, the implementation of these two alone does not seem to prove totally sufficient (Bazari and Longva, 2011). Because the demand for shipping is closely linked to the development of the global economy, and since maritime transport carries around 90% of the international world trade (RICARDO-AEA, 2013), the projected world trade growth surpasses the achieved EEDI and SEEMP emission reductions in all scenarios, even though it shows considerable reductions against a BAU state (Bazari and Longva, 2011).

The EC (2013e) goes further and updates this previous forecast, while additionally including CO_2 emission statistics relative to the European Continent (see Figure 2.2). Currently, GHG emissions from maritime transport account for 4% of the total EU

GHG emissions (EC, 2013e). Furthermore, despite the adoption of the minimum ship efficiency standards, i.e. the EEDI, the shipping-related emissions in the EU alone are expected to increase further by 50% in 2050, compared to 2010 levels (RICARDO-AEA, 2013). Figure 2.1 and Figure 2.2 clearly illustrate that, in spite of practical energy efficiency measures, shipping-related GHG emissions are likely to keep increasing in the future (EC, 2013e).

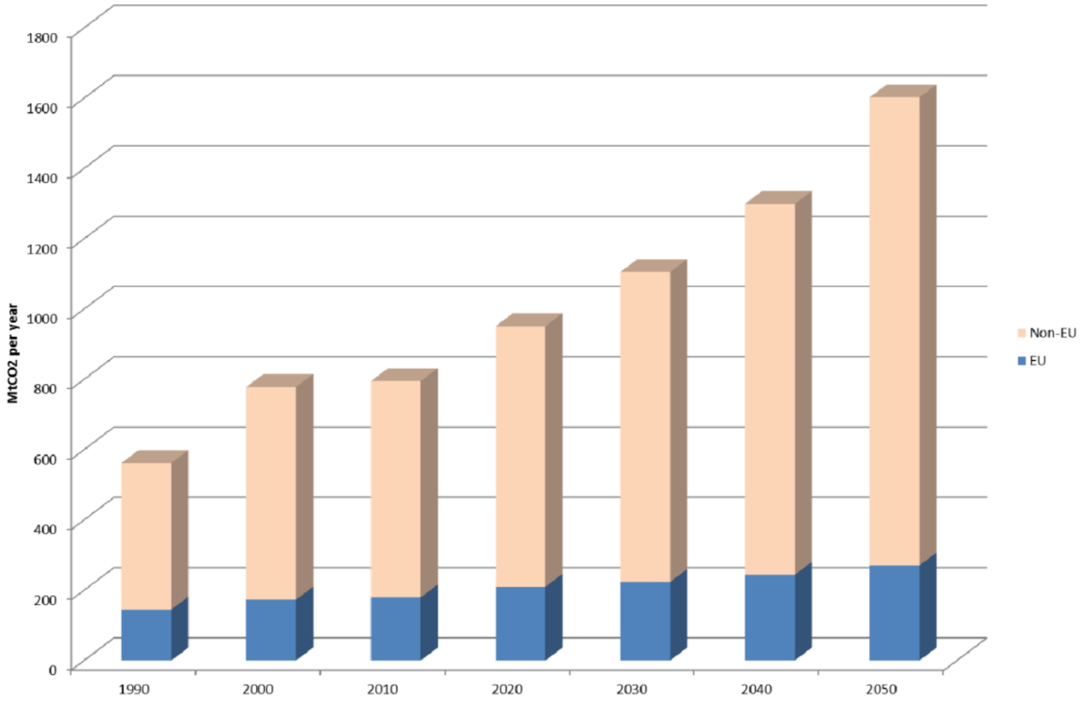

Figure 2.2: EU and global shipping CO_2 emission projections, considering EEDI implementation (EC, 2013e)

Worthy of note as well, is that although the EU has reduced its GHG emissions by 379.8 million tonnes of CO_2 equivalents (CO_2eq[3]) between 1990 and 2007, during that same period, maritime transport related emissions have increased by 66 million tonnes of CO_2 in the EU, seemingly undermining EU's efforts to mitigate climate change (EC, 2013c). The above underscores first, that there is a serious trend for decarbonisation; and second, that as various sectors decarbonise, and as international

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[3] GHG emissions are characterised and aggregated as equivalents under the Global Warming Potential impact category, using CO_2's own warming potential as reference.

shipping emissions continue to rise, they will logically represent an even larger share of global CO_2 emissions (Gilbert et al., 2010).

Moreover, Gilbert et al. (2010) emphasise that the shipping sector must take serious measures to completely decarbonise within two to three decades, for a reasonable chance of avoiding temperatures rising above 2ºC. They conclude that this level of decarbonisation is not currently being contemplated by the shipping industry, and that a step-change in policies is required. Some consider that if the shipping industry is left unchecked and without more efficient regulation in place, as others sectors progress with emissions mitigation, the shipping's CO_2 emissions could represent as much as 17 to 25% of the global total in 2050 (CCC, 2011).

In summary, in spite of the positive emissions reduction potential that the current IMO measures-in-place forecast, supplementary policies are likely required to be implemented, in order to offset further estimated emissions due to the ever increasing shipping demand. These policies, or MBMs, should aim at providing proficient industry incentives for the general uptake of the available (i.e. EEDI and SEEMP) – and future– mandatory measures, as well as other voluntary options (e.g. EEOI). Other options or alternatives, such as LCA, could also consequently aid in the implementation of the already available energy efficiency regulations, by allowing simpler widespread application of the measures, and additionally potential homogenisation across industries.

2.4 Current IMO energy efficiency regulatory measures

The following includes a discussion focusing into the actual regulatory measures in place by IMO, i.e. the EEDI and the SEEMP –and their implementation methodology–, while also underlining other available voluntary metrics. The aim of this section is to pragmatically present what do these metrics measure, and how do they measure it, while additionally highlighting relevant information with regards to their current application.

The current supporting guidelines are the following:

1. 2014 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships, namely MEPC.245(66), superseding resolution MEPC.212(63), as amended by resolution MEPC.224(64) (IMO, 2014b),
2. 2012 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP), namely MEPC.213(63) (IMO, 2012c),
3. 2012 Guidelines on survey and certification of the Energy Efficiency Design Index (EEDI), namely MEPC.214(63) and amended by MEPC.234(65) (IMO, 2012d, 2013c),
4. 2013 Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI), namely MEPC.231(65) (IMO, 2013a), and
5. 2013 Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI) for cruise passenger ships having non-conventional propulsion, namely MEPC.233(65) (IMO, 2013b).

2.4.1 EEDI

The IMO defines the EEDI as “a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in specific ship design to the industry. As long as the required energy efficiency level is attained, ship designers and builders are free to use the most cost-efficient solutions for the ship to comply with the regulations" (IMO, 2011b, 2012g).

The above summarises the EEDI as a measure that highlights a minimum energy efficiency requirement level for new ships –which actually depends on ship type and size–, while stimulating the continuous technical development of all the components which influence the fuel efficiency of a ship. This measure aims to reduce GHG emissions from newbuilds, by focusing on the energy efficiency improvement of ships, via design features and/or by the application of energy efficient technologies.

The EEDI is based in the fundamental characteristic that fuel consumption is the most direct measure of energy use onboard. Similarly, CO_2 emissions are directly proportional to fuel consumption; therefore, as explained by Kedzierski and O'Leary (2012), the amount of CO_2 emitted by a ship can be calculated using the fuel consumption relative to that ship, and an emission factor relative to that fuel. Fuel mass to CO_2 conversion factors, additionally, have been established by the IMO for marine diesel, light and heavy fuel oils, liquefied petroleum and natural gas (IMO, 2014b) (see Appendix B.2); thus, the CO_2 calculation is as simple as multiplying the fuel consumption by the carbon conversion factor (Kedzierski and O'Leary, 2012).

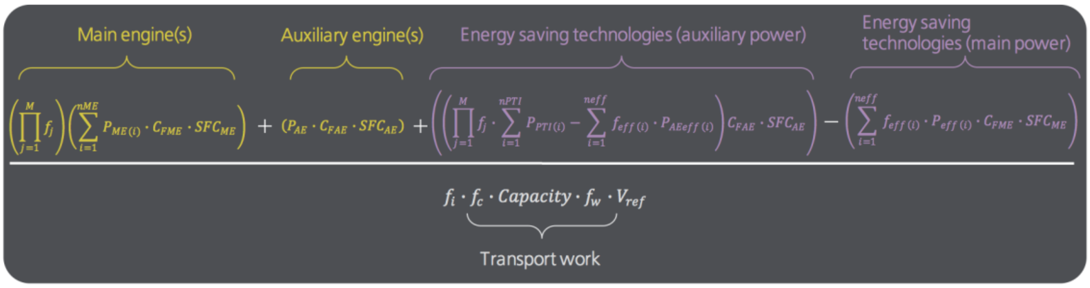
"The difference between the amount of energy that is put into a machine in the form of fuel effort, etc. and the amount that comes out of it in the form of movement" defines *efficiency* (Cambridge-Dictionary, 2014). Therefore, the above part relative to fuel consumption and emissions only comprises the first input of the energy efficiency definition, being the second part the amount of work produced, or in the case of ships known as transport-work (transport-work encompasses elements such as the distance sailed, the available capacity, the cargo carried, the ship speed, etcetera) (Kedzierski and O'Leary, 2012).

Before offering a straightforward definition of what does the EEDI actually measure, Kedzierski and O'Leary (2012) underscore a relevant difference between calculating technical and operational efficiency. The first, also known as design efficiency, is based on the out-of-the-box state of the engines and equipment including the overall ship design, while the latter is focused –and therefore varies accordingly– on the actual ship fuel consumption under operational conditions and the transport-work carried out.

Following the above, the EEDI is understood as a measure which reflects the theoretical design efficiency of a newbuild ship –mostly based on assumptions regarding the specific fuel consumption of the engines compared to the power installed on the ship–, and ultimately provides an estimate of CO_2 emissions per capacity-mile (Kedzierski and O'Leary, 2012). The full EEDI formula includes various adjustment factors, applicable to specific types of ships and alternative configurations; however, Kedzierski and O'Leary (2012) pragmatically summarise the formula as follows, highlighting its basic elements composition:

$$\mathrm{EEDI} = \frac{Power\ installed\ \times\ Specific\ fuel\ consumption\ \times\ Carbon\ conversion}{Available\ capacity\ \times\ Speed}$$

The full EEDI formula is specified by IMO (2014b); however, there are various publicly available documents that offer guidance with regards to the formula, its elements, and its calculation. Of relevance, and with the aim of being more specific about the variables and factors found in the formula, Lloyd's-Register (2012b) identifies and categorises the main components of the formula as follows (see Figure 2.3).



$$\frac{\overbrace{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}^{\text{Main engine(s)}} + \overbrace{\left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}\right)}^{\text{Auxiliary engine(s)}} + \overbrace{\left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right)}^{\text{Energy saving technologies (auxiliary power)}} - \overbrace{\left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}^{\text{Energy saving technologies (main power)}}}{f_i \cdot \underbrace{f_c \cdot Capacity \cdot f_w}_{\text{Transport work}} \cdot V_{ref}}$$

Figure 2.3: The EEDI formula (Lloyd's-Register, 2012b)

The equation calculates the CO_2 produced as a function of the ship's transport-work performed (Lloyd's-Register, 2012b), which is considered as the *attained* EEDI, and equates to a figure of grams of CO_2 over tonnes per nautical mile (gCO_2/tonne-nm). In summary, the top part of the formula characterises the CO_2 emitted by the engines considering the product of power, specific fuel consumption and the carbon factor for the specific type of fuel used. Additionally, CO_2 emission reductions due to innovative technologies are also considered; these may include, for example, reductions due to waste heat recovery systems, use of wind power or solar power, etcetera[4] (Lloyd's-Register, 2012b).

Table 2.3: Reference values for calculating the required EEDI (GL, 2013), as adapted from (IMO, 2013a, b)

Ship type	a	b	c
Bulk carriers	961.79	DWT	0.477
Gas carriers	1120.20	DWT	0.456
Tankers	1218.80	DWT	0.488
Container ships	174.22	DWT	0.201
General cargo ships	107.48	DWT	0.216
Refrigerated cargo ships	227.01	DWT	0.244
Combination carriers	1219.00	DWT	0.488
Vehicle/car carriers	(DWT/GT)−0.7 × 780.36 where DWT/GT < 0.3; (DWT/GT)−0.7 × 1812.63 where DWT/GT ≥ 0.3	DWT	0.471
Ro-Ro cargo ships	1405.15	DWT	0.498
Ro-Ro passenger ships	752.16	DWT	0.381
LNG carriers	2253.7	DWT	0.474
Cruise passenger ships having non-conventional propulsion	170.84	GT	0.214

The bottom part of the equation relates the CO_2 generated by the top part, with regards to the ship capacity and speed (transport-work). Additionally, as mentioned previously, there are various correction factors which moderate the equation with regards to the ship type and operating configuration. These factors account for ship design factors (e.g. Ice-Class and shuttle tankers), weather factor for decrease in speed in representative conditions, and capacity correction for chemical tankers and LNG ships, among others (Lloyd's-Register, 2012b). The reader should refer to GL

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[4] A non-exhaustive list of EEDI reduction methods can be found in Lloyd's-Register, 2012b. Implementing the Energy Efficiency Design Index (EEDI): Guidance for owners, operators, shipyards and tank test organisations, Documents and publications, http://www.lr.org/Images/EEDI%20Guidance%20Notes%20for%20Clients%20v3.0_tcm155-240648.pdf.

(2013), for detailed guidance on the calculation of emission reductions due to implemented technologies, and corrective factors for ship type and configuration.

By regulation, the *attained* EEDI shall be calculated for all ships of 400 gross tonnes (GT) and above (GL, 2013), defined by the types found in Table 2.3. A ship's *attained* EEDI must be equal to or less than the *required* EEDI for that ship type and size (Lloyd's-Register, 2012b). The *required* EEDI –which is calculated for all ships using 100% of the deadweight (DWT) at summer load draft, except for passenger ships where GT is used (GL, 2013)–, is a function of the reference line value (see Table 2.3), defined by the following formula:

Equation 1

$$Required\ EEDI = a \times b^{-c}$$

The EEDI reference lines refer to statistically average EEDI curves derived from data for existing ships; they are additionally ship specific and much dependent on ship type and size (Lloyd's-Register, 2012b).

The *required* EEDI will be gradually reduced by an X% each five years, in much the same way as NO_x and SO_x limits (see Figure 2.4), based on the initial value (Phase 0) and depending on the vessel size (GL, 2013; Lloyd's-Register, 2012b). It is relevant to highlight that below a certain size, no reduction applies; and above a certain ship size, the reduction is in general 10% for each reduction phase (see Table 2.4 for more details on the reduction intervals) (GL, 2013).

Table 2.4 is often accompanied by strict advice with regards to when in the building phase of a ship a specific vessel befalls in each relevant phase, e.g. "the required EEDI for Phase 0 applies to all ships… for which the building contract date is place in phase 0, and the delivery is before 1st January 2019…" (GL, 2013), establishing clear guidance for newbuilds and their expected requirement as far as EEDI compliance.

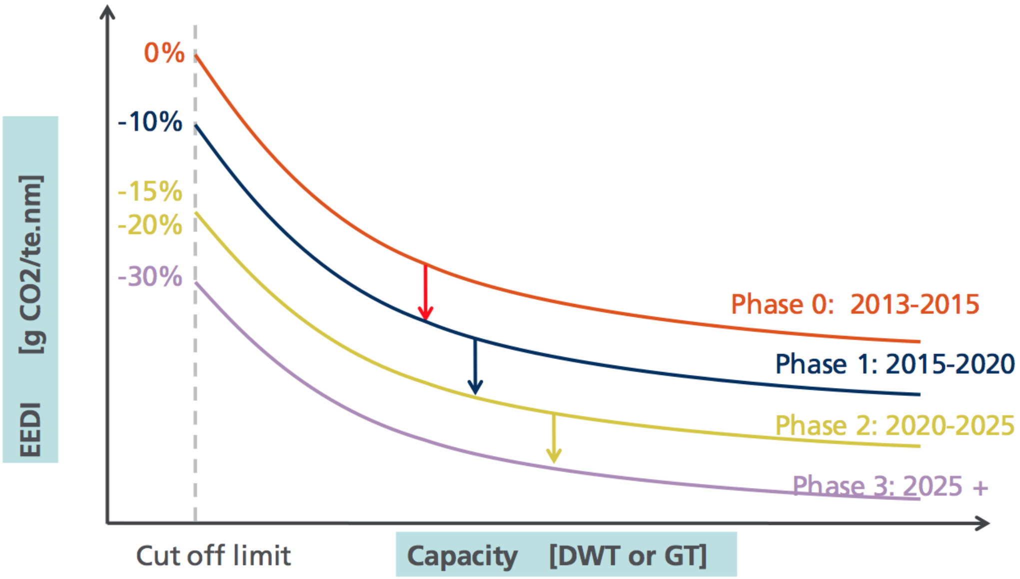


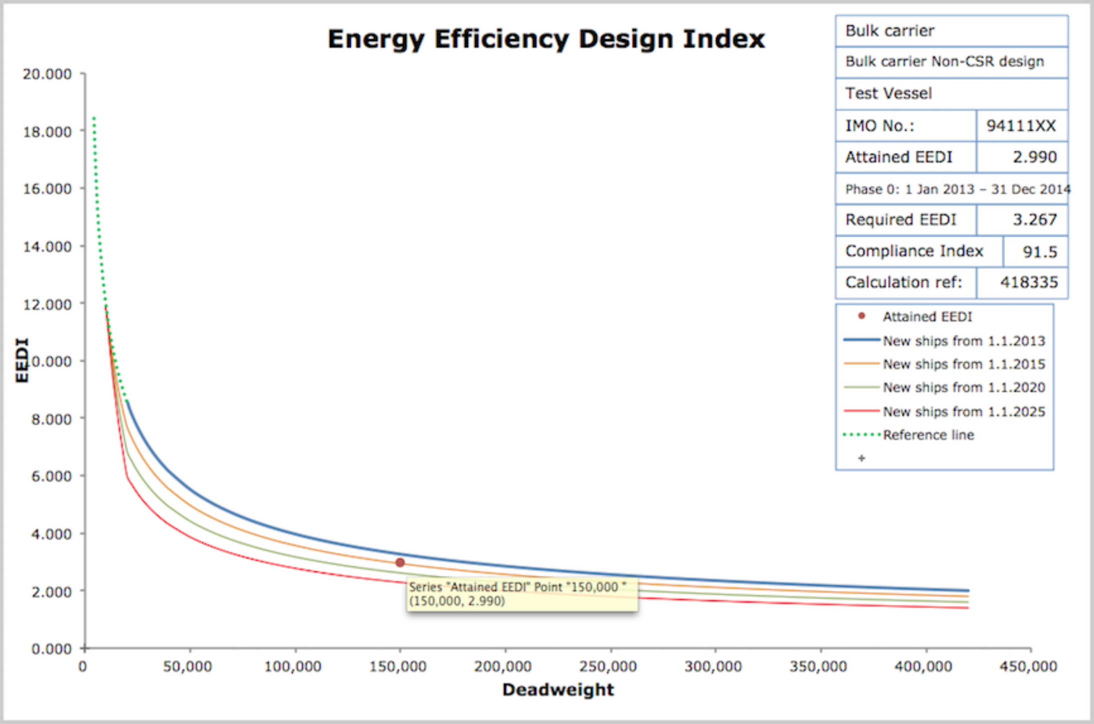
Figure 2.4: EEDI reduction phases (Lloyd's-Register, 2012b)

An excerpt from IMO (2012d), which includes an EEDI technical file sample, along with the calculation of an attained EEDI and further correction by weather factor, has been provided for the reader's guide in Appendix A.1. Additionally, the reader should note that there are publicly available EEDI calculators in the Web. For the purpose of the required EEDI calculations included in this work, an EEDI calculator developed and provided by BIMCO (2011) is used to reiterate the results provided by the EEDI formulation (see calculator screenshot in Appendix A.2).

Table 2.4: Required EEDI reduction intervals as adapted from (GL, 2013)

Ship type	Size in DWT (GT only for passenger ships)	Phase 0 1 Jan 2013 – 31 Dec 2014	Phase 1 1 Jan 2015 – 31 Dec 2019	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Jan 2025 and onwards
Bulk carriers	10.000 – 20.000	n/a	0-10	0-20	0-30
Tankers	2.000 – 10.000	n/a	0-10	0-20	0-30
Gas carriers	4.000 – 20.000	n/a	0-10	0-20	0-30
Container ships	10.000 – 15.000	n/a	0-10	0-20	0-30
General cargo ships	3.000 – 15.000	n/a	0-10	0-20	0-30
Refrigerated cargo ships	3.000 – 5.000	n/a	0-10	0-20	0-30
Combined carrier	4.000 – 20.000	n/a	0-10	0-20	0-30
Vehicle/car carrier	10.000 and above	n/a	5	15	30
Ro-Ro cargo ships	1.000 – 2.000	n/a	0-5	0-20	0-30
LNG carriers	10.000 and above	n/a	10	20	30
Cruise passenger ships	25.000 – 85.000 GT	n/a	0-5	0-20	0-30
Ro-Ro passenger ships	1.000 – 4.000 GT	n/a	0-5	0-20	0-30

Using the basic data for the sample Bulk Carrier found in the IMO (2012d) excerpt, and implementing this information within the BIMCO (2011) EEDI calculator, a user may obtain the following results (see Figure 2.5). As Figure 2.5 shows, within Phase 0 (1 Jan 2013 to 31 Dec 2014), the *attained* EEDI of 2.99 gCO_2/tonne-nm is well within the Bulk Carrier reference values as defined by Table 2.3 (which ultimately equals to 3.27 gCO_2/tonne-nm, using the formula and reference values).



Bulk carrier
Bulk carrier Non-CSR design
Test Vessel

IMO No.:	94111XX
Attained EEDI	2.990

Phase 0: 1 Jan 2013 – 31 Dec 2014

Required EEDI	3.267
Compliance Index	91.5
Calculation ref:	418335

Series "Attained EEDI" Point "150,000 "
(150,000, 2.990)

Figure 2.5: Sample EEDI calculation, screenshot from BIMCO (2011) calculator

Nevertheless, applying the 10% reduction described in Table 2.4 for the following Phase, i.e. Phase 1, the Bulk Carrier in question would be found non-compliant, as the *required* EEDI would then be 2.94 gCO_2/tonne-nm. In theory, the last demonstrates that the smaller the *attained* EEDI is, the more energy efficient is the ship design (Cazzulo, 2013).

Once the *attained* EEDI is calculated, a two-stage verification process begins (see Appendix A.3), which comprises the design stage and ultimately the completion of sea trials and commissioning (Lloyd's-Register, 2012b). The documents to be submitted for EEDI examination, and the different responsibilities by the classification society (as verifier), the shipbuilder, and the shipowner, are described by IMO (2012d).

Once the EEDI is verified, it is included in the International Energy Efficiency Certificate (IEEC) for new ships, issued by the verifier. This EEDI value is valid for the lifetime of the ship, unless this ship goes through a major conversion, in which a reassessment of the EEDI will become necessary, along with the issue of a new certificate (GL, 2013; IMO, 2012d).

Lastly, worthy of mention is that the IMO (2014q) considers the EEDI to serve the largest and most energy intensive segments of the world merchant fleet, and strongly believes that it will embrace up to 72% of emissions from new ships, while covering oil tankers, bulk carriers, gas carriers, general cargo, container ships, refrigerated cargo and combination carriers.

2.4.2 SEEMP

The Ship Energy Efficiency Management Plan, in short SEEMP, is aimed at providing a potential approach for monitoring and optimising the ship and fleet –operational– efficiency performance over time. IMO (2012c) underscores that the purpose of the SEEMP is to establish a mechanism of performance improvement that while focused on ship-specific issues, is carried out as a broader corporate energy management policy, particular to companies that act as shipowners or operators.

Lloyd's-Register (2012a) describes the SEEMP as a *live* document, which contains energy improvement measures defined and implemented onboard the specific ship by the shipowner. The document is to be frequently reviewed, in order to identify the relevance and impact of each acknowledged measure over the ship, and –ultimately– over the fleet operations. As documented by Lloyd's-Register (2012a), and emphasised by IMO (2012c), the SEEMP may also form part of the ship’s Safety Management System (SMS), and/or the Environmental Management System (EMS) under ISO 14001 if in place; these measures may supplement the implementation of the SEEMP.

Four main processes define the structure of the SEEMP: Planning, Implementation, Monitoring, and Self-evaluation and Improvement (see Figure 2.6). Planning determines both the current status of the ship's energy usage, as well as the expected improvement in ship efficiency (IMO, 2012c); it additionally encompasses ship and company specific measures, as well as goal setting and human resources development aims (DNV, 2012). The Implementation phase includes attention to the establishment of an appropriate system to assess how each measure should be implemented, and who the responsible person(s) is, along with the definition of the implementation period (IMO, 2012c).

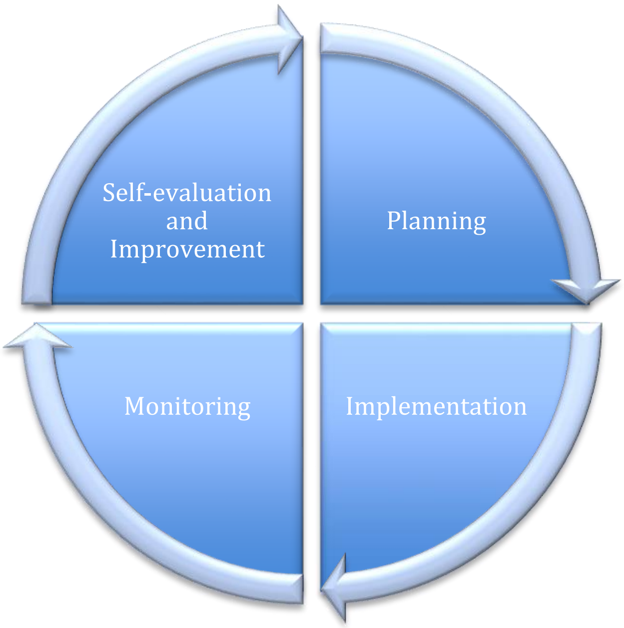


Figure 2.6: Structure of the SEEMP as adapted from IMO (2012c) and Lloyd's-Register (2012a)

The next phase, Monitoring, defines the tools that could provide a qualitative and quantitative basis for evaluation of the measures in place (DNV, 2012). It should be noted that while IMO (2012c) leaves the choice of tools or Performance Indicators (PIs) up to the user, it advises that the energy efficiency of a ship should be monitored quantitatively by an established method, giving preference to indicators supported by an international standard. IMO (2012c) additionally promotes the use of the EEOI as a valid ship and/or fleet energy efficiency indicator, but also recognises other tools could be appropriate as supplementary. The last is of relevance, when considering LCA as an complementary tool underlined by an international standard, which could in turn support the EEOI implementation, as it will be documented further in this document.

The final phase of the management cycle, Self-evaluation and Improvement, should provide relevant feedback for the continuous development of the cycle. The effectiveness of the measures in place is re-assessed and thoroughly documented for the enhancement of the applied processes, if applicable, and ultimately of the SEEMP (IMO, 2012c). Lastly, all interested parties or stakeholders are informed, with the aim of increasing the awareness and confidence in the overall management programme (DNV, 2012).

Worthy of note is that, aside from displaying a SEEMP sample form (see Appendix B.1), IMO (2012c) also offers guidance on the best practices for fuel efficient operation of ships, which includes a description of some of the measures which could be implemented to improve energy efficiency onboard. Such measures include improved voyage planning, weather routeing, optimised ship handling, hull maintenance, and waste heat recovery, among others. Ultimately this is aimed at encouraging shipowners and operators alike, to consider new technologies and practices at each stage of the plan (DNV, 2012).

It is significant to re-emphasise that IMO (2014q) endorses the use of the EEOI – which is currently a voluntary indicator–, specifically as a tool that enables operators to measure the fuel efficiency of a ship in operation, but additionally serves to gauge the effect of any of the changes brought about while implementing some of the measures in the aforementioned paragraph.

Similarly to the EEDI, the EEOI is based on the principle that CO_2 emissions are directly proportional to fuel consumption. The main difference between the two metrics is that contrary to the EEDI, the EEOI does not measure design efficiency but the operational efficiency of ships. As mentioned previously, the operational efficiency is described by taking into account the actual ship fuel consumption under operational conditions, and the transport-work carried out.

Aside from providing a basic version of the EEOI formula below, Kedzierski and O'Leary (2012) define the EEOI as a product of the operational fuel consumption and emissions factor, over the actual achieved transport-work (i.e. cargo mass, number of passenger carried, etcetera), which ultimately results in a figure of grams (or tonnes, depending on the measurement of fuel, as it will be further explained) of CO_2 emissions per tonnes per nautical mile (gCO_2/tonne-nm).

$$\mathrm{EEOI} = \frac{Fuel\ consumption\ \times\ Carbon\ conversion}{Distance\ sailed\ \times\ Cargo\ transported}$$

Kedzierski and O'Leary (2012) sustain that the EEOI is applicable to ships already in operation, and additionally agree that it may serve to gauge the effects of any changes, while implementing energy efficient measures onboard. Of relevance is that a lower EEOI indicates better efficiency (Ballou, 2013), and additionally that the EEOI can be improved by increasing the amount of cargo transported, or by implementing any measure which directly reduces fuel consumption (e.g. slow steaming, weather routing, etcetera) (Kedzierski and O'Leary, 2012).

Likewise to the EEDI, there are various public documents which offer guidance with regards to the EEOI, including several supporting leaflets produced by classification societies. However, the effective EEOI formulation has been defined by IMO (2009d) as follows (also included in Appendix B.2):

Equation 2

$$Average\ EEOI = \frac{\sum_i \sum_j (FC_{ij} \times C_{Fj})}{\sum_i (m_{cargo,i} \times D_i)}$$

Where:

- j is the fuel type
- i is the voyage number
- FC_{ij} is the mass of consumed fuel j at voyage i
- 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, and
- D is the distance in nautical miles corresponding to the cargo carried or work done.

As previously mentioned, the unit of the EEOI is expressed similarly to the EEDI in grams of CO_2 per tonnes per nautical mile (gCO_2/tonne-nm). Nevertheless, the unit for the EEOI can also be expressed in tonnes of CO_2/tonne-nm, given that fuel consumption is commonly measured in tonnes, or additionally depending on the measurement of cargo carried or work done, e.g. tonnes of CO_2/TEU-nm, tonnes of CO_2/person-nm, etcetera (IMO, 2009d).

IMO (2009d) advises that the EEOI should be performed as a representative value of the ship's energy efficiency operation over a consistent period of time, which ultimately should also strive to represent the overall trading pattern of the vessel. This last is why the EEOI is finally presented as a rolling average, with various inclusive voyages depending on the defined period of time. Worthy of mention is that ballast voyages, i.e. voyages in which the vessel commonly sails without cargo, should also be included in the calculation[5].

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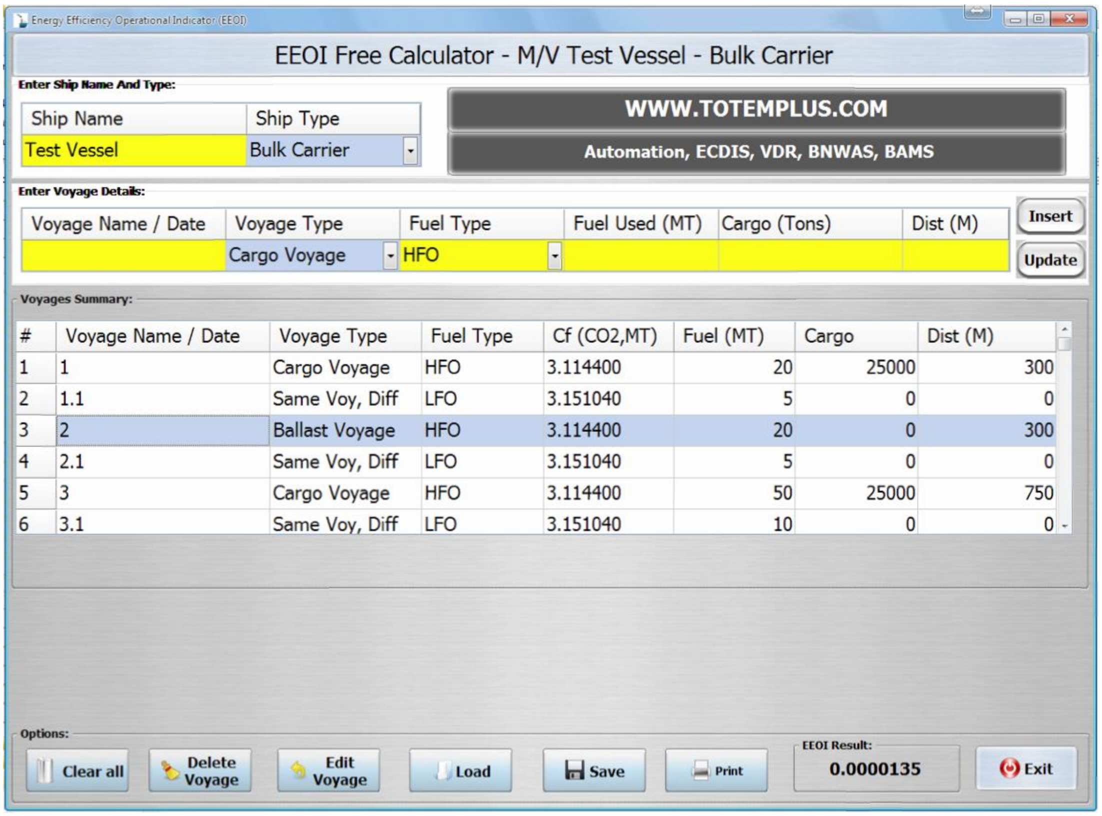
[5] A ballast voyage is calculated by including the amount and type of fuel consumed, while disregarding the distance travelled (i.e. multiplying the distance by zero cargo, see Appendix B.2).



Energy Efficiency Operational Indicator (EEOI)

EEOI Free Calculator - M/V Test Vessel - Bulk Carrier

Enter Ship Name And Type:

Ship Name	Ship Type
Test Vessel	Bulk Carrier

Enter Voyage Details:

Voyage Name / Date	Voyage Type	Fuel Type	Fuel Used (MT)	Cargo (Tons)	Dist (M)
	Cargo Voyage	HFO			

Voyages Summary:

#	Voyage Name / Date	Voyage Type	Fuel Type	Cf (CO2,MT)	Fuel (MT)	Cargo	Dist (M)
1	1	Cargo Voyage	HFO	3.114400	20	25000	300
2	1.1	Same Voy, Diff	LFO	3.151040	5	0	0
3	2	Ballast Voyage	HFO	3.114400	20	0	300
4	2.1	Same Voy, Diff	LFO	3.151040	5	0	0
5	3	Cargo Voyage	HFO	3.114400	50	25000	750
6	3.1	Same Voy, Diff	LFO	3.151040	10	0	0

EEOI Result: 0.0000135

Figure 2.7: Sample EEOI calculation, screenshot from Totem-Plus (2012) calculator

The EEOI can be understood as a fairly straightforward calculation and the data needed for collection is encompassed in its totality by the distance travelled, the quantity and type of fuel, and the cargo carried (or work done). This information is available commonly within the ship in sources such as the ship's logbook, and bunker delivery notes, for example (IMO, 2009d). A focus on proper collection and/or measurement of the data should be in place however, with the aim of improving the monitoring and verification of performance enhancements.

An excerpt from IMO (2009d), which includes an EEOI sample calculation, has been provided for the reader's guide in Appendix B.2. Similarly to the EEDI, there are publicly available EEOI calculators in the Web. For the purpose of the required EEOI calculations included in this work, an EEOI calculator developed and provided by Totem-Plus (2012) is used to reiterate the results obtained by the EEOI formulation (see calculator screenshot in Figure 2.7).

Using the basic data for the sample vessel found in the IMO (2009d) excerpt, and implementing this information within the Totem-Plus (2012) EEOI calculator, a user may obtain the following results (see partial data in Figure 2.7 and full results printout in Appendix B.3). As shown partially in Figure 2.7 and fully on Appendix B.3, the EEOI calculation encompasses the different types of fuel used –which in this case are HFO and LFO–, within each voyage and the cargo carried (or the designation of no cargo due to a ballast voyage) over the actual distance. The result coincides with the IMO (2009d) sample, totalling 13.5×10^{-6} tonnes of CO_2/tonne-nm; this can ultimately be expressed as 13.5 gCO_2/tonne-nm, as previously mentioned.

Once the EEOI is calculated for a period of time representative to that of the overall trade of the vessel, it can be used as a specific target, which in turn can aid in the *Planning* stage of the SEEMP. The target or the *goal setting*, serves to create a good incentive and increased commitment to the overall improvement of energy efficiency during *Planning* (IMO, 2012c). Lastly, IMO (2012c) also affirms that the EEOI meets the target or goal setting requirements of being measureable and easy to understand.

Similarly to the EEDI, the SEEMP is verified by the vessel's assigned classification society. GL (2012) states that the verification of the requirement to have the SEEMP onboard shall take place at the first intermediate or renewal survey –whichever is first–, on or after January 1st, 2013, and is applicable to new and existing vessels of 400 GT and above. Additionally emphasised by GL (2012), is the shipowner's responsibility of developing a SEEMP in accordance to the guidelines put forward by the IMO; also underlined is that upon proper compliance, the issue of an International Energy Efficiency Certificate (IEEC), attesting to the observance of the previously discussed energy efficiency measures, should follow.

2.4.3 Other available shipping energy efficiency metrics

Aside from the regulatory energy efficiency measures presented previously in this section, other metrics are also available –voluntary in nature–, but nevertheless aimed similarly at improving the efficiency of the vessel, and ultimately of the fleet. Some of these are available commercially, while others are in-house developments used within owner and/or operator companies. They are however designed to assist users to properly comply with the current and upcoming regulatory framework.

The following includes a brief discussion with regards to the more popular voluntary metrics available; not with the aim of developing an inclusive listing, but in order to offer the reader a context in which it is underlined that alternative metrics are often used as supplementary tools, to assist with the implementation of the aforementioned regulatory measures.

For example, one of the most known optional metrics is the Existing Vessel Design Index (EVDI) –developed by the Carbon War Room and Rightship (2013a) as a joint venture–, and aimed at being an attempt to formulate a single efficiency metric (Kedzierski and O'Leary, 2012); the last taking into consideration that it is allegedly applicable to both, newbuilds and existing vessels (Rightship, 2013a). The EVDI formulation is based on the IMO’s EEDI methodology, and can be calculated using the IHS Fairplay database, which is also IMO’s database choice for reference lines computation (Kedzierski and O'Leary, 2012).

The main difference between the two is data collection; whereas the EEDI utilises newbuild design data provided by the classification societies during certification, the EVDI exploits existing ship data from different sources, including the IHS Fairplay database, shipyards, owners, and classification societies (Kedzierski and O'Leary, 2012). While the data is eventually available for verification and correction by the shipowner or operator –once the service is commercially acquired–, the EVDI formulation is not publicly disclosed, proving difficult to assess its accuracy.

In summary, the EVDI calculation produces a score that quantifies the assessed ship's theoretical CO_2 emissions per nautical mile travelled (Rightship, 2013a). Rightship has also developed a GHG emissions rating scale –similar graphically to other available energy efficiency rating scales–, in which the score produced is catalogued, in order to classify the ship as environmentally efficient or not (see Figure 2.8). The scale rates the performance from a set of values ranging from 'A' through 'G'; 'A' being the most efficient, while 'G' the least. Rightship (2013a) advertises the calculation and the resulting score as an opportunity to compare peer vessels of similar type and size, under an environmentally performance context.

Figure 2.8: Rightship's GHG emissions rating scale depicted on the port bow of the M/V Emma Maersk (Rightship, 2013b)

Another method of measuring ship energy efficiency has been put forward by Smith et al. (2013), using satellite automatic identification systems (AIS) data in order to analyse the global efficiency of the fleet. AIS data is combined with established naval architecture and marine engineering analysis techniques, resulting in estimates of the assessed ship's annual fuel consumption and consequently its CO_2 emissions.

A relevant variance to the method employed by Smith et al. (2013), in comparison to that of Rightship (2013a), is that the former authors are not in favour of a single or simplified energy efficiency metric, designed for benchmarking the entire fleet. Actually, the AIS-based method is highly similar to that of the IMO's EEDI and EEOI, whereas the both offer separate formulations to assess design and operational efficiency, respectively.

Worthy of mention is that the AIS-based formulation is openly discussed by Smith et al. (2013), including a detailed account of its base input elements. Nevertheless, the methodology comprises a large number of assumptions from Buhaug et al. (2009), which in some cases may seem not so current, and additionally presents relevant uncertainty at times with regards to the actual available AIS data. The last signifies an opportunity for this novel method to be further refined.

Ballou (2013) is another author who agrees that no single metric should be used to indicate success or failure of overall efficiency improvement, but rather a comparative analysis of multiple metrics should be put in place. Additionally described by Ballou (2013) is a methodology in place by Jeppesen, a Boeing Company, which benchmarks the fuel efficiency of an actual operating ship voyage, ultimately comparing the fuel consumption of the actual route to that of the optimal route, supported by voyage optimisation software.

The commercially available solution described by Ballou (2013) incorporates routing algorithms, hydrodynamic and performance modelling, and ocean forecasts to find the best possible route solutions for a specified range of arrival times; the last with the main objective to minimise fuel consumption, while observing safety and user-defined limits. The main benefit of this methodology is that the baseline or target to which the assessed vessel's performance is compared to, is adjusted accordingly to unavoidable factors, e.g. weather, load conditions, and etcetera (Ballou, 2013). It additionally grants the opportunity to implement an improvement strategy within a fleet of ships which share similar trade routes, and in turn allows complementing the development and practice of the company's SEEMP.

Aside from the above-mentioned elective metrics, another measure worthy of reference is the European Commission's proposed regulation "on the monitoring, reporting and verification [MRV] of carbon dioxide emissions from maritime transport", which is targeted at regulating CO_2 emissions applicable to shipping transport within European waters (EC, 2013g).

The Commission recognises IMO's efforts with regards to the introduction of minimum energy efficiency standards for new ships, i.e. the EEDI, but in the other hand also acknowledges that emissions are expected to increase as a consequence –as mentioned previously–, of the ever increasing demand for maritime transport triggered by world trade growth (EC, 2013g).

Another reason behind the proposal is that the precise amounts of CO_2 emissions –and other hazardous releases with similarly potential negative effects–, are currently unknown with regards to EU-related maritime transport, due to the lack of a pragmatic system for the monitoring and reporting of such emissions (EC, 2013g). Additionally, the aforementioned expected increase in shipping CO_2 emissions is out of line with regards to Europe's 2020 strategy, where strict emissions reduction targets are specified (EC, 2010, 2013b).

While the need for specific European action with regards to the monitoring and reporting of shipping-related GHG emissions is explicitly acknowledged by Faber et al. (2009), the European Council and Parliament also recall an established 2009 directive; it emphasises that the EU should make a proposal to encompass international maritime emissions within the Community's reduction objectives, in the event that an international agreement including such emissions and their reduction targets was not achieved through the IMO or the UNFCCC by December 2011 (RICARDO-AEA, 2013). Despite the reduction targets set forward by the above-recognised EEDI measure, the Commission grants that insufficient international action with regards to concise emission reductions has taken place, and thus preparatory activities to address GHG emissions from shipping are placed in motion (EC, 2013g).

The MRV proposal comprises three main stages; the first stage is focused on implementing an efficient methodology for the monitoring, reporting and verification of CO_2 emissions from vessels using EU ports; more significantly however, will be the resulting scale estimation of CO_2 emissions based on fuel consumption, fuel types, and energy efficiency data from available sources. The second and third stage comprise setting up a GHG baseline, and consequently developing reduction target measures for the shipping industry, respectively (EC, 2013g, 2014).

The 2nd and 3rd stage are significant due to the fact that after the proper monitoring and reporting of CO_2 emissions from shipping is implemented, specifically during a relevant elapsed period, e.g. 1 year, 5 years, and etcetera, what logically follows is the concise definition of future reduction targets aimed at regulating emissions within the maritime transport sector. The goals set or targets defined will give way to the application of MBM’s; these will have the ultimate aim to encourage industry stakeholders to adopt available measures to comply with the restrictions in place.

In its current form, the MRV proposal is applicable to all ships above 5000 GT calling into, out of, and in between EU ports, with a planned entering-into-force date of July 1st, 2015 (EC, 2013g). The regulatory requirements highlight the monitoring of CO_2 emissions per voyage and on a yearly basis, as well as having other parameters relative to energy efficiency metrics onboard expressed. Each company is required to produce a monitoring plan, which is ultimately evaluated by an external surveyor addressing the effectiveness and applicability of the plan onboard, while also screening data related to port information (e.g. date and time of arrival/departure, etcetera), CO_2 emissions, distance travelled, time spent at sea, and transport work, including cargo carried (EC, 2013g).

The MRV’s CO_2 emissions calculation consists on using estimated fuel consumption figures and the appropriate emissions factor for the fuel type being consumed (Lloyd's-Register, 2013), similarly performed to obtain the EEOI. The last is aimed at using already existing monitoring on ships, in order to alleviate administrative application burdens when implementing the MRV (EC, 2013g). Direct emissions monitoring is also allowed, as long as it is supported by the resulting fuel consumption figures. Lastly, companies are able to choose from the following methods to monitor fuel consumption: bunker fuel delivery notes, bunker fuel tank monitoring, flow meters for applicable combustion processes, or direct emission measurements, as mentioned previously (Lloyd's-Register, 2013).

It is interesting to underline the EC (2013e)'s emphasis on developing a *harmonised* MRV methodology which is able to provide consistent data with regards to GHG emissions from shipping, accentuating that reliability and accessibility of the information are key to guaranteeing proper carbon performance information flow, through all stakeholders shipping-related. It is relevant to point out as well that in the long term the MRV is aimed at addressing all emissions, including SO_x, NO_x and PM, in order to offer policy-makers the necessary information with regards to all affecting pollutants derived from maritime transport operations.

The above can be similarly related to LCA, as a consolidated methodology that aside from offering a consistent account of GHG, SO_x, NO_x, and PM, among other emissions, is also designed to provide improved reliability through its formulation, and even be utilised as a decision support tool as described by Blanco-Davis and Zhou (2014), Koch et al. (2013) and Hunkeler and Rebitzer (2005), among others.

For more information with regards to the MRV, including accompanying impact assessment of its application, the reader should refer to EC (2013f), EC (2013c), and EC (2013d).

2.4.4 Relevant limitations, criticism, and coverage gaps

As Faber et al. (2009) reiterate, the major difference between the EEDI and the EEOI is that the first assesses exclusively the design state of a vessel, while the latter strives to cover the operational phase of a particular ship. Table 2.5 shows the fundamental coverage differences between the EEDI and the EEOI, showing that while technical policy options are conceived to target mainly design measures in new ships, operational policy options, however, will in principle cover both design options in new ships and operational options in all ships (Faber et al., 2009).

Table 2.5: Comparison of areas which are covered by EEDI and/or EEOI (Faber et al., 2009)

	Areas covered by EEDI	**Areas covered by EEOI**
Design (new ships)		
Concept, speed & capability	Key aspects can be accounted for in the EEDI or technical standard.	All design and operational elements may implicitly be covered, as the resulting performance is the basis for the instrument.
Hull and superstructure		
Power and propulsion systems		
Low-carbon fuels	Capability can be included, but not necessarily used.	
Renewable energy		
Operation (all ships)		
Fleet management, logistics & incentives	No	
Voyage optimisation	No	
Energy management	No	

In addition to the apparent overlapping above, it is also noted that the majority of EEDI analyses presented up to its approval in 2011 were based on existing ships; this is possible since the data required to calculate an EEDI is available from a ship’s technical documentation, which in turn is often supported by classification societies. Therefore, theoretically it is possible to calculate the EEDI for existing vessels (Faber et al., 2009).

The above has caused extensive debating within the IMO, as conflicting views of the applicability of both measures have generated supporters in favour of each, attempting to make a case for their own policy acceptance (Faber et al., 2009). There are supporters which believe that the use of the EEOI, for example, should be encourage or mandated; and that this in turn will make the application of the SEEMP more effective, and additionally will involve more accurate and verifiable measurement of fuel consumption and resulting CO_2 monitoring (Bazari and Longva, 2011).

The Carbon War Room proposal to the IMO was an example of pursuing to have the EEDI cover all ships, both newbuilds and existing, aimed ultimately at providing transparency with regards to fuel efficiency. The International Chamber of Shipping (ICS) refuted this specific proposal by confirming their firm opposition to the application of the EEDI to existing ships, highlighting that the EEDI was developed specifically for the design of new ships, and that the complex formulae was inappropriate for existing vessels (World-Bunkering, 2011). Intercargo (2012) similarly opposes to the utilisation of the EEDI for all ships, stating that since the EEDI is a design target, there is little that can be of influence for ships in service to improve their EEDI scores, and it would be grossly unfair to the existing fleet.

Since the IMO has endorsed the use of the EEOI as a voluntary measure for ship owners and operators to evaluate shipping performance, and not as a metric under mandatory policy (Faber et al., 2009), and while the EEDI is advertised to cover cargo ships –the largest and most energy intensive segments of the world fleet–, embracing up to 72% of emissions from new ships (IMO, 2014q), ultimately the emissions for existing vessels are still not regulated (RICARDO-AEA, 2013).

According to Rightship (2013a), the EEDI framework not applying to existing vessels affects an unregulated existing fleet of 60,000 ships, which currently emit over one billion tonnes of CO_2 annually. Additionally, acknowledging the typical 25-year long lifecycle of a common commercial vessel, Rightship (2013a) estimates that less than 15% of the fleet will be subject to EEDI certification by 2020. Moreover, Kedzierski and O'Leary (2012) confirm that there is also strong opposition to making the EEOI indicator mandatory –which could be understood as an option to cover the EEDI gap for existing ships–, possibly due to the fact that some of the required data may be commercially sensitive, or ultimately as an underlying resistance from industry to have their operations regulated, at the expense of having its performance made public.

The above discussion can be related to the difficult task of striving to apply a single performance metric for different sections of the fleet, i.e. newbuilds and existing ships, as mentioned briefly in the previous section. Kedzierski and O'Leary (2012) for example, are in favour, stating that “a single efficiency metric would have the potential to serve as a clear benchmark of vessel energy efficiency”. Cazzulo (2013) also seems to agree with the single efficiency metric application, as the author expresses that he “shares the concerns of those who caution against attempts to develop a single metric for ships-in-service.”

There are other authors, such as Smith et al. (2013), which propose separate formulations for the assessment of technical and operational efficiency, respectively; and for example Ballou (2013), who is in favour of utilising –not a single metric but– supplementary tools to aid with the overall efficiency assessment. The reality of the current regulatory metrics is that they are not only aimed at separate sections of the fleet, i.e. newbuilds and existing ships, and that they measure efficiency differently, but they additionally produce scores that while may have the same unit, e.g. gCO_2/tonne-nm, are not originally designed to be equivalent within one another (i.e. EEDI ≠ EEOI).

Aside from the above-mentioned disadvantage, there is also a naturally inherent incomparability among some ship types when compared to others. The last is demonstrated by the different established EEDI reference values with regards to ship types (see Table 2.3). Therefore, it is rational to understand that a bulk carrier will have a different EEDI reference value from a containership, and that this in turn will produce a non-equivalent efficiency score among the two ship types. The last is equally applicable to the EEOI.

In summary, while the single performance metric approach would be ideal for a harmonised regulation across the entire fleet, the reality of the current regulatory measures’ intrinsic shortcomings, prevents the use of one single metric to serve as a measure of overall efficiency for the entire fleet and different ship types. Taking into consideration the above, while also highlighting Ballou (2013)’s observation in favour of using supplementary metrics to support the current regulatory measures, an evident opportunity for the use of a standardised performance method –such as LCA–, is emphasised. As it will be documented further, LCA could serve as a supplementary environmental performance metric, while showing indication of compliance and support to the current regulatory framework.

2.5 Life Cycle Assessment background

The following section includes a brief summary of the background of the LCA methodology, aimed at providing the reader a historical reference of its development, as well as a context in which it is documented that LCA is widely accepted and practised, and additionally well referenced across academic and industry literature. Since a comprehensive review of the LCA methodology is out of the scope of this work, the reader should refer to the following works for more information on its particulars: Guinée et al. (2002), ISO (2006a), ISO (2006b), SAIC and Curran (2006), PE-International (2010), and the European Platform on Life Cycle Assessment by JRC (2013), which includes recent and complimentary information.

Additionally, it could be debated that other tools relative to environmental system analysis, such as Material Flow Accounting, Energy Analysis, or Environmental Accounting, could be implemented instead of LCA under the purpose proposed herein. Nevertheless, while these tools are employed to efficiently calculate and evaluate environmental aspects relative to production processes, they do not offer an option for the assessment of end-point environmental impacts (Fet et al., 2013) –such as carbon-footprinting–, required in this study. Further information with regards to other environmental system analysis tools is out of the scope of this work; the reader should refer to Finnveden and Moberg (2005) for an overview.

Lastly, the reader should note that the following definition for ‘carbon footprint’ by Wiedmann and Minx (2007) will be valid throughout the work herein: “the carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product.” Wiedmann and Minx (2007) also emphasise that “the task of calculating carbon footprints can be approached methodologically… [by] strive[ing] to capture the full life cycle impacts, i.e. inform a full Life Cycle Analysis/Assessment (LCA)”.

2.5.1 Historical overview

With increasing public environmental awareness, specifically on issues such as environmental degradation and natural resource depletion, it is not surprising to witness a shift in industry in ways to appraise their activities under a more 'eco-friendly' label; this is often driven by the need to advertise a superior *greener* product than their competitors. Therefore, many companies have started to develop and implement environmental and energy management systems (such as the ISO 50000 series), as a way to enhance their social fronts and consequently improve their financial benefits.

Moreover, nowadays consumers are more environmentally conscious with regards to the choice of products and services, often weighting the pros and cons for each particular product selection. Environmental questions are logically raised when it comes down to options such as paper or plastic bags at the grocery store, paper versus cotton diapers, or glass versus plastic or carton with regards to milk packaging, and etcetera (Guinée et al., 2011).

Initial life cycle assessments produced amazement on most people, due to the fact that the analyses showed that the more 'natural' of the logical choices, for example paper over plastic bags, were not that obviously superior in terms of using less energy and materials, or even producing less waste and emissions than the manufacturing of the latter (Hendrickson et al., 2006). These types of concerns, propelled as well by the emerging environmental management programs for companies, gave way to the use and analysis of data by various techniques, which ultimately resulted in the scientific study of the life cycle of a product, and the development of LCA.

The first assessments involving life cycle aspects of production and materials date back to the 1960s, and they were mostly focused on issues such as energy efficiency, raw material consumption, natural resources depletion and waste disposal (Jensen et al., 1998). One of the first life cycle analyses, for example, was carried out in 1969 in the United States by the Coca-Cola Company (Guinée et al., 2011). The analysis was based on the comparison of different beverage containers as a way to determine which container offered the lowest releases to the environment, and affected the supply of natural resources the least (SAIC and Curran, 2006).

A similar approach was being carried out in Europe by Ian Boustead (UK), when in 1972 he calculated the total energy used in the production of several types of beverage containers, including glass, plastic, steel and aluminium. This method was later termed 'Ecobalance' (Jensen et al., 1998). During this time, explicit industrial data was not publicly available, therefore government documents or technical papers were used instead. Similar to Ecobalance, the process of data gathering and quantification of resource use and environmental releases was known in the U.S. as Resource and Environmental Profile Analysis (REPA) (Guinée et al., 2011). Various REPAs were performed between 1970 and 1975; during this period, a more defined methodology was being developed (SAIC and Curran, 2006).

Throughout these studies, energy use was considered a priority over waste and releases. This was a direct consequence of the oil shortages in the 1970s, thus the discipline was mainly focused on energy supply and demand for both fossil and renewable alternative fuels. Additionally, there was little distinction between inventory development and the interpretation of actual environmental impacts. Once the influence of the oil crisis began to fade, between 1975 to the early 1980s, the interest in these kinds of studies began to decrease. During this time, public concern shifted to issues of hazardous and household waste management. Interest on LCA rekindled during the late 1980s, as governments in developed countries began to face the complications brought about by sizeable amounts of solid waste accumulating in the cities and countrysides (LeVan, 1995).

Through the 1990s, the LCA methodology developed beyond the inventory to the actual impact assessment. During the same time, various organisations were working towards creating a more uniform framework methodology. This evolution was mainly aimed at methodological elaborations and building a consensus on the general approaches and procedures (Hunkeler and Rebitzer, 2005). Worthy of note are the Society of Environmental Toxicology and Chemistry (SETAC) –through its North American and European branches (Guinée et al., 2011)–, and the U.S. Environmental Protection Agency (EPA), as key players in bringing consistency to the procedures (Hendrickson et al., 2006), and getting LCA practitioners, users and scientists to collaborate together on the development and harmonisation of the LCA framework, terminology and methodology (Guinée et al., 2011).

Specifically in 1991, a widespread concern for improper use of LCA techniques for wrongly advertising products in the U.S. was raised; this along with pressure from several international environmental agencies, finally led to the development of the LCA Standards (SAIC and Curran, 2006). While SETAC working groups were mainly in charge of the development and harmonisation of the approach, it was ultimately the International Organization for Standardization (ISO) which adopted the formal task of the standardisation of the methods and procedures (Guinée et al., 2011), through their 14000 series spanning from 1997 through 2002 (SAIC and Curran, 2006).

The standards regarding life cycle assessment were comprised of the following: ISO 14040:1997, ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000 (ISO, 1997, 1999, 2000a, b). These standards consolidated the procedures and methods of LCA; their success contributed to the widespread acceptance of the approach by related stakeholders and the international community. A remarkable growth of scientific and coordination activities worldwide was also reflected in the number of workshops organised through this decade; and additionally, the first scientific journal papers started to appear in the likes of the Journal of Cleaner Production, in Resources, Conservation and Recycling, in the International Journal of LCA, and in the Journal of Industrial Ecology, among others (Guinée et al., 2011).

By 2006, however, the above-mentioned standards were revised. The new standards according to ISO (2006c) "will facilitate the process of evaluating the impacts that a product has on the environment over its entire life, thereby encouraging the efficient use of resources and decreasing liabilities." The revision encompassed the previous four standards; they were technically revised, cancelled and replaced by the publication of the two current standards, ISO 14040 and ISO 14044 (ISO, 2006a, b).

Table 2.6: Chronological review of some of the most relevant events in LCA development (Blanco-Davis, 2011), in turn derived from (Finkbeiner et al., 2006; Hendrickson et al., 2006; Jensen et al., 1998; LeVan, 1995; SAIC and Curran, 2006)

Year	Individuals/Organisations	Event	Place
1963	Harold Smith[6]	Calculation of cumulative energy at World Energy Conference	U.S.
1969	The Coca-Cola Co.	Performed 1st LCA	U.S.
1970s		Oil Crisis Era: focus on energy supply and demand	Int'l.
1972	Ian Boustead[7]	Development of Ecobalance	Europe
1972	Meadows et al.	Published *The Limits to Growth*	U.S.
1972	Goldsmith et al.	Published *A Blueprint for Survival*	U.S.
1970-1975		REPAs and Ecobalance: Quantification of resource use and environmental releases	U.S. and Europe
1979	Ian Boustead	Published the *Handbook of Industrial Energy Analysis*	Europe
1975-1980s		Oil Crisis Era ends: interest in LCA decreases	Int'l.
1980s	European Commission	Establishment of an Environment Europe Directorate (DG X1), increases LCA interest	Europe
1988		Solid waste worldwide issue: LCA emerges as a tool for analysing environmental problems	Int'l
1991	SETAC	Published *A Technical Framework for Life Cycle Assessment*	U.S.
1992	U.N. Earth Summit	LCA emerges as a prominent tool for environmental management tasks	Int'l.
1993	SustainAbility, SPOLD and Business in the Environment	Published *The LCA Sourcebook*	Europe
1993	SETAC	Published *Guidelines for Life Cycle Assessment: A 'Code of Practice'*	U.S.
1993	Keoleian et al.[8]	Published *Life Cycle Guidance Manual*	U.S.
1994	Vigon et al.[9]	Published *Life-Cycle Assessment: Inventory Guidelines and Principles*	U.S.
1996	Curran, M.A.	Published *Life Cycle Analysis*	U.S.
1997	SETAC	Published *Life Cycle Impact Assessment: The State-of-the-Art*	U.S.
1997-2002	ISO	Published 14000 series including ISO 14040:1997, ISO 14041:1999, ISO 14042:2000 and ISO14043:2000	Int'l.
2006	ISO	Revision, cancellation and replacement of previous LCA standards. Published current ISO standards 14040:2006 and ISO 14044:2006	Int'l.

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[6] As cited by SAIC and Curran (2006)

[7] As cited by Jensen et al. (1998)

[8] As cited by Hendrickson et al. (2006)

[9] As cited by LeVan (1995)

The main part of the revision was focused on improving the readability and the removal of errors and inconsistencies; the core part of the technical contents remained largely unchanged, however. With regards to the technical side, worth of mention is the following changes and upgrades: the addition of the principles for LCA, the addition of an annex about its applications, the addition of several definitions, as well as clarifications concerning LCA while applied to comparative assertions and being disclosed to the public, and lastly clarifications concerning system boundary definition (Finkbeiner et al., 2006). Table 2.6 presents a compilation of the more relevant events that led to the development and standardisation of the LCA methodology.

After years of work, including efforts from stakeholders such as natural and social scientists, as well as engineers and practitioners, the establishment of a quite well accepted LCA methodology is observable. The resulting understanding of the methodology is essential for the widespread application of LCA, and in turn a relevant component for making sustainable development operational (Hunkeler and Rebitzer, 2005). Worthy of mention, however, is also the establishment and improvement of several software tools and open databases regarding products' life cycle information. The last has assisted in the acceptance and widespread practice of the methodology in companies, universities and research institutions (Blanco-Davis and Zhou, 2014).

Governments all over the world in the likes of the European Union, the USA, Japan, Korea, Canada, Australia and upcoming booming economies such as India and China, among others, encourage the use of LCA, as the methodology has become a core element in the support of environmental policy or in voluntary action application. The popularity of LCA has spanned creatively to waste incineration, building materials, military systems and even tourism; additionally, environmental impact categories have expanded to include complex impacts such as biodiversity and noise. The above documents that LCA is thriving in application, breadth, and depth (Guinée et al., 2011).

LCA, which is sometimes termed as Environmental Life Cycle Assessment –to accentuate the environmental pillar from social and economic aspects–, has developed rather quickly over the past three decades (Guinée et al., 2011; Hunkeler and Rebitzer, 2005); merely from energy analysis to a comprehensive environmental burden analysis in the 1970’s and a fully established life cycle impact assessment (Guinée et al., 2011), to the inclusion of life cycle costing models in the 1980s and 1990s, followed by social LCA and consequential LCA in the first decade of the 21st century (Guinée et al., 2011). The first two, life cycle costing (LCC) and social life cycle assessment (SLCA), were introduced by the need to properly assess sustainability while encompassing its three fundamental characteristics: environmental, economic and social aspects (Hunkeler and Rebitzer, 2005; Weidema, 2006).

LCC which is defined as “an assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (supplier, producer, user/consumer, end-of-life actor), with complimentary inclusion of externalities that are anticipated to be internalized in the decision-relevant future” (Hunkeler and Rebitzer, 2005), is considered an evolutionary factor of LCA, that while has served as complimentary, is not regarded as compulsory. The development and practice has been very well documented by Rebitzer and Hunkeler (2003), Swarr et al. (2011), Klöpffer and Ciroth (2011), and most significantly by Rebitzer (2005) in his PhD thesis work, exemplifying the application of LCC within industrial uses.

While LCC considers economic implications in a life cycle perspective, SLCA aims at facilitating companies to conduct business in a socially responsible manner by proving information about the potential social impacts on people caused by the activities in their products’ life cycle (Dreyer et al., 2006). While this may be considered as one of the more recent evolutionary factors from LCA, it has gathered quite a popular interest, and it is being pursued strongly by the United Nations Environmental Programme and SETAC, in a joint enterprise. Mentioned as early as 1996 by O’Brien et al. (1996), significant works include Dreyer (2009)’s PhD thesis and subsequent papers (Dreyer et al., 2010a, b), Andreas Jorgensen's work encompassing (Jørgensen, 2012; Jørgensen et al., 2009; Jørgensen et al., 2008) among others, and ultimately Benoît and Mazijn (2010) and Benoît-Norris et al. (2011), as the UNEP/SETAC partnership.

With regards to the UNEP/SETAC partnership, it is relevant to mention that it was formally launched in 2002 and termed the Life Cycle Initiative. This international initiative's main focus was formulated as putting life cycle thinking intro practice, while improving the supporting tools through better data and indicators. Consequently, the Initiative's progress has allowed life cycle thinking to grow in importance within European policy. In response to this, the European Platform on Life Cycle Assessment was established in 2005, in order to promote the availability, exchange and use of quality-assured life cycle data, methods and studies specifically for decision support within EU public policy and business. Worthy of note is that the US employs the EPA to promote LCA similarly as above, and that this widespread encouragement has brought about various life cycle-based carbon footprint standards to be established (Guinée et al., 2011).

While ISO (2006a) never really meant to standardise LCA methods in detail, stating that "there is no single method for conducting LCA", the method originally developed and known as the SETAC-EPA approach –based on a process model assessment–, may be considered by many the more *standardised* or common approach. An additional method commonly used in the U.S. is the Economic Input-output assessment approach (EIO-LCA), derived from the Input-Output Analysis (IOA). The latter, developed by economist W.W. Leontief in the 1940's, utilises direct requirement U.S. economy tables –these are based on industry reports to Federal authorities–, and ultimately allow for the analysis of change in outputs required from each activity to produce an output of a product for final consumption (Weidema and Ekvall, 2009). Basically, the 'input-output' tables (IOT) or database, currently developed by the U.S. Department of Commerce, represents data on resources extracted and environmental discharges, tied to economic variables.

An IOT could become a powerful compliment to LCA practitioners, when the information on average resources use and environmental emissions from each sector are included in the database. In this way, the database can be used to estimate the environmental interventions generated throughout the upstream supply-chain to deliver a certain amount of different goods and services (Finnveden et al., 2009). Hendrickson et al. (2006), serious supporters of the EIO-LCA, additionally claim that "the advantage of the EIO-LCA approach is that it does not need to draw any boundary and so covers the entire economy, including all the material and energy inputs." The most visible disadvantage to this approach would be linking the fluctuating currency values to that of physical units, and its limited applicability in different economies.

Moreover, many LCA practitioners do not find the IO-LCA approach an attractive alternative to process-LCA for detailed product-level LCA, as its sector resolution is much too coarse for major LCA applications such as raw materials selection and process redesign. As a result, what emerged was a hybrid technique which combines the advantages of both process-LCA and IO-LCA, which has become widely acknowledged by LCA practitioners during the late 1990s and early 2000s (Finnveden et al., 2009). Both the environmental input-output based LCA (EIO-LCA) and the hybrid LCA, may be considered to have certain contradictions with regards to the basic principles found in the ISO standards (Guinée et al., 2011).

Consequential LCA, as mentioned briefly, is another relevant distinction worthy of mention between types of LCA. As explained by SAIC and Curran (2006) and Rebitzer et al. (2004), attributional LCA serves to describe a product system and its environmental exchanges, while consequential LCA serves to describe how the environmental exchanges of the system can be expected to change as a result of actions taken in the system.

While Weidema and Ekvall (2009) seemingly argue that every decision-supporting LCA will be ultimately underlined as consequential, due to having further consequences in external systems because of the actions or decisions undertaken by the assessment; the main difference is that attributional LCA will account for flows and/or impacts of pollutants, resources, and exchanges among processes within a chosen temporal window, while consequential LCA attempts to account for the flows and/or impacts that are caused beyond the immediate system in response to a change to the system (SAIC and Curran, 2006). The reader should note that the work herein utilises the more common LCA approach, under the attributional distinction.

Current developments highlight LCA evolving into Life Cycle Sustainability Analysis (LCSA), which according to Guinée et al. (2011) is a framework which will broaden the scope of current LCA from mainly environmental impacts only, to covering all three dimensions of sustainability (people, planet and prosperity, i.e. social, environmental and economic aspects). Other current work worthy of mention is uncertainties within LCA (Finnveden et al., 2009), risk-based LCA (Benetto et al., 2007), and dynamic LCA (Collinge et al., 2013), among others (Guinée et al., 2011); lastly including the ever developing refinement of impact assessment methods, both in the midpoint and endpoint categories (not further expanded herein, but properly explained by Guinée et al. (2002) and SAIC and Curran (2006)), including multimedia approach for assessing potentially human and ecotoxic emissions. An interesting prospect with regards to the last is emphasised by Frischknecht et al. (2013), with relation to the impact caused by alien invasive species, which remains yet to be framed within the LCA framework.

2.5.2 LCA application within shipping and shipbuilding & repair

While not an all-inclusive listing, the following section is aimed at offering the reader a reference into some of the published works that encompass the application of LCA –or another methodology within the life cycle perspective–, in relation to shipping, shipbuilding and/or shiprepair. The reader should note that while traditionally the practice of the life cycle perspective or specific LCA implementation has been somewhat passive within the shipping industry –as opposed to other similar industries (e.g. car manufacturing)–, in these recent years there has been a surge of interest in analysing various parts of the shipping sector using indeed a life cycle perspective (Brynolf, 2014).

With regards to the application of life cycle perspective methodologies in relation to shipping, arguably the most prolific author has been Professor Annik Magerholm Fet. Her works are comprised extensively among environmental engineering and management practices, to even corporate social responsibility. As early as 1996, the author produced a study implementing LCA and LCC on a Platform Supply Vessel; some of the key findings of the study include the emphasis on minimising emissions to air during the operation of ships (i.e. emissions from fuel combustion), as this represents a major contribution to environmental impact (Fet et al., 1996).

Another relevant work, also highlighting the operational phase of ships as the main contributor to most environmental impact categories during a ship's life cycle, is the "Screening Life Cycle Assessment of M/V Color Festival", which is a highly valuable LCA report of a Roll-on/Roll-off (Ro-Ro) passenger vessel, remarkably encompassing the construction and scrapping phases of the lifespan of the ship (Johnsen and Fet, 1998).

The above-mentioned work involving the Ro-Ro passenger vessel consists of the description of an LCA model for this particular ship; this model is utilised within the work herein as a template and development model for subsequent case studies, which will be further explained ahead. Also utilised herein is Fet (1998)'s definition of the system life cycle of a ship, which includes four main phases: planning, construction, operation/maintenance, and scrapping. The LCA modelling in this work will include construction, the separation of operation and maintenance into two different phases, and lastly scrapping, as consequently described.

Of relevance is that Fet, while encouraging the application of the ISO 14000 standard series on environmental management, has also proposed other tools for shipping and shipbuilding, aside from LCA (e.g. Environmental Accounting, Environmental Auditing, Design for the Environment, and Environmental Performance Evaluation, among others) (Fet, 1998). Similarly, the collection of works Fet (1999), Fet (2002), Fet (2003), and Fet et al. (2013) –this last including a combined approach for ships' life cycle designs–, expand on these tools to offer methods of environmental indication and efficiency reporting.

On the above works, worthy of mention is the author's emphasis on the development and use of Environmental Performance Indicators, mostly as a way to benchmark an organisation's performance against one another. The last could be likely applied to ships in the context of environmental indication and energy efficiency reporting, and interpreted as a basis to what will be further underlined in this work. Nevertheless, the context used by Fet, or other authors' available works with regards to the potential of LCA as an indicator of environmental performance for ships, is not similar to the context proposed herein. Other relevant works by the aforementioned academic include Fet and Sørgård (1998), Fet and Michelsen (2000), and Fet (2001).

A mention of fishing vessels, as well as LCA and LCC implementation is included in Ellingsen et al. (2002) and Utne (2009), respectively. The former, also co-authored by Fet, is an effort to include LCA software tools in the design stage, while specifically documenting a fishing vessel case study; the paper ultimately concludes that the application of the tool could be useful for ship designers, yards and shipowners, while also highlighting the need for developing better LCA databases with relation to ships. The latter interestingly presents a relation of LCC and the social dimension of sustainability applied to the life cycle of a fishing vessel.

Another significant work concerning ship design has been presented by Jivén et al. (2004). The authors summarise a Swedish project undertaken from 2002 to 2004, in which the main objectives were to establish methods, tools, and collect data, in order to be able to perform analyses of LCA for ship transport. Ultimately a software tool termed *LCA-ship* was developed, aimed at implementing LCA and energy analyses on vessels and ship transportation, but unfortunately the current state of the tool is unknown and not publically disclosed.

A few studies with regards to alternative power sources are also worthy of mention. Alkaner and Zhou (2006), for example, produced an LCA comparative assessment on molten carbon fuel cells versus diesel engines; one of the key findings was that the manufacture of the molten carbon fuel cell components, including the supply of materials and energy for production, was significantly higher with regards to that of the diesel engine. A similar paper by Strazza et al. (2010), commenting on the use of onboard solid oxide fuel cells instead, relevantly emphasised that the application of LCA was useful as a decision making tool for process selection and environmental improvement.

In the other hand, Selma Brynolf, née Bengtsson, has carried out a number of relevant works concerning the environmental assessment of fuels within marine applications, namely the following: Bengtsson et al. (2011), Bengtsson et al. (2012) and Bengtsson et al. (2014). Ultimately Brynolf (2014), in her PhD thesis work remarkably concludes, among other deductions, that there is a large potential to reduce the environmental impact from shipping through a change of fuels and/or through the use of exhaust abatement technologies.

With regards to the assessment of marine technologies, the papers by Cabezas-Basurko and Mesbahi (2012) and Blanco-Davis and Zhou (2014) are worthy of note. Both of the papers underscore the assessment of ballast water treatment systems; however, the former highlights a methodology to encompass social sustainability assessment complementing the other two pillars (i.e. environmental and economic aspects); while the latter significantly concludes that LCA is a beneficial tool for shipowners and fleet managers, to use in selecting a design associated with the lowest environmental impacts. In addition, Blanco-Davis et al. (2014a) present an interesting LCA study regarding the benefits shown in retrofitting a fouling release polymer coating system, over a conventional antifouling paint scheme.

Other relevant works containing LCA applications within shipbuilding and ship operation are as follows: Hayman et al. (2000), Kameyama et al. (2005), Kameyama et al. (2007), and Tincelin et al. (2007). More recent work similarly related to ship operation and shiprepair, nevertheless, is encompassed within the framework of the EC-FP7 collaborative R&D project named “Eco innovative refitting technologies and processes for shipbuilding industry promoted by European Repair Shipyards”, in short Eco-REFITEC. Among many objectives, the Eco-REFITEC project documented the use of LCA as a relevant tool not only for shipowners and fleet managers, but also potentially advantageous for ship designers and shipyards.

The project overview and some of its main results are included in del Castillo and Blanco-Davis (2012) and del Castillo et al. (2014), respectively. Relevant to the Eco-REFITEC project as well, Koch et al. (2013) present a simulation solution encompassing environmental and economic aspects for the assessment of marine retrofits. Other significant documents from the project include Blanco-Davis (2013a), Blanco-Davis (2013b), Blanco-Davis (2014), and Blanco-Davis et al. (2014b); these will be further explained and referenced herein, as elements from the former are relevant to this work.

In summary, the above reports the growing increase in application of life cycle perspective methodologies –and specifically LCA–, within the shipping and shipbuilding and repair industry. Worthy of note as well is that very likely, additional LCA appraisals have been performed but remained undisclosed, as they have probably served as in-house company practices; the increase in exercise and the subsequent publication with regards to these approaches, would be an added benefit to the shipping sector. Lastly, the reader should refer to Brynolf (2014) for an alternate literature listing, more in relation to the author’s work on marine fuels, but complementary nevertheless.

Table 2.7 presents an overview listing of the literature references mentioned in this section.

Table 2.7: Overview reference of some of the publicly available works implementing Life cycle perspective/LCA in relation to shipping, shipbuilding and repair

Topic	Author(s)	Title
Life cycle perspective & shipping	Fet et al. (1996)	Environmental Impacts and Activity Based Costing during Operation of a Platform Supply Vessel
	Johnsen and Fet (1998)	Screening Life Cycle Assessment of M/V Color Festival
	Fet (1998)	ISO 14000 as a Strategic Tool for Shipping and Shipbuilding
	Fet and Sørgård (1998)	Life Cycle Evaluation of Ship Transportation - Development of Methodology and Testing
	Fet (1999)	Environmental management tools and their application: a review with reference to cases studies
	Fet and Michelsen (2000)	Life Cycle Assessment of transport systems
	Fet (2001)	Cleaner Production and Industrial Ecology
	Fet (2002)	Environmental reporting in marine transport
	Fet (2003)	Eco-efficiency reporting exemplified by case studies
	Fet et al. (2013)	Systems engineering as a holistic approach to life cycle designs
Ship design, shipbuilding & operation	Hayman et al. (2000)	Technologies for reduced environmental impact from ships: Ship building, maintenance and dismantling aspects
	Jivén et al. (2004)	LCA-ship, design tool for energy efficient ships, A life cycle analysis program for ships
	Kameyama et al. (2005)	Development of LCA Software for Ships and LCI Analysis based on Actual Shipbuilding and Operation
	Kameyama et al. (2007)	Study on Life Cycle Impact Assessment for Ships
	Tincelin et al. (2007)	A life cycle approach to shipbuilding and ship operation
Fishing & LCA / LCC	Ellingsen et al. (2002)	Tool for Environmental Efficient Ship Design
	Utne (2009)	Life cycle cost (LCC) as a tool for improving sustainability in the Norwegian fishing fleet
Alt. power sources	Alkaner and Zhou (2006)	A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application
	Strazza et al. (2010)	Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships
Marine fuels	Bengtsson et al. (2011)	A comparative life cycle assessment of marine fuels liquefied natural gas and three other fossil fuels
	Bengtsson et al. (2012)	Environmental assessment of two pathways towards the use of biofuels in shipping
	Bengtsson et al. (2014)	Fuels for short sea shipping: A comparative assessment with focus on environmental impact
	Brynolf (2014)	Environmental Assessment of Present and Future Marine Fuels
Marine technologies / coating	Cabezas-Basurko and Mesbahi (2012)	Methodology for the sustainability assessment of marine technologies
	Blanco-Davis and Zhou (2014)	LCA as a tool to aid in the selection of retrofitting alternatives
	Blanco-Davis et al. (2014a)	Fouling release coating application as an environmentally efficient retrofit: a case study of a ferry type ship
EC-FP7 Eco-REFITEC	del Castillo and Blanco-Davis (2012)	Eco Innovative Refitting Technologies and Processes for Shipbuilding Industry: Project Overview
	Koch et al. (2013)	Analysis of Economic and Environmental Performance of Retrofits using Simulation
	Blanco-Davis (2013a)	LCA Tool and User Manual: Guidelines to the Ship's Life Cycle's data gathering and LCA prototype modelling
	Blanco-Davis (2013b)	LCA for Eco-REFITEC selected cases: Report of implementation of LCA for shipyards, including owner costs and results of case ships
	Blanco-Davis (2014)	LCA impact assessment of greening existing fleet: Potential environmental impact of the technological eco-innovation for greening existing fleet
	del Castillo et al. (2014)	Eco innovative refitting technologies and processes for shipbuilding industry: Project results
	Blanco-Davis et al. (2014b)	Energy efficiency optimisation, through the use of an absorption cooling system onboard fishing vessels

2.6 Concluding remarks

The following are the most significant remarks comprised in the chapter, and underscored in the form of bullet points for the reader's ease:

- IMO, as shipping's main regulatory body, is responsible of staying in the forefront of marine environment protection, as well as proactively liaising with international environmental protection bodies, such as the UNFCCC.

- Regulatory requirement to state shipping efficiency in terms of an environmental context was expressed by IMO as early as 2003.

- As early as 2005, the IMO offered the first ship energy efficiency and environmental performance metric for existing ships. Three years later, the first IMO-based environmental performance metric aimed at improving ship design was offered.

- International shipping corresponds currently to 3% of the global GHG emissions total. Additionally, GHG emissions from shipping are likely to keep increasing in the future, due to the anticipated demand for maritime transport.

- July 2011's amendments to MARPOL's Annex VI underline the EEDI for new ships, and the SEEMP for all ships, as mandatory since January 1st, 2013. It is regarded as the first ever global and legally binding instrument, underscoring energy efficiency regulations for any industrial sector.

- A 1º to 2ºC increase in global mean temperatures poses relevant risks. Therefore, a requirement to lower and stabilise GHG concentrations in the atmosphere, is in order to prevent climate change impacts.

- There is a relevant potential for GHG reduction, found through a range of technical and operational measures currently, or soon-to-be available[10]. These, together with the implementation of suitable policies, are regarded as a competitive instrument to mitigate increasing emissions.

- There is a current serious trend for industry sectors to decarbonise. Alarmingly, the shipping industry could represent up to 25% of the global CO_2 emissions total in 2050, if the required technological measures and enticements are not in place, to allow for suitable decarbonisation of the maritime sector.

- The EEDI has been summarised as an energy efficiency requirement level for new ships, which reflects the theoretical design efficiency –depending on ship type and size–, and ultimately aimed at stimulating continuous technical development of all the components which influence the fuel efficiency on a ship.

- By regulation, the attained EEDI shall be calculated for all ships of 400 GT and above. Also, the attained EEDI must be equal to or less than the required EEDI for that ship type and size. Consequently, the required EEDI will gradually be reduced by a specified per cent each five years, based on the initial value (Phase 0).

- The Ship Energy Efficiency Management Plan, in short SEEMP, is aimed at providing a potential approach for monitoring and optimising the ship and fleet –operational– efficiency performance over time.

- IMO endorses the use of the EEOI, as a voluntary indicator applicable to the SEEMP. The EEOI will enable operators to measure the fuel efficiency of a ship in operation.

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[10] These measures are not mentioned herein, since they are outside the scope of this document. The reader should refer to Buhaug et al. (2009) for more information.

- The main difference between the EEDI and the EEOI is that the former measures design efficiency, while the latter measures operational efficiency. The design efficiency reflects the theoretical efficiency of a newbuild vessel, based on the out-of-the-box state of the engines and equipment, and including the overall ship design. Operational efficiency is described by taking into account the actual ship fuel consumption under operational conditions, and the transport-work carried out.

- Aside from the regulatory energy efficiency measures, other metrics are also available –voluntary in nature–, but nevertheless aimed similarly at improving the efficiency of the vessel, and ultimately of the fleet. Some of these are available commercially, while others are in-house developments used within owner and/or operator companies.

- It is interesting to underline the EC's emphasis on developing a harmonised MRV methodology, which is able to provide consistent data with regards to GHG emissions from shipping. It is also relevant to point out that in the long term the MRV is aimed at addressing all emissions, including SO_x, NO_x and PM. The above can be related to LCA, as a consolidated methodology that can offer a consistent account of GHG, SO_x, NO_x, and PM.

- The discussion to the difficult task of striving to apply a single performance metric for different sections of the fleet, i.e. newbuilds and existing ships, has been presented. The reality of the current regulatory metrics is that they are not only aimed at separate sections of the fleet, i.e. newbuilds and existing ships, and that they measure efficiency differently, but they additionally produce scores that while may have the same unit, e.g. gCO_2/tonne-nm, are not originally designed to be equivalent within one another (i.e. EEDI $\neq$ EEOI).

- The gaps carried forward by the available performance measures underline the issues of applicability within the different metrics (e.g. newbuilds and existing vessels), the incomparability or non-equivalency of the scores between them, the on-going discussion of a single metric approach, and their partial coverage and application. Thus, an evident opportunity for the use of a standardised performance method is emphasised. LCA could serve as a supplementary environmental performance metric, while showing indication of compliance and support to the current regulatory framework.

- A brief summary of the background of the LCA methodology, aimed at providing the reader a historical reference of its development, as well as a context in which it is documented that LCA is widely accepted and practised, was presented. Academic and industry literature reference has been provided, in an effort to evidence the rise in interest of the application of life cycle perspective methodologies and LCA, in relation to shipping, shipbuilding and shiprepair.

3 Approach Adopted

3.1 Introductory remarks

This chapter will comprise three main sections. The first is aimed at mentioning the basics of the LCA methodology, while the next one will address the context in which LCA is applied herein, and additionally expand on certain elements with regards to the development of the ships' LCA model. The last section will entail a brief discussion with regards to the advantages and disadvantages of the LCA application relative to the EEDI and EEOI.

As mentioned previously, is not within the aim of this work to go further into the description of the LCA methodology, as there are various available resources that do just that. Therefore the reader is encouraged to refer to some of the works mentioned in the *Literature Review* chapter, to complement their own documentation.

3.2 Basics of LCA

There are two current regulatory LCA standards, developed by the International Organization for Standardization (ISO), which define the concept and describe the methodology, respectively: the ISO 14040 and the ISO 14044 (ISO, 2006a, b). ISO 14040 defines LCA as a method which "addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal" (ISO, 2006a).

Life Cycle Assessment (LCA), which is also known by other names such as 'life cycle analysis', 'life cycle approach', 'cradle to grave analysis' or 'Ecobalance', is a methodology which involves several techniques in order to evaluate certain aspects – mostly environmental– of a process, product, service or system, through all stages of its life cycle, in order to efficiently assess any resulting potential environmental impact (Blanco-Davis, 2011).

Simply explained, the methodology aids in compiling and evaluating the inputs and outputs, and the potential environmental impacts of a product system, during a product's lifetime (PE-International, 2011); but more significantly, it is characterised by including impacts not often considered in traditional analysis, for example raw material extraction, material transportation, ultimate product disposal, and etcetera (SAIC and Curran, 2006).

In summary, the standardised LCA methodology is based on a process model assessment, which includes a thorough inventory of resource inputs and environmental outputs (i.e. input and output flows), while also calculates mass and energy balances, and evaluates potential environmental damage (Koch et al., 2013). LCA offers an all-inclusive view by means of a holistic approach, and thus a more detailed representation of the actual environmental trade-offs related to a process, product, service or system. One of the most relevant benefits of the methodology, comes from serving as a decision support tool, in order to assist in the selection of a process or product, and ultimately advantageous in favour of choosing the least environmental burdensome (Blanco-Davis and Zhou, 2014).

The above-mentioned input and output *flows* are considered as *elemental flows* under the LCA methodology, and are defined as “material or energy entering the system being studied that has drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation” (ISO, 2006a). Koch et al. (2013) describe the above as flows that enter the technosphere (i.e. the system being assessed) from nature, such as resource flows (e.g. iron ore); and flows that leave the technosphere system to nature as emissions, whether they are directed to air, water and/or soil.

Currently, the methodology is commonly employed for two main purposes: to assess the potential environmental impacts of a certain product including the product’s past history and forecast, in order to generate its environmental score; while the other purpose is to assess the product versus an alternative, making a pragmatic comparison among the available options (Blanco-Davis and Zhou, 2014). In either of the two, the comprehensive view offered by LCA, strives to prevent the potential underestimation of overlooked impacts, commonly found in transportation and ancillary processes, among others.

Additionally, LCA can identify potential impacts shifting from one life cycle stage to another, e.g. from use and reuse of the product to the raw material acquisition phase, as well as recognising the transfer of ecological impacts from one environment to the other, e.g. eliminating air emissions by in turn creating a wastewater effluent (SAIC and Curran, 2006). Another relevant benefit comprises the capability of quantifying exchanges to the environment, relative to each life cycle stage; this valuable information can also be linked to factors such as costs and performance data for a specific process or product, assisting in the design and enhancement of such (Blanco-Davis and Zhou, 2014).

Nevertheless, the methodology is also prone to certain inherent disadvantages; for example, it is known to require intensive data gathering, which could be potentially expensive and time-consuming. Also, compiling all material and energy data for each inclusive process is impractical; thus, the methodology calls for proper boundary setting to allow the assessment of extensive systems. Both boundary setting and data gathering can influence the results certainty; e.g. by erroneous and subjective adjustment in the first, and by lack of quality and/or availability in the latter (Koch et al., 2013).

The methodological framework of LCA consists of four phases. The relationship between each phase is shown in Figure 3.1. These phases are:

1. Goal and scope definition: the scope as well as the system boundary and level of detail are defined within this phase. The goal, for example, will be particular to the subject and intended use of the study; thus, the depth and breadth of an LCA will vary accordingly (ISO, 2006a).
2. Life cycle inventory analysis (LCI): it comprises an inventory of the input and output data with regard to the system being assessed. It also involves a collection of the required data to meet the needs defined previously by the goal of the study (ISO, 2006a).
3. Life cycle impact assessment (LCIA): the purpose of this phase is to provide additional information to help assess a product system's LCI results in order to offer a clearer understanding of their environmental significance (ISO, 2006a).
4. Life cycle interpretation: the final phase comprises the results of an LCI or an LCIA, or both, summarised and discussed as a basis for conclusions, recommendations and decision-making in accordance to the previously defined goal and scope of the study (ISO, 2006a).

Worthy of mention is the iterative relationship between the phases of an LCA, represented graphically by the double-arrow feature in Figure 3.1. This could be better explained when, for example, performing an impact assessment it becomes clear that information is missing or erroneous, which would in turn mean that the inventory analysis phase must be improved, and could also include revising the goal and scope of the study. In this form, the methodology is enhanced through its own procedure, while maintaining a clear and consistent formulation (Blanco-Davis and Zhou, 2014).

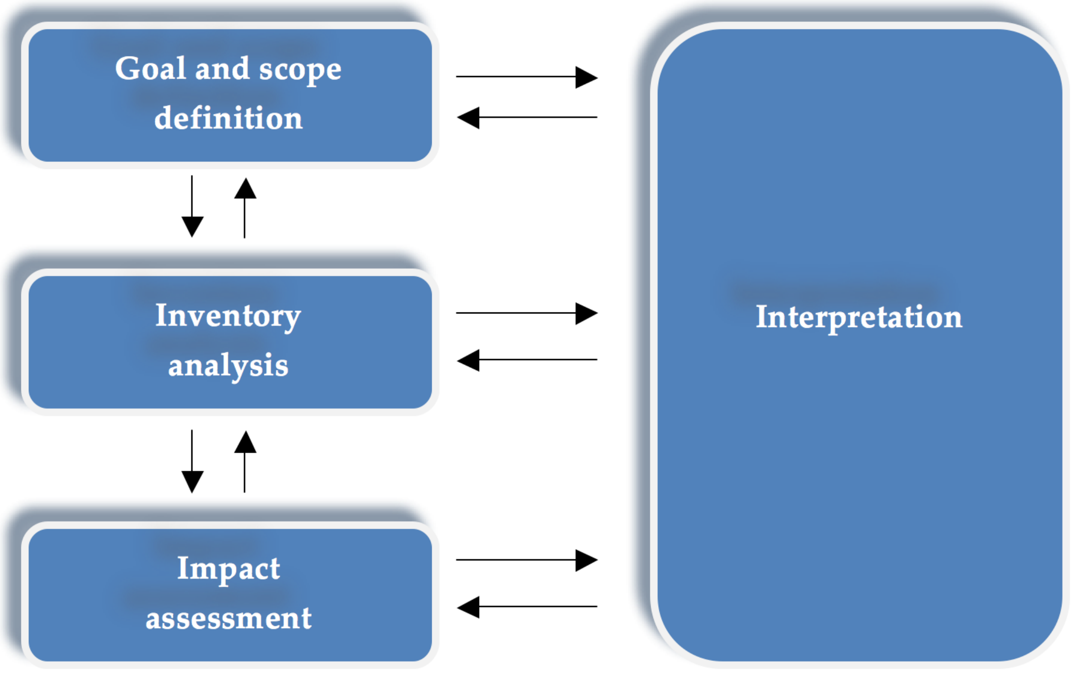


Figure 3.1: Life cycle assessment framework, phases of an LCA (ISO, 2006a)

With regards to the goal of an LCA, as mentioned previously, the primary goal is usually to choose the most evident product, process, or service with the least effect on human health and environment (SAIC and Curran, 2006). Secondary goals can include information to support environmental appraisals, to develop a baseline database for a product or system, to support public policy or product certification such as EPDs (Environmental Product Declarations), and etcetera (Blanco-Davis and Zhou, 2014).

The scope definition includes an explanation of the boundaries of the study, in which it is defined what is to be included in the system, characterised by the type of information and the level of detail. It is determined, as well, whether one, a few, several, or all of the stages of a product are to be included within the scope of the assessment (see Figure 3.2 for a summary of the stages of a product). The required accuracy of the results, the available time and the resources of the study are also described.

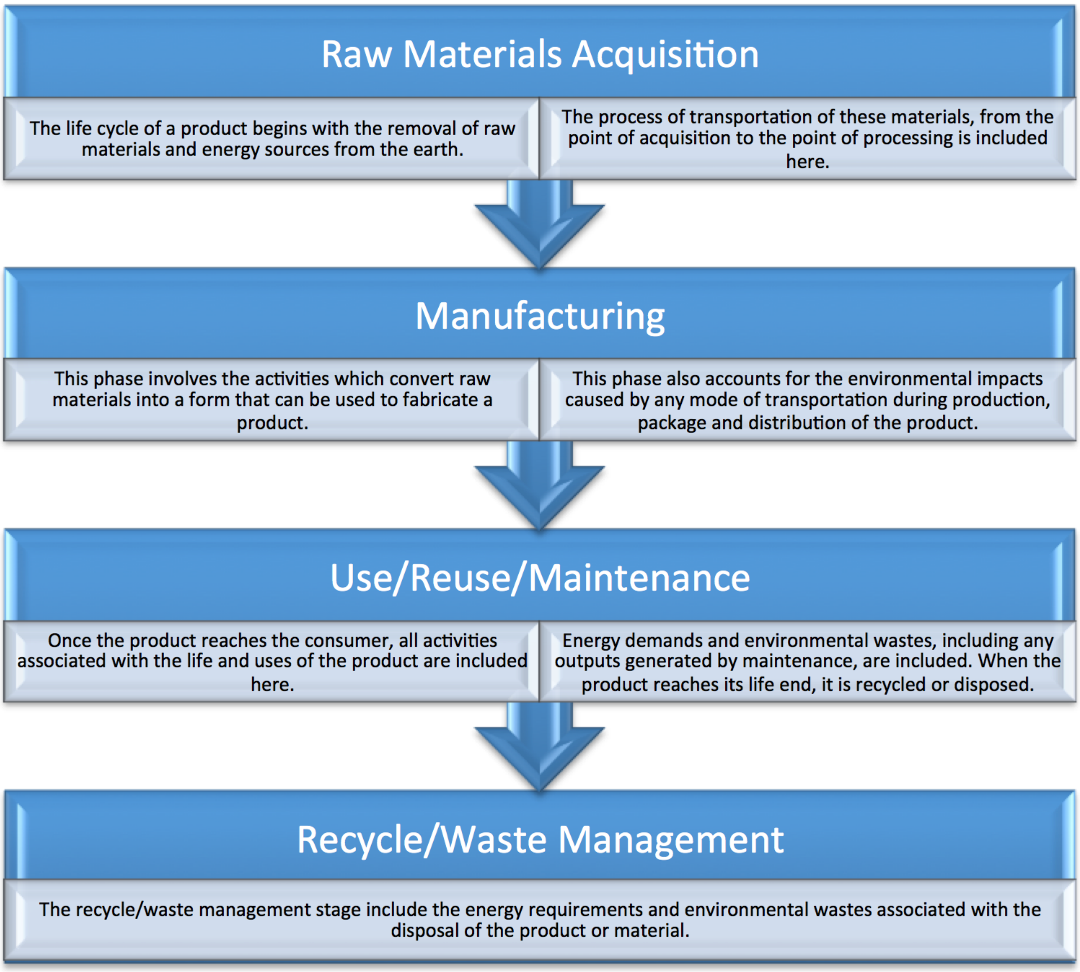


Figure 3.2: The four main stages of a product's life cycle (Blanco-Davis, 2011)

During the LCI, data gathering –classified often as the most work intensive part of the life cycle assessment–, is required to specify information on single processes within the life cycle system and quantify elemental flows. The type of data, however, can be of the quantitative or qualitative type, and is normally presented in a table listing all material and energy inputs and outputs for the system being appraised.

These data is often classified under energy inputs, raw material inputs, product wastes, emissions, and etcetera (Blanco-Davis and Zhou, 2014).

The data, which has served to quantify elemental flows, is classified during the impact assessment under various impact categories and further characterised, i.e. the relative effects of the resource consumption and the resulting releases are calculated. GHG emissions, for example, are aggregated into a specific impact category relative to global warming potential. This phase results in more concise information, which is easier to interpret (Brynolf, 2014).

Lastly, the specific results to each appraised system are compiled and interpreted, in order to draw conclusions, identify limitations, and make recommendations regarding, for example, which product is the least burdensome to human health and environment. The interpretation phase also offers the opportunity to describe specific areas of concern, or areas with potential for redesign and improvement.

3.3 Ships' life cycle model

3.3.1 Introduction

When taking into consideration the lifetime of a ship –a period that usually spans from 25 to 30 years for a common commercial vessel–, there are various relevant phases which need to be underlined. These phases have been previously defined by Fet (1998), and are similarly portrayed by Figure 3.3.

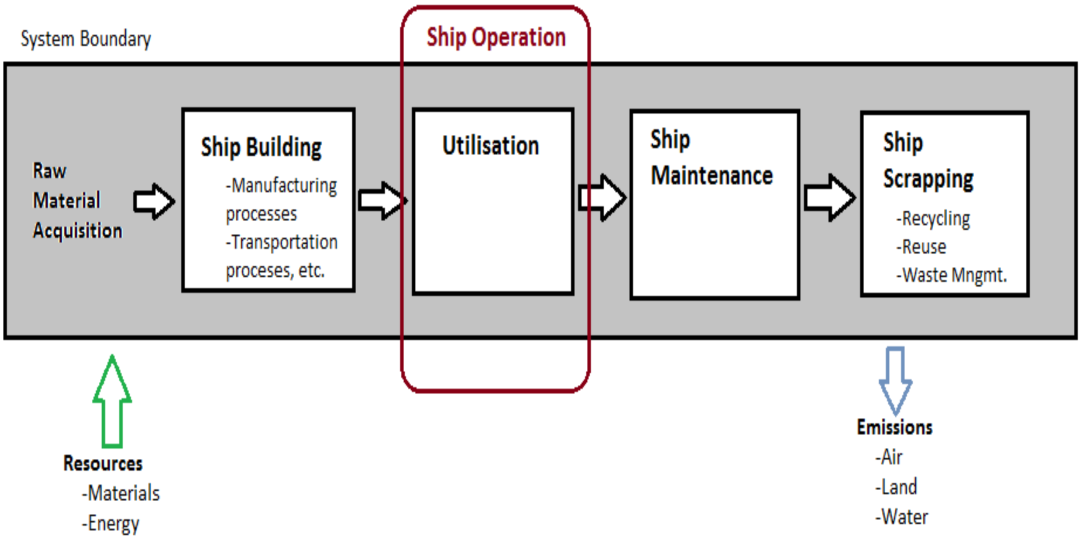


Figure 3.3: Main phases within the life cycle of a ship

In order to assess the potential resources consumed and the emissions emitted by a specific ship, a baseline LCA model is required. This model needs to feature the type and trade of the ship, and emphasise on the ship's most typical operations over a significant period of time (e.g. a year; this grants the possibility to extrapolate results to an assumed lifetime of e.g. 25 or 30 years, in order to assess the ship's whole life cycle). The last underscores that the operational profile of the ship –including its consumption parameters–, and any additional information from the construction phase to the assumed end-of-life scenario, proves ultimately essential to develop the ship's life cycle model.

Once the baseline LCA model is developed for a specific ship, the potential environmental impacts produced by the ship's operational profile can be assessed; this by accounting for the environmental history of the ship, as well as being able to extrapolate to potential future impacts. Any difference with regards to the most habitual behaviour within the operational profile of the ship, can now be assessed against the previously calculated baseline model (e.g. the switch to low-sulphur fuel) (Blanco-Davis, 2013a). Significantly, the above comparison also offers the end-user the possibility of adjusting relevant operational inputs related to the original systems –or even applied retrofits–, in order to improve the calculated future environmental scores of the assessed system(s) (Koch et al., 2013). The above is also applicable to the building phase of a ship, in the case of ship re-design and system enhancement.

Therefore, in order to have a full cradle-to-grave environmental assessment of a specific ship, the most relevant phases of its life cycle need to be included and calculated, e.g. ship construction, ship operation and maintenance, and ultimately ship decommissioning or scrapping. The operational phase of a ship's life cycle is the longest phase during the ship's total life span. During its operational life, a vessel emits effluents, harmful gases, and generates all sorts of wastes from its operational activities and consumables. The operational phase additionally dominates the contribution to greenhouse gas effects, acidification, and human and eco toxicology, among other impact categories (Fet and Sørgård, 1998).

The operational profile of the assessed vessel(s) needs to be defined, in order to determine the demand of consumables for their effective operation in different operational scenarios. Furthermore, the details of the vessel's equipment are also required in order to appraise the consumption quantities encompassing the various consumables, and ultimately assess the emissions resulting from the operational period under assessment. The data needed for the development of the operational and maintenance phase of the LCA model, can be broadly classified within the following categories:

1. Vessel equipment specifications
2. Vessel voyage(s) information and defined operational profile
3. Consumable supplies for typical operations
4. Maintenance and repair data
5. Wastes and additional effluents generated from operations.

Aside from the above mentioned categories –which are further explained by Blanco-Davis (2013a), for the reader's reference–, any data with regards to the disposal and/or recycling of the waste generated from ship operations, both onboard and onshore, is of great relevance. This may include any specific procedures or guidelines to treat slops, garbage, plastic wastes, sludge, worn out and replaced spares, and etcetera.

The construction phase is of great importance as well; this phase will encompass major production operations in shipbuilding and repair to the likes of cutting, welding and painting, among others. All of these are relevant operations, which may represent significant environmental impacts to air, land and water. Both Johnsen and Fet (1998) and Blanco-Davis (2013a) offer guidance with regards to the development of the processes relative to shipbuilding and repair, and the data needed for the establishment of this phase of the LCA model.

Lastly, and often the hardest phase to formulate –due to the often scarcity of information–, is the end-of-life phase or ship scrapping. Any potential decommissioning information related to the case vessels, whether provided by sister ships, for example, or other sources –including other vessels' end-of-life scenarios–, are required in order to strive to develop a realistic ship-scrapping phase. While not all-inclusive, a practical data-gathering list for the above-mentioned phases is included for the reader's reference in Appendix C.1.

3.3.2 Building the ships' LCA model

For the purpose of this work, the GaBi 6 software tool (GaBi, 2013) will be utilised to aid in the development of the ships' LCA model, as well as used for the environmental assessment of the vessels' resources consumed and emissions released. GaBi 6 is a software package for comprehensive life cycle balances, permitting –aside from the environmental aspect–, the assessment of technical and economic impacts of products, services and systems (PE-International, 2007). Worthy of mention is the additional use of the GaBi Professional Database, which contains various LCI results for common manufacturing and industry practices, and thus helpful in reducing the data gathering procedure for commonly required processes (PE-International, 2013).

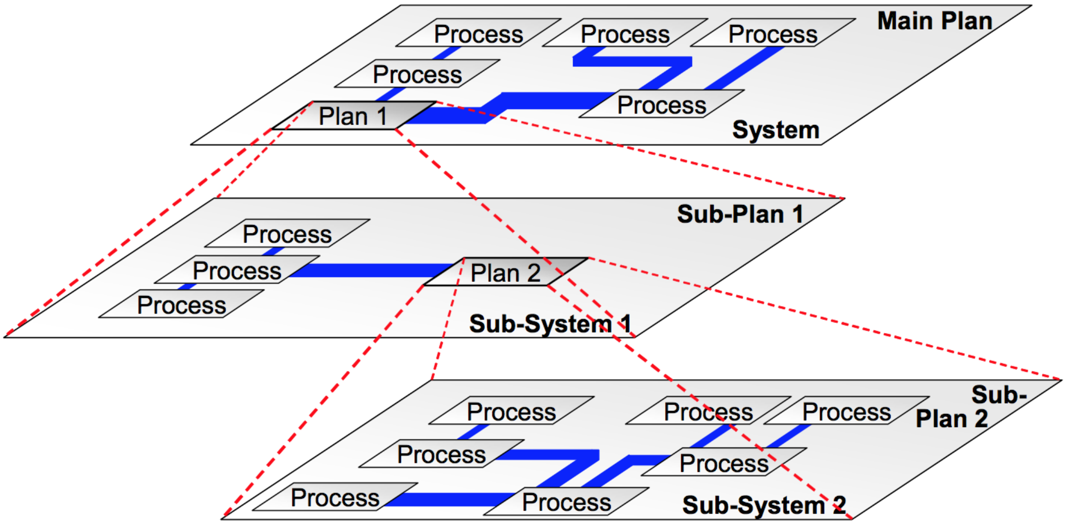
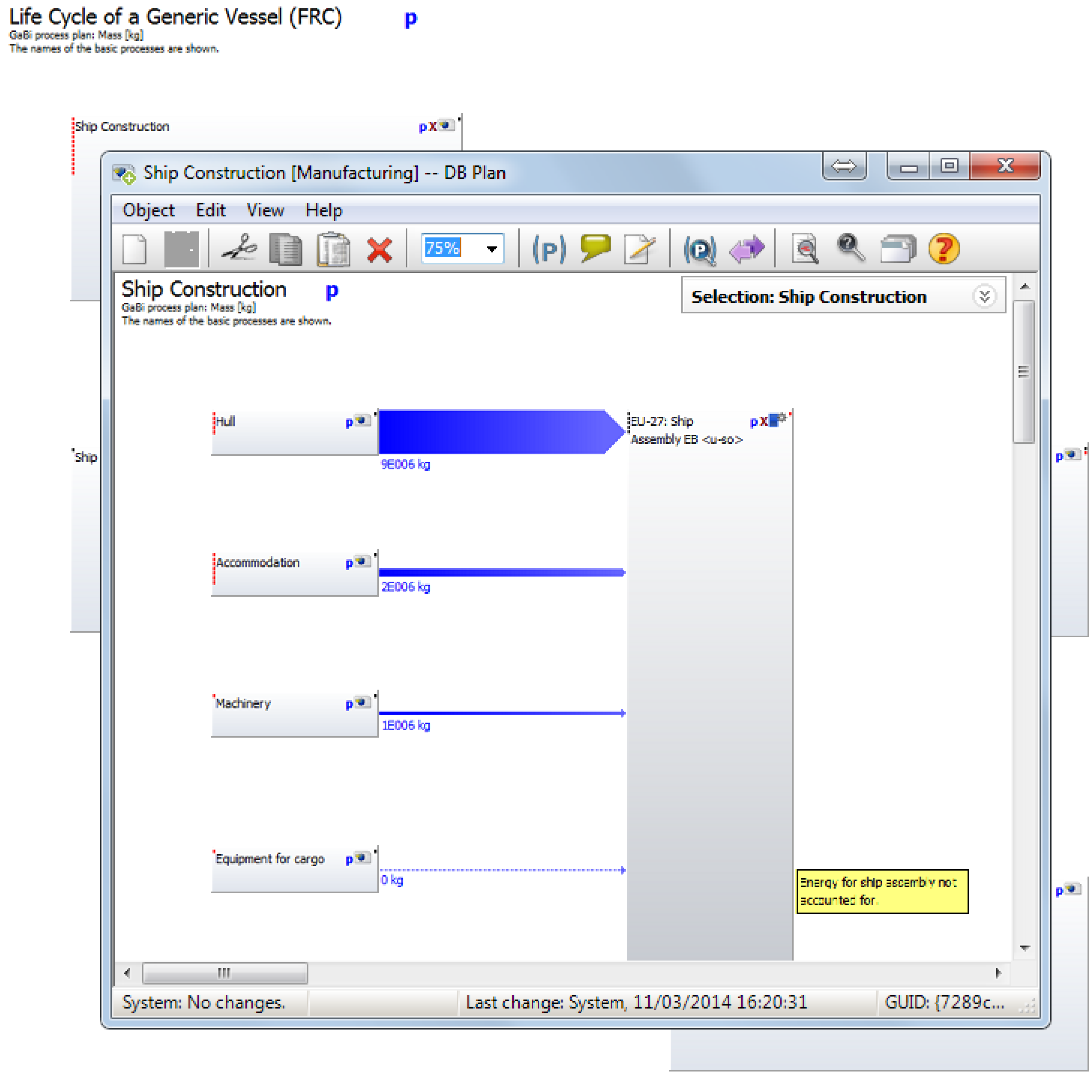


Figure 3.4: Modular structure of processes and plans (PE-International, 2007)

Ganzheitliche Bilanzierung (German for holistic balancing), in short GaBi, works in a modular framework, which consists of plans, processes and flows which function in an integrated unit(s) (see Figure 3.4). One of the main advantages of the tool is that it automatically tracks all material, energy, and emissions flows, with the aim to analyse, summarise, and account for in various environmental impact categories (PE-International, 2007). Ultimately the user is able to see the representation of a model in a flow-diagram style (see Figure 3.5), i.e. with plans and/or processes represented as boxes, which have flow inputs and outputs –additionally representing material and energy inputs and outputs–, coming in and out of these boxes. This is particularly helpful to keep track of resources and emissions resulting from a single process, or a combination of these.

Figure 3.5: Ship LCA model representation, with a reference flow of kilograms of steel

Take for instance the graphical architecture of the GaBi software in Figure 3.4, similarly represented in Figure 3.5, under the example of the life cycle of a ship. The last includes different phases, such as construction, operation, maintenance and end-of-life or scrapping. The modular architecture from the software permits to have plans inside of plans; this in turn assists in organising and accounting for the different life phases of the system, but it additionally isolates a phase in the required case of individual phase appraisal. If one were to open the ‘Ship Construction’ plan, for example, an additional module including other plans and/or processes comprising the construction phase would pop up as a graphical representation (see Figure 3.6).



Life Cycle of a Generic Vessel (FRC)

GaBi process plan: Mass [kg]

The names of the basic processes are shown.

Ship Construction [Manufacturing] -- DB Plan

Ship Construction

GaBi process plan: Mass [kg]

The names of the basic processes are shown.

Selection: Ship Construction

Energy for ship assembly not accounted for.

System: No changes.

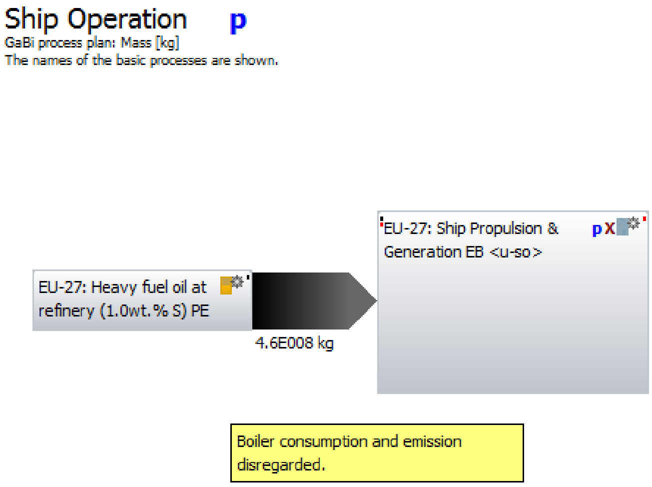
Last change: System, 11/03/2014 16:20:31

GUID: {7289c...

Figure 3.6: Ship construction plan inside the main Ship LCA model

A user could keep going further and open the ‘Hull’ or ‘Accommodation’ plans, which in turn would open other modules encompassing the different processes which form these plans. Again, this is rather helpful in order to track the balance of energy and material inputs and outputs throughout the entire system, but additionally offers the edge of pinpointing the potential for plan and/or process design improvement, once the overall environmental picture is appraised. The above also serves to evidence the magnitude of the assessment of a system as complex as that of a ship, which includes several unit processes within plans, and ultimately different major phases along its life cycle.

Figure 3.7 shows the operational phase of the Ship LCA model. While it may seem a simpler phase in comparison to others within the model, e.g. construction and maintenance –which comprise many unit processes–, the operational phase is one of the more significant throughout the entire life of a vessel, as mentioned previously, due to the relevant exchanges related to resources and emissions consumed and generated, respectively. The plan is comprised of two processes: one that is meant to resemble the consumption of Heavy Fuel Oil throughout the driven requirements of the remaining process, which is meant to resemble the electricity generation and propulsion requirements of the ship throughout the defined period of time.

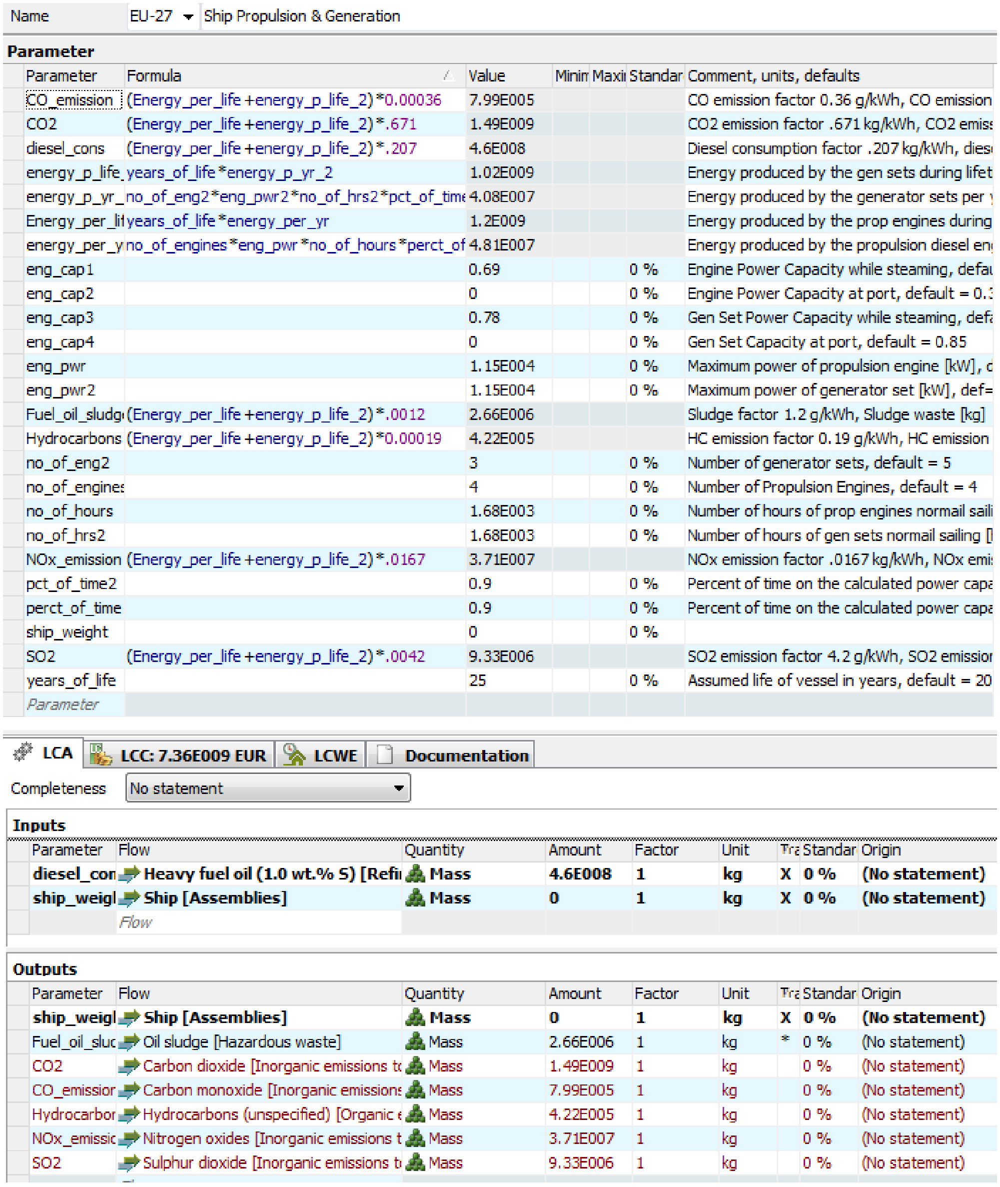


The names of the basic processes are shown.

Boiler consumption and emission disregarded.

Figure 3.7: Ship operation plan inside the main Ship LCA model

The ‘ship propulsion & generation’ process also serves as a good candidate to evidence the formulation of a process within the model. Figure 3.8 shows a partial screenshot of the ‘inside’ of the process, including the definition of the parameters that will tailor the behaviour of the process, as well as the inclusion of the inputs and outputs, which are additionally influenced by the already defined parameters. In summary, the screenshot in Figure 3.8 depicts the formulation of the consumption of HFO as an input, influenced by a defined parameter including a consumption factor (e.g. 0.207 kg/kWh for diesel consumption), and in turn a number of releases – considered as outputs–, similarly influenced by parameters underlining further emission factors (e.g. 0.671 kg/kWh for CO_2 emission, among others)[11].



Name EU-27 Ship Propulsion & Generation

Parameter

Parameter	Formula	Value	Minin	Maxi	Standar	Comment, units, defaults
CO_emission	(Energy_per_life +energy_p_life_2) *0.00036	7.99E005				CO emission factor 0.36 g/kWh, CO emission
CO2	(Energy_per_life +energy_p_life_2) *.671	1.49E009				CO2 emission factor .671 kg/kWh, CO2 emis
diesel_cons	(Energy_per_life +energy_p_life_2) *.207	4.6E008				Diesel consumption factor .207 kg/kWh, dies
energy_p_life_	years_of_life *energy_p_yr_2	1.02E009				Energy produced by the gen sets during lifet
energy_p_yr_	no_of_eng2*eng_pwr2*no_of_hrs2*pct_of_time	4.08E007				Energy produced by the generator sets per
Energy_per_li	years_of_life *energy_per_yr	1.2E009				Energy produced by the prop engines during
energy_per_y	no_of_engines*eng_pwr *no_of_hours *perct_of	4.81E007				Energy produced by the propulsion diesel en
eng_cap1		0.69			0 %	Engine Power Capacity while steaming, defa
eng_cap2		0			0 %	Engine Power Capacity at port, default = 0.
eng_cap3		0.78			0 %	Gen Set Power Capacity while steaming, def
eng_cap4		0			0 %	Gen Set Capacity at port, default = 0.85
eng_pwr		1.15E004			0 %	Maximum power of propulsion engine [kW],
eng_pwr2		1.15E004			0 %	Maximum power of generator set [kW], def=
Fuel_oil_sludg	(Energy_per_life +energy_p_life_2) *.0012	2.66E006				Sludge factor 1.2 g/kWh, Sludge waste [kg]
Hydrocarbons	(Energy_per_life +energy_p_life_2) *0.00019	4.22E005				HC emission factor 0.19 g/kWh, HC emission
no_of_eng2		3			0 %	Number of generator sets, default = 5
no_of_engines		4			0 %	Number of Propulsion Engines, default = 4
no_of_hours		1.68E003			0 %	Number of hours of prop engines normail sail
no_of_hrs2		1.68E003			0 %	Number of hours of gen sets normail sailing [
NOx_emission	(Energy_per_life +energy_p_life_2) *.0167	3.71E007				NOx emission factor .0167 kg/kWh, NOx emi
pct_of_time2		0.9			0 %	Percent of time on the calculated power capa
perct_of_time		0.9			0 %	Percent of time on the calculated power capa
ship_weight		0			0 %	
SO2	(Energy_per_life +energy_p_life_2) *.0042	9.33E006				SO2 emission factor 4.2 g/kWh, SO2 emissio
years_of_life		25			0 %	Assumed life of vessel in years, default = 20
Parameter						

Completeness No statement

Inputs

Parameter	Flow	Quantity	Amount	Factor	Unit	Tra	Standar	Origin
diesel_con	**Heavy fuel oil (1.0 wt.% S) [Refi**	**Mass**	**4.6E008**	**1**	**kg**	**X**	**0 %**	**(No statement)**
ship_weigl	**Ship [Assemblies]**	**Mass**	**0**	**1**	**kg**	**X**	**0 %**	**(No statement)**
	Flow							

Outputs

Parameter	Flow	Quantity	Amount	Factor	Unit	Tra	Standar	Origin
ship_weigl	**Ship [Assemblies]**	**Mass**	**0**	**1**	**kg**	**X**	**0 %**	**(No statement)**
Fuel_oil_sluc	Oil sludge [Hazardous waste]	Mass	2.66E006	1	kg	*	0 %	(No statement)
CO2	Carbon dioxide [Inorganic emissions t	Mass	1.49E009	1	kg		0 %	(No statement)
CO_emissior	Carbon monoxide [Inorganic emissions	Mass	7.99E005	1	kg		0 %	(No statement)
Hydrocarbor	Hydrocarbons (unspecified) [Organic e	Mass	4.22E005	1	kg		0 %	(No statement)
NOx_emissic	Nitrogen oxides [Inorganic emissions t	Mass	3.71E007	1	kg		0 %	(No statement)
SO2	Sulphur dioxide [Inorganic emissions t	Mass	9.33E006	1	kg		0 %	(No statement)

Figure 3.8: Partial screenshot of ship propulsion & generation process, including parameters' definition

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[11] Please refer to Appendix C.2 for more details on model definition and sample calculations.

Worthy of emphasis is that the model presented herein is based on an LCA predecessor model formulated by Johnsen and Fet (1998), as mentioned earlier. The predecessor model by Johnsen and Fet (1998) is highly significant, mostly due to the fact that it encompasses consumption and emissions data for phases such as construction and scrapping, which usually represent a challenge when it comes to a specific ship's data gathering.

The predecessor model has been utilised as a baseline template, in which the reported data has been initially used for the model herein. This model however, differs from its predecessor in that the model presented by Johnsen and Fet (1998) is based specifically for a Ro-Ro passenger vessel, and the current model can be adjusted to encompass different types of ships. The last is done by allowing the end-user the flexibility of editing consumption and emission ratios and factors accordingly, with regards to the specific vessel to be appraised. For example, the user can include within the assessment 'equipment for cargo' (see plan in Figure 3.6) and 'auxiliary machinery', in the case that the assessed ship is not a Ro-Ro passenger vessel but a tanker. Additionally, the maintenance phase herein is more refined in comparison to that of its predecessor model.

Moreover, some of the initial data from Johnsen and Fet (1998) has been replaced with updated data, data from the GaBi Professional Database, and/or data more related to the specific ship to be assessed; all of the above ultimately in relation to the case study at hand. More of the aspects of the present model will be described in the next chapter, *Case Studies*, with the use of a case vessel in order to underline some of the model's particulars. As a sample of the method of utilisation of the data from the predecessor model, Table 9.0.5 found in Appendix D.2, summarises some of the consumption and emission factors for medium speed diesel engines described by Johnsen and Fet (1998) (notice that an average SFC is used, as SFC curves for the engine listed herein are not publicly available); these factors are similarly found in the definition of the 'ship propulsion & generation' process shown in Figure 3.8.

In turn, Appendix D.6 comprises the specification of the MAN B&W diesel engine utilised on the second case study, including the SFC values at different loads (see Table 9.0.9), and the emission factors representative of slow speed diesel engines as reported by Moldanová et al. (2012) (see Table 9.0.10).

3.3.3 Notes on impact assessment and carbon accounting

There are various developed impact categories within the LCA methodology, and furthermore, different damage approaches, e.g. midpoint and endpoint (see Figure 3.9); thus, the selection of the specific impact category or categories must be comprehensive in a way that they cover the significant environmental issues pertaining to the system under appraisal (JRC, 2010c). In relation to the shipping industry, the focus gathers mainly on climate change –specifically highlighted under the Global Warming Potential impact category–, or additionally known or described as carbon footprint analysis. Other impact categories relative to shipping environmental assessments encompass the Ozone Layer Depletion Potential, the Acidification Potential and the Human Toxicity Potential, among others (see Table 3.1).

Impact categories are usually based on a reference substance (see Table 3.1). Global Warming Potential, for example, is based and calculated in kilograms of carbon dioxide equivalents (CO_2eq), meaning that for each emission with the radiative capability of a greenhouse gas, a characterisation takes place in order to define its potential under a common unit and substance, i.e. kg of CO_2-equivalents. Moreover, the residence time of these warming gases in the atmosphere is emphasised within the calculation, and therefore the inclusion of a time range within the assessment is also specified; this being customarily a period of 100 years for GWP (Blanco-Davis, 2013a).

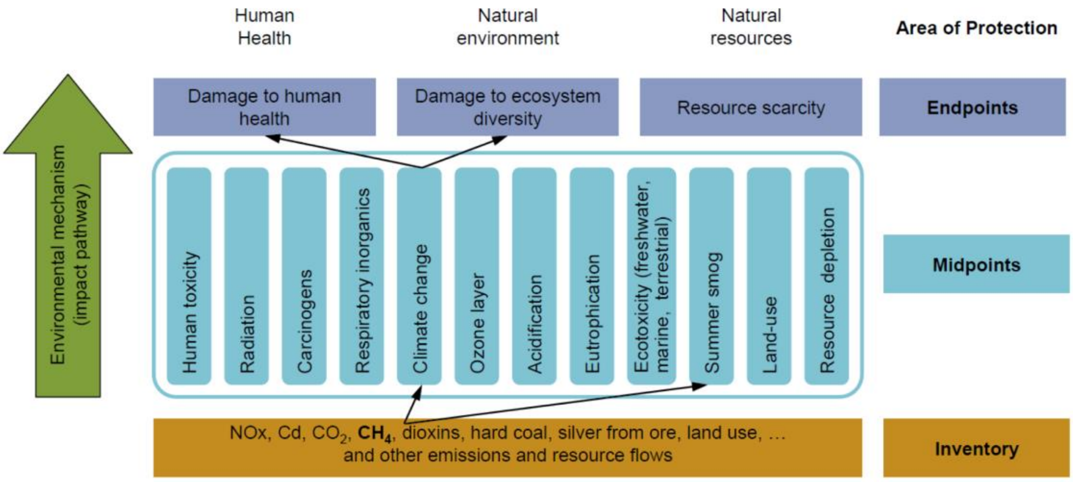

Figure 3.9: Schematic pathway from life cycle inventory to impact category endpoints (JRC, 2010c)

For example, carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH_4), among other emissions, are all gases with greenhouse warming capabilities; the first two are also fine examples of emissions produced through the operational life of a ship. The first mandatory element of impact assessment is classification, in which the inventory emission results are assigned to one or more impact categories; the above gases would then be classified into the GWP category (or any other additional category they would contribute to) (see Figure 3.10).

During the next element, characterisation, these results are quantified and aggregated; the above substances have specific –and scientifically assigned– characterisation factors, which in turn result in aggregated units of Global Warming Potential, or CO_2 equivalents. For example, Figure 3.10 shows –among various emissions–, a sample quantity of CO_2 being multiplied by a factor of 1, understanding that CO_2 is the reference substance. With the same logic, CO is multiplied by a factor of 3, underlining that CO has 3 times the warming potential that CO_2 has. These factors –namely global warming potentials–, have been developed by the IPCC using the Bern carbon cycle model (JRC, 2010b); additional global warming potentials are put forward by the IPCC (2007b).

In summary, when a process or a system is appraised under the Global Warming Potential impact category in a 100 years, for example, all emissions which contribute to this potential in the allotted period of time are collected, balanced, characterised – each using their own characterisation factor–, and ultimately presented under a unified carbon footprint or kg of CO_2eq score. For further information with regards to impact assessment methodologies, the reader should refer to JRC (2010a).

Table 3.1: Sample comparison between the CML and TRACI impact methods (PE-International, 2011)

CML	Reference Unit	TRACI	Reference Unit
Global Warning Potential (GWP 100 years)	[kg CO2-Equiv.]	Global Warming Air	[kg CO2-Equiv.]
Ozone Layer Depletion Potential (ODP, steady state)	[kg R11-Equiv.]	Ozone Depletion Air	[kg CFC 11-Equiv.]
Acidification Potential (AP)	[kg SO2-Equiv.]	Acidification Air	[mol H+ Equiv.]
Eutrophication Potential (EP)	[kg Phosphate-Equiv.]	Eutrophication Air Eutrophication Water	[kg N-Equiv.]
Photochem. Ozone Creation Potential (POCP)	[kg Ethene-Equiv.]	Smog Air	[kg NOx-Equiv.]
Human Toxicity Potential (HTP inf.) Terrestric Ecotoxicity Potential (TETP inf.)	[kg. DCB-Equiv.]	Human Health Cancer Air Human Health Cancer Water	[kg Benzene-Equiv.]
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	[kg. DCB-Equiv.]	Ecotoxicity Air Ecotoxicity Water	[kg 2,4-Dichlorophenoxyace]
Abiotic Depletion (ADP)	[kg Sb-Equiv.]	Human Health Criteria Air-Point Source	[kg PM2,5-Equiv.]
		Human Health Non Cancer Air Human Health Non Cancer Water	[kg Toluene-Equiv.]

Keeping in mind the above explanation with regards to LCA carbon accounting, it is of interest to reassess the way carbon accounting is done in turn for the EEDI and the EEOI. With the aforementioned difference that the former underscores design efficiency while the latter operational efficiency, both are meant to provide an estimate of CO_2 emissions per transport-work. The last is done by underlining the ship's fuel consumption and additionally using an emission factor relative to that specific fuel(s); therefore, CO_2 emission factors are utilised similarly as the characterisation factors above explained.

The first clear difference between the two methodologies, LCA and EEDI/EEOI, would be shown in the way of –not only the numerical distinction between factors–, but the fact that LCA encompasses additional substances in its carbon accounting through the GWP classification and characterisation, e.g. carbon monoxide, methane, and CFCs among others emissions; the EEDI/EEOI carbon accounting is solely referenced to the quantities of CO_2 released per tonne of fuel consumed (or to be consumed), and does not emphasise on additional substances emitted through the operational phase –or other phases, for that matter– of the life of a ship. The last would seem to qualify LCA's carbon accounting as more comprehensive, indicating –at first instance–, its capability for properly underlining shipping environmental performance.

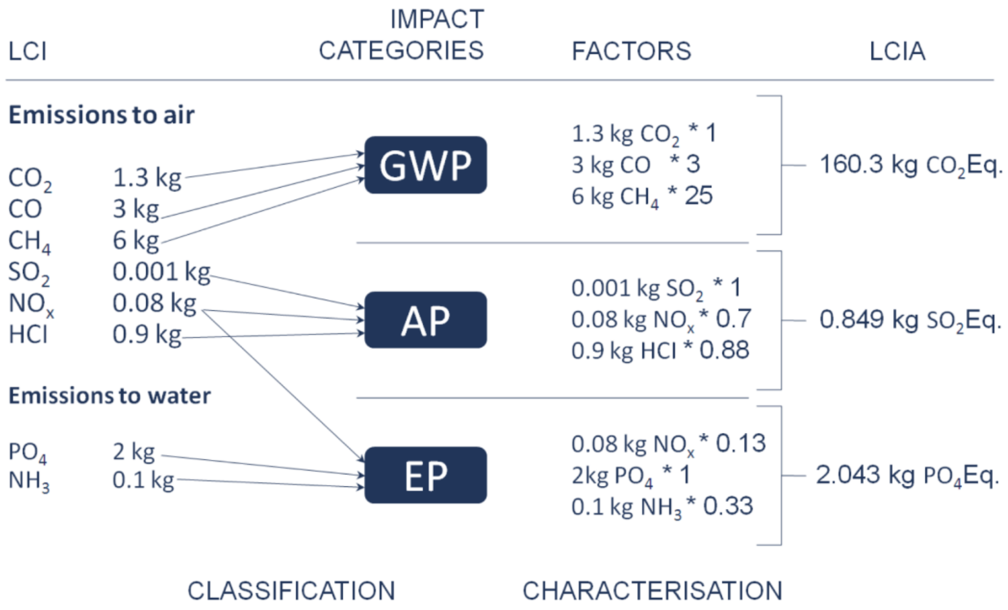

Figure 3.10: Sample of emission classification and characterisation under different impact categories (PE-International, 2011)

Another apparent difference between the two methodologies is what ultimately gives way to the measure of energy efficiency, i.e. the definition of transport-work. This is defined by the available capacity and the design speed in the case of the EEDI, and by the actual distance sailed and cargo transported in the case of the EEOI. As previously discussed, the two metrics are expressed in grams of CO_2 per tonnes per nautical mile (gCO_2/tonne-nm). Aside from being able to measure environmental performance, for the LCA to give proper indication that it could additionally be utilised to highlight energy efficiency, the methodology would have to encompass a suitable definition of transport-work, relative to a shipping context.

This is done in LCA by defining the *functional unit* of the system to be assessed. The functional unit is the quantified definition of the function of a product or system (PE-International, 2011), that additionally serves as the unit of comparison which assures that products being compared (e.g. ships) provide an equivalent level of function or service (SAIC and Curran, 2006). In the case of a ship, for example, the vessel’s trade would be taken into consideration, in order to define its main function. Similarly as stated above in the case of the EEOI, a ship’s quantified performance would usually be expressed in terms of cargo carried per distance sailed over a relevant period of time (e.g. a year); this description would serve to define the functional unit of a ship appraised under an LCA.

The relevance of the LCA’s functional unit is that ultimately all gathered results are linked to the chosen functional unit; e.g. a certain emissions estimate of kg of CO_2eq *per* tonne-mile per year. In this way, LCA results can be presented similarly as the EEDI/EEOI scores, i.e. an estimate of CO_2 emissions *per* transport-work. Although the above-discussed differences between the two methodologies are noteworthy, succeeding sections will demonstrate that the results between the two are not only able to be similar, but also equivalent. The case studies will be utilised to see how the metrics fare against each other, and to ultimately assess if LCA could prove itself as an efficient supplementary alternative to the current shipping energy metrics.

3.3.4 Adopted formulae

The following is the complete set of formulae utilised in the *Case Studies* chapter, in order to assess the different metrics against one another. Equations 1, 2 and 15 belong to the original EEDI and EEOI formulations, and have been described previously during the *Literature Review* chapter (see sections 2.4.1 and 2.4.2, respectively).

Equation 1: Required EEDI as defined by IMO (2013a) and IMO (2013b)

$$Required\ EEDI = a \times b^{-c}$$

Where:

- b is DWT or GT as per defined by IMO (2013a) and IMO (2013b), and underlined in Table 2.3.
- a and c are reference values as per defined by IMO (2013a) and IMO (2013b), and underlined in Table 2.3.

Equation 2: Average EEOI as per defined by IMO (2009d)

$$Average\ EEOI = \frac{\sum_i \sum_j (FC_{ij} \times C_{Fj})}{\sum_i (m_{cargo,i} \times D_i)}$$

Where:

- C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j
- D is the distance in nautical miles corresponding to the cargo carried or work done
- FC_{ij} is the mass (grams) of consumed fuel j at voyage i
- m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships
- i is the voyage number
- j is the fuel type.

Equations 3 to 7 are comprised within IMO (2014b)’s most current EEDI guidelines. Some of the equations are applicable specifically to one of the chosen case studies, due to the vessel’s designation type; this last will be further expanded during the *Case Studies* chapter.

Equation 3: EEDI equation, not including energy saving technologies applied to main engines and auxiliary power, as adapted from (IMO, 2014b)

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME_{(i)}} \cdot C_{FME_{(i)}} \cdot SFC_{ME_{(i)}}\right) + \left(P_{AE_{(i)}} \cdot C_{FAE_{(i)}} \cdot SFC_{AE_{(i)}}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

Where:

- *Capacity* as per defined by IMO (2014b) in tonnes
- C_F is the conversion factor between fuel consumption and CO_2 emission
- *P* refers to power in kW
- *SFC* is the specific fuel consumption in g/kWh
- V_{ref} is the ship speed in knots
- $_{AE}$ refers to the auxiliary engines
- f_c is the cubic capacity correction factor
- f_i is the capacity correction factor
- f_j is correction factor for ship specific design elements
- f_l is the correction factor for general cargo ships equipped with cranes and other cargo-related gear
- f_w is the weather factor
- $_i$ is the index of summation
- $_j$ is the index of multiplication
- $_{ME}$ refers to the main engines.

Equation 4: Required auxiliary engine power supply in normal maximum sea load, applicable to ships with a total propulsion power of 10,000 kW or above, and not including shaft motors, as adapted from IMO (2014b)

$$P_{AE} = \left[0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME_{(i)}}\right)\right] + 250$$

Where:

- *MCR* is the maximum continuous rating of the engine(s) in kW

- P_{AE} is the power of auxiliary engines in kW
- $_i$ is the index of summation.

Equation 5: Correction factor to account for specific design elements relative to Ro-Ro cargo and Ro-Ro passenger ships, as per defined by IMO (2014b)

$$f_{jRoRo} = \frac{1}{F_{n_L}^{\alpha} \cdot \left(\frac{L_{BP}}{B_s}\right)^{\beta} \cdot \left(\frac{B_s}{d_s}\right)^{\gamma} \cdot \left(\frac{L_{BP}}{\nabla^{\frac{1}{3}}}\right)^{\delta}}$$

Where:

- ∇ is the volumetric displacement in cubic metres
- B_s is the breadth in metres
- d_s is the summer load line draught in metres
- F_{jRoRo} is the correction factor for ship specific design elements relative to Ro-Ro cargo and Ro-Ro passenger ships
- F_{nL} is the Froude number
- L_{BP} is the length between perpendiculars in metres
- Ro-Ro passenger ship exponents: $\alpha = 2.50$, $\beta = 0.75$, $\gamma = 0.75$, $\delta = 1.00$ as per defined by IMO (2014b).

Equation 6: Froude number as per comprised in IMO (2014b)

$$F_{n_L} = \frac{0.5144 \cdot V_{ref}}{\sqrt{(L_{BP} \cdot g)}}$$

Where:

- F_{nL} is the Froude number
- g is the gravitational acceleration in m/s^2
- L_{BP} is the length between perpendiculars in metres
- V_{ref} is the ship speed in knots.

Equation 7: Cubic capacity correction factor relative to Ro-Ro passenger ships having a DWT/GT ratio of less than 0.25, as per defined by IMO (2014b)

$$f_{cRoPax} = \left[\frac{\left({}^{DWT}/_{GT}\right)}{0.25}\right]^{-0.8}$$

Where:

- DWT is the capacity as per defined by IMO (2014b) in tonnes
- f_{cRoPax} is the cubic capacity correction factor for Ro-Ro passenger ships
- GT is the gross tonnage in accordance with the International Convention of Tonnage Measurement of Ships 1969, as referenced by IMO (2014b).

Equations 8 to 14 have been constructed in order to demonstrate the potential equivalency between the LCA formulation and the regulatory metrics; therefore, many of the equations' factors hold similarity to that of the factors of the previously documented EEDI and EEOI equations.

Equation 8: LCA energy efficiency CO_2 score

$$LCA_{eff_{CO_2}} = \frac{\sum_i gCO_{2_i}}{\sum_i \left(m_{cargo,i} \times D_i\right)}$$

Where:

- D is the distance in nautical miles corresponding to the cargo carried or work done
- gCO_2 is the LCA CO_2 inventory aggregate in grams
- LCA_{effCO2} is the LCA energy efficiency CO_2 score in gCO_2/tonne-nm
- m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships
- $_i$ is the index of summation.

Equation 9: LCA energy efficiency GWP score

$$LCA_{eff_{GWP}} = \frac{\sum_i gGWP_i}{\sum_i \left(m_{cargo,i} \times D_i\right)}$$

Where:

- D is the distance in nautical miles corresponding to the cargo carried or work done
- $gGWP$ is the LCA CO_2 inventory aggregate in grams comprising classification and characterisation of releases analogous to CO_2
- LCA_{effGWP} is the LCA energy efficiency GWP score in gCO_2/tonne-nm
- m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships
- $_i$ is the index of summation.

Equation 10: CO_2 emissions based on the direct relation of quantity of emissions released per consumed fuel

$$Quantity\ of\ released\ gCO_{2_{Ship\ propulsion}} = FC_{ME} \cdot C_{FME}$$

Where:

- C_{FME} is the conversion factor between fuel consumption and CO_2 emission
- FC_{ME} is the mass (grams) of consumed fuel by the main engine(s).

Equation 11: Carbon conversion factor based on the relation of CO_2 emissions factor per specific fuel consumption

$$C_{FME} = \frac{CO_{2_{emission\ factor}}}{SFC_{ME}}$$

Where:

- C_F is the conversion factor between fuel consumption and CO_2 emission

- SFC is the specific fuel consumption in g/kWh
- $_{ME}$ refers to the main engines.

Equation 12: Fuel consumption relative to the main engine(s) output power and designated specific fuel consumption

$$FC_{ME} = \left(\sum_{i=1}^{nME} MCR_{ME_{(i)}} \cdot \%Load_{ME_{(i)}} \cdot SFC_{ME_{(i)}} \right) \cdot T$$

Where:

- $\%Load_{ME}$ is the main engine(s) output power
- FC_{ME} is the mass (grams) of consumed fuel by the main engine(s)
- MCR_{ME} is the maximum continuous rating of the engine(s) in kW
- T is the duration in *hours* corresponding to period underlining the fuel consumption calculation, e.g. duration of the trip
- $_i$ is the index of summation.

Equation 13: Summarised EEDI equation not including auxiliary power and energy saving technologies applied to the main engines, as adapted from IMO (2014b)

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_j \right) \left(\sum_{i=1}^{nME} P_{ME_{(i)}} \cdot C_{FME_{(i)}} \cdot SFC_{ME_{(i)}} \right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

Where:

- *Capacity* as per defined by IMO (2014b) in tonnes
- C_F is the conversion factor between fuel consumption and CO_2 emission
- P refers to power in kW
- SFC is the specific fuel consumption in g/kWh
- V_{ref} is the ship speed in knots
- f_c is the cubic capacity correction factor
- f_i is the capacity correction factor

- f_j is correction factor for ship specific design elements
- f_l is the correction factor for general cargo ships equipped with cranes and other cargo-related gear
- f_w is the weather factor
- $_i$ is the index of summation
- $_j$ is the index of multiplication
- $_{ME}$ refers to the main engines.

Equation 14: LCA energy efficiency CO₂ score for ship propulsion processes, including equivalent EEDI correction factors

$$LCA_{eff_{CO2\,(s.p.)}} = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} MCR_{ME_{(i)}} \cdot \%Load_{ME_{(i)}} \cdot C_{FME_{(i)}} \cdot SFC_{ME_{(i)}}\right)}{f_i \cdot f_c \cdot f_l \cdot m_{cargo} \cdot f_w \cdot V_{ref}}$$

Where:

- $\%Load_{ME}$ is the main engine(s) output power
- C_F is the conversion factor between fuel consumption and CO_2 emission
- m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships
- MCR_{ME} is the maximum continuous rating of the engine(s) in kW
- SFC_{ME} is the specific fuel consumption of the main engine(s) in g/kWh
- V_{ref} is the ship speed in knots
- f_c is the cubic capacity correction factor
- f_i is the capacity correction factor
- f_j is correction factor for ship specific design elements
- f_l is the correction factor for general cargo ships equipped with cranes and other cargo-related gear
- f_w is the weather factor
- $_i$ is the index of summation
- $_j$ is the index of multiplication
- $_{ME}$ refers to the main engines.

Equation 15: Single trip EEOI as per defined by IMO (2009d)

$$EEOI_{single\ trip} = \frac{\sum_j \left(FC_j \times C_{Fj}\right)}{m_{cargo} \times D}$$

Where:

- C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j
- D is the distance in nautical miles corresponding to the cargo carried or work done
- FC_j is the mass (grams) of consumed fuel j
- m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships
- j is the fuel type.

The above equations will be more thoroughly described and further elucidated, with dedicated case vessels in the succeeding *Case Studies* chapter.

3.4 LCA's advantages/disadvantages relative to the regulatory metrics

The previous sections have aimed at theoretically placing LCA as a valid aid to the current regulatory measures, by way of singling out relevant characteristics relative to the methodology, which seemingly underscore LCA as an advantageous tool applicable to shipping and shipbuilding and repair. Some of the advantages from the methodology have been emphasised, especially those that may be of direct service to the shipping industry. Nevertheless, the methodology is also inherent to significant disadvantages that must be mentioned. The following is a brief discussion of the benefits of the methodology relative to the current regulatory metrics, including as well some of its shortcomings.

LCA, which has been comprehensively described in the previous sections, offers a general approach which enjoys widespread acceptance. It also has the backing of extensive literature and case application samples –a great part of it being information openly accessible–, while additionally being supported by a standardised methodology proposed by the ISO. The last catalogues LCA as a generally accepted methodology for properly assessing environmental performance. Furthermore, a case has been made to present the methodology as a tool valuable to additionally highlight energy efficiency with regards to environmental scores.

As the following chapter will show, the LCA methodology can be applied to any ship (while slightly outside the scope of this document, Blanco-Davis et al. (2014a) show indication of LCA being applicable to even appraise a section of the fleet); it can be utilised to assess the environmental impact of a single voyage, a yearly average of them, or even go as far as extrapolating potential environmental impact results to underscore the entire life of the ship. Moreover, and of relevance, the methodology can also include retrofits undertaken during the lifespan of the vessel, and accurately appraise the difference in operational performance and environmental efficiency (Blanco-Davis et al., 2014a; Blanco-Davis and Zhou, 2014). These last papers also document LCA's potential to link environmental scores to technical and economic aspects, relative to a shipping context; for example, performing a cost-benefit analysis with regards to different retrofit alternatives, ultimately appraising which is the least environmentally burdensome option, while also highlighting which option is most financially favourable.

Worthy of mention as well, is the capability of an LCA to be managed in such a way that a company undertaking the appraisal can protect sensitive data, and therefore its practice can positively emphasise on confidentiality issues. Reviews and audits are specifically underscored within the ISO standards, but are highly dependent of the practitioner's own requirements and preferences; e.g. an internal review or audit can be performed by in-house company personnel or external consultants, reliant on the practitioner's choice and goal and scope of the assessment.

As LCA is widely accepted as a method to assign environmental scores to product and services, e.g. EPDs, and recognised by governmental organisations and private enterprises as well, it could be a useful tool to assist in the implementation of MBMs and incentives within the shipping industry. Several already existing models and policies pertaining to other industries use LCA to encourage these types of incentives. For example, the application of a system similar to the EU emissions trading system (EU ETS) (EC, 2013a) within the shipping industry, could be facilitated with the use of broadly recognised LCA appraisals among the different involved stakeholders.

Of interest is the EU's MRV proposal objective to extend past the shipping CO_2 emissions into the accounting of SO_x, NO_x and PM in longer term (EC, 2013e), emphasising the necessity of monitoring and reporting of other significant shipping contaminants. LCA can encompass the assessment of these and other contaminants, whether in individual form –i.e. during the life cycle inventory aggregation–, or by ways of impact assessment, and consequently the substance classification and characterisation within a specific impact category (e.g. SO_x within the Acidification Potential impact category). Furthermore, LCA aside form accounting CO_2 emissions, can encompass any other substance or emission produced during the life of a ship that has a warming potential analogous to CO_2, comprehensively covering all releases under this category.

It is recognised, nevertheless, that LCA has its own intrinsic limitations. Guinée et al. (2002) summarise some of the most relevant as follows:

1. One of LCA's major strengths is also a significant limitation, being its 'holistic' nature. The broad scope of analysing a product's complete life cycle can only be achieved at the expense of simplifying other aspects, i.e. compiling *all* material and energy balances for each relevant process is impractical, as mentioned previously. Thus, the methodology calls for well-defined boundary setting, and in some cases process simplification; both can result in being subjective.
2. While there is some recent advancement with regards to the time appraisal aspect, LCA is generally a steady-state methodology, rather than a dynamic approach.
3. Similarly, some progress has been made with regards to reducing LCA as a tool based on linear modelling, i.e. LCA generally regards all processes as linearly scaled, both in the environment and the economy.
4. Environmental impacts are treated as 'potential impacts', due to the fact that they are not specified in time and space, and are related to what could be understood by some as an arbitrarily defined functional unit.
5. Another limitation befalls on the current availability of data. While it is true that LCA-related public information and commercial databases are growing in numbers, there is still a relevant unavailability relative to specific systems, e.g. ships. Additionally, some of the data available is often obsolete, incomparable or of unknown quality.
6. Lastly, while LCA's nature is underlined as an analytical tool –which is able to provide information for decision support–, it cannot replace the decision making process itself; i.e. LCA should be regarded as a tool among other aids or evidence in order to ultimately underscore a decision.

Aside from the above, it should be recalled that LCA data gathering could be potentially expensive and time-consuming, while also data quality can influence results certainty significantly. Moreover, however, the implementation of the methodology requires knowledgeable staff; perhaps not to the extent of dedicated personnel, but staff familiar with the guidelines of the approach.

Lastly, and worthy of note as well, is that the incomparability issues mentioned previously with regards to different types of ships may still hold true for LCA; meaning, for example, that it is not practical to compare a container ship to a Ro-Ro, under the context of different transport-work, and consequently different environmental efficiency (Blanco-Davis, 2014). The same is applicable to the current regulatory measures, however, as Faber et al. (2009) explain: "it is hard if not impossible to compare the EEOI across ship types, even the most important ship types, in terms of CO_2 emissions: bulkers, tankers, container ships and Ro-Ro ships."

In summary, the application of LCA comprises as many benefits and limitations as the implementation of the EEDI and the EEOI. Nevertheless, its potential should not be neglected as a complementary tool which in parallel to the application of the regulatory measures, can not only support their widespread practice, but additionally offer much needed reliability and accessibility of information, aside from a standardised framework providing efficient reporting and verification of environmental scores and energy efficiency.

3.5 Concluding remarks

The following are the most significant remarks comprised in the chapter, and underscored in the form of bullet points for the reader's ease:

- The above chapter includes a discussion of the basics of the LCA methodology, as well as an explanation of how the methodology is to be utilised herein. Additionally, some elements of the development of the ships' LCA model have been addressed.

- The LCA methodology is commonly employed for two main purposes: to assess the potential environmental impacts of a certain product including the product's past history and forecast, while the other purpose is to assess the product versus an alternative.

- In order to have a full cradle-to-grave environmental assessment of a specific ship, the most relevant phases of its life cycle need to be included and calculated, e.g. ship construction, ship operation and maintenance, and ultimately ship scrapping.

- A baseline LCA model is required, in order to assess the potential resources consumed and the emissions emitted by a specific ship. This model needs to feature the type and trade of the ship, and emphasise on the ship's most typical operations over a significant period of time. This grants the possibility to extrapolate results to an assumed lifetime of e.g. 25 or 30 years, in order to assess the ship's whole life cycle.

- Any difference with regards to the most habitual behaviour within the operational profile of the ship can be assessed against the previously calculated baseline model. The above comparison also offers the possibility of adjusting relevant operational inputs related to the original systems –or even applied retrofits–, in order to improve the calculated future environmental scores of the assessed system(s). The above is also applicable to the building phase of a ship, in the case of ship re-design and system enhancement.

- The model presented herein is based on an LCA predecessor model formulated by Johnsen and Fet (1998). The predecessor model is significant due to the fact that it encompasses consumption and emissions data for phases such as construction and scrapping, which represent a challenge when it comes to a specific ship's data gathering.

- The predecessor model has been utilised as a baseline template, in which the reported data has been initially used for the model herein. The model herein however, differs from its predecessor in that the current model can be adjusted to encompass different types of ships, and has a more refined maintenance phase.

- The relevance of the LCA's functional unit is that all gathered results are linked to the chosen functional unit. In this way, LCA results can be presented similarly as the EEDI/EEOI scores, i.e. an estimate of CO_2 emissions per transport-work. Although the discussed differences between the two methodologies are noteworthy, succeeding sections will demonstrate that the results between the two are not only able to be similar, but also equivalent.

- As the following chapter will show, the LCA methodology can be applied to any ship (or even a section of the fleet, as suggested by Blanco-Davis et al. (2014a)); it can be utilised to assess the environmental impact of a single voyage, a yearly average of them, or even go as far as extrapolating potential environmental impact results to underscore the entire life of the ship.

- The EU's MRV proposal objective to extend past the CO_2 emissions into the accounting of SO_x, NO_x and PM in longer term, emphasises the necessity of monitoring and reporting of other significant shipping contaminants. LCA can encompass the assessment of these and other contaminants, whether in individual form or by ways of category impact assessment. Furthermore, LCA aside from accounting CO_2 emissions can encompass any other produced emission that has a warming potential analogous to CO_2.

- LCA's potential should not be neglected as a complementary tool, which in parallel to the application of the regulatory measures, can offer reliability and accessibility of information, aside from providing efficient reporting and verification of environmental scores and energy efficiency.

4 Case Studies

4.1 Introductory remarks

The following chapter comprises two case vessels which will be utilised to validate the LCA methodology and model presented previously; both case vessels will serve to assess LCA in comparison to the EEDI and EEOI, respectively. The first case vessel will also be utilised to expand on some of the details regarding the formulation of the ships' LCA model, while making direct relations to the case vessel particulars.

Because of time and space constraints –and in order to strive for a reasonable comparison–, the reader should know that the formulation and explanation of the ships' LCA model included herein is summarised; this is done in relation to the characteristics and factors holding similitude to the factors found in the formulation of the EEDI and EEOI. For example, although it has been previously explained that a full cradle-to-grave LCA assessment would encompass various life phases such as construction, operation, maintenance and scrapping, the following LCA studies will only comprise the appraisal of the operational phase of the vessels; this is due to the fact that the EEDI as well as the EEOI are designed to use data from the operational stage of the ship, and do not directly involve factors from other stages such as construction, scrapping, and etcetera.

Similarly, although some specific contaminants will be presented in the life cycle inventory –such as NO_x and SO_x–, the only impact category underlined within the following LCA studies will be GWP, due to the fact that the EEDI and EEOI ultimately highlight resulting CO_2 emissions. The above serves to emphasise the possibility of including additional life phases, contaminants, and impact categories, underscoring the comprehensively nature of LCA; nevertheless, this also testifies to the ability of tailoring the study to achieve the end-user's needs. Appendix C.2

provides more information with regards to the model definition and sample calculations. Although not directly applied herein, the reader should refer to Blanco-Davis (2013b) and Blanco-Davis et al. (2014a) for more information on the ships' LCA model.

Worthy of mention is that the case vessels are presented in the form of an LCA report, following the requirements, guidelines and suggestions of the ISO 14040 and 14044 international standards for the implementation of LCA. The last stage of the LCA appraisal –Life Cycle Interpretation– will be included at the end of both case reports, comprising results and accounts from both vessels. Lastly, one of the case vessels encompasses a relevant retrofit application, in order to enrich the comparison between LCA and EEDI/EEOI, and allowing for the appraisal of the before and after phase of a retrofit among the different metrics.

4.2 ASTANDER case study

4.2.1 Case study introduction

Figure 4.1: Ro-Ro passenger vessel while at dry-dock in ASTANDER shipyard

The case ship facilitated by ASTANDER shipyard is a Ro-Ro passenger ship, designed to carry wheeled cargo such as automobiles, trucks, trailers, and etcetera. The ship also serves as a cruise ferry, meaning that it transports passengers as well (see Figure 4.1); some passengers travel with the ship to enjoy the cruise experience, staying a few hours at the destination port –or not leaving the ship at all–, while others only utilise the ship as a transportation means. Often these types of ships offer luxury areas, shops, restaurants and casinos.

Table 4.1 lists the vessel's main characteristics. Additionally, for the reader's context, Appendix D.1 comprises more information with regards to the main engines, accommodation facilities, and vessel speed and voyage profile. Some of this information will be referred to during the next few sections.

Table 4.1: ASTANDER vessel particulars

Type of vessel:	Ro-Ro passenger ship	**Deadweight (DWT):**	6,515 tonnes
Year of built:	2001	**Gross tonnage (GT):**	32,728 tonnes
Length overall (LOA):	203.9 metres	**Net tonnage (NT):**	13,081 tonnes
Length between perpendiculars (LBP):	185.6 metres	**Decks:**	9, including one hoistable deck
Breadth:	25.0 metres	**Hull materials:**	Naval A grade steel
Draft:	6.4 metres	**Hull connections:**	Welded
Displacement:	20,150 tonnes	**Power (main engines):**	48,000 kW at 510 rpm (4 diesel engines).

The chosen retrofit application for this vessel is the switch from conventional antifouling coating, to a novel silicone paint system termed Fouling Release Coating (FRC). The FRC scheme prevents bio-fouling (i.e. barnacles, algae, and etcetera) from attaching to the underwater hull of a ship, by creating a smooth surface; fouling is therefore prevented or removed by the hydrodynamic forces developed while the ship is in motion. The importance of an efficient antifouling coating is underscored by the currently high prices of fuel; i.e. the hull fouling increases drag on the vessel's motion, which has a direct negative effect on fuel consumption.

Aside from the above implied benefits of the improvement of hull resistance, and the reduction of the fuel and lube oil consumption, there are also the environmental benefits which may be procured by the application of this type of paint system; i.e. the reduction in the resource consumption of hydrocarbons, and consequently the reduction in burdensome emissions. Blanco-Davis (2013b) and Blanco-Davis et al. (2014a) offer more information on the FRC system and its implementation.

4.2.2 Goal and scope of the study

The goal of the study is to validate the LCA methodology as a suitable environmental indicator supplement to the EEDI and EEOI metrics, while additionally offering evidence of its ability to highlight energy efficiency. Furthermore, the assessment of the retrofit proposed will emphasise the metrics ability to highlight any differences in the results, with regards to the before and after stages of the retrofit.

Although the ships' LCA model encompasses all the vessel's life stages, the scope of the study herein only comprises the operational phase of the ASTANDER Ro-Ro passenger ship. The vessel is broken down into system, sub-systems, system elements and ultimately processes, following Johnsen and Fet (1998)'s predecessor model formulation (see Figure 4.2). The operational phase, however, will only account for elements and/or processes which engage on environmental exchanges during this phase, i.e. processes related to resources consumption and/or emissions release (e.g. diesel engines, and etcetera).

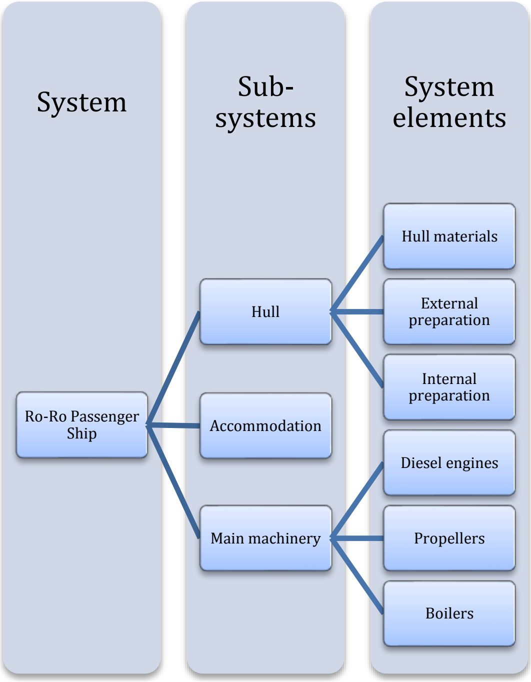

Figure 4.2: Graphical representation of the system under assessment, as adapted from Johnsen and Fet (1998)

Worthy of mention –and underscored previously–, is that due to close similarities with the ASTANDER vessel, some of the predecessor model and ship's data from Johnsen and Fet (1998) has been utilised herein (e.g. consumption and emission factors found in Table 9.0.5). When used and of significance, an explanation and reference will follow; otherwise, data provided by ASTANDER is utilised.

4.2.2.1 Operational profile

The ASTANDER Ro-Ro passenger vessel was built in 2001, and currently operates from the North of Spain to the South of England and back, with a frequency of 3 trips per week. Considering the two different locations in Spain and England, the average distance per trip is 560 nautical miles. The original vessel service speed was 28 knots (see Appendix D.1); however, its current ‘economic’ speed averages 25 knots per trip. The above would mean that the average sailing time for each trip is 22.4 hours[12].

The vessel has a fairly regular yearly schedule, which additionally comprises 2 weeks of downtime for maintenance not involving dry-docking. It can therefore be assumed that the ship is in operation 50 weeks per year, except every 2.5 years when the ship is scheduled to undergo heavy maintenance at a yard. Disregarding major maintenance, it could be assumed that the ship completes 150 trips each year (3 trips/week × 50 weeks/year); this would account for 3360 hours of sailing per year (150 trips/year × 22.4 hours/trip). Consequently, a resulting 5400 hours per year the ship is considered at port, while using shore power and having their main engines offline.

An additional relevant assumption for the original ships’ LCA model is that whilst every 2.5 years the vessel undergoes major maintenance at a yard, and assuming the ship having a total lifetime of 25 years, then subsequently the ship would undergo dry-docking 10 times during its lifetime, including initial construction. Lastly, the ship is assumed to sail for Asia for scrapping after 25 years of operation. While the above is worthy of mention, the construction, maintenance and scrapping assumptions do not hold relevance during the operational phase under assessment

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[12] The mentioned case study disregards the transit through ECAs, assuming no changeover between lower sulphur content fuels.

(this particular LCA model considers maintenance to be separated from the operational phase, for practical modelling formulation).

4.2.2.2 Function of the system

Given the multi-functional characteristics of a ship such as the Ro-Ro passenger vessel, the main function of this ship is not easily underlined. It should be taken into consideration that the vessel aside from providing transportation of passengers and cargo, additionally offers accommodation facilities and entertainment, similar to a pleasure/hotel vessel (i.e. the main function of the ship is not transportation of maximum mass).

The last emphasises the previously mentioned incomparability issue with regards to different types of ships. It is therefore relevant to recognise that the environmental scores procured from this assessment, are only comparable to scores to that of a similar type of ship, with the same functional performance. With regards to this vessel and study, the function of the system is understood to be the transportation of passengers, cars and trailers.

4.2.2.3 Functional unit

Based on the consideration that the system’s function is the transportation of passengers, trailers and cars, then the functional unit should be defined as:

- (Passengers × nm) + (cars × nm) + (trailers × nm) per year between the two port destinations.

Furthermore, the average weight for passengers, cars and trailers should be considered, using the accommodation data found in Appendix D.1. If the ship has a total capacity of 850 passengers and 500 cars, and assuming that in average 85% of this capacity is reached, then roughly 725 persons and 425 cars would be onboard per trip. Moreover, assuming that 70% of the cars are actual automobiles and the rest are trailers, a total of 300 cars and 125 trailers are being transported onboard.

Given that the vessel carries out 150 trips per year, and assuming the included weights for each, the total transported cargo per year would amount to:

- 108,750 passengers/year × 0.075 tonnes = 8156.25 tonnes/year
- 45,000 cars/year × 1 tonne = 45,000 tonnes/year
- 18,750 trailers/year × 20 tonnes = 375,000 tonnes/year
- TOTAL: 428,156.25 tonnes/year.

Thus, the functional unit of the system is **tonne × nm transported per year** between the two port destinations, with a functional performance of 428,156.25 tonnes/year × 560 nautical miles = 2.40×10^8 tonne-nm per year. While not necessarily required for the assessment herein, the lifetime functional performance could be extrapolated by using the assumed 25 years of operation totalling 5.99×10^9 tonne-nm per 25 years.

4.2.2.4 Explanation of the system boundary

With regards to the boundary setting, the original ships' LCA model comprised the representation of a cradle-to-grave system, meaning that the appraisal would account for significant material and energy inputs and outputs from the raw material extraction phase, through manufacturing and operation, and ultimately to the end-of-life stage. Nevertheless, the boundary setting for the study herein is adjusted to assess solely the operational phase of the ship.

Worthy of note as well is that no allocation procedures are undertaken during the operational phase, ultimately because the material and energy exchanges between processes are assumed to only take place throughout this phase and not involve others; i.e. the exchanges are assumed balanced within the operational stage.

Lastly, the original ships' LCA model utilises data mostly from Europe (EU-27), as far as geographical boundaries go, specifically cradle-to-gate analyses for some of the processes found within the construction, operation and maintenance phases. Aside from ASTANDER and Johnsen and Fet (1998), data from the GaBi

Professional Database has been used (PE-International, 2013). More information with regards to specific processes and the origin of the data is emphasised by Blanco-Davis (2013b).

4.2.2.5 Assumptions and limitations

The following list of assumptions is associated mostly to the operational phase:

1. Consumption and emission factors are taken from Johnsen and Fet (1998). These factors are used to define the 'ship propulsion & generation' process, which has been simplified to only include factors found in Table 9.0.5. Other diesel engine contaminant emission factors such as soot, Arsenic, Cobalt, Vanadium, and etcetera, have been disregarded for the purpose of providing a more straightforward comparison to the EEDI and EEOI metrics, given that these last are designed to underscore CO_2 emissions only.
2. As previously mentioned, in order to account for the complete life cycle of the vessel, the lifetime of the ship has been assumed to be that of 25 years for the original model. Nevertheless, to assist the comparison between LCA scores and the EEDI/EEOI –instead of using results extrapolated to 25 years–, results for one trip of operation will be utilised against the EEDI, while results mostly for one year of operation (150 trips) will be used versus the EEOI. This is done because neither of the regulatory metrics is designed to carry out lifetime appraisals.
3. Aside from the abovementioned consumption and emission factors, fuel consumption onboard is also based on data from the cradle-to-gate process 'heavy fuel oil at refinery (1.0wt. % S) (EU-27)' (PE-International, 2013), which includes 1% Sulphur HFO production and supply data relative to European countries.
4. Engine performance is assumed constant, disregarding operation of the engines at port, if any.
5. Boiler(s) consumption and emissions have been disregarded, understanding also that specific boiler consumption and emissions are not emphasised in the

formulation of the EEDI and EEOI (the EEOI however, underlines total fuel consumption per trip, which would account for any additional consumption and emissions procured by operational boilers. In this case, however, fuel consumption in its majority is a result of the main engines).

6. As mentioned previously, maintenance is regarded as a separate phase from the operational stage. Aside from practical issues, it also serves to provide a more rational comparison to the EEDI and EEOI metrics, given that –aside from the fact that the EEDI may require reassessment under major conversions–, the metrics disregard maintenance/repair emissions (even if the EEDI required reassessment, it would not account for the emissions released during maintenance, but the inclusion of an energy saving technology, if applied). The last is also applicable to resource consumption or emissions generated during the construction or scrapping phases.

4.2.2.6 Impact categories selected and methodology of impact assessment

The impact category to be used is the Global Warming Potential by CML[13], in a hundred years' time frame. The classification and characterisation of emissions will be according to CML 2001, with a characterisation factor form November 2010 (CML, 2010).

4.2.2.7 Initial data quality requirements

A medium emphasis has been put on data quality. The currently gathered data allows for the model to be validated, and it is thought that subsequent use –understanding that more refined data is needed for further assessment of other specific ships–, will improve the model and the accuracy of its results.

As underscored earlier, the majority of the data comes from ASTANDER and Johnsen and Fet (1998); a smaller fraction comes from PE-International (2013) in the

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[13] The CML (Centre for Environmental Studies, University of Leiden) impact assessment method focuses on environmental impact categories expressed in terms of emissions to the environment. It includes classification, characterisation, and normalisation. More information is available at their website.

form of a database integrated to the software framework, while an even smaller fraction is procured through certain required calculations and estimations, where no data was openly available.

The following issues are considered with regards to data quality:

- Time-related coverage: the data used within the study dates as far back as a maximum of fifteen years. This could be regarded as a limitation, and should be included as a relevant point for future improvements.
- Geographical coverage: the coverage of data extends to the European countries (EU-27). Further recommendations may include the redefinition of these boundaries in order to account for more specific countries or regions.
- Technology coverage: the majority of the technology accounted for is done so within the construction and maintenance phases; this data was accessed through shipyard-generated documents, and was provided mostly by ASTANDER.
- Precision: the data used from the shipyard-generated documents and available references has been represented as precise as it has been reported.
- Completeness: the majority of the data utilised and/or developed while modelling, is a product of calculations regarding the data previously reported by literature and shipyards. Only less than 15% of this data is estimated, where certain specific processes were not publicly available.
- Representativeness: while the overall ship's LCA model may contain global references with regards to certain manufacturing processes, the operational phase of the study herein is representative of processes with the EU-27 designation.
- Consistency: the homogeneity of the methodology applies throughout the assessment of all systems' components fairly, since all systems are weighted equally within an equivalent functional unit. Additionally, the acquired data has proven consistent to prior estimation and assumption.

- Reproducibility: while originally the results were meant to be utilised internally, the data values could be interpreted and scaled properly for future recommendations on other assessments.

4.2.3 Life cycle inventory analysis

The following section quantifies and compiles all the energy and material inputs and outputs for the assessed system(s). Relevant user-defined inputs relate data to unit processes and ultimately to the functional unit. The definition of system key components (e.g. the electrical consumption of specific equipment, etc.) then allows using these data to generate process model flow diagrams such as the one in Figure 3.6. The generation of the graphical model facilitates the balancing of the system –assisted by the software–, which additionally allows for the complete summarising of the life cycle inventory tables, referenced to the system’s overall consumption of resources and emissions released (see Table 4.2 and Table 4.3).

4.2.3.1 Notes on process modelling

With regards to the operational phase of the ASTANDER ship, the most significant assumption is that the main engines are constantly running at sea, while at port, shore power is connected and the engines remain offline. The last emphasises that the environmental impact from the engines is only appraised during sailing. It should be noted that the ship’s propulsion and generation plant is diesel-electric; the main engines provide ship propulsion, as well as electricity onboard.

While the ship does have 5 smaller auxiliary generators (see Appendix D.1), these will be disregarded trough the LCA modelling; this given that the EEOI does not specifically account for these in its formulation, but the total fuel consumption per trip (which in this case is a result of the main engines, as mentioned previously). The EEDI however, does account for auxiliary engines, and its inclusion in the EEDI calculation –whilst of trivial impact–, will be appraised and explained further.

In order to compute the energy output on the four engines, the following calculation from the predecessor model has been utilised in the 'ship propulsion and generation' process (see Figure 3.8):

- $E = 4 \times 12{,}000$ kW $\times$ 3360 hours/year $\times 0.5 \times (0.85 + 0.3) = 9.27\times10^{7}$ kWh/year

The above formulation begins with 4, which is the number of engines available onboard at MCR capacity of 12,000 kW (11,500 kW has been used to account for lower output efficiency due to age and wear, see Figure 3.8), multiplied by the operational time (time at sea). It is assumed by Johnsen and Fet (1998) for their model that 85% of the engine capacity is used for 50% of the time, while the rest of the time the engines run at 30%; additionally, an efficiency equal to 1 has been assumed for the engines.

While the original formula is used to define the 'ship propulsion and generation' process, the end-user has the flexibility to change the factors at their convenience, which will alter the energy output accordingly. Figure 3.8 shows a partial screenshot of the parameters of the 'ship propulsion and generation' process, which have been tailored to account for the main engines of the ASTANDER Ro-Ro passenger vessel to run at about 62% load most of the time (and separately, 3 engines at 70% load). The last will be explained in the succeeding sections.

Table 9.0.5 also comprises consumption and emissions factors adapted from Johnsen and Fet (1998). These factors are also designed to serve as end-user inputs, with the logic of being able to adjust the values for other ships under assessment. Lastly, as mentioned previously, micro pollutants (e.g. soot, Arsenic, Cobalt, Vanadium, and etcetera) have been disregarded due to the fact that they are not considered within the EEDI/EEOI formulation.

As mentioned previously, information with regards to the model definition and sample calculations can be found in Appendix C.2. Additionally, although not particularly applicable herein, more information with regards to how the graphical model was developed, the definition of the manufacturing processes of the engines, boilers, propellers, and etcetera –and additionally their assumed disposal–, as well as other main components' life stages, is discussed further by Blanco-Davis (2013b) and Blanco-Davis et al. (2014a).

4.2.3.2 Inventory results

The following results are presented as an aggregation of the material and energy inputs and outputs of the system; as mentioned previously, these are assessed during the operational phase. The resources consumed and the emissions released are comprised under the physical unit of kilograms of mass. The overall set of results is divided between system inputs (consumed resources, see Table 4.2) and outputs (released emissions, see Table 4.3).

As mentioned previously, the EEDI and EEOI metrics are not designed to generate lifetime assessments; therefore, the following operational results are not extrapolated to include various years of operation (otherwise commonly performed during conventional LCA studies). Additionally, understanding that the inclusion of a retrofit application may enhance the appraisal of the metrics, the results are gathered between the following categories: 1 operational trip with the original conventional antifouling hull paint, 1 operational trip with the applied FRC retrofit, and 1 year of operation (150 trips in total; 75 trips with conventional antifouling and 75 trips with FRC).

Given that the EEDI is a measure of technical efficiency, reflecting the theoretical design efficiency of a newbuild ship, both one-trip results –conventional A/F and FRC–, will be used against the scores obtained by the design efficiency of the Ro-Ro passenger vessel. Furthermore, the 150-trips results –which underline that the retrofit takes place halfway through the operational year–, will be compared against the EEOI scores obtained by calculating the operational efficiency.

Worthy of mention is that the conventional A/F scenario assumes the constant operation of the 4 main engines at an average 62% load, while the FRC scenario takes under consideration that the improvement of hull resistance is significant, and the ship is now able to use 3 out of its 4 engines, at an average 70% load. While the last load figures may not be the most representative for operational conditions, they are procured by using the assumed SFC, and additionally an average fuel consumption figure that went from 132 tonnes with 4 engines in operation, to an approximate 112 tonnes with 3 engines online (additionally confirmed by the Ro-Ro passenger owner was that the vessel has been able to maintain the original schedule, by using 3 out of their 4 main engines online, and ultimately rotating one engine per voyage for maintenance purposes).

Table 4.2: Mass balance, Ro-Ro passenger vessel operational phase – Resources – Absolute values (kg) – 1 trip vs. 150 trips (1 year) results for Conventional A/F & FRC

Flows	1 Trip A/F	1 Trip FRC	150 Trips A/F & FRC
Non-renewable energy resources	1.39E+05	1.18E+05	1.93E+07
Renewable energy resources	5.39E-09	4.57E-09	7.46E-07
Energy resources	1.39E+05	1.18E+05	1.93E+07
Non-renewable elements	8.60E+01	7.29E+01	1.19E+04
Non-renewable resources	1.37E+04	1.16E+04	1.89E+06
Renewable resources	1.64E+07	1.39E+07	2.27E+09
Material resources	1.64E+07	1.39E+07	2.27E+09
Resources (total)	**1.65E+07**	**1.40E+07**	**2.29E+09**

Table 4.2 shows the aggregated totals for resources consumed by the system, gathered between the previously explained groups (or columns). The most relevant flows comprising the aggregated consumed resources include energy resources and material resources (land use, and other flows which may contribute to the inputs of the system have been disregarded, given that this particular system under the operational phase has negligible results under other omitted flows). Sample calculations comprising the most significant results can be found in Appendix C.2.

Between the two relevant flows found in Table 4.2, it is visible that the material resources flow is the most influential to the aggregated total. This flow category comprises subcategories such as non-renewable elements, non-renewable resources, and renewable resources. The first two subcategories contain trivial results, while the last one is yet again subdivided by flows such as water, air, carbon dioxide, nitrogen, and oxygen.

Aside from water, the consumption of the above elements is irrelevant; the vital, but renewable liquid, comprises 98.9% of the total resources consumed for all three columns. This amounts to 1.63E+07 kg (16,326 tonnes) of water used specifically under the 1-trip A/F grouping (out of the material resources total of 1.64E+07), and it belongs to the production requirements of the cradle-to-gate process HFO at refinery; 1.38E+07 kg (13,841 tonnes) and 2.26E+09 kg (2,262,537 tonnes) are representative of the water used for 1-trip FRC and 150 trips, respectively. These preliminary results show a small but visible improvement with regards to the water consumption between the two painting schemes on the 1-trip groups, in favour of the FRC application (see the aggregated resources total between the conventional A/F and FRC graphically represented in Figure 4.3).

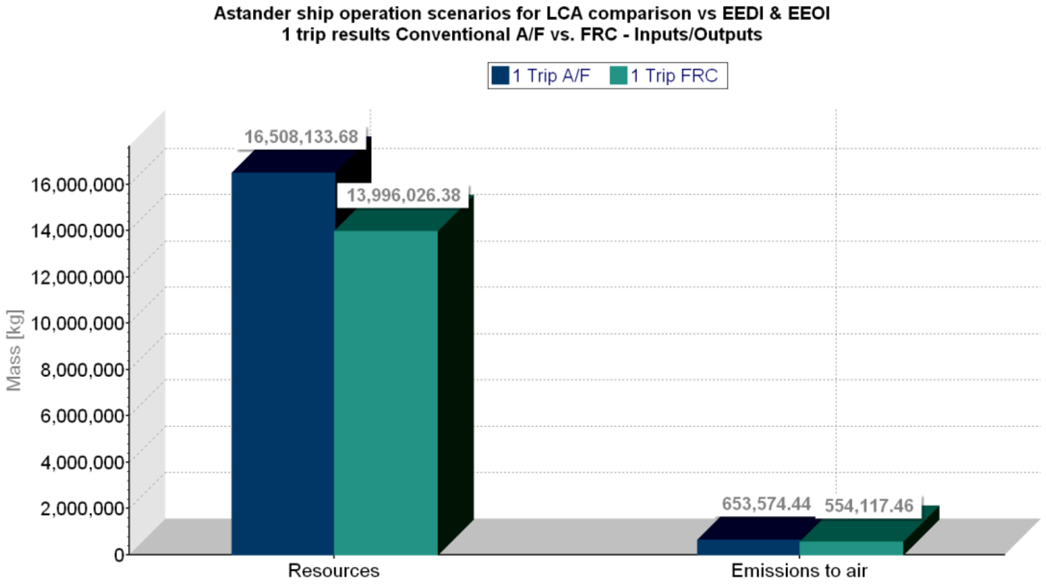


Figure 4.3: Mass balance, Ro-Ro passenger vessel operational phase – Resources & Emissions to air – Absolute values (kg) – 1 trip, results for Conventional A/F & FRC

Although less sizeable in quantity than its counterpart, the energy resources flow is comprised of the following subcategories: renewable energy resources and non-renewable energy resources; the results of the first are unimportant, while the latter underlines the consumption of resources such as crude oil, coal, natural gas, peat, and etcetera. The consumption of crude oil under this subcategory is worthy of mention, amounting to 0.78% of the resources aggregated total, and similarly belonging to the production requirements of the HFO process (the last emphasises that water and crude oil –holding their specific ratios–, comprise 99.68% of the total resources consumed).

The specific quantities of crude oil consumed relative to 1-trip A/F, 1-trip FRC, and 150-trips are as follows: 1.28E+05 kg (128.47 tonnes), 1.09E+05 kg (108.92 tonnes), and 1.78E+07 kg (17,804 tonnes), respectively. Again, an improvement over the consumption of crude oil is visible due to the upgrade brought about by the FRC retrofit, on the 1-year groups. Lastly, Figure 4.6 shows the graphical magnitude of the resources consumption between the three different groupings.

Table 4.3: Mass balance, Ro-Ro passenger vessel operational phase – Emissions to air – Absolute values (kg) – 1 trip vs. 150 trips (1 year) results for Conventional A/F & FRC

Flows	1 Trip A/F	1 Trip FRC	150 Trips A/F & FRC
Heavy metals to air	1.29E-01	1.09E-01	1.78E+01
Inorganic emissions to air	6.33E+05	5.36E+05	8.77E+07
Organic emissions to air (group VOC)	6.92E+02	5.87E+02	9.59E+04
Other emissions to air	2.02E+04	1.71E+04	2.80E+06
Particles to air	8.78E+00	7.44E+00	1.22E+03
Emissions to air (total)	**6.54E+05**	**5.54E+05**	**9.06E+07**

In turn, Table 4.3 shows the output of the system; similarly as with resources, some irrelevant flows have been omitted due to little to non-existent contribution under the system appraised (e.g. emissions to fresh water, emissions to agricultural soil, emissions to industrial soil, and etcetera). Therefore, the most significant flow is considered to be emissions to air, which additionally has subcategories such as heavy metals to air, inorganic emissions to air, organic emissions to air (group VOC), other emissions to air, and particles to air.

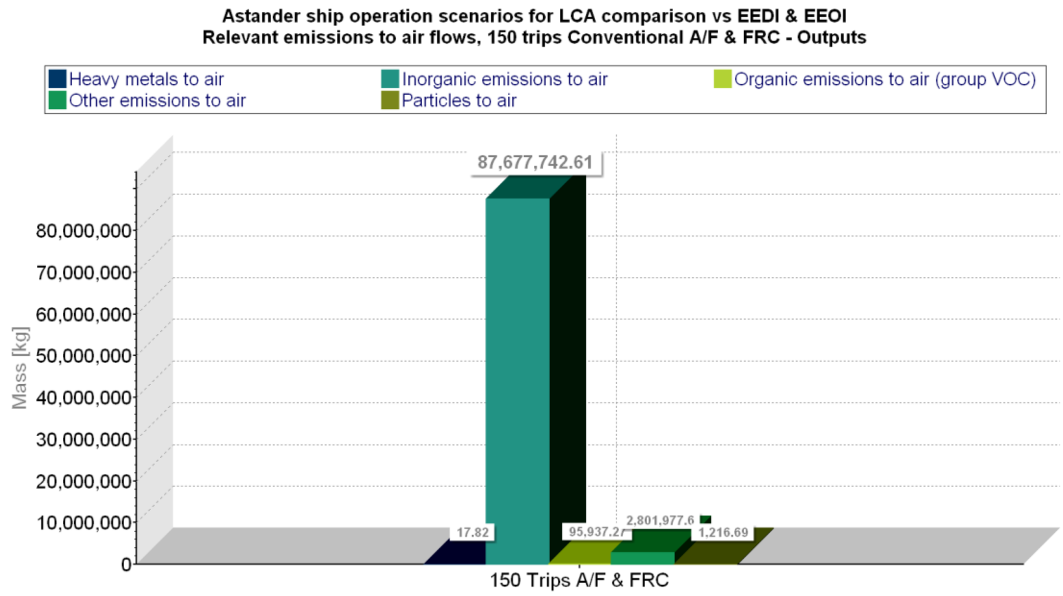


Figure 4.4: Mass balance, Ro-Ro passenger vessel operational phase – Relevant emissions to air flows – Absolute values (kg) – 150 trips, results for Conventional A/F & FRC

From these subcategories, the most relevant are inorganic emissions to air, organic emissions to air (group VOC), and other emissions to air, with a relative contribution to the emissions to air total of 96.8%, 0.106%, and 3.09%, respectively. Together they comprise 99.99% of the aggregated totals on each different column (see Figure 4.7 for the graphical comparison between the 1-trip results, and Figure 4.4 for the results relative to the 150-trips column).

Although the above-mentioned flows are the most important, heavy metals to air and particles to air are worthy of notice specifically under the 150-trips (1-year of operation) grouping. The first amounts to 17.8 kg –in its majority formed by iron, lead, manganese, nickel, vanadium and zinc–; all micro pollutants belonging to releases related to the production of HFO at refinery (the reader should recall that micro pollutants relative to the main engines are being disregarded). The latter, similarly belonging to the HFO at refinery process, amounts to 1,217 kg, in its majority comprised of particulate matter or dust (PM2.5-PM10) (see Figure 4.4). These two scores would be greater, with the inclusion of the main engines' releases.

While having a small contribution, the organic emissions to air (group VOC) is formed mostly by methane, and in less quantity by volatile organic compounds and released hydrocarbons. The first two are relative to the production of HFO at refinery, while the latter is mostly due to the emission factor specified in Table 9.0.5, and relative to the main engines' combustion (i.e. unburned hydrocarbons).

With regards to the other emissions to air flow, this is formed in its majority by exhaust (2.98%), which in turn is comprised mostly by nitrogen and water vapour; this particular flow is also linked to the production releases of the HFO at refinery process. The most relevant flow, inorganic emissions to air, will be explained further in the succeeding paragraphs; nevertheless, it is significant to note the preliminary savings between the 1-trip results, with regards specifically to the FRC application, and belonging not only to resources, but also to emissions (see Figure 4.3). Lastly, Figure 4.5 shows the overall graphical comparison among inputs and outputs of the three groupings.

As mentioned previously, the inorganic emissions to air flow comprises 96.8% of the emissions to air total; in turn, the following releases form the inorganic emissions in its majority: carbon dioxide (72.6% of the aggregated total), nitrogen oxides (1.66%), sulphur dioxide (0.45%), and water vapour (19.1%). With the exception of water vapour –which was not defined within the main engines' emission factors–, the above releases aggregate a contribution of both, the HFO at refinery process, and the ship propulsion and generation process.

Worthy of relevance is that from the carbon dioxide 72.6% contribution, 65.8% comes from the ship propulsion & generation process (meaning that main engines CO_2 releases form 65.8% of the aggregated total of emissions to air), while only 6.8% belongs to the releases linked to the HFO at refinery process. The significance underlining the amount of this particular emission (i.e. CO_2), is that the ratio is so much higher for the operation of the engines, than other ancillary processes (i.e. HFO production at refinery) taking place during the operational phase.

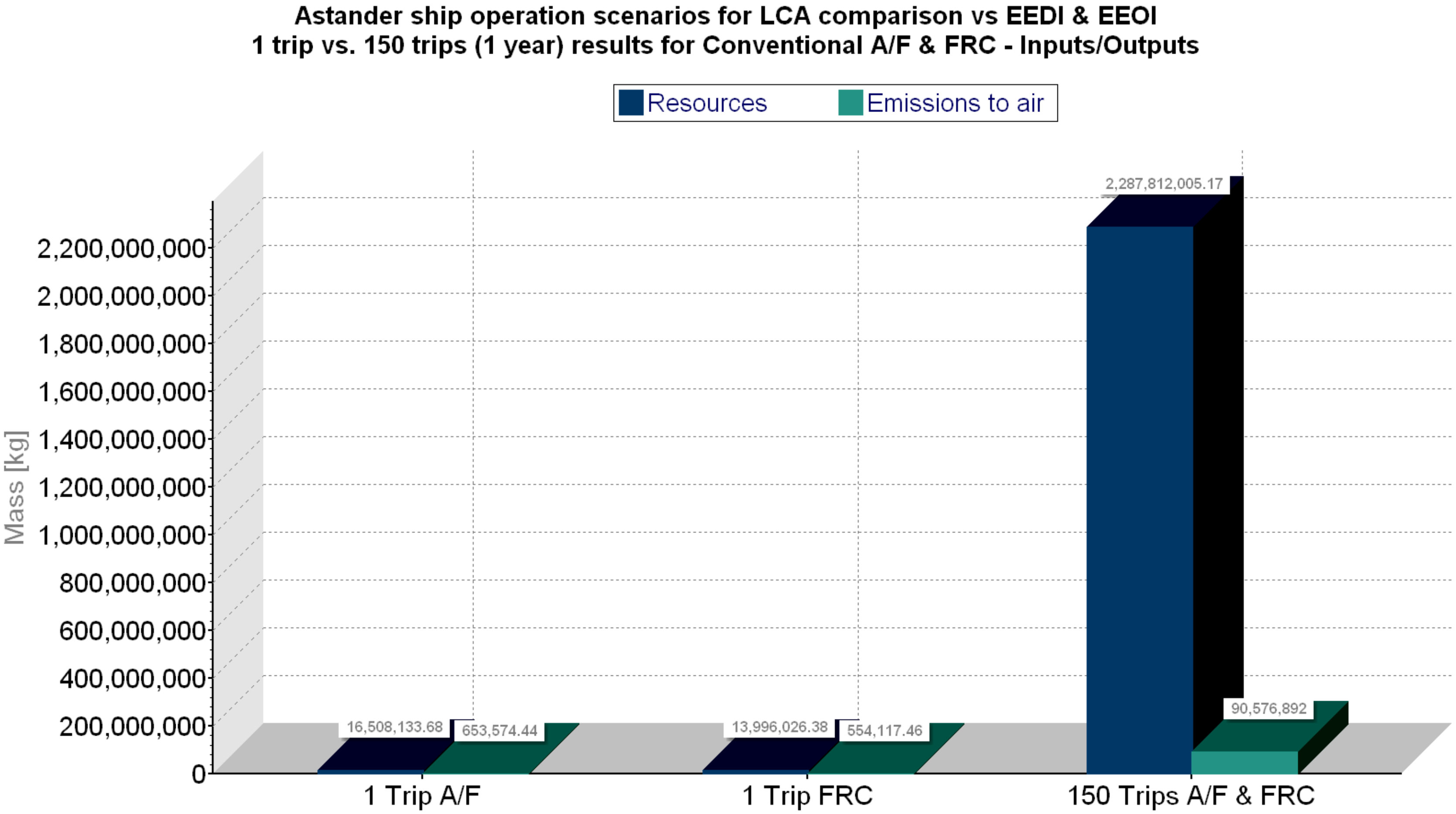


Figure 4.5: Mass balance, Ro-Ro passenger vessel operational phase – Resources & Emissions to air – Absolute values (kg) – 1 trip vs. 150 trips, results for Conventional A/F & FRC

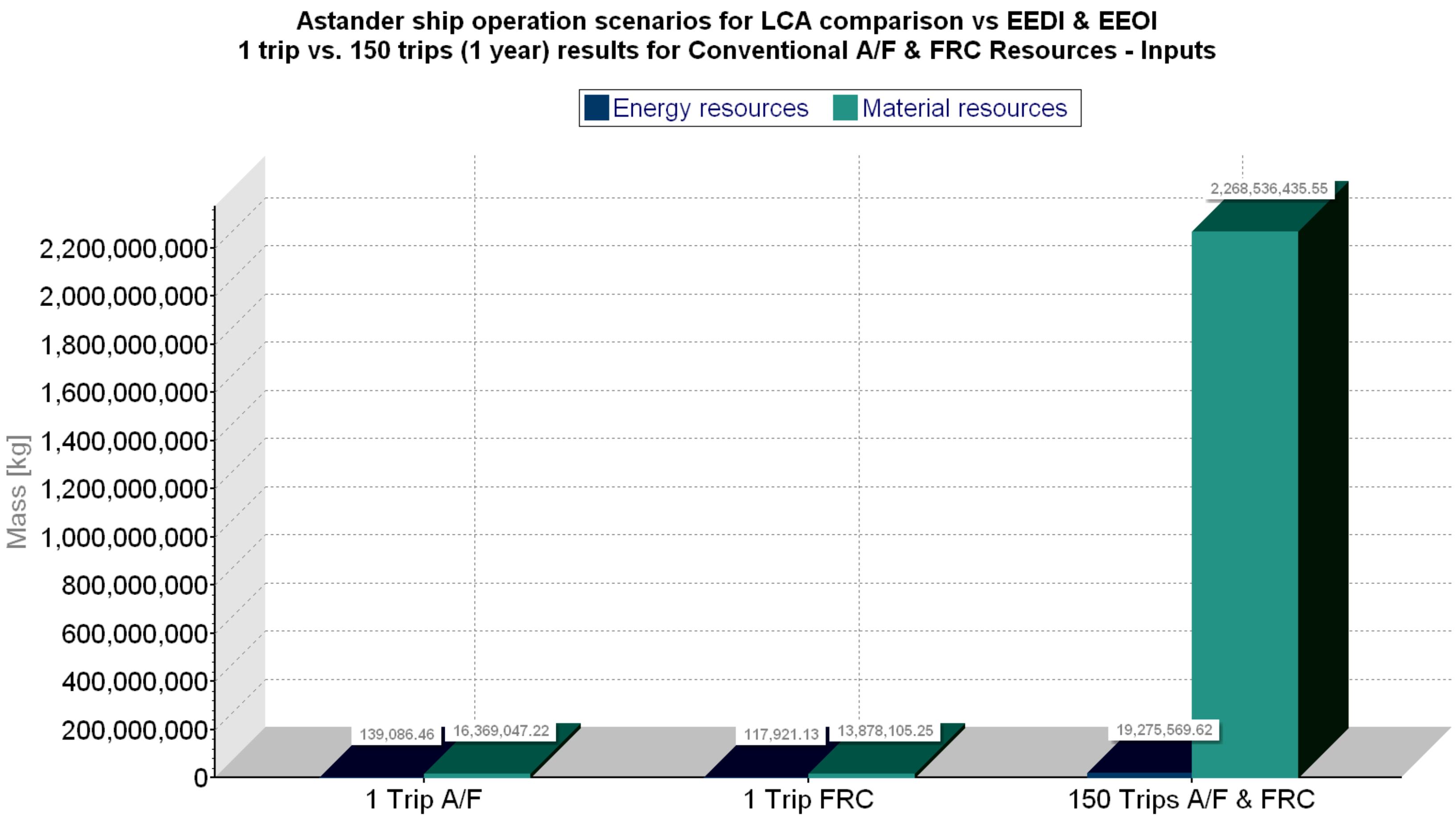


Figure 4.6: Mass balance, Ro-Ro passenger vessel operational phase – Relevant resources flows – Absolute values (kg) – 1 trip vs. 150 trips, results for Conventional A/F & FRC

Table 4.4: Mass balance, life cycle of Ro-Ro passenger vessel – Relevant emissions to air during all life phases and aggregated totals – Absolute values (kg) (Blanco-Davis et al., 2014a)

Flows	Total	Ship Construction	Ship Maintenance	Ship Operation	Ship Scrapping
Carbon dioxide	1.67E+09	2.64E+07	3.84E+06	1.64E+09	4.26E+04
Carbon monoxide	1.42E+06	3.56E+05	4.14E+04	1.02E+06	1.15E+02
Nitrogen oxides	3.76E+07	4.21E+04	6.15E+03	3.75E+07	1.03E+03
Sulphur dioxide	1.03E+07	5.17E+04	8.44E+03	1.02E+07	6.81E+02
Hydrocarbons (unspecified)	4.22E+05	2.90E+01	7.39E+00	4.22E+05	6.44E-03

With the above logic in mind, although not quite relevant to the study herein, Table 4.4 is included with a summary of significant emissions to air produced during the lifetime of the ship. As previously mentioned by Fet et al. (1996), the operational phase of the lifecycle of a ship represents a major contribution to the ship's overall environmental impacts. Reiterated by Blanco-Davis et al. (2014a), the contribution by this phase is not only substantial, but it also exceeds the emissions produced by other phases at relevant differences (see Table 4.4).

Table 4.5 shows the same relevant flows, but relative to the 1-trip and 150-trips results. The values have been calculated by the software using in its majority the emission factors found in Table 9.0.5, and the defined parameters from the ship propulsion and generation process (see Figure 3.8), while ultimately –in less proportion–, aggregating contributions from the HFO at refinery process. The 1-trip results clearly reemphasise the benefits brought forward by the switch from conventional A/F to FRC; the last is consistent with the improvement on hull resistance, and consequently with the newfound ship's ability to use only 3 out of its 4 main engines, directly lowering fuel consumption and emissions release.

Table 4.5: Mass balance, Ro-Ro passenger vessel operational phase – Relevant emissions to air – Absolute values (kg)

Flows	1 Trip A/F	1 Trip FRC	150 Trips A/F & FRC
Carbon dioxide	4.74E+05	4.02E+05	6.58E+07
Carbon monoxide	2.95E+02	2.50E+02	4.09E+04
Nitrogen oxides	1.08E+04	9.18E+03	1.50E+06
Sulphur dioxide	2.95E+03	2.50E+03	4.09E+05
Hydrocarbons (unspecified)	1.22E+02	1.03E+02	1.69E+04

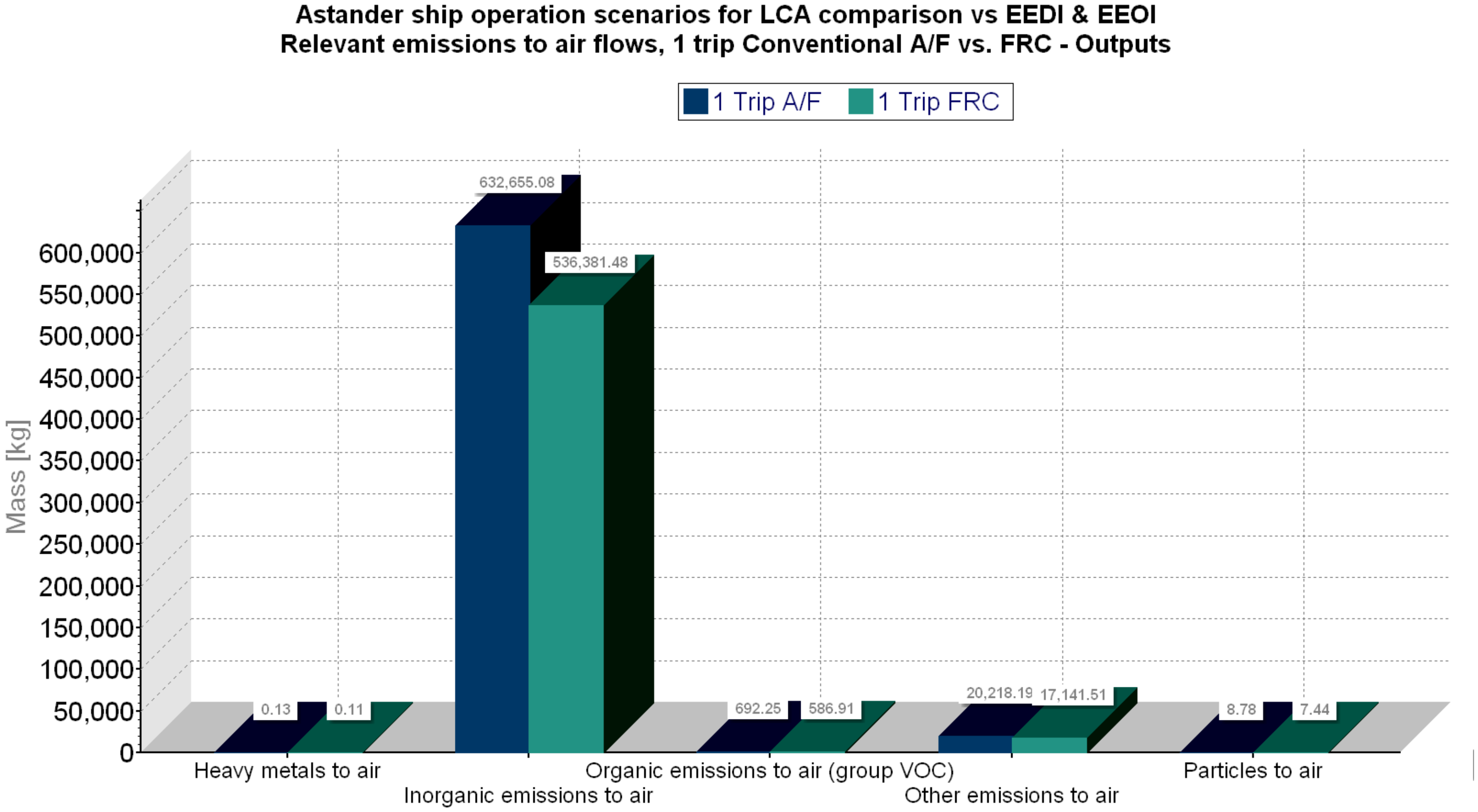


Figure 4.7: Mass balance, Ro-Ro passenger vessel operational phase – Relevant emissions to air flows – Absolute values (kg) – 1 trip, results for Conventional A/F & FRC

Worthy of mention is that a single trip by the vessel under its conventional antifouling paint generates 4.74E+05 kg of CO_2 (474.48 tonnes), 1.08E+04 kg of NO_x (10.8 tonnes), and 2.95E+03 kg of SO_2 (2.95 tonnes) (carbon monoxide and hydrocarbon values are negligible, in comparison to the magnitude of the other flows). Because the ratio of emission factors is proportional in the 1-trip FRC scenario, the emission savings amount to 15.22% less releases for each flow. The last equals significant savings in the amount of 72,204.84 kg of CO_2 (72.2 tonnes), 1,647.67 kg of NO_x, and 448.56 kg of SO_2 for one single trip with the applied FRC retrofit.

Although Table 4.5 does not really show any benefits with regards to the 150-trips results, the reader should recall that the scores encompass the application of the FRC retrofit halfway through the operational year; therefore, half year savings are included within the results shown (the reader should refer to Blanco-Davis et al. (2014a) for more information with regards to the potential resources, emissions and economic benefits underlined by the FRC application). Due to the consistent schedule of the ship, these results are extrapolated to 25 years in the ship operation column of Table 4.4.

Lastly, and of relevance, out of the 6.58E+07 kg of CO_2 (65,758 tonnes) generated by the vessel in a year (see Table 4.5), 6.15E+06 kg (6,151 tonnes) belong to the HFO at refinery process (9.35% of the aggregated CO_2 total), while the rest –5.96E+07 kg (59,607 tonnes)–, belong to the ship propulsion and generation process (90.65% of the aggregated CO2 total). The last underscores the importance of LCA's ability to incorporate relevant indirect emissions, although they might not be directly generated by the ship's propulsion plant.

A mention with regards to the inherited uncertainty of the results gathered is included to conclude this section; this uncertainty is relative to the procedure of how data was collected and used, and also how the boundaries of the system were set. Although this uncertainty has been minimised as much as possible, the following should be considered as its main sources, and therefore should be refined further for future assessments:

- Different sources of data were used across different levels.
- Due to time constraints, some data has not been crosschecked with other datasets or references.
- For some cradle-to-gate data, broad representations are used, instead of geographical specification.
- Boundary setting could influence the results significantly; e.g., by the inclusion or exclusion of certain processes, and due to integrated allocation. Allocation was non-existent, as advised by the ISO (2006a); nevertheless, the exclusion of micro pollutants and particulate matter from the ship propulsion and generation process should be emphasised, given that its addition to the scores above presented would increase their values.

4.2.4 Life cycle impact assessment

While the previous section presented absolute values for the inputs and outputs of the system under assessment, and although these results offer a preliminary context of the kind of consumption and emissions figures the system entails, the impact assessment will grant a broader view of the potential impacts incurred, making it easier to interpret the results in terms of negative effects. For example, it was demonstrated that a large quantity of water was utilised as an input resource for the system; this input flow however, is not expected to propose parallel damages to that of the output flow of carbon dioxide, within the global warming context. The last underscores the benefit of the application of the impact assessment, in order to gauge specific flows' burdensome potential.

This phase of the study requires that all available information relative to previous phases be taken into consideration, as well as reassessing the goal and scope definitions and system boundaries. Recalling the goal and scope definition, the impact category to be utilised is the Global Warming Potential by CML 2001 in a hundred years' time frame, with a characterisation factor from November 2010.

Table 4.6: CML2001 - Nov.2010, Global Warming Potential (GWP 100 years) – Relevant emissions to air flows and aggregated totals – Benchmark (A/F) vs. Alternative (FRC) scenario – kg CO_2eq

Flows	Benchmark (Conv. A/F)	Alternative (FRC)
Inorganic emissions to air	1.81E+09	1.68E+09
Organic emissions to air (group VOC)	4.70E+07	4.36E+07
Emissions to air (total)	**1.86E+09**	**1.72E+09**

As a starting point, Table 4.6 from the original assessment by Blanco-Davis (2013b), has been included to show the benefits from the alternative scenario (a 7.53% drop in global warming emissions, totalling 139,123 tonnes of CO_2eqs). The alternative scenario shows the reduction in emissions through 25 years of operation –due to the FRC retrofit application halfway through the ship's life–, in comparison to the benchmark scenario, which alludes to the vessel's lifetime releases with its conventional antifouling paint (both scenarios also comprise the construction, maintenance, operation and scrapping phases).

Table 4.7: CML2001 - Nov. 2010, Global Warming Potential (GWP 100 years) – Relevant emissions to air flows and aggregated totals – kg CO_2eq

Flows	1 Trip A/F	1 Trip FRC	150 Trips A/F & FRC
Inorganic emissions to air	4.75E+05	4.03E+05	6.58E+07
Organic emissions to air (group VOC)	1.19E+04	1.01E+04	1.65E+06
Emissions to air (total)	**4.87E+05**	**4.13E+05**	**6.75E+07**

Correspondingly, the same impact assessment could be applied solely to the operational phase of the Ro-Ro passenger vessel (see Figure 4.8). Table 4.7 includes Global Warming Potential scores in a 100 years for the following groups: 1-trip with A/F, 1-trip with FRC, and 1-year of operation (150 trips; 75 trips with A/F, 75 trips with FRC). The most relevant flows under the GWP impact category are inorganic emissions to air and organic emissions to air (group VOC); the first holds 97.56% of contribution to the aggregated totals, while the latter complements the rest (2.44%, see Figure 4.9).

Worthy of note are the substances which contribute in its majority to the above-mentioned significant flows. For example, the inorganic emissions to air flow is formed in its majority by carbon dioxide (97.5% of the emissions to air aggregated total); other substances within this flow are trivial in comparison to CO_2 (this substances however, include carbon monoxide, nitrogen triflouride, nitrous oxide, and sulphur hexafluoride). With regards to organic emissions to air (group VOC), methane corresponds to 2.25% of the emissions to air total, while also being influenced minimally by VOCs and unspecified hydrocarbons. Both relevant flows aggregate emissions from the HFO at refinery process (e.g. CO_2 and CH_4), and the ship propulsion and generation process (e.g. CO_2 and hydrocarbons).

With that in mind, it is important to recognise the ratio which forms the most influential release within the impact category, i.e. CO_2. From the aggregated total of 97.5%, 9.1% belongs to the emissions procured during the production of HFO at refinery, while 88.4% is generated through the main engines internal combustion.

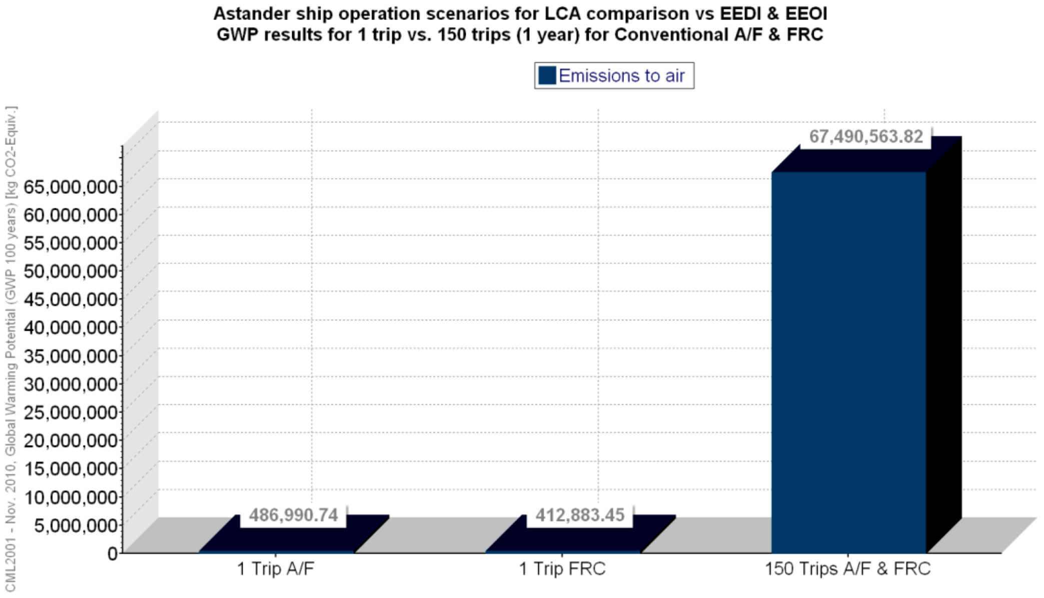


Figure 4.8: GWP 100 years, Ro-Ro passenger vessel operational phase – Aggregated totals – kg CO2eq – 1 trip vs. 150 trips, results for Conventional A/F & FRC

Additionally, the CO_2 scores generated through inventory (see Table 4.5), can be subtracted from the GWP scores of Table 4.7; this results in a difference of 2.57%

(meaning that methane represents most of this difference), namely 1.25E+04 kg of CO_2eq (12.5 tonnes), 1.06E+04 kg of CO_2eq (10.6 tonnes), and 1.73E+06 kg of CO_2eq (1,733 tonnes), with respect to the three different groupings (1-trip with A/F, 1-trip with FRC, and 1-year of operation). These values represent the contribution by way of classification and characterisation of releases other than CO_2, but with similar warming capabilities.

The above two paragraphs once again demonstrate that aside from being able to properly account for CO2 emissions, LCA can comprise other emissions with a warming potential analogous to CO2, and therefore comprehensively cover all releases under this impact category.

With regards to the GWP savings procured by the FRC retrofit in comparison to the conventional A/F, a total of 7.41E+04 kg of CO_2eq (74.11 tonnes) is procured. The last corresponds to 7.23E+04 kg of CO_2eq (72.30 tonnes) of inorganic emissions to air, and 1.81E+03 kg of CO_2eq (1.81 tonnes) of organic emissions to air (group VOC) (see Table 4.7 and Figure 4.9).

Lastly, Table 4.8 is included to represent the different GWP contributions specific to each life stage, while additionally gathering results under the benchmark and alternative scenarios (the aggregated totals are comprised within Table 4.6). It is clear that the construction and scrapping scenarios represent no improvement with regards to the two scenarios; this is due to the fact that the FRC retrofit takes place during the maintenance (FRC installation and upkeep) and operation phases. Of relevance is that the operational phase shows a drop of 7.65% in the alternative scenario, in comparison to the benchmark scenario (totalling 138,951 tonnes of CO_2eq). The last ultimately underlines the environmental effectiveness of the proposed retrofit.

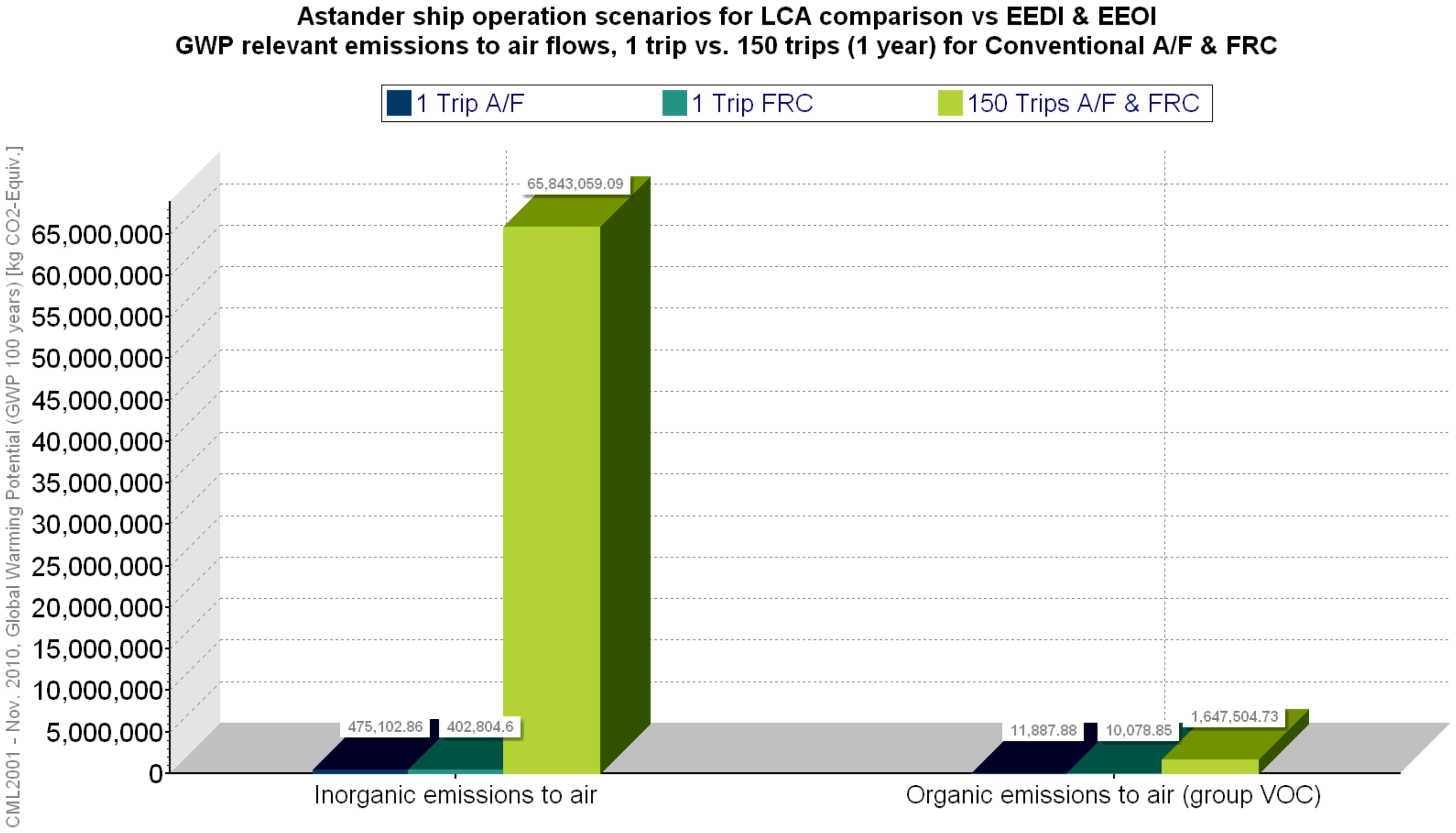


Figure 4.9: GWP 100 years, Ro-Ro passenger vessel operational phase – Relevant emissions to air flows – kg CO2eq – 1 trip vs. 150 trips, results for Conventional A/F & FRC

Table 4.8: CML2001 - Nov. 2010, Global Warming Potential (GWP 100 years) – Life cycle of Ro-Ro passenger vessel – Scenario comparison between Conventional A/F & FRC application – kg CO_2eq (Blanco-Davis et al., 2014a)

Benchmark (Conventional A/F)				**Alternative (FRC)**			
Ship Construction	Ship Maintenance	Ship Operation	Ship Scrapping	Ship Construction	Ship Maintenance	Ship Operation	Ship Scrapping
2.89E+07	4.71E+06	1.83E+09	4.40E+04	2.89E+07	4.54E+06	1.69E+09	4.40E+04

It should be noted that all LCIA results are relative accounts and expressions, and do not predict impacts on category endpoints, the exceeding of thresholds, or safety margins and/or risks.

4.3 CONSAR case study

4.3.1 Case study introduction

The case vessel proposed by CONSAR is a capesize bulk carrier, which has a worldwide operation and often transports grain. The actual vessel had recently forecasted a ballast water treatment system (BWTS) retrofit to be implemented onboard; nevertheless, the underlined retrofit has irrelevant impact with regards to overall fuel and energy efficiency (other than a trivial rise in energy consumption, in the grand scheme of things). For this last reason, the retrofit in question has not been taken into consideration for the study herein.

Table 4.9: CONSAR vessel particulars

Type of vessel:	Bulk carrier	**Deadweight (DWT):**	84,607 tonnes
Year of built:	2009	**Gross tonnage (GT):**	51,255 tonnes
Length overall (LOA):	229.2 metres		
Length between perpendiculars (LBP):	222.0 metres	**Hull materials:**	Naval A grade steel
Breadth:	38.0 metres	**Hull connections:**	Welded
Draft:	14.9 metres	**Power (main engine):**	14,280 kW at 105 rpm

Table 4.9 lists the ship’s main particulars, while additionally, Appendix D.5 inventories information with regards to the vessel’s main engine, hold capacity, speed and voyage profile.

4.3.2 Goal and scope of the study

Similarly as the previous case vessel, the goal of the study is to validate the LCA methodology as a fitting environmental indicator supplement to the EEDI and EEOI metrics, while additionally being able to underline energy efficiency outcomes. It should be noted that the case ship will be assessed using the previously explained ships’ LCA model, but similarly as the preceding vessel, the scope of the study will only comprise the operational phase of the CONSAR bulk carrier.

Worthy of note as well is that, given that the previous vessel report comprised an account of the ships’ LCA model, the following study report has been recapped to avoid repeating certain similar or matching sections with regards to the previous case ship. However, certain required similarities must be and are addressed, as well as relevant differences mentioned and expanded herein.

4.3.2.1 Operational profile

The CONSAR bulk carrier was built in 2009, and currently operates cargo routes from Europe to Africa, and across Western Asia, whilst also being able to call on ports differing from the above routes. The last proves as a difficulty for developing an operational profile that ultimately accommodates a regular yearly schedule. For this reason, the voyage profile considered herein has been summarised in order to provide a more simple calculation and comparison between the different metrics. Nevertheless, this should be underscored as a potential limitation, and should be listed further to enhance future appraisals.

The voyage profile considered for the purpose of the study, highlights the vessel travelling from Port Kirkenes, Norway, to Port Said, Egypt, and back (see Appendix D.5). Considering the two different locations, the average distance between the two is 5808 miles. Additionally, the vessel undertakes a loaded voyage to arrive to its destination, while coming back unloaded, i.e. a ballast voyage. Since the vessel's service speed is 12 knots, then the average sailing time for each trip or voyage is 484 hours (20.17 days). Lastly, it is assumed the vessel carries out 10 trips per year, resulting in 4840 hours of operation a year while using its main engine (see Appendix D.5); the rest of the time is either spent at port loading and unloading cargo, and performing maintenance while using shore power and having its main engine offline.

4.3.2.2 Function of the system

The function of this type of vessel is to transport unpackaged cargo in bulk, such as grains, ore, cement, coal, and etcetera. Therefore, its main defined function would be the transportation of maximum mass, i.e. cargo. Similarly as the previous case vessel, the environmental scores obtained from this appraisal are only comparable to scores to that of similar types of ships, with the same functional performance.

4.3.2.3 Functional unit

Based on the consideration that the system's main function is the transportation of maximum cargo, thus the functional unit should be defined as:

- (Cargo transported × distance) per year between the two port destinations.

Moreover, according to the hold capacity described in Appendix D.5, the ship's maximum carrying potential amounts to 100,300 cubic meters. Assuming that in average 85% of this capacity is reached, and additionally that the vessel undertakes transport of grains of wheat –with a density of 790 kg/m^3–, then the total transported cargo per trip would amount to:

- (100,300 m^3 × .85 × 790 kg/m^3) ÷ (1/1000 tonne/kg) = 67,351.45 tonnes/trip.

Considering the above, the functional unit of the system is defined as **tonne × nm transported per trip** between the two port destinations, with a functional performance of 67,351.45 tonnes/trip × 5808 nautical miles = 3.91×10^8 tonne-nm per loaded trip.

4.3.2.4 Explanation of the system boundary

The boundary setting for this study is adjusted to appraise solely the operational phase of the ship. Additionally, no allocation procedures are performed during the operational phase, due to the fact that the material and energy exchanges taking place are assumed balanced within this phase.

4.3.2.5 Assumptions and limitations

The list of assumptions previously addressed for the ASTANDER ship is applicable for the CONSAR vessel (see section 4.2.2.5), with the exception of the following:

1. Consumption and emission factors are taken from MAN-Diesel (2009) and Moldanová et al. (2012), respectively. These factors are used to redefine the 'ship propulsion & generation' process, which has been simplified to only include factors found in Table 9.0.9 and Table 9.0.10, *with the exception* of the CO_2 emission factor. This last is different for the CONSAR case vessel, and amounts to 520 g/kWh for the CO_2 emission factor; the last so that there is consistency while using IMO's carbon conversion factor for HFO (i.e. 520 g/kWh ÷ 167 g/kWh = 3.114). Other diesel engine contaminant emission factors, such as micro pollutants, continue to be disregarded for the purpose of providing a more straightforward comparison to the EEDI and EEOI metrics.

4.3.2.6 Impact categories selected and methodology of impact assessment

The impact category to be used is the Global Warming Potential by CML, in a hundred years' time frame. The classification and characterisation of emissions will be according to CML 2001, with a characterisation factor form November 2010 (CML, 2010).

4.3.2.7 Initial data quality requirements

A medium emphasis has been put on data quality. It is also thought that subsequent use of the model for the evaluation of other ships, will further improve the model and the accuracy of its results.

The issues previously mentioned for the ASTANDER Ro-Ro passenger vessel are likewise applicable to the CONSAR bulk carrier (see section 4.2.2.7), with the exception of the underscored difference pointed out in section 4.3.2.5.

4.3.3 Life cycle inventory analysis

The following section quantifies and compiles all the energy and material inputs and outputs for the assessed system. The complete summarising of the life cycle inventory tables is referenced to the system's overall consumption of resources and emissions released (see Table 4.10 and Table 4.11, respectively).

4.3.3.1 Notes on process modelling

The CONSAR case vessel incorporates some of the notes and issues raised previously for the ASTANDER ship (see section 4.2.3.1), with the exception of a few differences. With regards to the operational phase of the ship, likewise the most relevant assumption is that the main engine is constantly running at sea, while at port the engine is offline. Additionally, the bulk carrier vessel has a conventional diesel engine propulsion plant, meaning that electricity generation befalls on auxiliary generators onboard.

The auxiliary generators are similarly disregarded through the LCA modelling, due to the fact that the EEOI does not specifically account for these in its formulation. Nevertheless, this exclusion should be considered and underscored as a potential limitation, and should be listed under recommendations for further studies. The EEDI will account for the auxiliary power onboard; this inclusion will be evaluated and explained in succeeding sections.

Lastly, while the original formula defined in the 'ship propulsion and generation' process is still applicable to the CONSAR vessel, some of the factors have been changed accordingly to allow appraisal of a different engine operation and voyage profile. The changes include the SFC and the CO_2 emissions factor, as mentioned previously in section 4.3.2.5, as well as the power (14,280 kW) and the number of engines (1), hours of operation per trip (484 hours), and engine load (75% load). The above will be discussed in subsequent sections.

4.3.3.2 Inventory results

The following results are presented as an aggregation of the material and energy inputs and outputs of the system, appraised during the operational phase of the ship. The resources consumed and the emissions released are comprised under the physical unit of kilograms of mass. Furthermore, as mentioned previously, the overall set of results is divided between system inputs (consumed resources, see Table 4.10) and system outputs (released emissions, see Table 4.11). Lastly, the results are gathered between the following groups (or columns): 1 operational trip, and 1 year of operation (10 trips). The aggregated results for inputs and outputs for both groups are represented graphically in Figure 4.10.

Table 4.10: Mass balance, Bulk carrier vessel operational phase – Resources – Absolute values (kg) – 1 trip vs. 10 trips (1 year) results

Flows	**1 Trip**	**10 Trips (1 Year)**
Non-renewable energy resources	9.07E+05	9.07E+06
Renewable energy resources	3.51E-08	3.51E-07
Energy resources	9.07E+05	9.07E+06
Non-renewable elements	5.61E+02	5.61E+03
Non-renewable resources	8.91E+04	8.91E+05
Renewable resources	1.07E+08	1.07E+09
Material resources	1.07E+08	1.07E+09
Resources (total)	**1.08E+08**	**1.08E+09**

Table 4.10 shows the aggregated totals for resources consumed by the system. Similarly as with the ASTANDER case vessel, some flows with irrelevant contributions to the inputs of the system during the operational phase have been disregarded. The reader should recall that the consumption and emission factors utilised for the CONSAR vessel can be found in Appendix D.6. Sample calculations comprising the most significant results can be found in Appendix C.2.

Similarly as with the previous case vessel, the most important flows within the resources category are energy resources and material resources, which are also divided in subcategories; water, which contributes relevantly to the renewable resources subcategory, comprises 98.9% of the total resources consumed. This amounts to 1.06E+08 kg (106,470 tonnes) of water used under the 1-trip grouping (out of the material resources total of 1.07E+08 kg), belonging to the production requirements of the HFO at refinery process; 10 times this result is representative of the water used for 1 year of operation. The last evidences that while some of the consumption and emission ratios between the two vessels are similar, the values differ considerably due to their contrasting operational profiles (e.g. 16,326 tonnes of water used under the 1-trip with A/F grouping vs. 106,470 tonnes of water used under 1 bulk carrier trip).

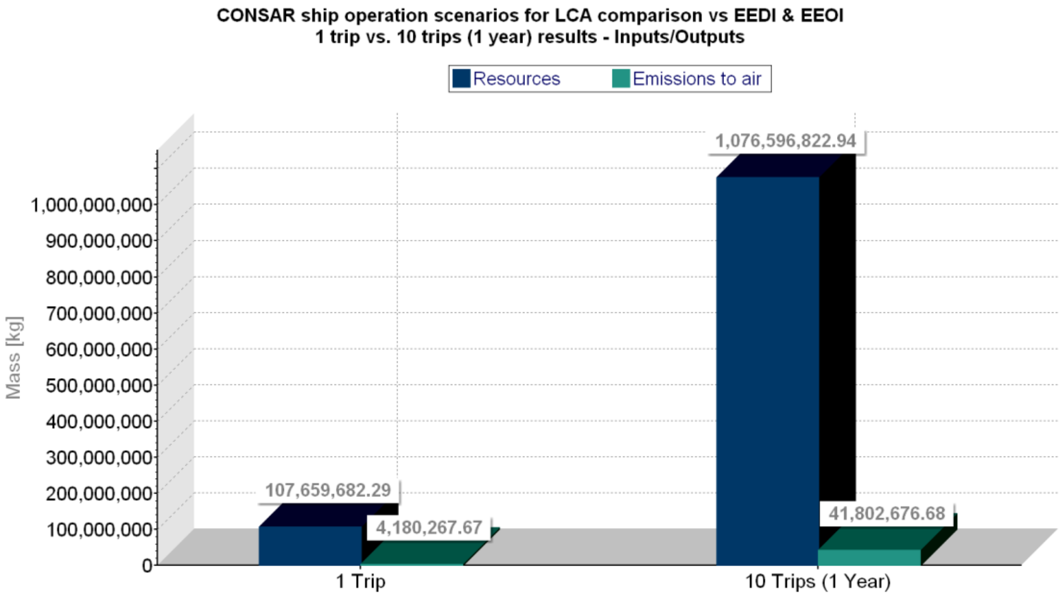


Figure 4.10: Mass balance, Bulk carrier vessel operational phase – Resources & Emissions to air – Absolute values (kg) – 1 trip vs. 10 trips results

The consumption of crude oil under the non-renewable energy resources amounts to 0.78% of the resources aggregated total, driven by the requirements of HFO production as well. While holding their specific ratios, water and crude oil both comprise 99.68% of the total resources consumed. This amounts specifically to 8.38E+05 kg (837.8 tonnes) and 8.38E+06 kg (8,378 tonnes) of crude oil for 1 operational trip and 1 year of operation, respectively. Figure 4.11 shows the aggregated resources totals between the energy and material resources flow categories, while Figure 4.12 shows the graphical magnitude between the most relevant resources flow subcategories for the 1 year of operation grouping.

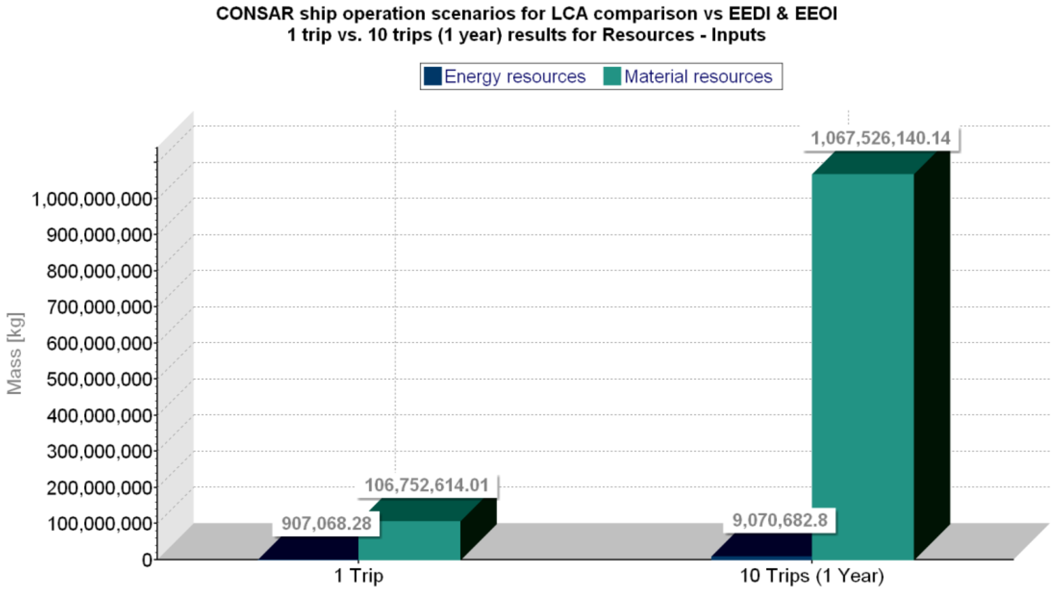


Figure 4.11: Mass balance, Bulk carrier vessel operational phase – Relevant resources flows – Absolute values (kg) – 1 trip vs. 10 trips results (I)

In contrast, Table 4.11 represents the aggregated totals for the outputs of the system, under the most relevant subcategories forming the main flow category, i.e. emissions to air, and gathered between the two columns previously mentioned (1 operational trip, and 1 year of operation).

With regards to the subcategories, the most relevant are still inorganic emissions to air, other emissions to air, and organic emissions to air (group VOC); nevertheless, in comparison to those of the previously assessed case ship, their ratios vary slightly as follows: 96.7%, 3.15%, and 0.13%, respectively. Together they comprise 99.98% of the aggregated total of emissions to air. Figure 4.13 represents these ratios graphically for the 1 year of operation results.

Under that same column –1 year of operation–, heavy metals to air and particles to air are worthy of mention. The former amounts to 8.39 kg, while the latter totals 572.55 kg. As previously mentioned, heavy metals to air comprise elements such as Antimony, Arsenic, Cadmium Cobalt, Iron, Lead, and etcetera, while the particles to air flow is formed in its majority by particulate matter (PM2.5-PM10) (see Figure 4.13). Both of these contributions are linked to the production of HFO at refinery.

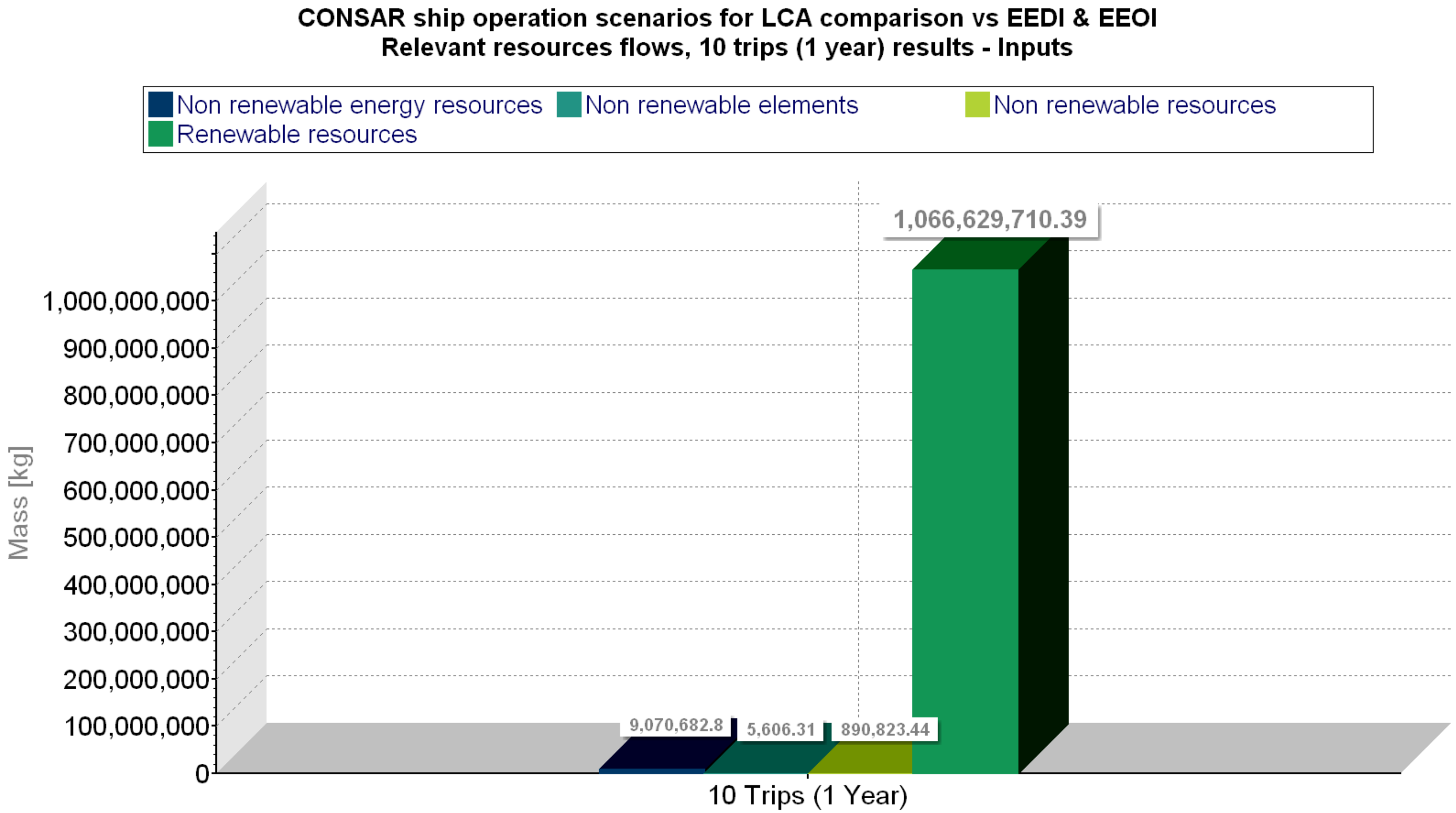


Figure 4.12: Mass balance, Bulk carrier vessel operational phase – Relevant resources flows – Absolute values (kg) – 1 trip vs. 10 trips results (II)

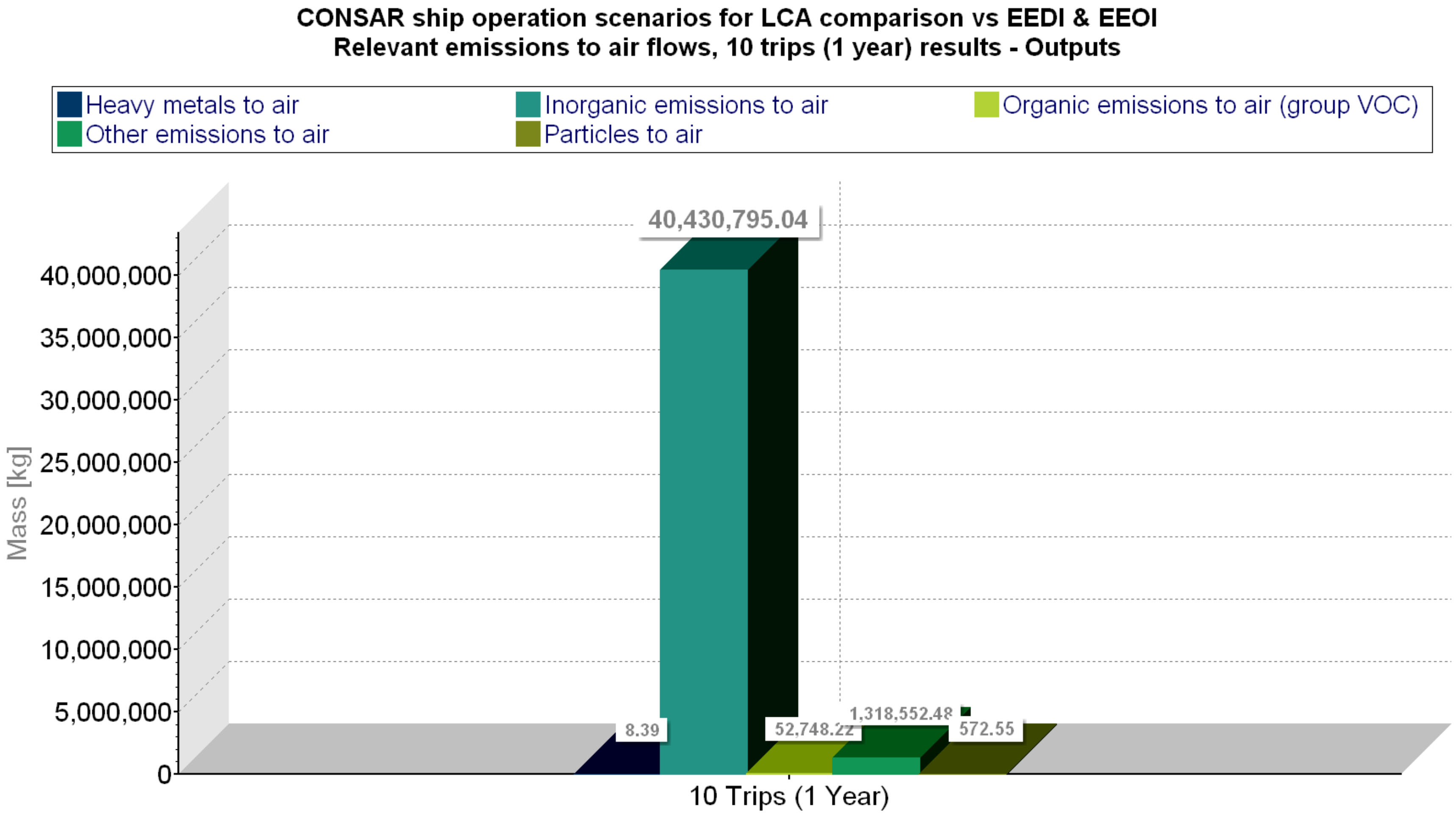


Figure 4.13: Mass balance, Bulk carrier vessel operational phase – Relevant emissions to air flows – Absolute values (kg) – 10 trips results

Table 4.11: Mass balance, Bulk carrier vessel operational phase – Emissions to air – Absolute values (kg) – 1 trip vs. 10 trips (1 year) results

Flows	1 Trip	10 Trips (1 Year)
Heavy metals to air	8.39E-01	8.39E+00
Inorganic emissions to air	4.04E+06	4.04E+07
Organic emissions to air (group VOC)	5.27E+03	5.27E+04
Other emissions to air	1.32E+05	1.32E+06
Particles to air	5.73E+01	5.73E+02
Emissions to air (total)	**4.18E+06**	**4.18E+07**

Exhaust still forms in its majority the other emissions to air flow subcategory with a slight increase on its ratio –which is 3.04% of the emissions to air total–, as a consequence of the HFO production. In the other hand, Methane, VOCs and unspecified hydrocarbons constitute the lesser contribution from the organic emissions to air (group VOC) subcategory. The first two are relative to the HFO production process, while the latter is mostly a factor from the main engine's combustion.

Out of the 96.7% which forms the inorganic emissions to air flow contribution to the emissions to air total, the following releases are the most relevant: carbon dioxide (71.4% of the aggregated total), nitrogen oxides (2.26%), sulphur dioxide (0.523%), and water vapour (19.5%). With the exception of water vapour, similarly as with the ASTANDER case ship, the aforementioned releases aggregate a contribution of both, the ship propulsion process and the HFO production process at refinery.

From the total carbon dioxide contribution (71.4%), a total of 64.5% comes from the ship propulsion process, while 6.9% is attributed to the CO_2 generation by ways of the production of HFO. The above percentages amount to 2.69E+06 kg (2,694 tonnes) of carbon dioxide generated through the main engines during 1 operational trip, and 2.89E+05 kg (289 tonnes) of CO_2 linked to the HFO at refinery process. Figure 4.14 depicts a representation of the magnitude of these two values, while Table 4.12 aggregates the two contributions.

Table 4.12 also offers relevant emissions to air flows within the 1 trip and 1 year of operation groupings, while indicating the contribution by both, the HFO at refinery process and the ship propulsion and generation process. One single trip by the bulk carrier vessel generates an aggregated total of 2.98E+06 kg (2,984 tonnes) of carbon dioxide, 3.01E+03 kg (3 tonnes) of carbon monoxide, 9.46E+04 kg (94.6 tonnes) of nitrogen oxides, 2.19E+04 kg (22 tonnes) of sulphur dioxide, and 1.55E+03 kg (1.55 tonnes) of released hydrocarbons. A full year of operation of the vessel entails the previous results tenfold (29,839 tonnes of CO_2, 30 tonnes of CO, 946 tonnes of NO_x, 219 tonnes of SO_2, and 15.6 tonnes of hydrocarbons).

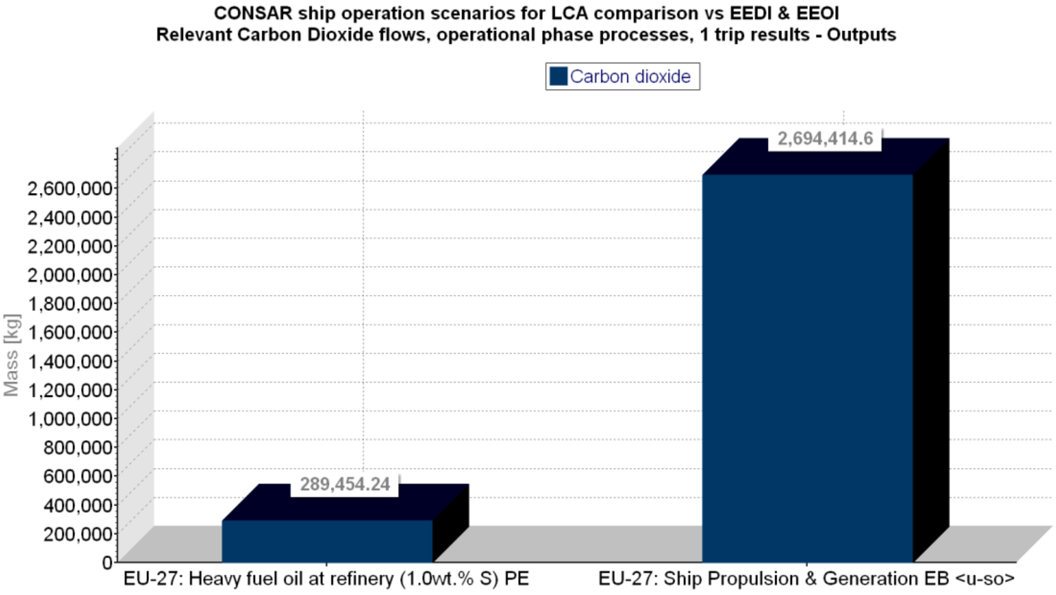


Figure 4.14: Mass balance, Bulk carrier vessel operational phase – Relevant carbon dioxide emission flows – Absolute values (kg) – 1-trip results

Although not practically comparable, due to their different functional performance, it is interesting to note that the above results turn out to be rather different between the two vessels. For example, 2,984 tonnes of CO_2 from 1 trip of the bulk carrier versus 474.48 tonnes of CO_2 for 1 trip A/F of the Ro-Ro passenger vessel, and 29,839 tonnes against 65,758 tonnes of CO_2 in a year between the CONSAR and the ASTANDER vessel, respectively). The above differences are a function of the variance in the ships' operational profile, and their diesel plant arrangements.

Lastly, similarly as the ASTANDER case vessel, a minimum inherited uncertainty is relative to the procedure of how data was collected and used, and specifically the way the boundaries of the system were set. The main sources for the uncertainty representative to the ASTANDER case ship are applicable to the bulk carrier case ship, and are noted as potential improvement candidates for future assessments.

4.3.4 Life cycle impact assessment

This phase of the study has taken into consideration all available information relative to the previous phases, as well as reassessing the goal and scope definition and system boundaries. Recalling the goal and scope definition, the impact category to be applied is the Global Warming Potential by CML 2001 in a hundred years' time frame, with a characterisation factor from November 2010.

Table 4.13 comprises the GWP scores in a 100 years for the following groups: 1 operational trip, and 1 year of operation. Additionally, similarly as Table 4.12, Table 4.13 incorporates the specific Global Warming Potential contribution relative to the different processes: production of HFO at refinery and ship propulsion & generation. It is clear that the most significant flows under the GWP impact category are inorganic emissions to air and organic emissions to air (group VOC); the former represents 97.3% of contribution to the aggregated impact totals, while the latter complements the rest (2.7%, see Figure 4.16 for a graphical representation of the flows proportion).

Although with a slight difference in the composition ratio, the significant substances that contribute to the inorganic emissions to air flow are analogous to the ones mentioned previously for the ASTANDER case ship: carbon dioxide, carbon monoxide, nitrogen triflouride, nitrous oxide, and sulphur hexafluoride. Carbon dioxide, however, holds 97.2% of contribution to the GWP totals, while the rest of the substances is considered to have marginal influence. In the other hand, methane, from the organic emissions to air (group VOC), holds 2.33% of the emissions to air total. Together –while holding their specific ratios–, CO_2 and CH_4 constitute 99.53% of the GWP aggregate; this total collects emissions from the HFO production process (e.g. CO_2 and CH_4), as well as the ship propulsion and generation process (e.g. CO_2 and hydrocarbons).

Additionally, it is interesting to point out that from the 97.2% of the aggregate total carbon dioxide contribution, 87.7% belongs to the ship propulsion and generation process –generated through the main engine's internal combustion–, while 9.5% belongs to the HFO at refinery process (see Table 4.13).

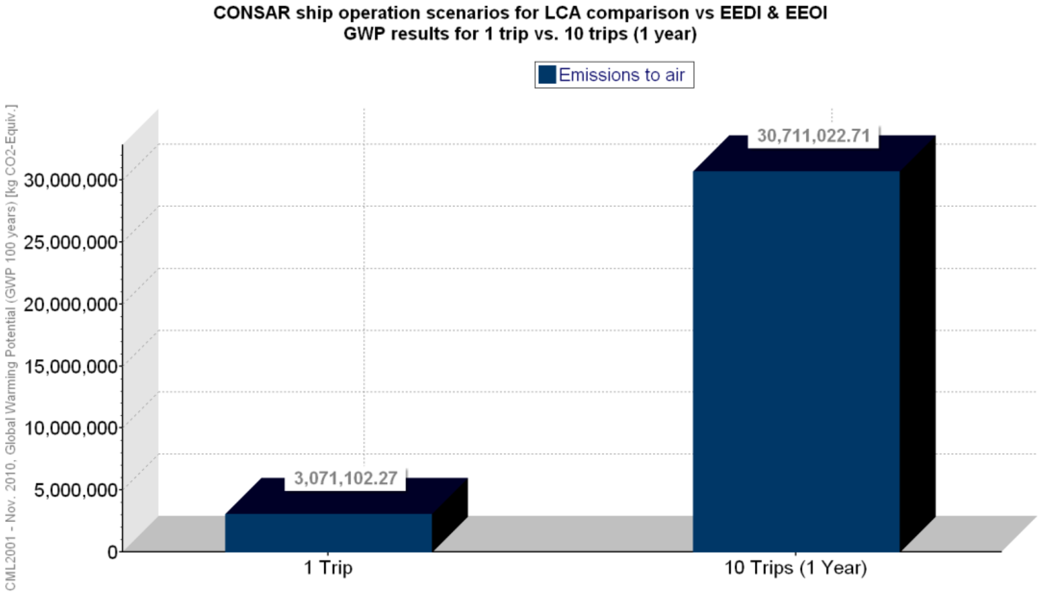


Figure 4.15: GWP 100 years, Bulk carrier vessel operational phase – Aggregated totals – kg CO2eq – 1 trip vs. 10 trips results

Figure 4.15, as well as Table 4.13, summarise the aggregated GWP scores for the 1 operational trip, and 1 year of operation groups: 3.07E+06 kg (3,071 tonnes) of CO_2eq and 3.07E+07 kg (30,711 tonnes) of CO_2eq, respectively. The difference between the above aggregate results and the CO_2 scores generated through inventory (see Table 4.12), represents the additional contribution by ways of classification and characterisation of releases analogous to CO_2. This difference results in 2.84% of the aggregated total, and amounts to 8.72E+04 kg (87.23 tonnes) of CO_2eq and 8.72E+05 kg (872.33 tonnes) of CO_2eq, for the 1 trip and 1 year of operation results, respectively.

Table 4.12: Mass balance, Bulk carrier vessel operational phase – Relevant emissions to air – Absolute values (kg)

		1 Trip			**10 Trips (1 Year)**	
Flows	**Total (1 trip)**	HFO at refinery (1.0 wt.% S)	Ship propulsion & generation	**Total (10 trips)**	HFO at refinery (1.0 wt.% S)	Ship propulsion & generation
Carbon dioxide	**2.98E+06**	2.89E+05	2.69E+06	**2.98E+07**	2.89E+06	2.69E+07
Carbon monoxide	**3.01E+03**	4.21E+02	2.59E+03	**3.01E+04**	4.21E+03	2.59E+04
Nitrogen oxides	**9.46E+04**	8.02E+02	9.38E+04	**9.46E+05**	8.02E+03	9.38E+05
Sulphur dioxide	**2.19E+04**	1.67E+03	2.02E+04	**2.19E+05**	1.67E+04	2.02E+05
Hydrocarbons (unspecified)	**1.55E+03**	4.58E-01	1.55E+03	**1.55E+04**	4.58E+00	1.55E+04

Table 4.13: CML2001 - Nov. 2010, Global Warming Potential (GWP 100 years) – Relevant emissions to air flows and aggregated totals – kg CO2eq

		1 Trip			**10 Trips (1 Year)**	
Flows	**Total (1 trip)**	HFO at refinery (1.0 wt.% S)	Ship propulsion & generation	**Total (10 trips)**	HFO at refinery (1.0 wt.% S)	Ship propulsion & generation
Inorganic emissions to air	**2.99E+06**	2.93E+05	2.69E+06	**2.99E+07**	2.93E+06	2.69E+07
Organic emissions to air (group VOC)	**8.32E+04**	7.16E+04	1.17E+04	**8.32E+05**	7.16E+05	1.17E+05
Emissions to air (total)	**3.07E+06**	3.65E+05	2.71E+06	**3.07E+07**	3.65E+06	2.71E+07

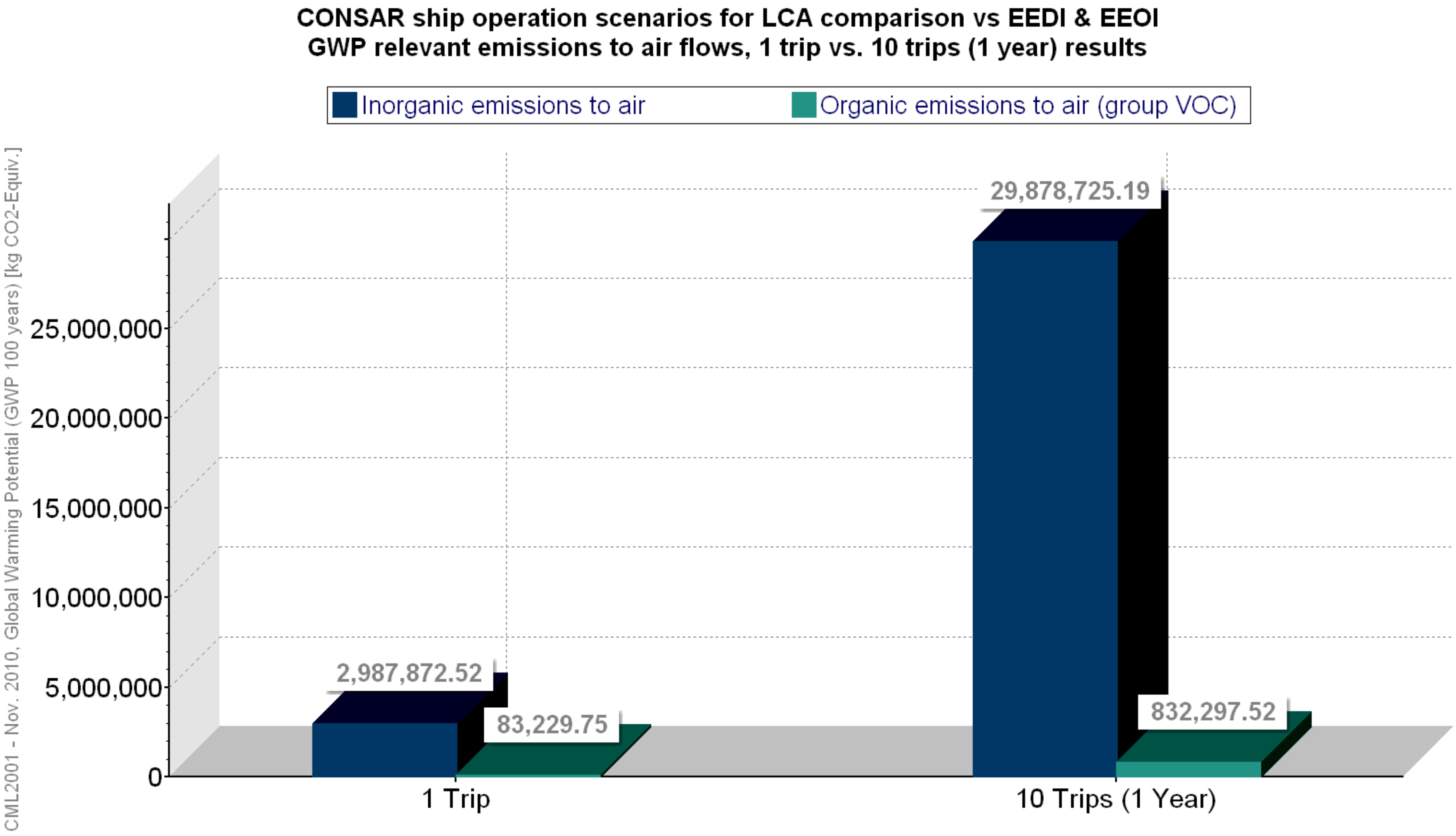


Figure 4.16: GWP 100 years, Bulk carrier vessel operational phase – Relevant emissions to air flows – kg CO2eq – 1 trip vs. 10 trips results

Lastly, as mentioned similarly for the ASTANDER case ship, it should be noted that all LCIA results are relative accounts and expressions, and do not predict impacts on category endpoints, the exceeding of thresholds, or safety margins and/or risks.

4.4 Life cycle interpretation (both cases)

The last phase of the assessment will strive to make a reasonable comparison between the scores produced by the EEDI and EEOI metrics, against the scores generated by performing the LCA appraisal. The differences underlining the score values will be addressed, as well as any specific benefits or disadvantages, particular to the choosing of a certain metric or method over the remaining ones.

The results pertaining the EEDI valuation will be presented in first order for each case vessel, followed by the EEOI outcomes; the comparison among the different methods will follow the documentation of the results, giving way to the recognition of significant issues. Ultimately, conclusions for the assessment and future recommendations will be underscored. Worthy of note is that this phase entails a review of the evaluated data and results, following the guidelines relative to emphasising the consistency of the goal and scope definition(s) throughout the study.

4.4.1 Evaluation of the results and significant issues (ASTANDER case)

Table 4.14 recalls some of the inputs respective to the operational profile of the ASTANDER Ro-Ro passenger vessel. Some of these inputs have been utilised for the calculation of the EEDI and EEOI scores, while the majority have been recorded for the modelling phase relative to performing the LCA appraisal as well. Nevertheless, while the below is applicable to the succeeding EEDI calculation, the following exception contrasts from the value listed in Table 4.14: the use of 12,000 kW (x4) MCR_{ME} to account for the original main engines' output rating, following EEDI recommendations (see inputs used on EEDI calculator on Appendix D.3).

Table 4.14: ASTANDER vessel relevant operational profile inputs

MCR_{ME}:	11,500 kW (x4)	**V_{ref}:**	25 knots
SFC_{ME}:	207 g/kWh	**Cargo (transported / trip):**	2,854.38 tonnes
CO_{2} emission factor:	671 g/kWh	**Cargo (transported / year):**	428,156.25 tonnes
T (time / trip):	22.4 hours	**Capacity (DWT):**	6,515 tonnes
# Trips per year:	150	**D (distance):**	560 miles
T (time / year):	3,360 hours	**SFC_{AE}:**	215 g/kWh
$\%\text{Load}_{\text{ME}}$:	$62\%_{\text{(4 engines)}}$, $70\%_{\text{(3 engines)}}$	**C_F (IMO factor for HFO):**	3.1144 $\text{gCO}_2/\text{gFuel}$

Recalling Table 2.3: Reference values for calculating the required EEDI (GL, 2013), as adapted from (IMO, 2013a, b), and Equation 1 for obtaining the required EEDI value, while also recalling IMO (2014b)'s 2014 EEDI guidelines which define that for Ro-Ro passenger ships deadweight should be used as *capacity*, the following is calculated:

$$Required\ EEDI = a \times b^{-c} = (752.16) \times (6{,}515)^{(-0.381)} = 26.498$$

Thus, the required EEDI for phase 0, which runs from January 1st, 2013 to December 31st, 2014, is equal to 26.498 gCO_2/tonne-nm for the ASTANDER Ro-Ro passenger vessel, with a deadweight capacity of 6,515 tonnes.

The following is the EEDI corrected calculation for the ASTANDER case ship as per the latest EEDI guidelines, released in April 2014. Worthy of mention is that the succeeding equations (3, 4, 5, 6, and 7) are sourced from these guidelines, namely the 2014 Guidelines on the method of calculation of the attained EEDI for new ships (IMO, 2014b). The reader should refer to the last for specifics with regards to the following calculations.

Although GL (2013) defines a "low friction coating" as an "innovative energy efficiency technology", it also adds that it "cannot be separated from the overall performance of the ship", and hence its effect shall not be calculated under the energy saving technology part of the EEDI equation; rather this technology should be appraised under the main section of the EEDI calculation, while evaluating the impact on power and its corresponding reference speed. Therefore, theoretically the EEDI formulation can account for a retrofit such as the implementation of the FRC, while establishing the reduction in power, evaluating the impact on speed, and re-running the calculation with the corrected power and speed inputs.

With the above in mind (i.e. innovative energy saving output not applicable, $P_{eff} = 0$), and assuming that the ASTANDER Ro-Ro passenger vessel is not equipped with a shaft motor (i.e. P_{PTI} = 0), then the EEDI formula is abbreviated as shown in Equation 3.

Equation 3

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME_{(i)}} \cdot C_{FME_{(i)}} \cdot SFC_{ME_{(i)}}\right) + \left(P_{AE_{(i)}} \cdot C_{FAE_{(i)}} \cdot SFC_{AE_{(i)}}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

As mentioned previously, while the auxiliary generators are disregarded through the LCA modelling and EEOI, the EEDI formulation does account for the auxiliary engine power. It does not do so by considering the actual installed auxiliary engines or generators rated capacity (shown as inputs for the BIMCO calculator in Appendix D.3, for example), but by calculating the necessary power required for propulsion machinery, systems, and accommodation while operating at normal maximum sea load as per defined by IMO (2014b). Taking into consideration that the ASTANDER case ship is not equipped with a shaft motor (i.e. P_{PTI} = 0), and that its combined total propulsion power is 10,000 kW or above, the auxiliary engine power is calculated using the abbreviated Equation 4.

Equation 4

$$P_{AE} = \left[0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME_{(i)}}\right)\right] + 250$$

$$P_{AE} = [0.025 \times (48{,}000\ kW)] + 250 = 1{,}450\ kW$$

Having calculated the auxiliary power, the additional required inputs for Equation 3 are the power correction factor (f_{jRoRo}), and the cubic capacity correction factor (f_{cRoPax}). The former is a non-dimensional coefficient and is calculated using Equation 5, the Froude number expressed by Equation 6, some of the vessel particulars found in Table 4.1, and the following defined Ro-Ro passenger ship exponents: $\alpha = 2.50$, $\beta = 0.75$, $\gamma = 0.75$, $\delta = 1.00$ (IMO, 2014b).

Equation 5

$$f_{jRoRo} = \frac{1}{F_{n_L}^{\alpha} \cdot \left(\frac{L_{BP}}{B_s}\right)^{\beta} \cdot \left(\frac{B_s}{d_s}\right)^{\gamma} \cdot \left(\frac{L_{BP}}{\nabla^{\frac{1}{3}}}\right)^{\delta}}$$

Equation 6

$$F_{n_L} = \frac{0.5144 \cdot V_{ref}}{\sqrt{(L_{BP} \cdot g)}}$$

Before solving the power correction factor in Equation 5, the Froude number –also dimensionless–, should be calculated using the ship speed (V_{ref}) found in Table 4.14, the length between perpendiculars (L_{BP}) found in Table 4.1, and the gravitational acceleration, which is equal to 9.81 m/s^2.

$$F_{n_L} = \frac{0.5144 \cdot 25\ knots}{\sqrt{(185.6\ m \cdot 9.81\ m/s^2)}} = 0.3014$$

The above value is used as an input in Equation 5, along with the previously mentioned required variables and exponents, and additionally the volumetric displacement (∇). The volumetric displacement is acquired by dividing the displacement found in Table 4.1 (20,150 tonnes), by the seawater density (1,025 kg/m^3).

$$f_{jRoRo} = \frac{1}{0.3014^{2.5} \cdot \left(\frac{185.6\ m}{25\ m}\right)^{0.75} \cdot \left(\frac{25\ m}{6.4\ m}\right)^{0.75} \cdot \left(\frac{185.6\ m}{(19{,}658.54\ m^3)^{\frac{1}{3}}}\right)^{1}} = 0.2334$$

According to IMO (2014b), and similarly as with some of the other available correction factors, the cubic capacity correction factor (f_c) should be assumed to be one (1.0) if the necessity of the factor is not granted. Nonetheless, for Ro-Ro passenger vessels having a DWT/GT ratio of less than 0.25 –which is the case for the ASTANDER ship–, then the cubic capacity correction factor (f_{cRoPax}) should be applied as shown in Equation 7, while also using the DWT capacity and the GT value described in Table 4.1.

Equation 7

$$f_{cRoPax} = \left[\frac{\left({}^{DWT}/_{GT}\right)}{0.25}\right]^{-0.8}$$

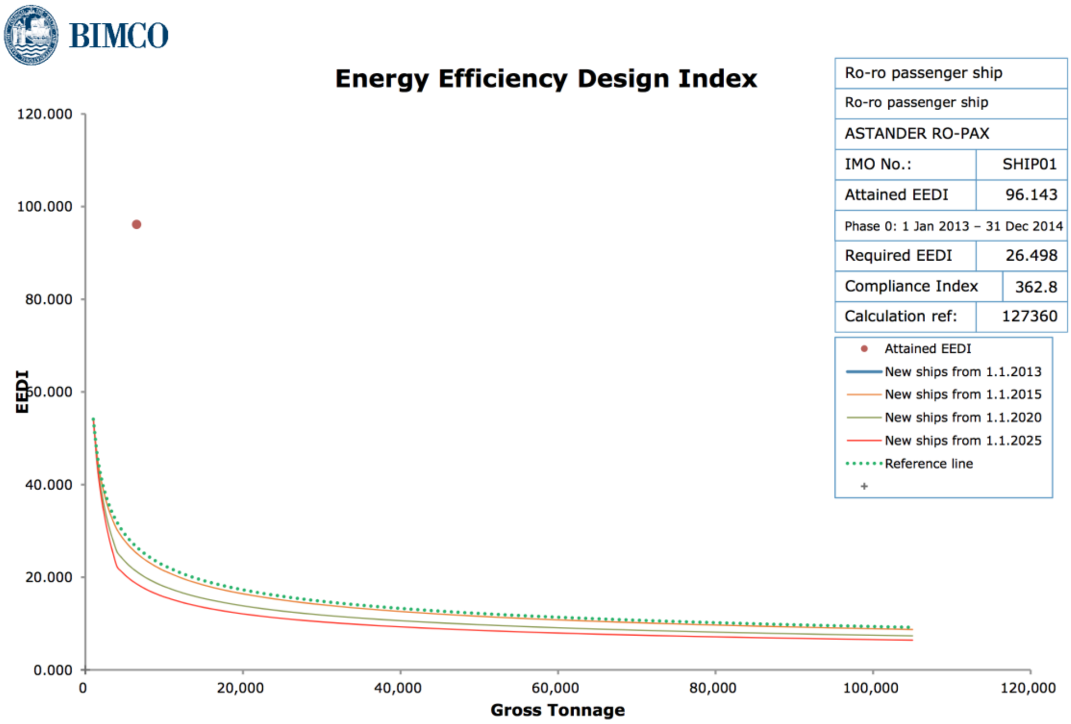
$$f_{cRoPax} = \left[\frac{\left({}^{6{,}515\ tonnes}/_{32{,}728\ tonnes}\right)}{0.25}\right]^{-0.8} = 1.1999$$

Before recalling Equation 3 and calculating the corrected EEDI value for the ASTANDER case ship, it is relevant to point out that the main engine power input (P_{ME}) required in the EEDI formulation, is considered to be 75% of the aggregated rated installed power ($\Sigma MCR_{ME(i)}$). Additionally, the carbon conversion factor (C_F) found in Table 4.14 –and sourced from IMO (2014b)– is applicable to both, the main and auxiliary engines, due to the fact that all of these utilise HFO. Lastly, the SFC for main and auxiliary engines can be found in Table 4.14, as well as the capacity and the reference speed; the capacity correction factor (f_i), the cargo-related gear correction factor (f_l), and the weather correction factor (f_w) are all assumed to be one (1.0).

$$Attained\ EEDI_{Corrected}$$
$$= \frac{(0.2334)(36{,}000\ kW \cdot 3.1144 \cdot 207\ g/kWh) + (1{,}450\ kW \cdot 3.1144 \cdot 215\ g/kWh)}{1 \cdot 1.1999 \cdot 1 \cdot 6{,}515\ tonnes \cdot 1 \cdot 25\ knots}$$
$$= 32.679\ gCO_2/tonne \cdot\ mile$$

The above-obtained result seems a more logical alternative to the following inaccurate computed value shown in Figure 4.17, and also, it brings the plotted point (6,515, 32.679) closer to the reference line curve. Nevertheless, the obtained score would still be under-compliant of the requirements, given that the attained EEDI should be equal to or less than 26.498 gCO_2/tonne-nm, as mentioned earlier. It should be highlighted, however, than the ship in question was built in 2001, and it is not required to comply with the EEDI. The above exercise is still interesting in order to gauge where the vessel stands in terms of environmental design efficiency.

Figure 4.17 shows the plotted reference lines for the ASTANDER case ship, the required EEDI score, and additionally an erroneous result for the calculation of the attained EEDI.



Ro-ro passenger ship	
Ro-ro passenger ship	
ASTANDER RO-PAX	
IMO No.:	SHIP01
Attained EEDI	96.143
Phase 0: 1 Jan 2013 – 31 Dec 2014	
Required EEDI	26.498
Compliance Index	362.8
Calculation ref:	127360

Figure 4.17: ASTANDER case vessel EEDI plot result, screenshot from BIMCO (2011) calculator

Although BIMCO (2011) reassures its calculator is updated with regards to the latest EEDI guidelines additions, the error in the calculation of the above attained EEDI seems to be a result of utilising the wrong power correction factor (f_{jRoRo}), and the wrong cubic capacity correction factor (f_{cRoPax}) for the Ro-Ro passenger vessel. Appendix D.3 shows, aside from the inputs used for the calculation, the list of outcome parameters where the above-mentioned correction factors are both inaccurately listed as 1.

With the above logic in mind, it would also be interesting to evaluate the outcomes resulting from the LCA appraisal, and to compare these with the above result, in order to assess if the scores have any degree of equivalency. The LCA energy efficiency scores are calculated by using Equation 8 and Equation 9; the difference between them is that the first calculates the energy efficiency using the LCA CO_2 inventory aggregate, while the latter supplements this result with the contribution by ways of classification and characterisation of releases analogous to CO_2 (i.e. GWP). Additionally, the denominator in these equations is nothing more than the stated functional performance, relative to the previously defined functional unit of the system.

Equation 8

$$LCA_{eff_{CO2}} = \frac{\sum_i gCO_{2_i}}{\sum_i \left(m_{cargo,i} \times D_i\right)}$$

Equation 9

$$LCA_{eff_{GWP}} = \frac{\sum_i gGWP_i}{\sum_i \left(m_{cargo,i} \times D_i\right)}$$

Table 4.15: Ro-Ro passenger vessel CO2 and GWP aggregate 1-trip results, and respective uncorrected LCA energy efficiency scores while using DWT capacity (6,515 tonnes)

	ΣCO_2 (gCO_2)	ΣGWP (gCO_2eq)	$LCA_{eff(CO2)}$ (gCO2/tonne-nm)	$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)
1 trip A/F	4.74E+08	4.87E+08	130.05	133.48
1 trip FRC	4.02E+08	4.13E+08	110.26	113.17

Table 4.15 recalls the Ro-Ro passenger ship results from Table 4.5 and Table 4.7, while also converting them from kilograms to grams. Additionally, the resulting LCA energy efficiency scores have been already distributed between the 1-trip rows. Nevertheless, the succeeding calculation is a sample to demonstrate the computation of all four scores; the last will be done by using an equivalent functional performance to the previously calculated EEDI. In other words, instead of using the actual quantity of cargo transported, the deadweight tonnage will be utilised as in the EEDI,

denoting the ship's maximum loaded capacity. Lastly, recalling that the 1-trip LCA results would be used for comparison to the EEDI, thus the 1-trip distance is also recorded as an input for the equation (see Table 4.14).

$$LCA_{eff_{CO2\ (1\ trip\ A/F)}} = \frac{4.74\times10^{8} gCO_2}{(6{,}515\ tonnes \times 560\ nautical\ miles)} = 130.05\ \ gCO_2/tonne \cdot nm$$

The reader should note that having the CO_2 and GWP aggregate results in scientific format, might influence the precision of the LCA energy efficiency scores. Nevertheless, the above value does not seem to be in the vicinity of the previously calculated EEDI result (32.679 gCO_2/tonne-nm). The main reason for this difference is that the newly obtain value is not yet revised to account for the power correction factor (f_{jRoRo}), and the cubic capacity correction factor (f_{cRoPax}) performed for the EEDI. These two correction factors are established to account for the design differences this type of ship poses against others, which are ultimately designed for the transportation of maximum mass. These correction factors can only be practically applied to the resulting LCA energy efficiency scores, if their formulation shows a certain equivalency to the formulation performed to attain the EEDI.

Recalling that 90.65% of the LCA CO_2 aggregated total comes from the 'ship propulsion & generation process' contribution, while the rest –9.35%– is attributed to the production of HFO at refinery process (the ratio is proportional to the results shown at the end of section 4.2.3.2), then out of the 4.74E+08 gCO_2 for the 1 trip A/F aggregate balance shown in Table 4.15, a resulting 4.30E+08 gCO_2 belongs to the ship propulsion process contribution. As previously mentioned, this contribution is defined by the parameters found in Figure 3.8, and further by the predecessor engine consumption and emission model by Johnsen and Fet (1998); this last is essentially based on the total released CO_2 emissions, as a product of the fuel consumption (FC_{ME}) of the engines and the carbon content in the fuel, namely the carbon conversion factor (C_{FME}) (see Equation 10).

Equation 10

$$Quantity\ of\ released\ gCO_{2_{Ship\ propulsion}} = FC_{ME} \cdot C_{FME}$$

The carbon conversion factor (C_{FME}) utilised for the LCA modelling is not the same as the one provided by IMO (2014b) and shown in Table 4.14 (3.1144 $gCO_2/gFuel$)[14]. The C_{FME} is slightly higher for the LCA appraisal, and is defined by Equation 11, using inputs from the predecessor model (see Table 4.14).

Equation 11

$$C_{FME} = \frac{CO_{2_{emission\ factor}}}{SFC_{ME}}$$

$$C_{FME} = \frac{671\ g/kWh}{207\ g/kWh} = 3.2415\ \ gCO_2/g\ fuel$$

In turn, Equation 12 defines the fuel consumption for the 1 trip A/F contribution, recalling that 11,500 kW (x4) is used as the MCR to account for lower output efficiency due to engine age and wear, and additionally that the engines operate at a weighted average of 62% load. Lastly, the time (T) required for the completion of 1 trip is considered (see Table 4.14).

Equation 12

$$FC_{ME} = \left(\sum_{i=1}^{nME} MCR_{ME_{(i)}} \cdot \%Load_{ME_{(i)}} \cdot SFC_{ME_{(i)}} \right) \cdot T$$

$$FC_{ME} = [(4 \cdot 11{,}500kW) \cdot 0.62 \cdot 207\ g/kWh] \cdot 22.4h = 1.32 \times 10^8 g\ of\ Fuel$$

---

[14] "C_F is a non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in g based on carbon content" as expressed by IMO, 2014b; this carbon conversion factor can vary depending on the SFC and the CO_2 emission factor relative to the chosen fuel.

Recalling Equation 10, then the CO2 contribution from the 1 trip A/F ‘ship propulsion & generation’ process can be corroborated back to the previously mentioned value and ratio.

$$gCO_{2_{Ship\ propulsion}} = 1.32 \times 10^8 gFuel \cdot 3.2415\ gCO_2/gFuel = 4.30 \times 10^8 gCO_2$$

More importantly, however, is that it is noticeable that some factors from the above calculation are ultimately equivalent to the EEDI formulation. While it is true that the current LCA modelling does not account for the emissions resulting from the auxiliary engines, it does however supplement the aggregate score with the emissions generated by the production of HFO at refinery. Nevertheless, assuming that the auxiliary power is removed from Equation 3, then the EEDI formula is abbreviated as shown in Equation 13.

Equation 13

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME_{(i)}} \cdot C_{FME_{(i)}} \cdot SFC_{ME_{(i)}}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

Recalling Equation 8 and Equation 10 –and substituting the first factor in the numerator of Equation 10 with Equation 12–, while additionally replacing the distance factor (D) in the denominator of Equation 8 with the $D=V_{ref}\times T$ relation, the resulting Equation 14 can be substituted back into Equation 13, and consequently implement the power correction factor (f_{jRoRo}) and the cubic capacity correction factor (f_{cRoPax}) solely for the emissions generated by the main engines, as similarly performed by the EEDI.

$$LCA_{eff_{CO2\ (ship\ propulsion)}} = \frac{FC_{ME} \cdot C_{FME}}{m_{cargo} \cdot D}$$

$$LCA_{eff_{CO2\ (s.p.)}} = \frac{\left(\sum_{i=1}^{nME} MCR_{ME_{(i)}} \cdot \%Load_{ME_{(i)}} \cdot SFC_{ME_{(i)}}\right) \cdot T \cdot C_{FME}}{m_{cargo} \cdot D}$$

Equation 14

$$LCA_{eff_{CO2\,(s.p.)}} = \frac{\left(\sum_{i=1}^{nME} MCR_{ME_{(i)}} \cdot \%Load_{ME_{(i)}} \cdot SFC_{ME_{(i)}}\right) \cdot C_{FME} \cdot \cancel{T}}{m_{cargo} \cdot V_{ref} \cdot \cancel{T}}$$

$$LCA_{eff_{CO2\,(s.p.)}} = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} MCR_{ME_{(i)}} \cdot \%Load_{ME_{(i)}} \cdot C_{FME_{(i)}} \cdot SFC_{ME_{(i)}}\right)}{f_i \cdot f_c \cdot f_l \cdot m_{cargo} \cdot f_w \cdot V_{ref}}$$

$$\begin{aligned} LCA_{eff_{CO2\,(s.p.)}} &= \frac{(0.2334)([(4 \cdot 11{,}500kW) \cdot 0.62 \cdot 207\ g/kWh] \cdot 3.2415)}{1 \cdot 1.1999 \cdot 1 \cdot 6{,}515\ tonnes \cdot 1 \cdot 25\ knots} \\ &= 22.849\ gCO_2/tonne \cdot\ mile \end{aligned}$$

The aggregate LCA energy efficiency score for the 1 trip A/F contribution can now be calculated, adding the above corrected LCA efficiency score for the ship propulsion process, to the remaining attributed emissions of the production of HFO at refinery process consequently divided by the previously utilised functional performance.

$$\begin{aligned} & LCA_{eff_{CO2\,(1\ trip\ A/F, corrected)}} \\ &\quad = 22.849\ gCO_2/tonne \cdot\ mile + \frac{4.44 \times 10^7 gCO_2}{6{,}515\ tonnes\ \times\ 560\ nm} \\ &\quad = 35.015\ gCO_2/tonne \cdot\ mile \end{aligned}$$

The above value is much closer to the corrected EEDI result (32.679 gCO_2/tonne-nm). The slight difference between the two obtained results are due to the following reasons:

1. Engine MCR is regarded as 12,000 kW(x4) for the EEDI, while the LCA modelling utilises 11,500 kW(x4) as an input.
2. Main engine output power relative to the EEDI calculation is 75% of the rated installed power (MCR), while the LCA model utilises 62% of the rated installed power when 4 out of the 4 main engines are operational.

3. The carbon conversion factor used for the EEDI calculation is equal to 3.1144, while the factor utilised for the LCA modelling is slightly higher totalling 3.2415.
4. Lastly, although smaller in proportion to the emissions from the main engines, the EEDI result encompasses the emissions generated by the specified auxiliary power. In turn, the LCA modelling features the added emissions from the ancillary HFO production process.

The above-explained steps for the correction of the LCA energy efficiency scores, can be similarly applied to the LCA efficiency results relative to the GWP column (see Table 4.15); this can be performed by separating the emission contributions, applying the correction factors solely to the emissions generated by the main engines, and aggregating the results while observing the relative functional performance (see Table 4.16). The LCA GWP energy efficiency scores, although corrected, will turn out proportionally higher due to the increment by ways of the contribution of releases analogous to the warming potential of CO_2.

Table 4.16: Ro-Ro passenger vessel corrected and uncorrected LCA energy efficiency scores while using DWT capacity (6,515 tonnes), 1-trip results

	Uncorrected		**Corrected**	
	$LCA_{eff(CO2)}$ (gCO2/tonne-nm)	**$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)**	**$LCA_{eff(CO2)}$ (gCO2/tonne-nm)**	**$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)**
1 trip A/F	130.05	133.48	35.015	38.441
1 trip FRC	110.26	113.17	29.662	32.568

It is also clear that LCA energy efficiency scores procured by the 1 trip FRC retrofit can be similarly corrected –but more significantly–, due to the above evidenced equivalency between formulations, is understandable that the EEDI can emulate the inventory CO_2 savings resulting from the FRC retrofit LCA appraisal (respective solely to the main engines contribution), by correspondingly adjusting factors relative to the reduction in power and the impact on speed. Nevertheless, the savings generated through the reduction in HFO production, as well as the savings from emissions analogous to the detrimental effect of CO2, remain an added benefit to the application of the Life Cycle Assessment.

With regards to the EEOI –although also holding similitude to the EEDI formulation–, its equation is less complex, focusing mainly on the fuel consumed per voyage, and the actual distance and cargo transported. Thus, the main differences with regards to the EEDI formulation is that auxiliary power is not considered specifically, there is no specific input or variable for energy saving technologies, and there are no specified correction factors for weather or different ship types. Additionally, the EEOI uses a variant of the $D = V_{ref} \times T$ relation; i.e. instead of using the reference speed, it uses the distance factor. The EEOI is calculated using Equation 15 for a single trip, and Equation 2 for a rolling average comprising a number of trips.

Equation 15

$$EEOI_{single\ trip} = \frac{\sum_j \left(FC_j \times C_{Fj} \right)}{m_{cargo} \times D}$$

Worthy of mention is that, likewise to the EEDI, the EEOI guidelines also recognise ship types such as passenger vessels –including Ro-Ro passenger ships–, to be designed for a multi-functional purpose and not only specific to the transport of maximum mass; the last is underlined by IMO (2009d)'s suggestion of utilising the vessel's gross tonnes as the specified quantity of cargo mass carried, when involving the above-mentioned ship types in the calculation.

Nevertheless, IMO (2009d) also underscores that for such types of vessels, which carry a mixture of cargo –including passengers and freight–, end users are encouraged to consider a certain weighted averaged to represent the work performed relative to the ship's particular service or trade. This last is considered to be equivalent to the definition of the ASTANDER Ro-Ro passenger vessel functional performance described in section 4.2.2.3, and therefore applicable to the succeeding EEOI calculations.

Of relevance is that the following computations are in accordance to the assumption that the Ro-Ro passenger vessel has a constant quantity of cargo carried per year –

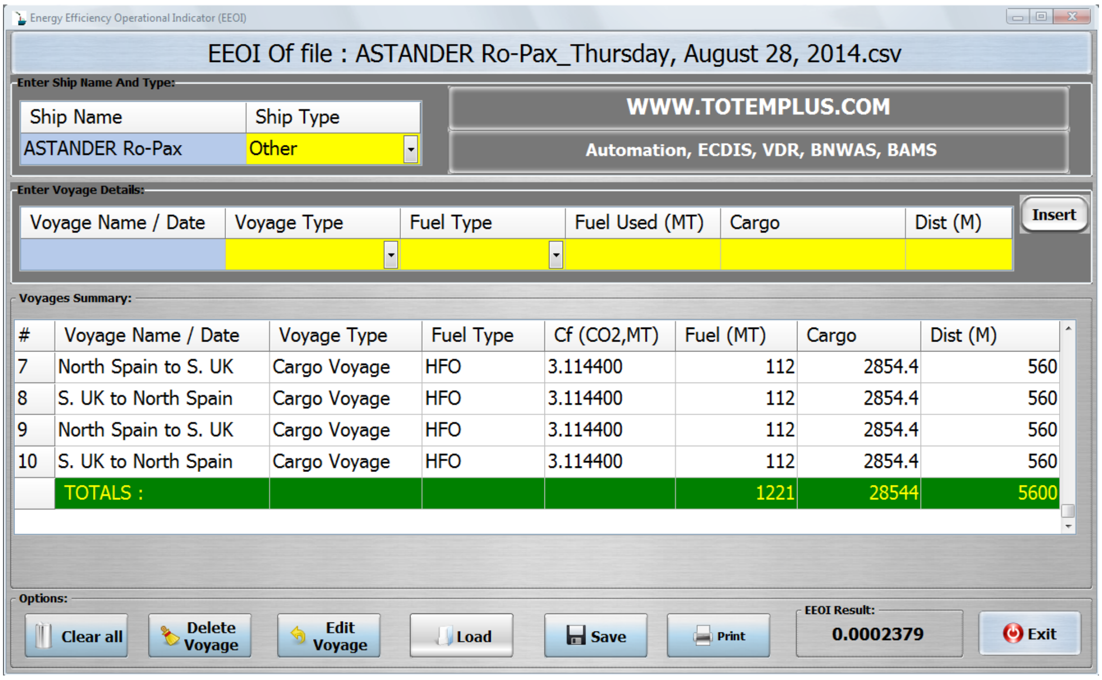
and therefore per trip–, as per defined by section 4.2.2.3. Although this last is due to the public unavailability of data with regards to the ship's cargo manifest, it also allows for a more direct comparison to the LCA methodology, given the shared similarity with regards to the utilised inputs. Nevertheless, this should be underlined as a potential limitation, which should be listed as another candidate for enhancement of further studies.

Recalling Equation 15, as well as the values for the carbon conversion factor, the single trip distance, and the quantity of cargo carried per trip –all found in Table 4.14–, and additionally recalling the fuel consumption relative to the 1-trip A/F result of Equation 12, the following defines the EEOI score for a single trip under the antifouling coating scheme:

$$EEOI_{1-trip\ A/F} = \frac{\left(1.32 \times 10^{8} g\ of\ Fuel \cdot 3.1144\ {}^{gCO_2}\!/_{gFuel}\right)}{(2{,}854.38\ \text{tonnes} \cdot 560\ nautical\ miles)}$$
$$= 257.658\ gCO_2/tonne \cdot\ mile$$

The EEOI score for a single trip under the FRC retrofit can be calculated correspondingly, by using the above formula and values –with the exception of the fuel consumption–, which would have to be calculated again using Equation 12, and adjusting accordingly for the number of engines and weighted average load (i.e. 3 engines and 70% load). Table 4.17 gathers the EEOI single trip results for both, the A/F and FRC schemes.

In turn, Figure 4.18 shows a screenshot of the Totem-Plus (2012) calculator, depicting the resulting average EEOI score for a total of 10 trips –5 trips under the A/F coating, and 5 trips under the FRC scheme–; as the result is originally shown in tonnes of CO_2 over cargo tonnes per nautical mile, the conversion would total 237.918 gCO_2/tonne-nm. Additionally, Appendix D.4 shows the complete list of voyage inputs, which clearly regard information related to the operational profile of the vessel (correspondingly found in Table 4.14).



EEOI Of file : ASTANDER Ro-Pax_Thursday, August 28, 2014.csv

Ship Name	Ship Type
ASTANDER Ro-Pax	Other

#	Voyage Name / Date	Voyage Type	Fuel Type	Cf (CO2,MT)	Fuel (MT)	Cargo	Dist (M)
7	North Spain to S. UK	Cargo Voyage	HFO	3.114400	112	2854.4	560
8	S. UK to North Spain	Cargo Voyage	HFO	3.114400	112	2854.4	560
9	North Spain to S. UK	Cargo Voyage	HFO	3.114400	112	2854.4	560
10	S. UK to North Spain	Cargo Voyage	HFO	3.114400	112	2854.4	560
	TOTALS :				1221	28544	5600

EEOI Result: 0.0002379

Figure 4.18: ASTANDER case vessel EEOI result, screenshot from Totem-Plus (2012) calculator

Due to the nature of the EEOI rolling average formulation, the 10 trips discussed above are representative of the 150 trips the Ro-Ro passenger vessel undertakes each year, given that the results are equivalent if the ratio of the factors in the formula stays unchanged. The following computation will confirm this using Equation 2, while also recalling that it is assumed that the FRC retrofit takes place halfway through the yearly operational phase of the vessel (i.e. utilising the corresponding fuel consumption for 75 trips under the conventional A/F coating, and the fuel consumption for the remaining 75 trips with the FRC scheme), and lastly utilising cargo and distance data relative to this period (see Table 4.14).

$$Yearly\ Average\ EEOI = \frac{\sum_i \sum_j (FC_{ij} \times \ C_{Fj})}{\sum_i (m_{cargo,i} \ \times \ D_i)}$$

$$Yearly\ Average\ EEOI\ =$$

$$= \frac{3.1144\ {}^{gCO_2}/_{gFuel}\left[\left(1.32 \times 10^8 gFuel \cdot 75\ trips\right) + \left(1.12 \times 10^8 gFuel \cdot 75\ trips\right)\right]}{560\ \text{nautical miles}\left[\left(2854.375\ tonnes\right) \cdot \left(150\ trips\right)\right]}$$

$$= 237.918\ {}^{gCO_2}/_{tonne \cdot nm}$$

The above value is visibly equivalent to the previously obtained result due to the unchanged proportion between the fuel consumption, distance, and cargo-transported inputs. As another example, 10 and 150 trips under the A/F paint system proportional fuel consumption, would generate the same parallel score to the 1-trip result (257.658 gCO_2/tonne-nm), given that the ship travelled the same distance, and carried the same quantity of cargo per trip. This of course is ultimately caused by the assumption of constant cargo carried, and additionally by the regular schedule of the vessel. Correspondingly, the 150 trips A/F & FRC result above calculated, is also analogous to the average value between both 1-trip results (see Table 4.17).

Table 4.17: Ro-Ro passenger vessel EEOI and respective LCA energy efficiency scores, 1 trip and 150 trips (1 year) results

	EEOI (gCO2/tonne-nm)	**LCA$_{eff(CO2)}$ (gCO2/tonne-nm)**	**LCA$_{eff(GWP)}$ (gCO2eq/tonne-nm)**
1 trip A/F	257.658	296.843	304.664
1 trip FRC	218.178	251.671	258.302
150 trips A/F & FRC	237.918	274.257	281.483

Before proceeding to underline the resulting LCA energy efficiency scores –also gathered under Table 4.17–, it is interesting to note that the difference between the 1-trip EEOI results is that of 39.480 gCO_2/tonne-mile, which ultimately underscores the CO2 savings generated by the FRC retrofit, and it also demonstrates that this is directly highlighted by the EEOI metric. Nevertheless, the savings amounting to a number of trips or voyages, would have to be calculated using only the numerator of the EEOI formula, as using the whole EEOI equation would just generate a score proportional to the 1-trip results as previously explained.

Table 4.17 evidences that the resulting LCA energy efficiency scores are not numerically far off with regards to the obtained EEOI values. These LCA scores are procured similarly to the previously demonstrated results in the EEDI section; the following is a sample calculation for one of the scores, recalling Equation 8 and the CO_2 aggregated total for a year of operation found in Table 4.5, as well as the resulting cargo transported and distance travelled found in Table 4.14.

$$LCA_{eff_{CO2\ (150\ trips\ A/F\ \&\ FRC)}} = \frac{6.58 \times 10^{10}\ gCO_2}{428{,}156.25\ tonnes \cdot 560\ nautical\ miles}$$
$$= 274.257\ \ gCO_2/tonne \cdot mile$$

The above LCA energy efficiency CO_2 value is relative to 1 year of operation –150 trips in total–, and takes into consideration the inventory aggregate for CO_2 emissions during that period, which in turn is comprised of emissions from the ship propulsion and generation process, as well as contributing releases from the production of HFO. Due to the fact that the previous ratios of contribution from these two different processes to the 1-trip CO_2 results apply (see the end of section 4.2.3.2), therefore the LCA efficiency can also be calculated solely for the main engines' emissions, recalling that 90.65% of the CO2 aggregated total is generated by the ship propulsion process.

$$LCA_{eff_{CO2\ S.P.(150\ trips\ A/F\ \&\ FRC)}} = \frac{0.9065 \cdot (6.58 \times 10^{10}\ gCO_2)}{428{,}156.25\ tonnes \cdot 560\ nautical\ miles}$$
$$= 248.603\ \ gCO_2/tonne \cdot mile$$

The above value is clearly closer to the previously obtained yearly average EEOI result (237.918 gCO_2/tonne-nm). The slight difference between the two obtained values is due to the following reason:

1. The carbon conversion factor used for the EEOI calculation is equal to 3.1144, while the factor utilised for the LCA modelling is slightly higher totalling 3.2415.

Although not applicable to the above due to the separation in emissions contribution, worthy of re-emphasis is that the LCA modelling –likewise as formerly described in the EEDI section–, features the added emissions from the ancillary HFO production process, while the EEOI does not account specifically for these releases.

Furthermore, and also in much the same way as previously explained for the EEDI, the LCA efficiency values compared to the EEOI and relative to the GWP column (see Table 4.17), are slightly higher in comparison to the other gathered scores, due to the aforementioned contribution of additional releases with warming capabilities.

Worthy of note as well is that the CO_2 savings procured by the FRC retrofit under the 1-trip results are obtained similarly as the EEOI savings outcome, totalling 45.172 gCO_2/tonne-mile (see Table 4.17). Nonetheless, the ability to identify exactly where do these savings occur in the matter of 1 year of operation or more, with regards to specific processes or even individual substance contribution, continues to underline a valuable advantage to the LCA application.

Lastly, and of significance, is that the previously numbered differences –both for the EEDI and EEOI–, where meant to establish a certain contrast within the formulation and end results among the energy efficiency metrics and LCA scores, with the end purpose of demonstrating that the two methods (i.e. EEDI and LCA, and EEOI and LCA) can be reasonably applied alternatively. The remaining samples will also evidence that the available flexibility on the part of the LCA formulation, allows the end-user to tailor the LCA model as required, in order to procure outcomes parallel to the existent metrics' results.

4.4.2 Evaluation of the results and significant issues (CONSAR case)

Table 4.18 recalls some of the inputs respective to the operational profile of the CONSAR bulk carrier. Similarly as with the ASTANDER case vessel, some of these inputs have been utilised for the calculation of the EEDI and EEOI scores, while the majority have been recorded for the modelling phase relative to performing the LCA appraisal, emphasising the definition differences mentioned in section 4.3.3.1 for the ship propulsion and generation process.

Table 4.18: CONSAR vessel relevant operational profile inputs

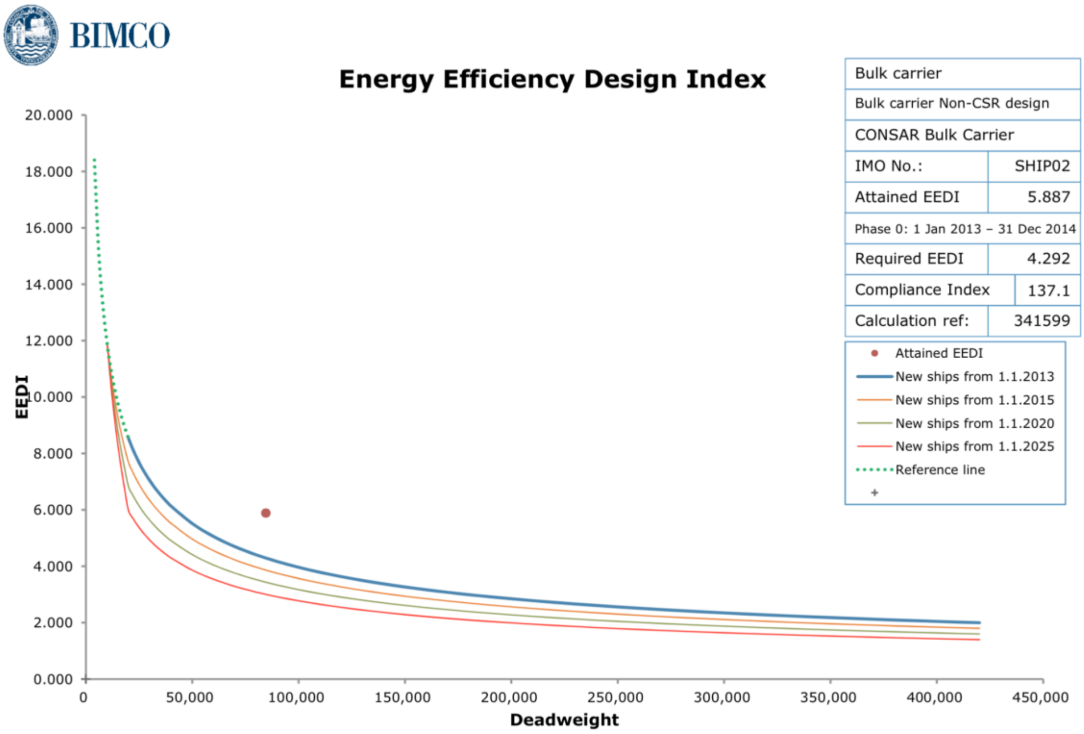
MCR$_{ME}$:	14,280 kW	***V$_{ref}$*:**	12 knots
SFC$_{ME}$:	167 g/kWh	**Cargo (transported / trip):**	67,351.45 tonnes
CO$_{2}$ emission factor:	520 g/kWh	**Cargo (transported / year):**	336,757.25 tonnes
T (time / trip):	484 hours	**Capacity (DWT):**	84,607 tonnes
# Trips per year:	10	**D (distance):**	5,808 miles
T (time / year):	4,840 hours	**SFC$_{AE}$:**	215 g/kWh
%Load$_{ME}$:	75%	**C$_{F}$ (IMO factor for HFO):**	3.1144 gCO$_2$/gFuel

Recalling Table 2.3: Reference values for calculating the required EEDI (GL, 2013), as adapted from (IMO, 2013a, b), and Equation 1 for obtaining the required EEDI value, while also recalling IMO (2014b)'s 2014 EEDI guidelines which define that for bulk carriers deadweight should be used as *capacity*, the following is calculated:

$$Required\ EEDI = a \times b^{-c} = (961.79) \times (84{,}607)^{(-0.477)} = 4.292$$

Therefore, the required EEDI for phase 0, which runs from January 1st, 2013 to December 31st, 2014, is equal to 4.292 gCO$_2$/tonne-nm for the CONSAR bulk carrier, with a deadweight capacity of 84,607 tonnes. Figure 4.19 shows the plotted reference lines for the CONSAR case ship, the required EEDI score, and additionally the plotted result for the calculation of the attained EEDI (5.887 gCO$_2$/tonne-nm). Additionally, Appendix D.7 evidences the inputs utilised for the calculation, and gathers the list of outcome parameters.

In contrast to the ASTANDER case vessel EEDI calculation, CONSAR's bulk carrier EEDI computation does not underscore the necessity for the application of correction factors; thus, the calculation is less complex. Moreover, the bulk carrier case vessel does not comprise the implementation of an innovative energy saving technology, nor is equipped with a shaft motor (i.e. $P_{eff} = 0$ and $P_{PTI} = 0$).



Bulk carrier	
Bulk carrier Non-CSR design	
CONSAR Bulk Carrier	
IMO No.:	SHIP02
Attained EEDI	5.887
Phase 0: 1 Jan 2013 – 31 Dec 2014	
Required EEDI	4.292
Compliance Index	137.1
Calculation ref:	341599

Figure 4.19: CONSAR case vessel EEDI plot result, screenshot from BIMCO (2011) calculator

Prior to recalling Equation 3 for the calculation of the EEDI observing the above-mentioned issues, the required auxiliary power should be calculated as per defined by IMO (2014b) using Equation 4 (while also re-highlighting that the ship in question is not equipped with a shaft motor, i.e. P_{PTI} = 0, and that its combined total propulsion power is 10,000 kW or above). Worthy of mention as well is that the auxiliary generators continue to be disregarded through the case's LCA modelling and EEOI appraisal, likewise to the previously assessed case ship.

$$P_{AE} = \left[0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME_{(i)}}\right)\right] + 250$$

$$P_{AE} = [0.025 \times (14{,}280\ kW)] + 250 = 607\ kW$$

Having calculated the auxiliary power, and recalling that the main engine power input (P_{ME}) required for the EEDI formulation is considered to be 75% of the aggregated rated installed power ($\Sigma MCR_{ME(i)}$), and additionally emphasising on the carbon conversion factor (C_F) and SFC for both main and auxiliary engines, the capacity, and the reference speed –all listed in Table 4.18–, and lastly assuming that the power correction factor (f_j), the cubic capacity correction factor (f_c), the capacity correction factor (f_i), the cargo-related gear correction factor (f_l), and the weather correction factor (f_w) are all equal to one (1.0), the following underlines the calculation for the vessel's attained EEDI:

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME_{(i)}} \cdot C_{FME_{(i)}} \cdot SFC_{ME_{(i)}}\right) + \left(P_{AE_{(i)}} \cdot C_{FAE_{(i)}} \cdot SFC_{AE_{(i)}}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

$$Attained\ EEDI$$
$$= \frac{(1)(10{,}710\ kW \cdot 3.1144 \cdot 167\ g/kWh) + (607\ kW \cdot 3.1144 \cdot 215\ g/kWh)}{1 \cdot 1 \cdot 1 \cdot 84{,}607\ tonnes \cdot 1 \cdot 12\ knots}$$
$$= 5.887\ gCO_2/tonne \cdot\ mile$$

Although the above-obtained result is relatively close to the phase 0 reference line, it is still under compliant of the regulatory framework as it is clear that the required EEDI is lower (4.292 gCO_2/tonne-nm). Nonetheless, this ship –similarly as the ASTANDER case vessel– is currently not required to comply with the EEDI, having been built in 2009; thus the above is purely a hypothetical exercise to review what would the ship's environmental design efficiency seem like at the time of construction.

Table 4.19: Bulk carrier CO2 and GWP aggregate 1-trip results, attained EEDI, and respective LCA energy efficiency scores while using DWT capacity (84,607 tonnes)

	ΣCO_2 (gCO_2)	**ΣGWP (gCO_2eq)**	**EEDI (gCO2/tonne-nm)**	**$LCA_{eff(CO2)}$ (gCO2/tonne-nm)**	**$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)**
1 trip	2.98E+09	3.07E+09	5.887	6.072	6.250

With regards to the LCA energy efficiency scores, Table 4.19 already encompasses the gathered values, while additionally including the bulk carrier aggregate emission results from Table 4.12 and Table 4.13 –converted from kilograms to grams–, and lastly the attained EEDI result. It is interesting to note that the obtained LCA energy efficiency scores are rather close to the attained EEDI; this last is mainly due to the fact that ship functionality correction is not necessary for the bulk carrier –given that this type of vessel is designed for the transportation of maximum mass–, and additionally due to the fact that the LCA model formulation has been modified slightly (see section 4.3.3.1), addressing some of the numbered differences previously mentioned during the ASTANDER case vessel appraisal description.

As demonstrated earlier, the LCA efficiency score for the CO_2 aggregate result in Table 4.19 can be calculated recalling Equation 8, the CO_2 aggregate value displayed in the same table, the capacity utilised for the EEDI calculation, and the single trip distance found in Table 4.18. Equation 9 can be utilised similarly to calculate the LCA energy efficiency score for the GWP aggregate result.

Both of these aggregate emission results, CO_2 and GWP, are comprised of the aforementioned contribution of releases from the HFO production process, as well as emissions from the ship propulsion process. Prior to highlighting the sole CO_2 contribution of the main engine’s emissions, likewise as mostly emphasised on the EEDI formulation, the following are the differences that have been addressed to enable a more parallel comparison between the EEDI and LCA results:

1. Engine MCR is regarded as 14,280 kW for the EEDI, as well as for the LCA modelling.
2. Main engine output power relative to the EEDI calculation is 75% of the rated installed power (MCR), as well as for the LCA modelling.
3. The carbon conversion factor used for the EEDI calculation is equal to 3.1144, as correspondingly utilised for the LCA modelling.

Perhaps the most significant of the above-mentioned issues is the carbon conversion factor, as the regarded MCR and utilised per cent load are not uncommon to the current ship’s operational profile and consequent LCA modelling. Thus, the emphasised model modification underlines the vessel's CO2 emission factor, in order to have an equivalent conversion value to that utilised by IMO on both, the EEDI and EEOI formulations (see the following calculation, while recalling Equation 11).

$$C_{FME} = \frac{520.10\ g/kWh}{167\ g/kWh} = 3.1144\ \ gCO_2/gFuel$$

Therefore, underlining the previously explained equivalency between the two formulations –the EEDI and the defined LCA emissions release function for the ship propulsion process (see Equation 10)–, in theory the aggregate releases generated by the main engine under the LCA process definition while recalling the functional performance of the vessel, should equal the attained EEDI result minus the auxiliary power contribution.

Recalling Equation 8, the CO2 separate ship propulsion contribution result from Table 4.12 (converted to grams), the capacity utilised for the EEDI calculation, and the single trip distance found in Table 4.18, the following denotes the LCA energy efficiency score solely for the CO2 emissions generated by the ship's propulsion plant:

$$LCA_{eff_{CO2\,(1\,trip\,S.P.)}} = \frac{2.69 \times 10^9 gCO_2}{(84{,}607\ tonnes\ \times\ 5808\ nautical\ miles)}$$
$$= 5.486\ \ gCO_2/tonne \cdot nm$$

Lastly, assuming that the auxiliary power is removed from the EEDI equation –due to the formerly highlighted fact that the current LCA model formulation does not include releases from auxiliary engines–, the following would be the theoretical attained EEDI exclusively for the main engine's emissions:

$$Attained\ EEDI_{(w/o\ aux\ pwr)} = \frac{(1)(10{,}710\ kW \cdot 3.1144 \cdot 167\ g/kWh)}{1 \cdot 1 \cdot 1 \cdot 84{,}607\ tonnes \cdot 1 \cdot 12\ knots}$$
$$= 5.486\ gCO_2/tonne \cdot\ mile$$

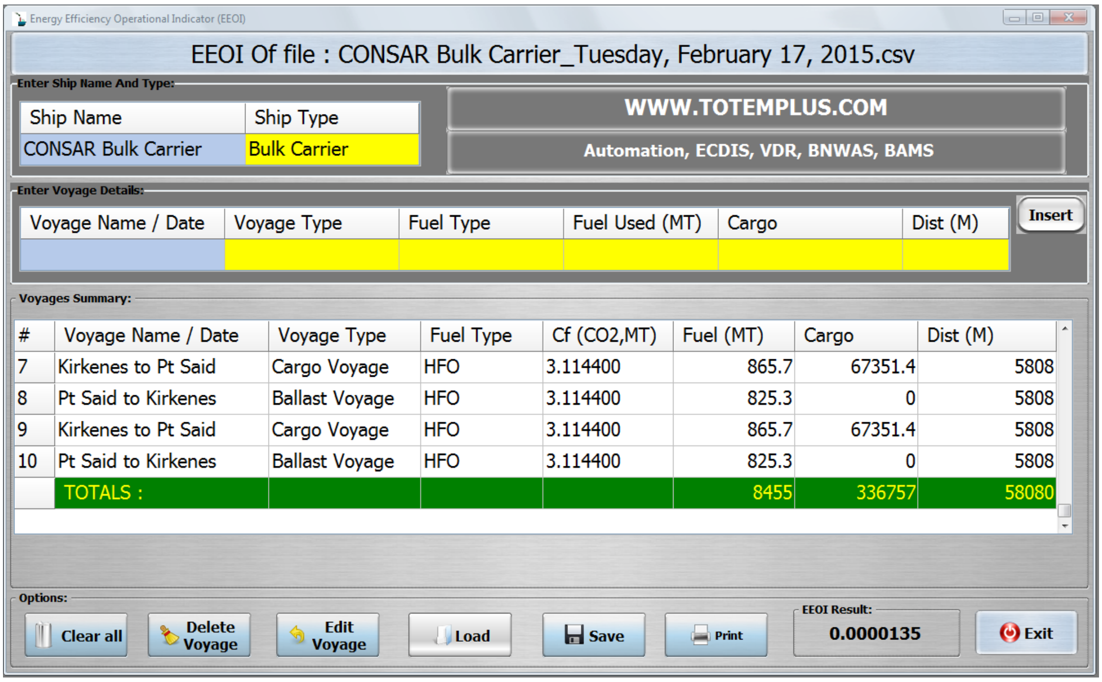
The above is merely an exercise in order to demonstrate the type of flexibility, which could allow the end user to adapt the LCA formulation –not only to be applied alternatively to the IMO efficiency metrics–, but also implemented in parallel to them when the need for further environmental efficiency information was required. While it is true that further work is necessary with regards to the LCA formulation explained herein –e.g. the inclusion of parameters allowing the simulation of releases related to auxiliary engines–, the present work is intended to demonstrate the possibility and advantages of the LCA application as a tool for highlighting shipping energy efficiency, as satisfactorily as the regulatory metrics.

The following and last sample regards the bulk carrier's appraisal under the EEOI metric, as well as its resulting LCA energy efficiency scores. It should be noted that, likewise to the ASTANDER case vessel, the following calculations are in accordance to the assumption that the bulk carrier transports a constant quantity of cargo per year –and thus per trip–, as per defined by section 4.3.2.3. Nonetheless, in contrast to the previously assessed case ship, the bulk carrier's assessment will comprise the inclusion of loaded, as well as ballast voyages (see section 4.3.2.1), with the aim of underlining any differences between the EEOI and LCA valuations.

The EEOI score for a single *loaded* trip is calculated by recalling Equation 15, as well as the values for the carbon conversion factor, the single trip distance, and the quantity of cargo carried per trip –all found in Table 4.18–, and additionally recalling Equation 12 for the fuel consumption, and adjusting accordingly for the number of engines, the MCR, the weighted average load, the SFC, and the trip duration (i.e. 1 engine, 14,280 kW, 75% load, 167 g/kWh, and 484 hours). Table 4.20 gathers the EEOI single loaded trip result.

It is relevant to note that the resulting fuel consumption for the single loaded trip averages 865.67 tonnes per trip. Underscoring information provided by CONSAR, the ship consumes 2 tonnes of fuel less per day during a ballast voyage. Recalling that each voyage lasts 20.17 days, the fuel consumption relative to a ballast voyage totals 825.33 tonnes per trip.

Figure 4.20 shows a screenshot of the Totem-Plus (2012) calculator, representing the resulting average EEOI score for a total of 10 trips (1 year), including the rounded fuel consumption for loaded as well as ballast voyages. The converted result totals 13.463 gCO_2/tonne-nm (see Table 4.20). Additionally, Appendix D.8 shows the complete list of voyage inputs, regarding their cargo status and consequently their respective fuel consumption values.



EEOI Of file : CONSAR Bulk Carrier_Tuesday, February 17, 2015.csv

Enter Ship Name And Type:

Ship Name	Ship Type
CONSAR Bulk Carrier	Bulk Carrier

WWW.TOTEMPLUS.COM

Automation, ECDIS, VDR, BNWAS, BAMS

Enter Voyage Details:

Voyage Name / Date	Voyage Type	Fuel Type	Fuel Used (MT)	Cargo	Dist (M)

Voyages Summary:

#	Voyage Name / Date	Voyage Type	Fuel Type	Cf (CO2,MT)	Fuel (MT)	Cargo	Dist (M)
7	Kirkenes to Pt Said	Cargo Voyage	HFO	3.114400	865.7	67351.4	5808
8	Pt Said to Kirkenes	Ballast Voyage	HFO	3.114400	825.3	0	5808
9	Kirkenes to Pt Said	Cargo Voyage	HFO	3.114400	865.7	67351.4	5808
10	Pt Said to Kirkenes	Ballast Voyage	HFO	3.114400	825.3	0	5808
	TOTALS :				8455	336757	58080

EEOI Result: 0.0000135

Figure 4.20: CONSAR case vessel EEOI result, screenshot from Totem-Plus (2012) calculator

Table 4.20 comprises both EEOI results –1 and 10 trips–, as well as the resulting LCA energy efficiency scores for the CO_2 and GWP aggregate results found in Table 4.19, and relative to the ship's functional performance for 1 and 10 trips, respectively (these scores are procured correspondingly as demonstrated for the previously appraised case vessel, see section 4.4.1).

Similarly as with the aforementioned EEDI values, the difference from the EEOI results to the LCA energy efficiency scores is minimal (see Table 4.20), understanding that the latter's formulation is rather analogous to the EEOI's. Nevertheless, both LCA efficiency scores are slightly higher in comparison to that of their EEOI's counterpart; the last is clearly due to the previously explained additional contribution that each LCA category, CO_2 and GWP, inherently supplies.

Table 4.20: Bulk carrier vessel EEOI and respective LCA energy efficiency scores, 1 trip and 10 trips (1 year) results

	EEOI (gCO2/tonne-nm)	**$LCA_{eff(CO2)}$ (gCO2/tonne-nm)**	**$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)**
1 trip **loaded**	6.892	7.628	7.851
10 trips **(5 loaded & 5 ballast)**	13.463	15.256	15.702

With the above in mind, it is also interesting to note that the resulting LCA energy efficiency score solely for the CO_2 ship propulsion contribution outcome (see Table 4.12), calculated using the single trip distance and cargo carried values –found in Table 4.18–, totals 6.892 gCO_2/tonne-nm, equalling the EEOI single loaded trip result (see Table 4.20). The last underlines once again the equivalency between both formulations, EEOI and LCA, and additionally the potential of using each other optionally.

Lastly, it is relevant to point out that a correction for the LCA energy efficiency scores relative to various voyages –comprising loaded and ballast fuel consumption results– would be required when the need for more precise amounts is underscored. Currently, although still generating similar values to that of the EEOI, the LCA formulation only takes into account the fuel consumption procured during loaded voyages. This difference may become higher when the number of voyages rises, and the amounts of cargo differ significantly.

A solution to address this is to add supplementary parameters within the LCA processes' definition, correspondingly to that of variables regarding specific trip fuel consumption and cargo transported, for example. The above will be highlighted subsequently as another issue worthy of revision for the improvement of the model formulation.

4.4.3 Conclusions, limitations and future recommendations

The goal of both, the ASTANDER and CONSAR case appraisals, was to validate the LCA methodology as a suitable environmental indicator supplement to the EEDI and EEOI metrics, while additionally offering evidence of its ability to highlight energy efficiency. Additionally, the ASTANDER case vessel included the evaluation of a proposed retrofit, in order to emphasise the metrics' potential to assess changes in the results, with regards to the retrofit's before and after phases.

The previous sections have demonstrated that the LCA formulation shows indication of compliance to both IMO regulatory metrics (i.e. EEDI and EEOI), not only as a practical environmental indicator, but also as a tool able to highlight energy efficiency, by ways of underscoring the amount of transport-work obtained through the ship's consumed energy.

Table 4.21: EEDI results for both case vessels, and respective LCA energy efficiency scores

		EEDI (gCO2/tonne-nm)	**$LCA_{eff(CO2)}$ (gCO2/tonne-nm)**	**$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)**
Ro-Ro Passenger Vessel	1 trip A/F	32.679	35.015	38.441
	1 trip FRC	-	29.662	32.568
Bulk Carrier	1 trip	5.887	6.072	6.250

In the case of the EEDI, for example, it is important to note it has been demonstrated that it is possible for LCA results to be used against already established reference lines for the different ship types, by implementing similar corrections to the LCA scores. Table 4.21 recalls the EEDI results for both vessels, and additionally their respective LCA obtained scores; the values are provided in order to summarise the outcomes between both, the EEDI and LCA valuations, and not to compare the environmental results between the different ships, as it has been mentioned earlier that due to their distinctive functional performance, these values are not equivalent.

Nevertheless, it is relevant to conclude that the LCA energy efficiency scores procured for both vessels, are numerically close to their respective EEDI outcomes. The last keeping in mind the differences in ship types; the Ro-Ro Passenger vessel, for example, required a correction due to its multipurpose design, while the Bulk Carrier's dispensable ship functionality correction provided for a more straightforward calculation. Lastly, although the EEDI formulation encompasses the defined auxiliary power emissions contribution, the LCA scores also provide supplementary impact with regards to ancillary processes (in the case of additional CO_2 for HFO production), and substances capable of global warming (in the case of the GWP category).

The above numerical difference among the EEDI and LCA scores can be further refined, in order to generate closer outcomes to that of the EEDI. This type of flexibility on the LCA part was also validated when certain model definitions were modified for the Bulk Carrier appraisal, ultimately generating closer LCA efficiency results to both, the EEDI and EEOI scores for the CONSAR vessel (see Table 4.21 and Table 4.22).

Table 4.22: EEOI results for both case vessels, and respective LCA energy efficiency scores

		EEOI (gCO2/tonne-nm)	**$LCA_{eff(CO2)}$ (gCO2/tonne-nm)**	**$LCA_{eff(GWP)}$ (gCO2eq/tonne-nm)**
Ro-Ro Passenger Vessel	1 trip A/F	257.658	296.843	304.664
	1 trip FRC	218.178	251.671	258.302
	150 trips A/F & FRC	237.918	274.257	281.483
Bulk Carrier	1 trip $_{\text{loaded}}$	6.892	7.628	7.851
	10 trips $_{\text{(5 loaded \& 5 ballast)}}$	13.463	15.256	15.702

Table 4.22 gathers the EEOI results for both case ships, and their respective LCA energy efficiency scores. Similarly as explained previously for the EEDI outcomes, the LCA results herein are considered satisfactorily close to their respective EEOI values. Worthy of mention, however, is that the LCA efficiency scores are the least similar to their EEOI counterparts for the Ro-Ro Passenger vessel; this last entails the significant difference by contribution of additional CO_2 and GWP, in their respective columns, and also a higher and influential carbon conversion factor, as mentioned during the ASTANDER case appraisal description (see section 4.4.1).

The above table also underlines the Bulk Carrier's inclusion of loaded as well as ballast voyages for the EEOI calculation, which turned out to be an interesting comparison among the EEOI and LCA valuations. The last emphasised that while values procured by the LCA were rather similar to that of the EEOI, the LCA formulation only took into account the fuel consumption procured during loaded voyages. Ultimately this translates into the following: as the number of voyages rises and the amounts of cargo differ significantly, the higher this difference may become. The last also underscores noted improvements to the model, which are highlighted in the following paragraphs.

Lastly both regulatory metrics, the EEDI and EEOI, as well as the LCA formulation, presented evidence of being able to incorporate the FRC retrofit in their respective calculations, and produce relative outcome savings. In the case of the EEDI, while the savings procured where not calculated (see Table 4.21), it was demonstrated that such a retrofit can be implemented by establishing the reduction in power and evaluating the impact on speed, and re-running the EEDI calculation with the obtained power and speed inputs (see section 4.4.1).

In turn, the EEOI was able to underscore CO_2 savings more directly, by summarising the difference in fuel consumption relative to the 1-trip trials, and consequently highlighting the savings in emissions (or more simply subtracting the difference among the 1-trip results in Table 4.22). This of course was straightforward for the 1-trip trials; nonetheless, the savings procured by a number of trips or voyages are to be calculated using only the numerator of the EEOI formula, as using the rolling average EEOI equation, could generate a score proportional to the 1-trip results, if the ship kept a consistent schedule and transported a regular amount of cargo on each voyage.

The LCA appraisal was able to efficiently highlight the savings procured by the FRC retrofit, not only on resulting CO_2, NO_x, SO_x or emissions capable of global warming (i.e. GWP), but additionally the savings generated through less consumption of energy and material inputs, such as crude oil and fresh water, respectively. The Life Cycle Assessment was also able to pinpoint these savings to their respective processes, satisfactorily addressing the before and after phases of the proposed retrofit.

While all three methods were able to emphasise on the chosen low friction coating retrofit, highlighting its environmental and energy operational savings, it would be interesting to analyse the metrics using another type of retrofit, such as waste heat recovery or the use of biodiesel, for example. The last is noted under recommendations for future research.

The following are certain benefits and disadvantages worthy of relevance, particular to the choosing of a certain metric or method over the remaining ones:

- An advantage of the LCA method over the EEDI/EEOI metrics is the ability of offering specific details to resources consumed and emissions released, such as the detailed descriptions found in the inventory results presented for both cases. LCA can be significantly more complex than the EEDI and EEOI, encompassing several resources and emissions flows specific to the assessed system’s different life stages.

- Additionally, it has been stated and briefly described that the Life Cycle Assessment could add the maintenance phase to the operational, and would supplement any relevant consumption and emission factors to the already appraised operational phase of the ship. The EEDI and EEOI metrics are not designed to include any additional releases generated by maintenance or repair operations. The last is also applicable to the construction and scrapping phases.

- Another characteristic edge of LCA over the regulatory metrics is the capacity to pinpoint and/or redesign environmental hotspots –not only during the operational phase of the vessel–, but also during construction, maintenance and scrapping, if required. Also, the example of the HFO production as an ancillary process to the operational phase of the ship, is just a minor evidence of the kind of supplementary processes that could be appraised, in order to evaluate the overall environmental impact of a ship's upstream or downstream supply chain.

- LCA, aside from being able to underscore NO_x and SO_x emissions efficiently, can ultimately appraise soot, Arsenic, Cobalt, Vanadium, Zn, and other contaminants if so required, depending on the end-user's need to address more specific environmental releases. The regulatory metrics are currently defined solely to highlight CO_2 emissions; nevertheless, an expressed need to address SO_x, NO_x, and PM emissions has been voiced through the MRV proposal.

- The EEDI is a widespread shipping efficiency metric, with a highly practiced and revised formulation, and additionally a clear timetable and limit reference lines for different ship types. The LCA formulation could benefit from parallel application to that of the EEDI, for further revision and general reception among the shipping stakeholders.

- While LCA's fuel consumption is commonly a yearly-extrapolated average, the EEOI's fuel consumption values belong to weekly data supplied by the ship's fuel log. Another advantage of the EEOI over LCA is that it can account for specific masses transported and distance per trip, while LCA normally uses averages related to the defined functional unit. This is significant when the case vessel does not have a regular trade schedule, and makes it difficult to outline a regular operational profile. The last underlines the necessity to avoid large variances within the results, by including further parameters within the LCA formulation, in order to address any changes within fuel consumption, distance, and cargo transported, relative to each different voyage.

- Lastly, the EEOI encompasses fuel consumption while on port and at sea, while the current LCA formulation disregards any use of the main engines while at port; i.e. the current LCA's environmental impact from the main engine(s) is only appraised during sailing.

The following are regarded as relevant limitations, which should be taken into consideration as recommendations to expand and/or improve certain aspects of the modelling appraisal, and to emphasise during further similar assessments:

- Due to the fact that the time-related coverage of data dates back to a maximum of fifteen years, the addition of more recent and crosschecked process-related data represents a significant possibility for model refinement.

- Additionally, more specific processes could be used, in order to enhance detailed modelling (e.g. the inclusion of micro pollutants to the engines' emissions, and the use of additional ancillary processes, such as the boilers' releases, for example).

- Main engine(s) performance is assumed constant, disregarding operation of the engines at port, as mentioned previously. As the current metric's appraisal is also considered a steady-state valuation of the engines' performance, the last may not be an important requirement for the LCA model. Nevertheless, additional parameters could be included to address the engines' performance while at port, if any.

- The above is similarly applicable to the inclusion of auxiliary generators, as they are disregarded during the current LCA application.

- The definition of regular operational profiles for the two case vessels, including the designation of their reached transport capacity (i.e. 85%), is noted as a limitation which could produce highly variant scores to that of ships which have differing operational schedules, and variable masses transported. Adding further parameters to the LCA formulation, relative to specific voyage fuel consumption, cargo, and distance values, could serve to address the last mentioned limitation.

In summary, this chapter is meant to emphasise on the characteristic flexibility of LCA to ultimately address the end-user’s needs, and produce a formulation generating values equivalent to that of the regulatory metrics (i.e. EEDI and EEOI) – not only to be applied alternatively to the IMO efficiency indicators–, but also capable of being implemented in parallel to them when the need for detailed environmental information was essential.

Although future work has been described as necessary for the LCA formulation, such as the inclusion of additional parameters which would allow for detailed modelling, the work herein is aimed at evidencing the possibility for the LCA tool to emphasise shipping energy efficiency, as satisfactorily as the current IMO-approved metrics.

4.5 Concluding remarks

The following are the most significant remarks comprised in the chapter, and underscored in the form of bullet points for the reader's ease:

- The above chapter encompasses an LCA appraisal regarding two case vessels. In preliminary context, the appraisal has generated relevant and specific resources consumption and emissions released results for both case vessels, respective to their operational phases, and including different processes comprised within.

- Additionally, the two case vessels are utilised to underline the LCA methodology and model presented previously. They also serve to assess LCA satisfactorily in comparison to the EEDI and EEOI metrics.

- It has been demonstrated that LCA displays indication of compliance as an efficient shipping energy and environmental performance metric, even during the appraisal of the before and after phase of a retrofit (this last referring to the ASTANDER case vessel).

- The LCA appraisal was –aside from being able to efficiently account for CO_2 emissions–, able to underscore relevant secondary emissions, not directly generated by the ship's propulsion plant (in reference to the contributions generated by the production of HFO at refinery process); while additionally being able to account for supplementary emissions, with a warming potential analogous to that of CO_2.

- Lastly, LCA was also validated to be able to produce outcomes relative to micro pollutants and NO_x and SO_x releases. Furthermore, the LCA appraisal was able to underline the savings generated through the reduction in HFO production and ship propulsion and generation emissions from the FRC retrofit, as well as the savings from emissions analogous to the detrimental effect of CO_2. The ability to identify exactly where do these savings occur in the matter of a single trip, 1 year of operation or more, with regards to specific processes or even individual substance contribution, continues to underline a valuable advantage to the LCA application.

5 Discussion

5.1 Introductory remarks

The following chapter comprises the most relevant findings presented throughout the work herein, and gathers them within the following sections: contributions to the field, difficulties encountered, and recommendations for future research and improvement.

5.2 Contributions to the field

The Life Cycle Assessment methodology has been put forward as an environmental performance indicator for ships, capable of also reporting energy efficiency. Moreover, it has been documented that the methodology maintains a standardised framework, which is reinforced openly by available guidelines and implementation literature, with additionally widespread practice.

LCA appraisals comprise various life phases such as construction, operation, maintenance and scrapping –all directly applicable to assessing the environmental performance of a ship's lifetime–. In the other hand, the EEDI as well as the EEOI, are designed to use data exclusively from the operational stage of the ship, and do not directly involve factors from other stages such as construction, scrapping, and etcetera.

An up-to-date literature review on the global problematic caused by shipping emissions and its potential impacts, as well as a contemporary listing of LCA studies linked to the shipping industry has been provided. The following are the most significant issues summarised through the literature review chapter:

- International shipping corresponds currently to at least 3% of the global GHG emissions total. Additionally, GHG emissions from shipping are expected to keep increasing in the future, due to the anticipated demand for maritime transport.

- July 2011's amendments to MARPOL's Annex VI underline the EEDI for new ships, and the SEEMP for all ships as mandatory since January 1st, 2013. The SEEMP additionally emphasises the EEOI as a voluntary indicator endorsed by the IMO. This last is regarded as the first ever global and legally binding policy, underscoring environmental efficiency regulations for any industrial sector, and showing IMO's concern towards emission control.

- Additionally to the above, it has been briefly documented that there is a relevant potential for GHG reduction, found through a range of technical and operational measures currently, or soon-to-be available. These, together with the implementation of suitable policies, are regarded as a competitive instrument to mitigate increasing emissions.

- Furthermore, it is interesting to underline the EC's emphasis on developing a harmonised MRV methodology, which is able to provide consistent data with regards to GHG emissions from shipping. It is also relevant to point out that in the long term the MRV is intended to address all emissions, including SOx, NOx and PM. The above can be directly related to LCA, as a consolidated methodology that can offer a consistent account of GHG, SOx, NOx, and PM.

- Of relevance as well, is the emphasised aim of supporting the single performance metric approach by some industry stakeholders, as an ideal tool for a harmonised regulation across the entire fleet. Nonetheless, it has been demonstrated that the reality of the current regulatory measures' intrinsic shortcomings, prevent the use of one single metric to serve as a measure of overall efficiency for the entire fleet and different ship types. Therefore, an evident opportunity for the use of a flexible standardised performance method is accentuated. LCA could serve as an alternative environmental performance metric, while showing indication of parallel compliance and support to the current regulatory framework.

- Lastly, a brief summary of the background of the LCA methodology has also been provided, with the intention of offering the reader a historical reference into its development, as well as a perspective into LCA's extensive recognition and implementation. Academic and industry literature reference has been provided, in an effort to evidence the rise in interest of the application of life cycle perspective methodologies and LCA, in relation to shipping, shipbuilding and repair. Additionally, some elements of the development of the ships' LCA model have been addressed.

The LCA methodology has been validated through the Case Studies' chapter as a tool able to be applied to different types of ships, and additionally utilised to assess the environmental impact of a single voyage, a yearly average of them, or even go as far as extrapolating potential environmental impact results to underscore the entire life of a vessel.

It has also been demonstrated that the LCA formulation developed herein shows indication of compliance to IMO's regulatory metrics. In the case of the EEDI, is important to note that it is possible to use the already established reference lines for the different ship types, by similarly implementing corrections factors to the LCA efficiency outcomes if necessary.

The above could represent an added benefit for the LCA formulation whilst used in parallel with the EEDI, as the regulatory framework is already in place; for example, LCA could supplement consumption and emission factors relative to other phases not included within the EEDI methodology (construction, maintenance, and etcetera), and assess further potential emissions based on theoretical fuel consumption and added releases relative to other ship phases, ultimately generating more comprehensive results than the actual EEDI. The last could entail redefinition of existing ship emission baselines and reference lines, but would strive to implement better emission control throughout the life of the vessel, rather than only the operational stage.

Several advantages towards LCA's conjoint application along the regulatory metrics have also been highlighted while summarising the Case Studies' chapter. One of the most relevant benefits is that LCA, aside from being able to underscore NO_x and SO_x emissions efficiently, can ultimately assess soot, Arsenic, Cobalt, Vanadium, Zn, and other contaminants if so needed, while additionally being able to underline material and energy requirements. Although not discussed herein, another benefit worthy of mention is LCA's ability to be linked to other technical performance and cost indicators, as demonstrated by Blanco-Davis and Zhou (2014) and Blanco-Davis et al. (2014a), among others.

Furthermore, given the articulated intention of the EC's MRV proposal to address the operational efficiency of the existing fleet (EC, 2013e), and additionally Ballou (2013)'s statement with regards to fleet management and the use of multiple efficiency metrics as necessary, it is interesting to highlight that LCA has been validated herein as compliant to IMO's current energy efficiency and environmental requirements, and additionally documented by Blanco-Davis et al. (2014a) as a tool with the possibility to assess fleet environmental performance.

It is also relevant to note that LCA utilises fuel consumption and the proper emissions factor relative to the fuel assessed, as directly as the EEOI and MRV formulation does. Underlining the already emphasised advantages of being able to generate micro pollutants as well as NO_x and SO_x outcomes, the implementation of LCA could be considered as a potential aid for the MRV's application. LCA could serve to monitor and report maritime transport emissions with a widely accepted methodology, capable of consistent application across not only shipping divisions, but additionally across industry sectors as a common performance metric.

5.3 Encountered difficulties

A list of limitations has been presented while summarising the Case Studies' chapter. The most relevant are due to the fact of the span of time regarding the coverage of the process-related data, and additionally the definition of the case vessels' profiles under constant cargo carried and distance travelled. Both of these limitations pose difficulties to gather more refined results, and they are caused by a lack of availability of open records, with regards to current LCA process-definition data for key system components, and more understandably so, ship cargo manifest and voyage logs. With regards to the LCA-related data that is available, some of it is often obsolete, incomparable, or of unknown quality.

Similarly, the model presented herein is based on a previous LCA model formulated by Johnsen and Fet (1998), given that current LCA models regarding ships are not publicly available. This predecessor model is significant due to the fact that it encompasses consumption and emissions data for phases such as construction and scrapping, which represent a challenge when it comes to a specific ship's data gathering. The last also underlines that while there is a relevant amount of LCA literature with regards to other industries, e.g. car manufacturing, the shipping industry in the other hand could benefit from the implementation and publishing of more LCA-related studies.

Other difficulties worthy of statement are also related to the nature of the LCA methodology. For example, given LCA's holistic characteristic, the simplification of certain aspects and factors of the assessed system(s) could have resulted in subjective and irrelevant outcomes.

Lastly, it should be recalled that LCA data gathering is time-consuming, and the implementation of the methodology requires a certain familiarity with the guidelines of the approach. While it is commonly unrealistic to gather all necessary data for the LCA appraisals, a major difficulty would have been underlined if the data for the available case ships had not been provided.

5.4 Recommendations for future research

The Case Studies' chapter brought forward certain issues that are worthy of notice for further lines of investigation. For example, the regulatory metrics –EEDI and EEOI–, as well as the LCA methodology, have presented evidence of being able to incorporate the FRC retrofit in their formulation, and produce relative savings. It would be interesting to note if similar results could be gathered with other types of retrofits, such as optimised propeller designs, hull air lubrication systems, waste heat recovery systems, the utilisation of wind or solar power, and etcetera.

Moreover, future work could also encompass including vessels with shaft generators and motors, and additionally other energy saving technologies into the LCA formulation, while also including these variables into the LCA process definition. The inclusion of parameters which would allow the appraisal of the environmental impact generated by the used of engines while at port, would also be relevant.

The above underlines the previously mentioned possibility for model improvement, emphasising the addition of further parameters within the LCA formulation, to address for example specific fuel consumption, distance, and cargo transported relative to each voyage. The addition of the auxiliary power definition into the LCA formulation, similarly as it is done in the EEDI, would also be essential for using both methods in parallel.

Furthermore, the micro pollutants which are characteristic of the main engines' operation, could be encompassed within the LCA formulation as well as other processes or phases –such as maintenance, for example–, making a more comprehensive assessment, which could ultimately underline specific substance(s) or phase redesign information as required.

The application of the proposed Life Cycle Assessment methodology on different case studies, including different types of ships, is essential to the potential application as a supplement to the current metrics. It would be interesting to see how the methodology fares against ships with less regular operational profiles, and ships with complex functionalities.

Lastly, while out of the scope of the work herein, it would be interesting to gauge LCA against the regulatory metrics for retrofits that are not deemed so influential within the operational phase of the ship. For example, Blanco-Davis et al. (2014b) have put forward an absorption cooling system implementation as a retrofit for a fishing vessel –and while it is true that ships under 400 gross tonnes are not required to comply with the regulatory metrics–, this retrofit shows indication of being able to provide cooling while using waste heat from the engine exhaust, without the need to be energised (the reader should refer to Blanco-Davis et al. (2014b), for further details).

This type of retrofit could entail an environmental benefit ultimately difficult to be appraised by the EEDI or EEOI, given that the system under assessment does not consume fuel directly. While further research with regards to an LCA appraisal was not carried out for the cooling system, there is strong suggestion that an LCA could evaluate the system in question more efficiently than the regulatory metrics.

Another such interesting retrofit could be the addition of a BWTS onboard. As the IMO’s Ballast Water Management Convention closes on ratification, these systems have become widely available, and are regarded as a first line of defence towards the transportation of alien invasive species. The last could also signify an environmental benefit, given that the risk for unwanted species is advertised as reduced by the implementation of these treatment systems.

This type of retrofit also poses a difficult assessment for the EEDI and EEOI, as they will not be able to gauge the environmental improvement resulting from its implementation. Interestingly so, the current alien invasive species framework is under research for application within the LCA methodology, and presently the approach would likewise not be able to draw environmental benefit outcomes, resulting from the reduction regarding the species’ transportation.

5.5 Concluding remarks

The following are the most significant remarks comprised in the chapter, and underscored in the form of bullet points:

- The LCA methodology has been put forward as an environmental performance indicator for ships, capable of also reporting energy efficiency.

- Furthermore, the methodology has been validated through the Case Studies' chapter as a tool able to be applied to different types of ships, and additionally utilised to assess the environmental impact of a single voyage, a yearly average of them, or even go as far as extrapolating potential environmental impact results to underscore the entire life of a vessel.

- It has also been demonstrated that the LCA formulation shows indication of compliance to IMO's regulatory metrics.

- Several advantages towards LCA's conjoint application along the regulatory metrics have also been highlighted while summarising the Case Studies' chapter. The most relevant emphasises that the implementation of LCA could be considered as a potential aid for the MRV's application, while serving as a tool to monitor and report maritime transport emissions with a widely accepted methodology.

- A list of encountered difficulties –as well as issues for further work–, have been documented with the intention of expanding and improving significant aspects of the modelling appraisal, and emphasising potential candidates for similar research refinement.

6 Conclusion

The work presented herein has initially documented a literary review underlining the widespread environmental problematic caused by human-generated detrimental emissions. Additionally demonstrated was how the shipping industry was related to this global problematic, and how the IMO has reacted proactively by establishing methods aimed at striving to get shipping emissions under control.

Nevertheless, the issue of greenhouse gas emissions is expected to intensify, before any substantial improvement may become factual. Therefore, IMO is expected to use all available technical and operational measures, as well as the implementation of suitable policies, in order to efficiently mitigate shipping emissions in a timely manner.

Life Cycle Assessment is one of those available measures, which can be readily used hand-in-hand with the existing regulatory metrics, in order to serve to monitor and report maritime transport emissions as a common performance metric, with the capability of also serving as aid to the implementation of the EU's MRV proposal.

The above proposal is intended to address in longer term the accounting of SO_x, NO_x, PM, and other significant contaminants produced by maritime transport. Aside from being able to efficiently appraise the above releases, LCA has shown a comprehensive accounting of CO_2 emissions, while additionally being able to underline any produced emission with a warming potential analogous to CO_2.

Lastly, LCA's potential should not be neglected as a complementary tool –applicable to both newbuilds and existing vessels–, and which in parallel to the implementation of the regulatory metrics, is able to offer reliability and accessibility of information, aside from providing efficient reporting and verification of environmental scores and energy efficiency.

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8 Publications

Finally, this chapter lists some of the author’s publications, which are related to the work presented herein.

Thesis work

1. Blanco-Davis, E., 2011, “Life Cycle Assessment: A comparative assertion between ballast water treatment systems onboard a case vessel”. MSc Thesis. Dept. of Naval Architecture, Ocean and Marine Engineering. University of Strathclyde, Glasgow. 106 pages.

Conference papers

2. Koch, T., Blanco-Davis, E., and Zhou, P. 2013, "Analysis of Economic and Environmental Performance of Retrofits using Simulation", in Computer and IT Applications in the Maritime Industries. Cortona, Italy: Technische Universität Hamburg-Harburg.

3. Blanco-Davis, E., et al., 2014, "Energy efficiency optimisation, through the use of an absorption cooling system onboard fishing vessels", in Transport Research Arena (TRA2014): Paris.

4. del Castillo, F., Blanco-Davis, E., et al., 2014, "Eco innovative refitting technologies and processes for shipbuilding industry: Project results", in Transport Research Arena (TRA2014): Paris.

5. del Castillo, F., Blanco-Davis, E., et al., 2014, "Eco-innovación tecnológica para hacer más ‘verde’ la flota existente. Evaluación del impacto ambiental a través del análisis del ciclo de vida", submitted to the 53rd Marine Engineering and Industry Conference, October 2014: Cartagena, Spain. 40 pages.

EC-FP7 project deliverables

6. Blanco-Davis, E., 2013, "Eco-REFITEC Life Cycle Assessment Tool and User Manual: Guidelines to the Ship's Life Cycle's data gathering and LCA prototype modelling". Deliverable 3.3 of the EC-FP7 Eco-REFITec project, CP-266268. http://eco-refitec.eu/. 54 pages.

7. Blanco-Davis, E., 2013, "LCA for Eco-REFITEC selected cases: Report of implementation of LCA for shipyards, including owner costs and results of case ships". Deliverable 5.1 of the EC-FP7 Eco-REFITec project, CP-266268. http://eco-refitec.eu/. 127 pages.

8. Blanco-Davis, E., 2014, "LCA impact assessment of greening existing fleet: Potential environmental impact of the technological eco-innovation for greening existing fleet". Deliverable 5.2 of the EC-FP7 Eco-REFITec project, CP-266268. http://eco-refitec.eu/. 41 pages.

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9. del Castillo, F. and Blanco-Davis, E., 2012, "Eco Innovative Refitting Technologies and Processes for Shipbuilding Industry: Project Overview". Procedia - Social and Behavioral Sciences. 48(0): p. 246-255.

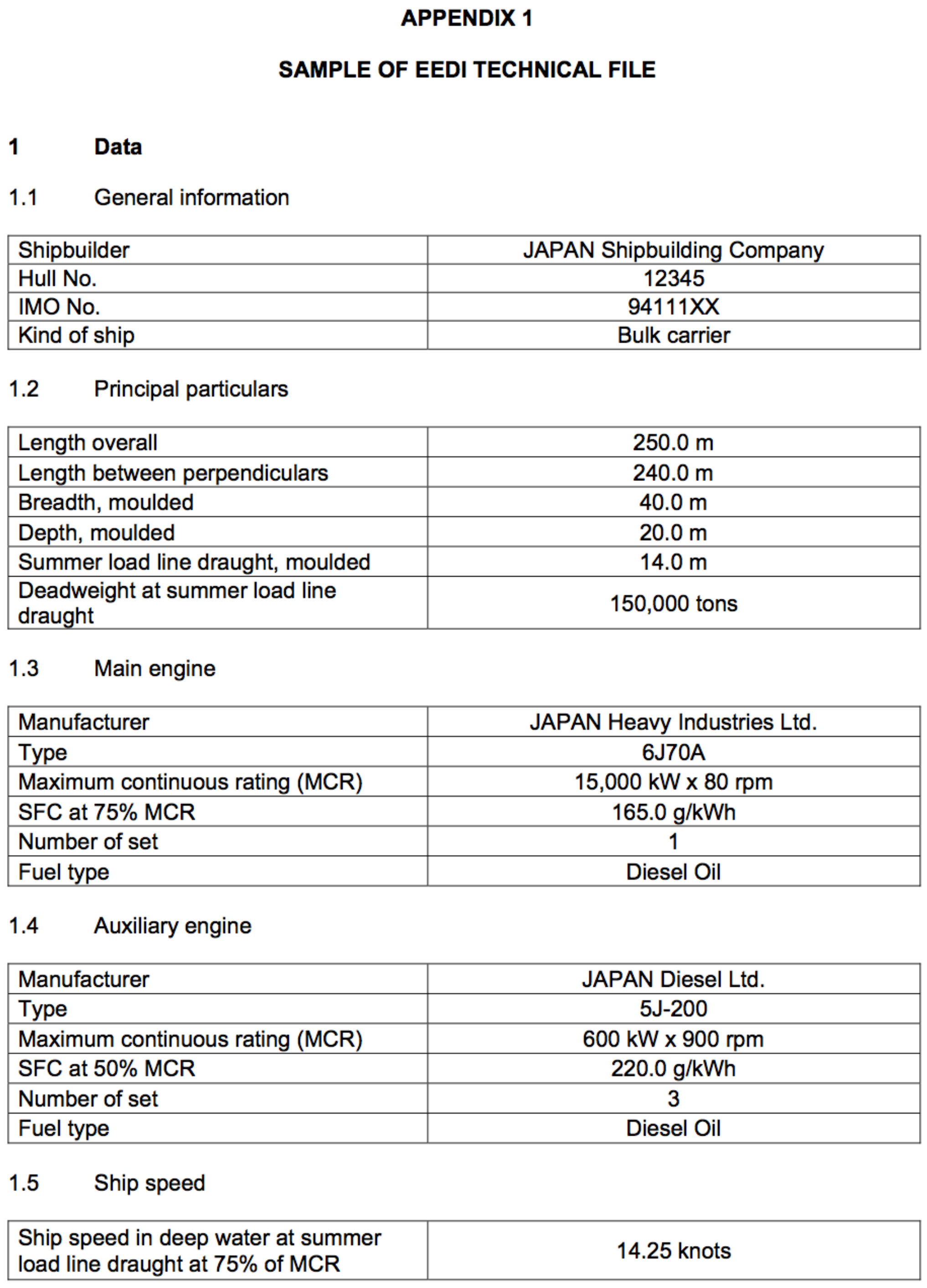
10. Blanco-Davis, E. and Zhou, P., 2014, "LCA as a tool to aid in the selection of retrofitting alternatives". Ocean Engineering. 77(0): p. 33-41.

11. Blanco-Davis, E., del Castillo, F., and Zhou, P., 2014, "Fouling release coating application as an environmentally efficient retrofit: a case study of a ferry type ship". Submitted to The International Journal of Life Cycle Assessment on 07 March, 2014. Accepted 30 June, 2014.

Appendices

Appendix A: EEDI sample calculation

A.1 Excerpt from IMO (2012d): 2012 Guidelines on survey and certification of the EEDI, Appendix 1



APPENDIX 1

SAMPLE OF EEDI TECHNICAL FILE

1 Data

1.1 General information

Shipbuilder	JAPAN Shipbuilding Company
Hull No.	12345
IMO No.	94111XX
Kind of ship	Bulk carrier

1.2 Principal particulars

Length overall	250.0 m
Length between perpendiculars	240.0 m
Breadth, moulded	40.0 m
Depth, moulded	20.0 m
Summer load line draught, moulded	14.0 m
Deadweight at summer load line draught	150,000 tons

1.3 Main engine

Manufacturer	JAPAN Heavy Industries Ltd.
Type	6J70A
Maximum continuous rating (MCR)	15,000 kW x 80 rpm
SFC at 75% MCR	165.0 g/kWh
Number of set	1
Fuel type	Diesel Oil

1.4 Auxiliary engine

Manufacturer	JAPAN Diesel Ltd.
Type	5J-200
Maximum continuous rating (MCR)	600 kW x 900 rpm
SFC at 50% MCR	220.0 g/kWh
Number of set	3
Fuel type	Diesel Oil

1.5 Ship speed

Ship speed in deep water at summer load line draught at 75% of MCR	14.25 knots

2 Power Curves

The power curves estimated at the design stage and modified after the speed trials are shown in figure 2.1.

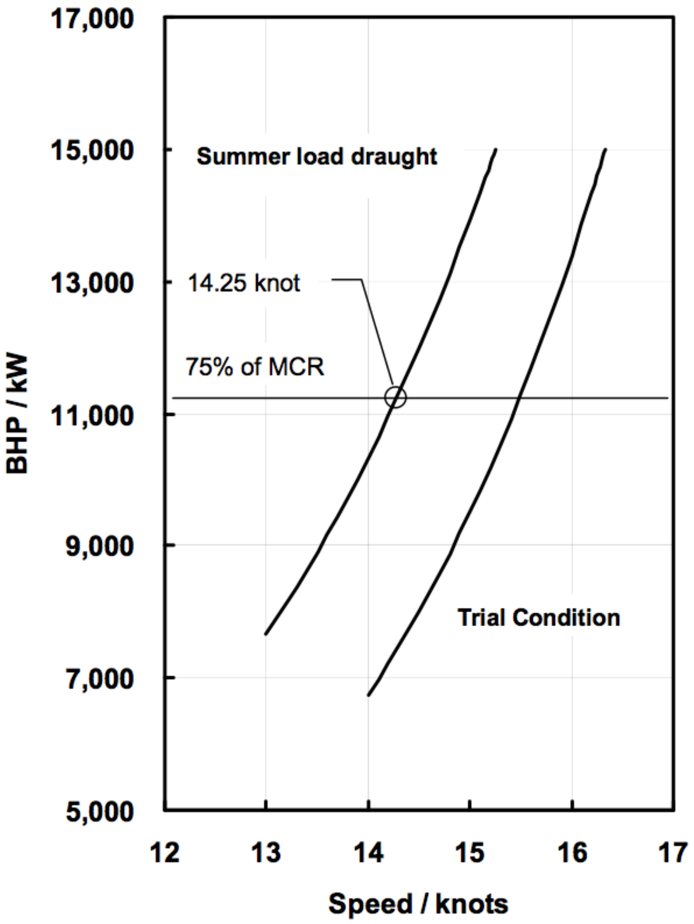


Figure 2.1: Power curves

3 Overview of Propulsion System and Electric Power Supply System

3.1 Propulsion system

3.1.1 Main engine

Refer to subparagraph 1.3.

3.1.2 Propeller

Type	Fixed pitch propeller
Diameter	7.0 m
Number of blades	4
Number of set	1

3.2 Electric power supply system

3.2.1 Auxiliary engines

Refer to subparagraph 1.4.

3.2.2 Main generators

Manufacturer	JAPAN Electric
Rated output	560 kW (700 kVA) x 900 rpm
Voltage	AC 450 V
Number of set	3

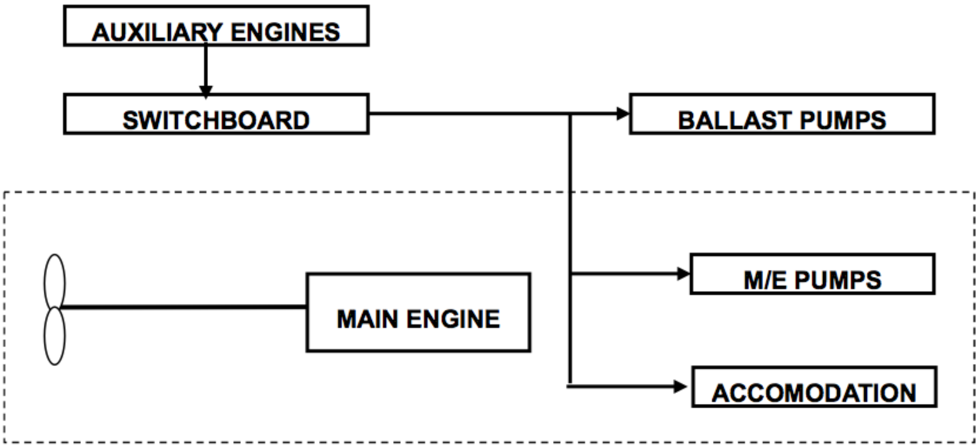


Figure 3.1: Schematic figure of propulsion and electric power supply system

4 Estimation Process of Power Curves at Design Stage

Power curves are estimated based on model test results. The flow of the estimation process is shown below.

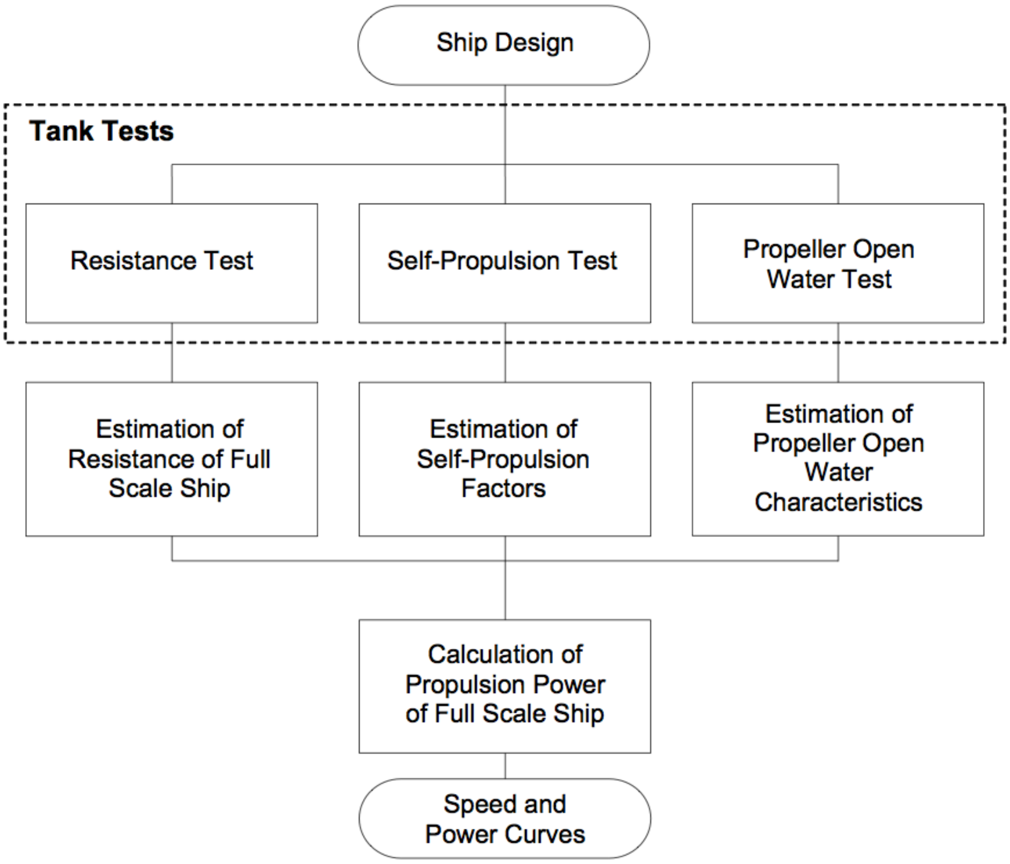


Figure 4.1: Flow-chart of process for estimating power curves

5 Description of Energy Saving Equipment

5.1 Energy saving equipment of which effects are expressed as $P_{AEeff(i)}$ and/or $P_{eff(i)}$ in the EEDI calculation formula

N/A

5.2 Other energy saving equipment

(Example)
5.2.1 Rudder fins

5.2.2 Propeller boss cap fins

(Specifications, schematic figures and/or photos, etc., for each piece of equipment or device should be indicated. Alternatively, attachment of the commercial catalogue may be acceptable.)

6 Calculated Value of attained EEDI

6.1 Basic data

Type of Ship	Capacity DWT	Speed V_{ref} (knots)
Bulk Carrier	150,000	14.25

6.2 Main engine

MCR_{ME} (kW)	Shaft Gen.	P_{ME} (kW)	Type of Fuel	C_{FME}	SFC_{ME} (g/kWh)
15,000	N/A	11,250	Diesel Oil	3.206	165.0

6.3 Auxiliary engines

P_{AE} (kW)	Type of Fuel	C_{FAE}	SFC_{AE} (g/kWh)
625	Diesel Oil	3.206	220.0

6.4 Ice class

N/A

6.5 Innovative electrical energy efficient technology

N/A

6.6 Innovative mechanical energy efficient technology

N/A

6.7 Cubic capacity correction factor

N/A

6.8 Calculated value of attained EEDI

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

$$= \frac{1 \times (11250 \times 3.206 \times 165.0) + (625 \times 3.206 \times 220.0) + 0 - 0}{1 \cdot 1 \cdot 150000 \cdot 1 \cdot 14.25}$$

$$= 2.99 \quad (\mathrm{g - CO_2/ton \cdot mile})$$

attained EEDI: 2.99 g-CO$_2$/ton mile

7 Calculated value of attained $EEDI_{weather}$

7.1 Representative sea conditions

	Mean wind speed	Mean wind direction	Significant wave height	Mean wave period	Mean wave direction
BF6	12.6 (m/s)	0 (deg.)*	3.0 (m)	6.7 (s)	0 (deg.)*

* Heading direction of wind/wave in relation to the ship's heading, i.e. 0 (deg.) means the ship is heading directly into the wind.

.

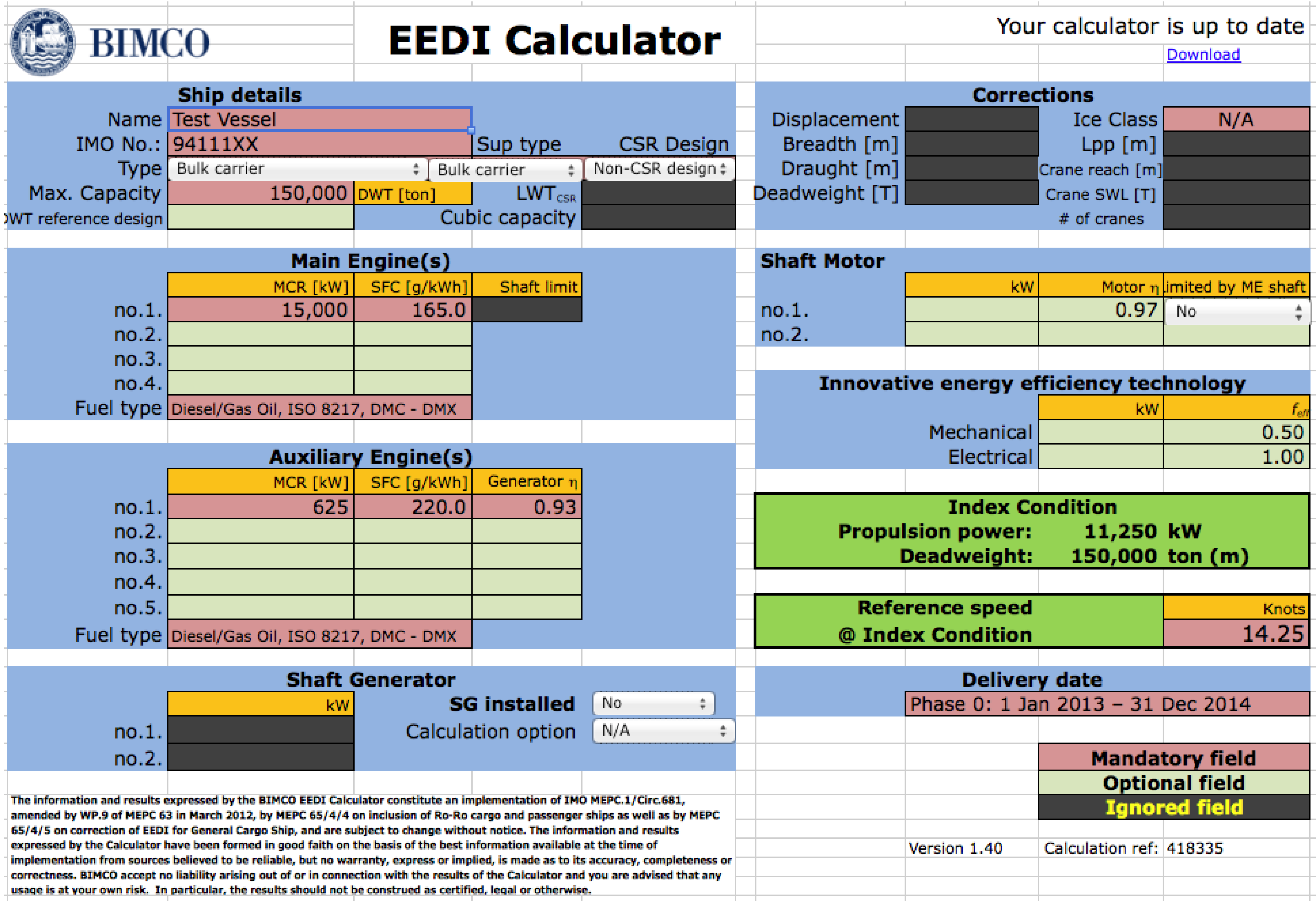
7.2 Calculated weather factor, f_w

f_w	0.900

7.3 Calculated value of attained $EEDI_{weather}$

attained $EEDI_{weather}$: 3.32 g-CO_2/ton mile

A.2 Screenshot of EEDI calculator by BIMCO (2011)



EEDI Calculator

Your calculator is up to date

Ship details

Name	Test Vessel			
IMO No.:	94111XX		Sup type	CSR Design
Type	Bulk carrier		Bulk carrier	Non-CSR design
Max. Capacity	150,000	DWT [ton]	LWT$_{CSR}$	
WT reference design			Cubic capacity	

Corrections

Displacement		Ice Class	N/A
Breadth [m]		Lpp [m]	
Draught [m]		Crane reach [m]	
Deadweight [T]		Crane SWL [T]	
		# of cranes	

Main Engine(s)

	MCR [kW]	SFC [g/kWh]	Shaft limit
no.1.	15,000	165.0	
no.2.			
no.3.			
no.4.			
Fuel type	Diesel/Gas Oil, ISO 8217, DMC - DMX		

Shaft Motor

	kW	Motor η	imited by ME shaft
no.1.		0.97	No
no.2.			

Innovative energy efficiency technology

	kW	f_{eff}
Mechanical		0.50
Electrical		1.00

Auxiliary Engine(s)

	MCR [kW]	SFC [g/kWh]	Generator η
no.1.	625	220.0	0.93
no.2.			
no.3.			
no.4.			
no.5.			
Fuel type	Diesel/Gas Oil, ISO 8217, DMC - DMX		

Index Condition
Propulsion power: 11,250 kW
Deadweight: 150,000 ton (m)

Reference speed @ Index Condition Knots 14.25

Shaft Generator

	kW
no.1.	
no.2.	

SG installed No
Calculation option N/A

Delivery date
Phase 0: 1 Jan 2013 – 31 Dec 2014

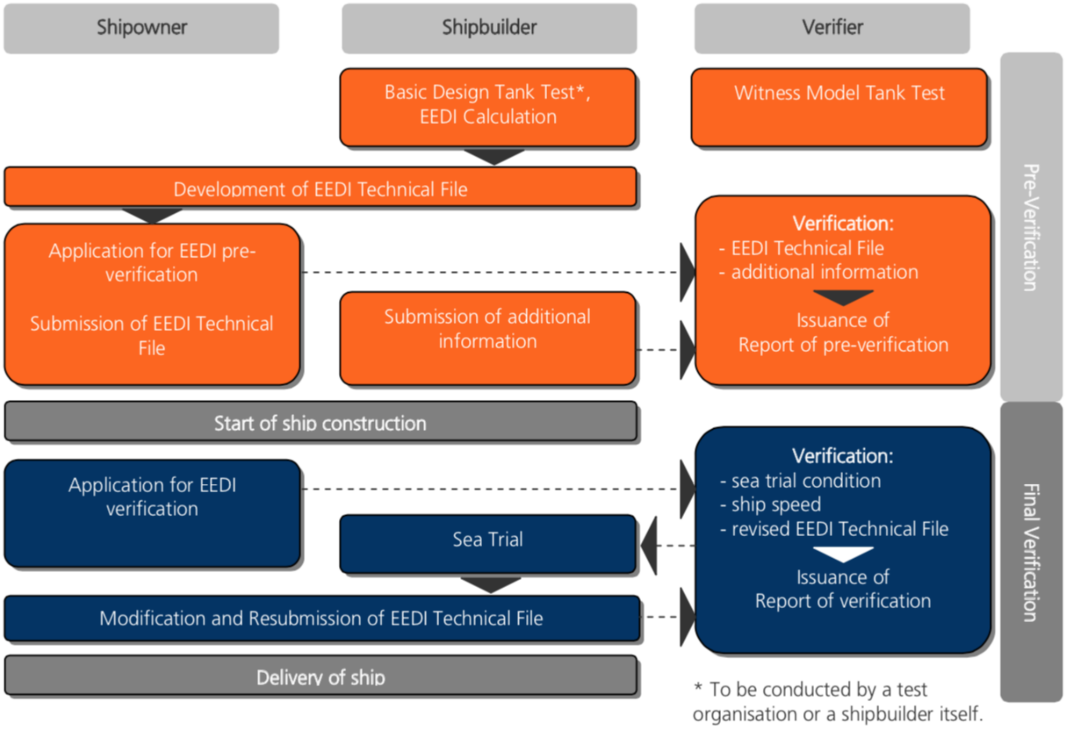
Mandatory field
Optional field
Ignored field

The information and results expressed by the BIMCO EEDI Calculator constitute an implementation of IMO MEPC.1/Circ.681, amended by WP.9 of MEPC 63 in March 2012, by MEPC 65/4/4 on inclusion of Ro-Ro cargo and passenger ships as well as by MEPC 65/4/5 on correction of EEDI for General Cargo Ship, and are subject to change without notice. The information and results expressed by the Calculator have been formed in good faith on the basis of the best information available at the time of implementation from sources believed to be reliable, but no warranty, express or implied, is made as to its accuracy, completeness or correctness. BIMCO accept no liability arising out of or in connection with the results of the Calculator and you are advised that any usage is at your own risk. In particular, the results should not be construed as certified, legal or otherwise.

Version 1.40 Calculation ref: 418335

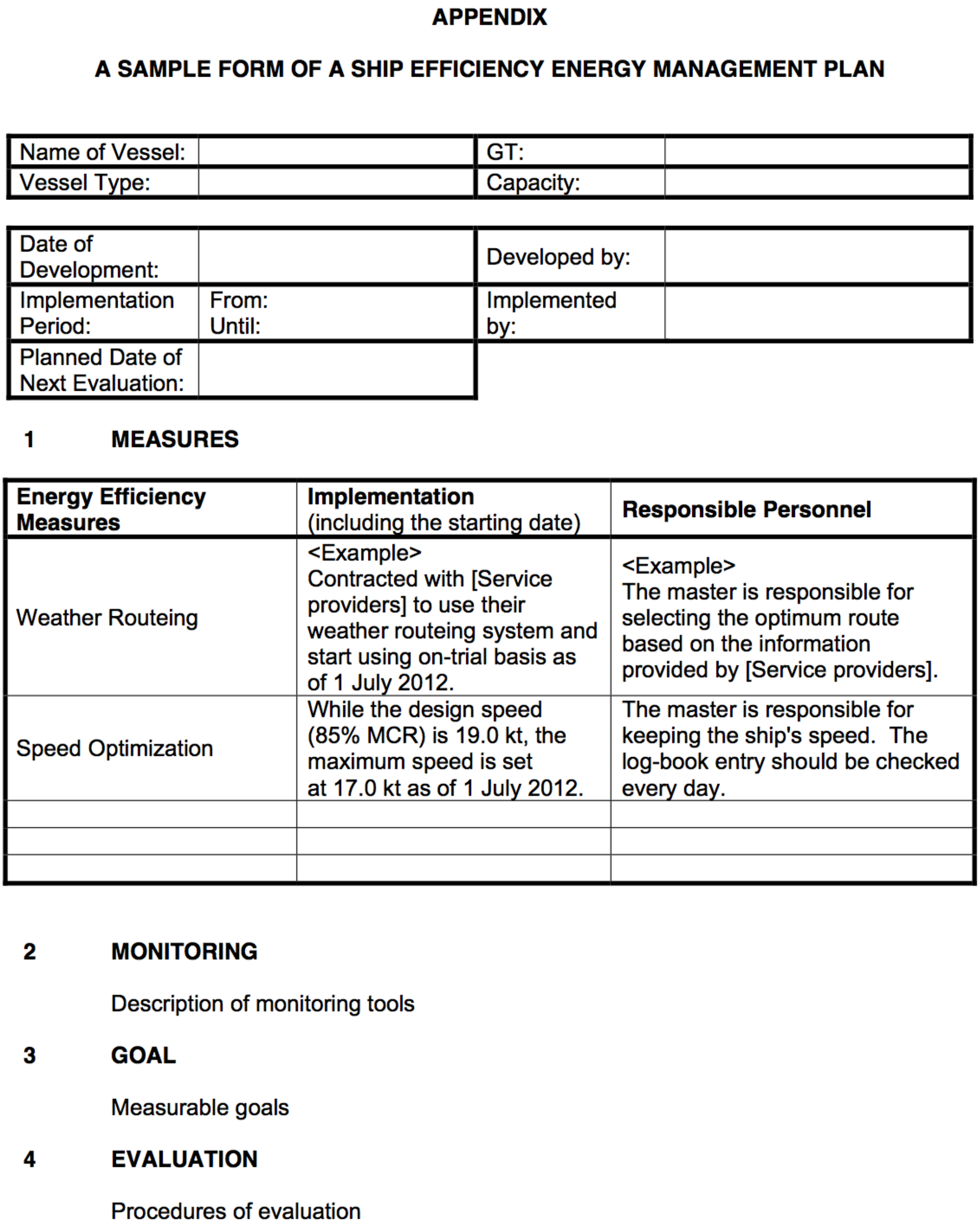
A.3 Excerpt from Lloyd's-Register (2012b): Verification processes for the attained EEDI, as derived from IMO (2012d)

Verification of the EEDI is in two stages; pre-verification which commences at the design stage and final verification upon completion of the sea trials and commissioning. Details of the verification methodology are given in IMO resolution MEPC.214(63) and the overview process is shown below:



Appendix B: Sample SEEMP form and EEOI Calculation

B.1 Excerpt from IMO (2012c): 2012 Guidelines for the development of a SEEMP, Appendix



APPENDIX

A SAMPLE FORM OF A SHIP EFFICIENCY ENERGY MANAGEMENT PLAN

Name of Vessel:		GT:	
Vessel Type:		Capacity:	

Date of Development:		Developed by:	
Implementation Period:	From: Until:	Implemented by:	
Planned Date of Next Evaluation:			

1 MEASURES

Energy Efficiency Measures	**Implementation** (including the starting date)	**Responsible Personnel**
Weather Routeing	<Example> Contracted with [Service providers] to use their weather routeing system and start using on-trial basis as of 1 July 2012.	<Example> The master is responsible for selecting the optimum route based on the information provided by [Service providers].
Speed Optimization	While the design speed (85% MCR) is 19.0 kt, the maximum speed is set at 17.0 kt as of 1 July 2012.	The master is responsible for keeping the ship's speed. The log-book entry should be checked every day.

2 MONITORING

Description of monitoring tools

3 GOAL

Measurable goals

4 EVALUATION

Procedures of evaluation

B.2 Excerpt from IMO (2009d): Guidelines for voluntary use of the ship energy efficiency operational indicator (EEOI), Appendix

APPENDIX

CALCULATION OF ENERGY EFFICIENCY OPERATIONAL INDICATOR (EEOI) BASED ON OPERATIONAL DATA

1 General

The objective of the Appendix is to provide guidance on calculation of the Energy Efficiency Operational Indicator (EEOI) based on data from the operation of the ship.

2 Data sources

Primary data sources selected could be the ship's log-book (bridge log-book, engine log-book, deck log-book and other official records).

3 Fuel mass to CO_2 mass conversion factors (C_F)

C_F is a non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in g based on carbon content. The value of C_F is as follows:

Type of fuel	Reference	Carbon content	C_F (t-CO_2/t-Fuel)
1. Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.206000
2. Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151040
3. Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.114400
4. Liquified Petroleum Gas (LPG)	Propane Butane	0.819 0.827	3.000000 3.030000
5. Liquified Natural Gas (LNG)		0.75	2.750000

4 Calculation of EEOI

The basic expression for EEOI for a voyage is defined as:

$$\text{EEOI} = \frac{\sum_j FC_j \times C_{F\,j}}{m_{cargo} \times D} \qquad \text{Equation 1}$$

Where average of the indicator for a period or for a number of voyages is obtained, the Indicator is calculated as:

$$\text{Average EEOI} = \frac{\sum_i \sum_j (FC_{i\,j} \times C_{F\,j})}{\sum_i (m_{cargo,i} \times D_i)} \qquad \text{Equation 2}$$

Where:

- j is the fuel type;
- i is the voyage number;
- FC_{ij} is the mass of consumed fuel j at voyage i;
- 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; and
- D is the distance in nautical miles corresponding to the cargo carried or work done.

The unit of EEOI depends on the measurement of cargo carried or work done, e.g., tonnes CO_2/(tonnes • nautical miles), tonnes CO_2/(TEU • nautical miles), tonnes CO_2/(person • nautical miles), etc.

It should be noted that Equation 2 does not give a simple average of EEOI among number of voyage i.

5 Rolling average

Rolling average, when used, can be calculated in a suitable time period, for example one year closest to the end of a voyage for that period, or number of voyages, for example six or ten voyages, which are agreed as statistically relevant to the initial averaging period. The Rolling Average EEOI is then calculated for this period or number of voyages by Equation 2 above.

6 Data

For a voyage or period, e.g., a day, data on fuel consumption/cargo carried and distance sailed in a continuous sailing pattern could be collected as shown in the reporting sheet below.

CO_2 Indicator reporting sheet

NAME AND TYPE OF SHIP						
Voyage or day (i)	Fuel consumption (FC) at sea and in port in tonnes				Voyage or time period data	
	Fuel type ( )	Fuel type ( )	Fuel type ( )		Cargo (m) (tonnes or units)	Distance (D) (NM)
1						
2						
3						

NOTE: For voyages with $m_{cargo}=0$, it is still necessary to include the fuel used during this voyage in the summation above the line.

7 Conversion from g/tonne-mile to g/tonne-km

The CO_2 indicator may be converted from g/tonne-mile to g/tonne-km by multiplication by 0.54.

8 Example:

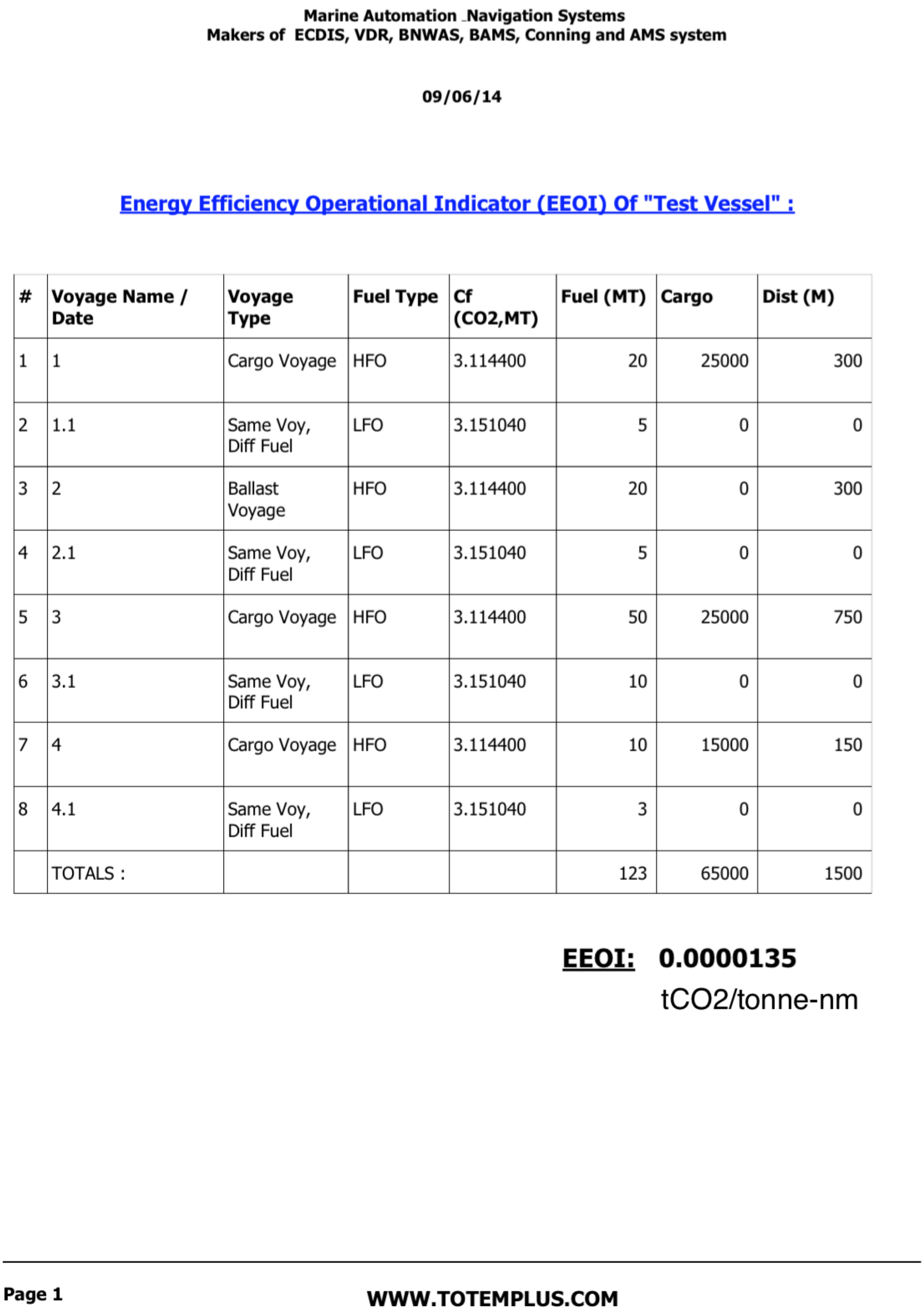
A simple example including one ballast voyage, for illustration purpose only, is provided below. The example illustrates the application of the formula based on the data reporting sheet.

NAME AND TYPE OF SHIP						
Voyage or day (i)	Fuel consumption (FC) at sea and in port in tonnes				Voyage or time period data	
	Fuel type (HFO)	Fuel type (LFO)	Fuel type ( )		Cargo (m) (tonnes or units)	Distance (D) (NM)
1	20	5			25,000	300
2	20	5			0	300
3	50	10			25,000	750
	10	3			15,000	150

$$EEOI = \frac{100 \times 3.114 + 23 \times 3.151}{(25{,}000 \times 300) + (0 \times 300) + (25{,}000 \times 750) + (15{,}000 \times 150)} = 13.47 \times 10^{-6}$$

unit: tonnes CO_2/(tons • nautical miles)

B.3 Sample EEOI results obtained with the Totem-Plus (2012) calculator



Marine Automation Navigation Systems
Makers of ECDIS, VDR, BNWAS, BAMS, Conning and AMS system

09/06/14

Energy Efficiency Operational Indicator (EEOI) Of "Test Vessel" :

#	Voyage Name / Date	Voyage Type	Fuel Type	Cf (CO2,MT)	Fuel (MT)	Cargo	Dist (M)
1	1	Cargo Voyage	HFO	3.114400	20	25000	300
2	1.1	Same Voy, Diff Fuel	LFO	3.151040	5	0	0
3	2	Ballast Voyage	HFO	3.114400	20	0	300
4	2.1	Same Voy, Diff Fuel	LFO	3.151040	5	0	0
5	3	Cargo Voyage	HFO	3.114400	50	25000	750
6	3.1	Same Voy, Diff Fuel	LFO	3.151040	10	0	0
7	4	Cargo Voyage	HFO	3.114400	10	15000	150
8	4.1	Same Voy, Diff Fuel	LFO	3.151040	3	0	0
	TOTALS :				123	65000	1500

EEOI: **0.0000135**
tCO2/tonne-nm

Page 1 **WWW.TOTEMPLUS.COM**

Appendix C: Building the ships' LCA model

C.1 List of required information per case ship (Blanco-Davis, 2013a)

1. *General*

- Ship's name
- Type of ship
- IMO Number (if applicable)
- DWT (if applicable)
- Flag and Register port
- Class (if applicable)
- Ship's particulars (LBP, LOA, Depth, Draft, Breadth, etc.)
- Service speed
- Year of built
- Shipyard's name
- Ship's building number

2. *Construction*

- List of building materials (including actual weight)
- List of machinery and equipment (including weights and specifications)
- List of outfittings (including weights and specifications)
- Hull Weight
- Building processes used

3. *Operation*

- Vessel's voyage plan (if applicable)
- Average sailing days per year, in loaded state
- Average sailing days per year in ballast state
- Average days per year at port while loading
- Average days per year at port while discharging
- Average days per year idling or at anchorage
- Average days per year for maintenance/dry-docking/surveys
- Average daily fuel/lube oil/other consumables consumption when sailing loaded
- Average daily fuel/lube oil/other consumables consumption when sailing in ballast
- Average daily fuel/lube oil/other consumables consumption when at port loading
- Average daily fuel/lube oil/other consumables consumption when at port discharging
- Average daily fuel/lube oil/other consumables consumption when idling/anchorage
- Average crew number on board
- Average waste/sludge/garbage produced per year

4. Maintenance

- Average paint/spares/chemicals consumed per year for “every day” maintenance
- Average paint/spares /chemicals consumed during dry-docking/repair period

5. Retrofitting (if applicable)

- Details drawings and description of the system(s) to be retrofitted
- Operation manual and energy/fuel consumption of the equipment
- Retrofitting procedures from shipyard and list of additional materials used

6. List of drawings

- General arrangement
- Capacity plan
- Profile and decks
- Machinery list
- Equipment and outfitting list.

C.2 Model definition and sample calculations

The following is aimed at expanding the definition of the LCA model applied herein, as well as offering an overview of some of its resulting outcomes. Previously shown, Figure 3.3 depicts the main phases that comprise the complete life cycle of a typical vessel. In turn, Figure 9.0.1 zooms in on the operational phase of the ship, including a flow diagram intended to further explain some of the underlined environmental exchanges taking place throughout the utilisation of the vessel.

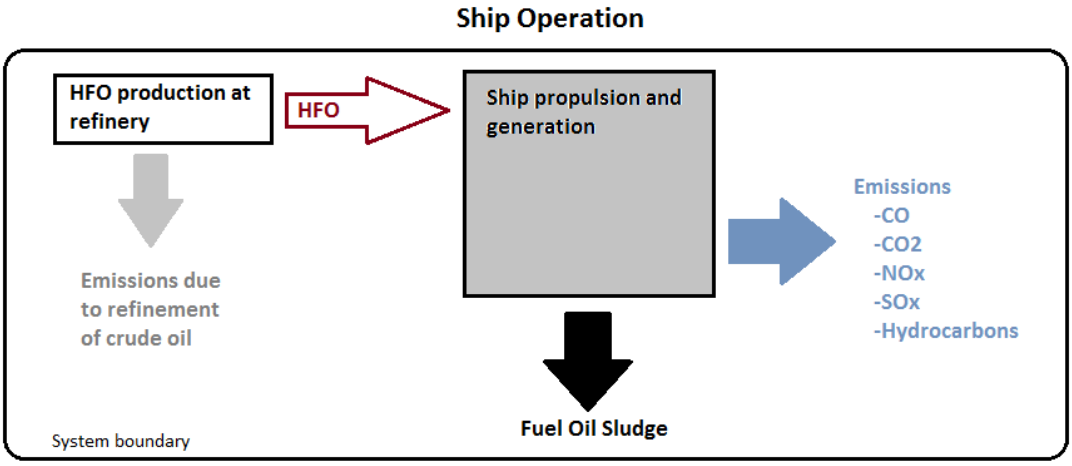
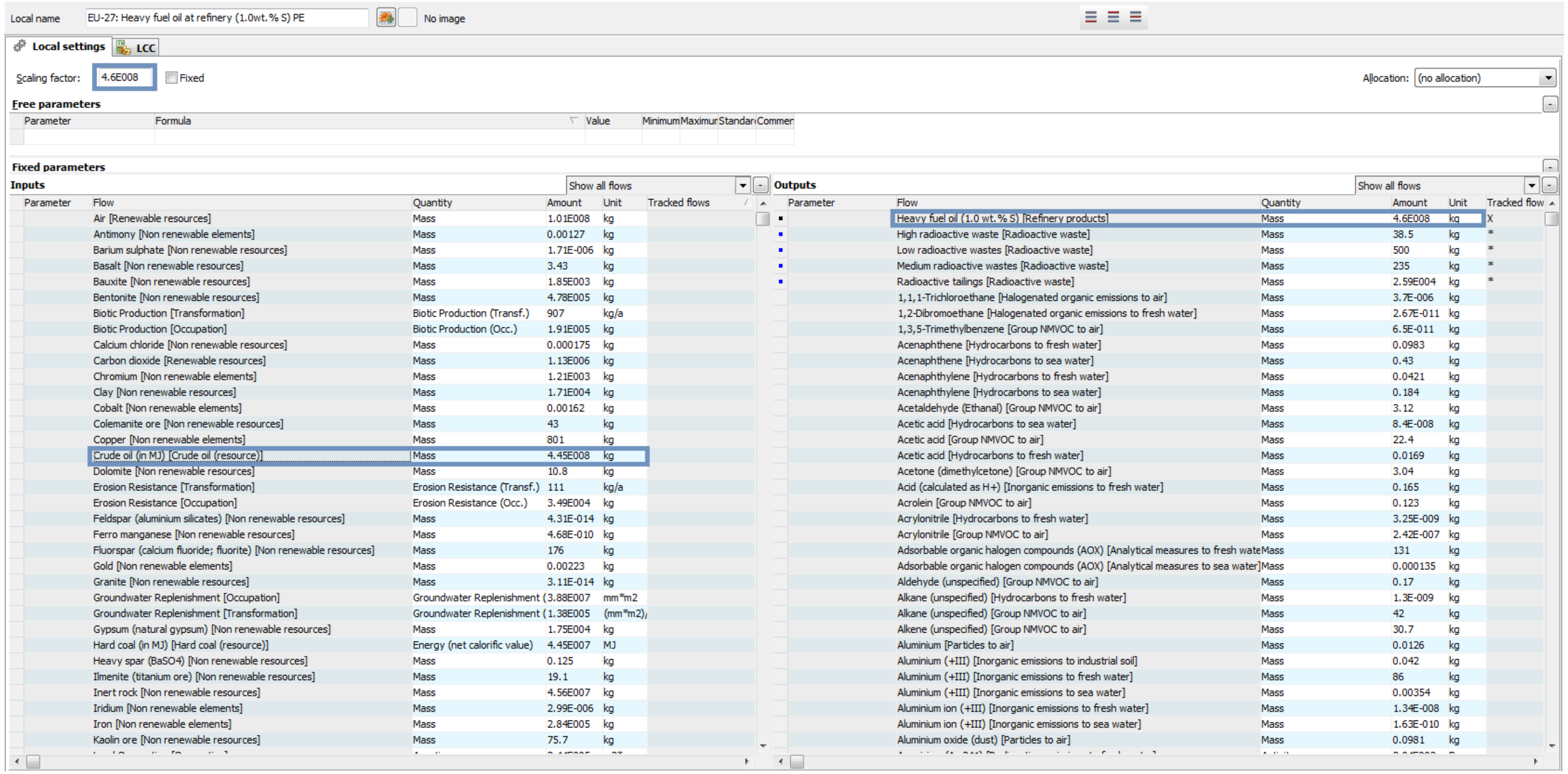


Figure 9.0.1: Ship operation phase flow diagram

As explained in Section 3.3.2 (building the ships' LCA model), two processes comprise the operational phase: the HFO production at refinery process, and the ship propulsion and generation process. The previous is utilised as defined by PE-International (2013); i.e. it is a predefined process that does not include any modifications. Figure 9.0.2 displays only some of its many inputs and outputs. The latter, however, is a user-defined process meant to emulate relevant consumption and emission exchanges, by the use of factors and formulas (see Figure 3.8).



Local name: EU-27: Heavy fuel oil at refinery (1.0wt.% S) PE

No image

Scaling factor: 4.6E008 ☐ Fixed

Allocation: (no allocation)

Free parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer

Fixed parameters

Inputs — Show all flows

Parameter	Flow	Quantity	Amount	Unit	Tracked flows
	Air [Renewable resources]	Mass	1.01E008	kg	
	Antimony [Non renewable elements]	Mass	0.00127	kg	
	Barium sulphate [Non renewable resources]	Mass	1.71E-006	kg	
	Basalt [Non renewable resources]	Mass	3.43	kg	
	Bauxite [Non renewable resources]	Mass	1.85E003	kg	
	Bentonite [Non renewable resources]	Mass	4.78E005	kg	
	Biotic Production [Transformation]	Biotic Production (Transf.)	907	kg/a	
	Biotic Production [Occupation]	Biotic Production (Occ.)	1.91E005	kg	
	Calcium chloride [Non renewable resources]	Mass	0.000175	kg	
	Carbon dioxide [Renewable resources]	Mass	1.13E006	kg	
	Chromium [Non renewable elements]	Mass	1.21E003	kg	
	Clay [Non renewable resources]	Mass	1.71E004	kg	
	Cobalt [Non renewable elements]	Mass	0.00162	kg	
	Colemanite ore [Non renewable resources]	Mass	43	kg	
	Copper [Non renewable elements]	Mass	801	kg	
	Crude oil (in MJ) [Crude oil (resource)]	Mass	4.45E008	kg	
	Dolomite [Non renewable resources]	Mass	10.8	kg	
	Erosion Resistance [Transformation]	Erosion Resistance (Transf.)	111	kg/a	
	Erosion Resistance [Occupation]	Erosion Resistance (Occ.)	3.49E004	kg	
	Feldspar (aluminium silicates) [Non renewable resources]	Mass	4.31E-014	kg	
	Ferro manganese [Non renewable resources]	Mass	4.68E-010	kg	
	Fluorspar (calcium fluoride; fluorite) [Non renewable resources]	Mass	176	kg	
	Gold [Non renewable elements]	Mass	0.00223	kg	
	Granite [Non renewable resources]	Mass	3.11E-014	kg	
	Groundwater Replenishment [Occupation]	Groundwater Replenishment (	3.88E007	mm*m2	
	Groundwater Replenishment [Transformation]	Groundwater Replenishment (	1.38E005	(mm*m2)/	
	Gypsum (natural gypsum) [Non renewable resources]	Mass	1.75E004	kg	
	Hard coal (in MJ) [Hard coal (resource)]	Energy (net calorific value)	4.45E007	MJ	
	Heavy spar (BaSO4) [Non renewable resources]	Mass	0.125	kg	
	Ilmenite (titanium ore) [Non renewable resources]	Mass	19.1	kg	
	Inert rock [Non renewable resources]	Mass	4.56E007	kg	
	Iridium [Non renewable elements]	Mass	2.99E-006	kg	
	Iron [Non renewable elements]	Mass	2.84E005	kg	
	Kaolin ore [Non renewable resources]	Mass	75.7	kg	

Outputs — Show all flows

	Parameter	Flow	Quantity	Amount	Unit	Tracked flow
■		Heavy fuel oil (1.0 wt.% S) [Refinery products]	Mass	4.6E008	kg	X
■		High radioactive waste [Radioactive waste]	Mass	38.5	kg	*
■		Low radioactive wastes [Radioactive waste]	Mass	500	kg	*
■		Medium radioactive wastes [Radioactive waste]	Mass	235	kg	*
■		Radioactive tailings [Radioactive waste]	Mass	2.59E004	kg	*
		1,1,1-Trichloroethane [Halogenated organic emissions to air]	Mass	3.7E-006	kg	
		1,2-Dibromoethane [Halogenated organic emissions to fresh water]	Mass	2.67E-011	kg	
		1,3,5-Trimethylbenzene [Group NMVOC to air]	Mass	6.5E-011	kg	
		Acenaphthene [Hydrocarbons to fresh water]	Mass	0.0983	kg	
		Acenaphthene [Hydrocarbons to sea water]	Mass	0.43	kg	
		Acenaphthylene [Hydrocarbons to fresh water]	Mass	0.0421	kg	
		Acenaphthylene [Hydrocarbons to sea water]	Mass	0.184	kg	
		Acetaldehyde (Ethanal) [Group NMVOC to air]	Mass	3.12	kg	
		Acetic acid [Hydrocarbons to sea water]	Mass	8.4E-008	kg	
		Acetic acid [Group NMVOC to air]	Mass	22.4	kg	
		Acetic acid [Hydrocarbons to fresh water]	Mass	0.0169	kg	
		Acetone (dimethylcetone) [Group NMVOC to air]	Mass	3.04	kg	
		Acid (calculated as H+) [Inorganic emissions to fresh water]	Mass	0.165	kg	
		Acrolein [Group NMVOC to air]	Mass	0.123	kg	
		Acrylonitrile [Hydrocarbons to fresh water]	Mass	3.25E-009	kg	
		Acrylonitrile [Group NMVOC to air]	Mass	2.42E-007	kg	
		Adsorbable organic halogen compounds (AOX) [Analytical measures to fresh wate	Mass	131	kg	
		Adsorbable organic halogen compounds (AOX) [Analytical measures to sea water]	Mass	0.000135	kg	
		Aldehyde (unspecified) [Group NMVOC to air]	Mass	0.17	kg	
		Alkane (unspecified) [Hydrocarbons to fresh water]	Mass	1.3E-009	kg	
		Alkane (unspecified) [Group NMVOC to air]	Mass	42	kg	
		Alkene (unspecified) [Group NMVOC to air]	Mass	30.7	kg	
		Aluminium [Particles to air]	Mass	0.0126	kg	
		Aluminium (+III) [Inorganic emissions to industrial soil]	Mass	0.042	kg	
		Aluminium (+III) [Inorganic emissions to fresh water]	Mass	86	kg	
		Aluminium (+III) [Inorganic emissions to sea water]	Mass	0.00354	kg	
		Aluminium ion (+III) [Inorganic emissions to fresh water]	Mass	1.34E-008	kg	
		Aluminium ion (+III) [Inorganic emissions to sea water]	Mass	1.63E-010	kg	
		Aluminium oxide (dust) [Particles to air]	Mass	0.0981	kg	

Figure 9.0.2: Partial screenshot of EU-27 Heavy fuel oil production at refinery (1.0wt. % S) process scaled to 4.6E+08 kg of HFO consumption, as per defined by PE-International (2013)

The HFO production process is driven by a consumption factor and formula applied through the ship propulsion process; i.e. the quantity of HFO will vary depending on the requirement by the propulsion process, and so will the different material/energy inputs and emission outputs required for the production of the amount of HFO needed.

To demonstrate the above, a set of sample calculations pertaining results from the CONSAR vessel are included below. Relevant resource flows, such as crude oil and water, are representative of only many of the resource flows that could be highlighted.

Resources calculation

By the use of the following energy formula, and characteristics from the CONSAR vessel –such as engine power, trip duration and SFC at chosen load–, the fuel consumption for the trip can be calculated.

$$Energy \ = \# \ of \ engines \ \times \ engine \ power \ \times \ \# \ of \ hours \ \times \ \% \ load$$

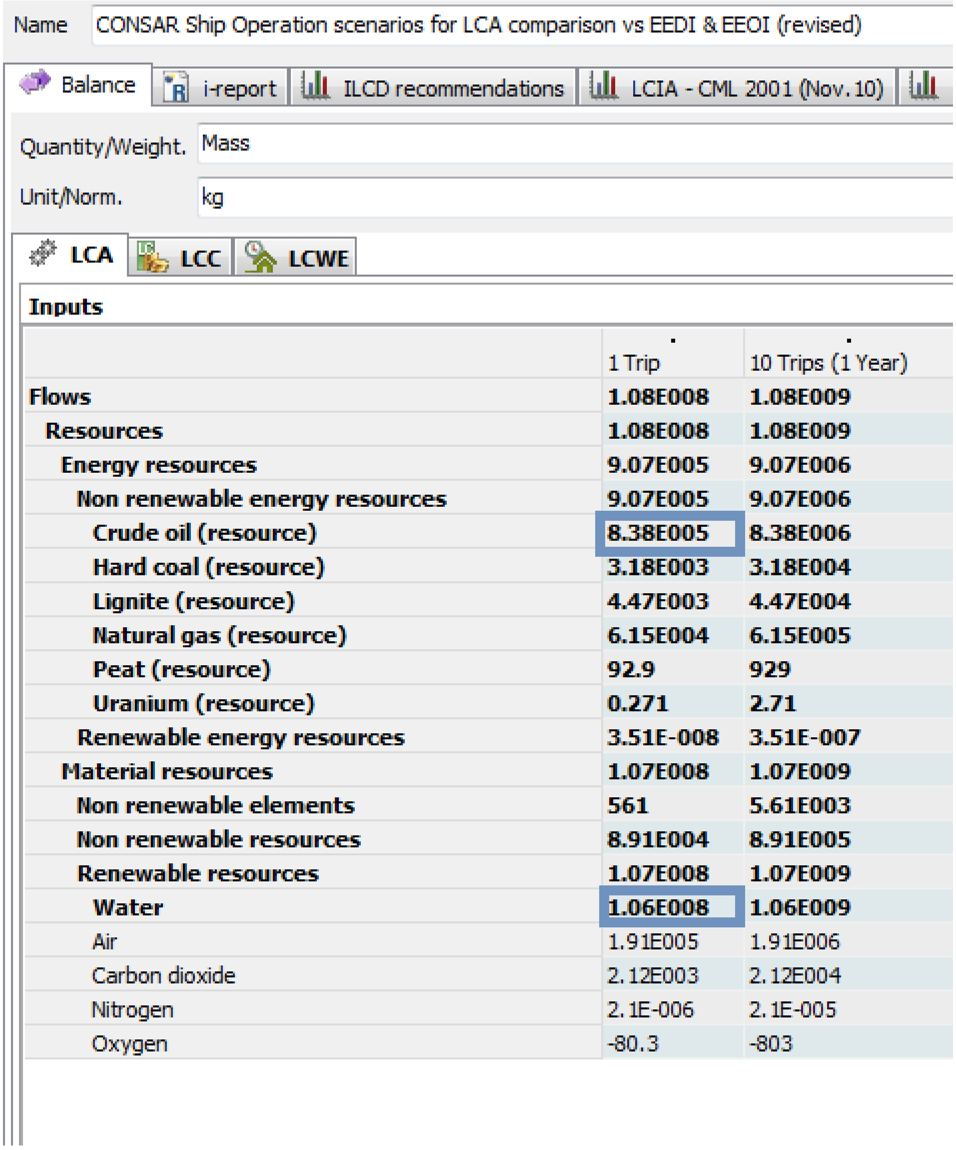
$$Energy \ = 1 \ \times \ 14{,}280 \ kW \ \times \ 484 \ hrs \ \times \ .75 \ = 5.18E + 06 \ kWh$$

$$\begin{aligned} Fuel \ consumption \ &= Energy \ \times \ SFC \ = 5.18E + 06 \ kWh \ \times \ 167 \ {}^{g}/_{kWh} \\ &= 8.65E + 05 \ kg \end{aligned}$$

According to Figure 9.0.2 and its scaling factor, for every 4.6E+08 kg of HFO requirement, among other various inputs, a linear input of 4.45E+08 kg of crude oil is compulsory. Using this ratio, the following is the total crude oil (non-renewable energy resource) consumption for the CONSAR vessel under the 1 trip category:

$$Crude \ oil \ consumption \ = 8.65E + 05 \ kg \ \times \ \frac{4.45E + 08}{4.6E + 08} \ = \ 8.38E + 05 \ kg$$

The above figure is underscored in Section 4.3.3.2 (inventory results), and additionally portrayed in Figure 9.0.3 as the most influential flow under the non-renewable energy resources category. These aggregated results are also included within Table 4.10: Mass balance, Bulk carrier vessel operational phase – Resources – Absolute values (kg) – 1 trip vs. 10 trips (1 year) results.



Name: CONSAR Ship Operation scenarios for LCA comparison vs EEDI & EEOI (revised)

Quantity/Weight.: Mass

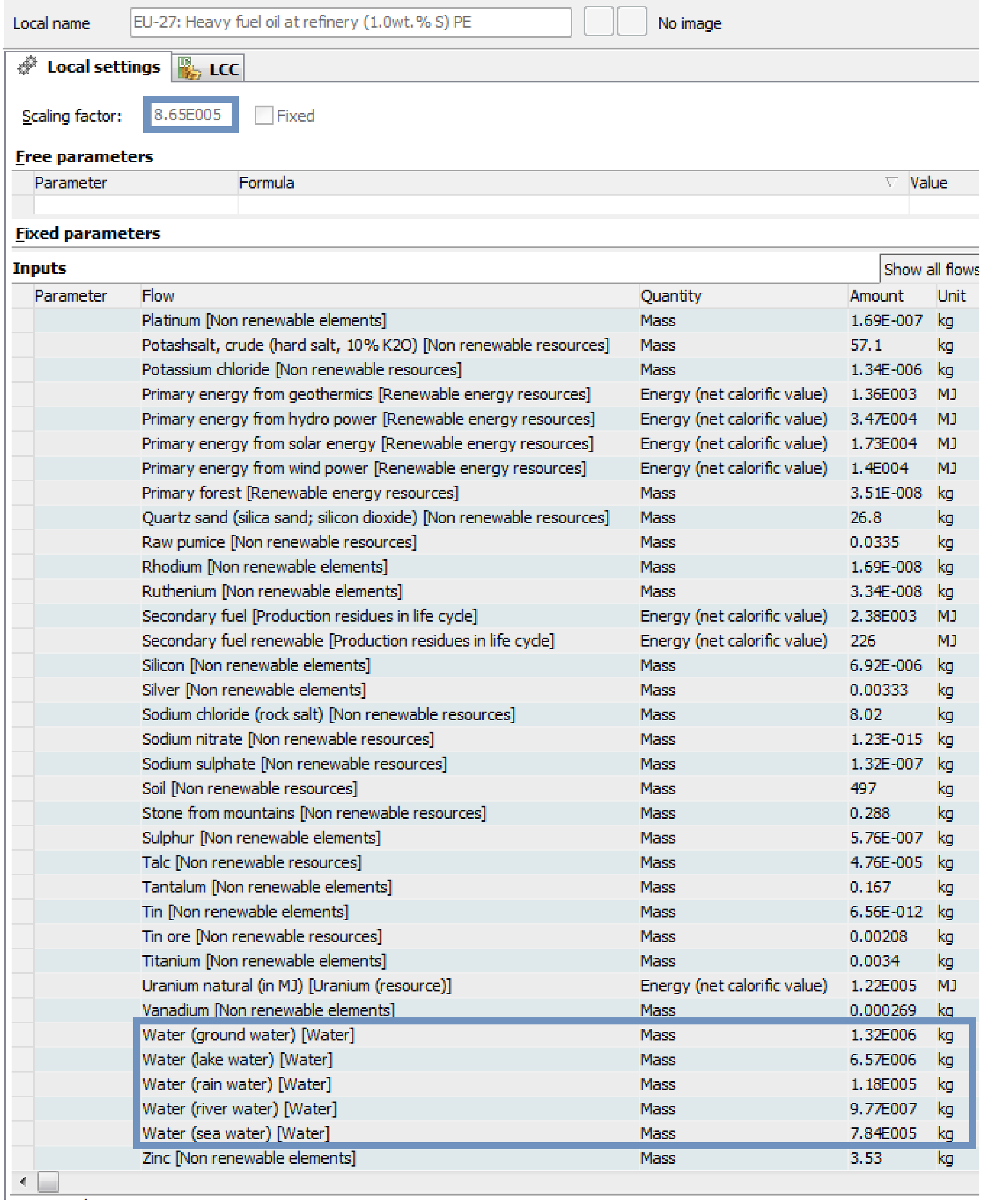
Unit/Norm.: kg

Inputs

	1 Trip	10 Trips (1 Year)
Flows	**1.08E008**	**1.08E009**
Resources	**1.08E008**	**1.08E009**
Energy resources	**9.07E005**	**9.07E006**
Non renewable energy resources	**9.07E005**	**9.07E006**
Crude oil (resource)	**8.38E005**	**8.38E006**
Hard coal (resource)	**3.18E003**	**3.18E004**
Lignite (resource)	**4.47E003**	**4.47E004**
Natural gas (resource)	**6.15E004**	**6.15E005**
Peat (resource)	**92.9**	**929**
Uranium (resource)	**0.271**	**2.71**
Renewable energy resources	**3.51E-008**	**3.51E-007**
Material resources	**1.07E008**	**1.07E009**
Non renewable elements	**561**	**5.61E003**
Non renewable resources	**8.91E004**	**8.91E005**
Renewable resources	**1.07E008**	**1.07E009**
Water	**1.06E008**	**1.06E009**
Air	1.91E005	1.91E006
Carbon dioxide	2.12E003	2.12E004
Nitrogen	2.1E-006	2.1E-005
Oxygen	-80.3	-803

Figure 9.0.3: Partial screenshot of mass balance results for resources, CONSAR vessel

In the other hand, water, which is the most relevant material resource consumed through the 1- trip category of the CONSAR vessel, is similarly calculated. Figure 9.0.4, using an HFO consumption ratio of 8.65E+05 kg (as calculated above), depicts the different consumption results for water obtained through different sources.



Local name: EU-27: Heavy fuel oil at refinery (1.0wt.% S) PE

Scaling factor: 8.65E005 ☐ Fixed

Free parameters

Parameter	Formula	Value

Fixed parameters

Inputs

Parameter	Flow	Quantity	Amount	Unit
	Platinum [Non renewable elements]	Mass	1.69E-007	kg
	Potashsalt, crude (hard salt, 10% K2O) [Non renewable resources]	Mass	57.1	kg
	Potassium chloride [Non renewable resources]	Mass	1.34E-006	kg
	Primary energy from geothermics [Renewable energy resources]	Energy (net calorific value)	1.36E003	MJ
	Primary energy from hydro power [Renewable energy resources]	Energy (net calorific value)	3.47E004	MJ
	Primary energy from solar energy [Renewable energy resources]	Energy (net calorific value)	1.73E004	MJ
	Primary energy from wind power [Renewable energy resources]	Energy (net calorific value)	1.4E004	MJ
	Primary forest [Renewable energy resources]	Mass	3.51E-008	kg
	Quartz sand (silica sand; silicon dioxide) [Non renewable resources]	Mass	26.8	kg
	Raw pumice [Non renewable resources]	Mass	0.0335	kg
	Rhodium [Non renewable elements]	Mass	1.69E-008	kg
	Ruthenium [Non renewable elements]	Mass	3.34E-008	kg
	Secondary fuel [Production residues in life cycle]	Energy (net calorific value)	2.38E003	MJ
	Secondary fuel renewable [Production residues in life cycle]	Energy (net calorific value)	226	MJ
	Silicon [Non renewable elements]	Mass	6.92E-006	kg
	Silver [Non renewable elements]	Mass	0.00333	kg
	Sodium chloride (rock salt) [Non renewable resources]	Mass	8.02	kg
	Sodium nitrate [Non renewable resources]	Mass	1.23E-015	kg
	Sodium sulphate [Non renewable resources]	Mass	1.32E-007	kg
	Soil [Non renewable resources]	Mass	497	kg
	Stone from mountains [Non renewable resources]	Mass	0.288	kg
	Sulphur [Non renewable elements]	Mass	5.76E-007	kg
	Talc [Non renewable resources]	Mass	4.76E-005	kg
	Tantalum [Non renewable elements]	Mass	0.167	kg
	Tin [Non renewable elements]	Mass	6.56E-012	kg
	Tin ore [Non renewable resources]	Mass	0.00208	kg
	Titanium [Non renewable elements]	Mass	0.0034	kg
	Uranium natural (in MJ) [Uranium (resource)]	Energy (net calorific value)	1.22E005	MJ
	Vanadium [Non renewable elements]	Mass	0.000269	kg
	Water (ground water) [Water]	Mass	1.32E006	kg
	Water (lake water) [Water]	Mass	6.57E006	kg
	Water (rain water) [Water]	Mass	1.18E005	kg
	Water (river water) [Water]	Mass	9.77E007	kg
	Water (sea water) [Water]	Mass	7.84E005	kg
	Zinc [Non renewable elements]	Mass	3.53	kg

Figure 9.0.4: Partial screenshot of EU-27 Heavy fuel oil production at refinery (1.0wt. % S) process scaled to 8.65E+05 kg of HFO consumption, as per defined by PE-International (2013)

By adding the water ratios found in the scaled HFO production process, the total requirement for water can be obtained as expressed below.

$$Water\ consumption = 1.32E+06\ kg + 6.57E+06\ kg + 1.18E+05\ kg + 9.77E+07\ kg + 7.84E+05\ kg = 1.06E+08\ kg$$

The above quantity is also emphasised through Section 4.3.3.2 (inventory results) and Figure 9.0.3. Table 4.10 additionally lists relative aggregate figures.

Emissions to air calculation

Emissions are similarly calculated by using the previously obtained energy per trip value, and additionally emission factors valid for the CONSAR vessel. The following are sample calculations underlining some of the most significant output flows analysed herein.

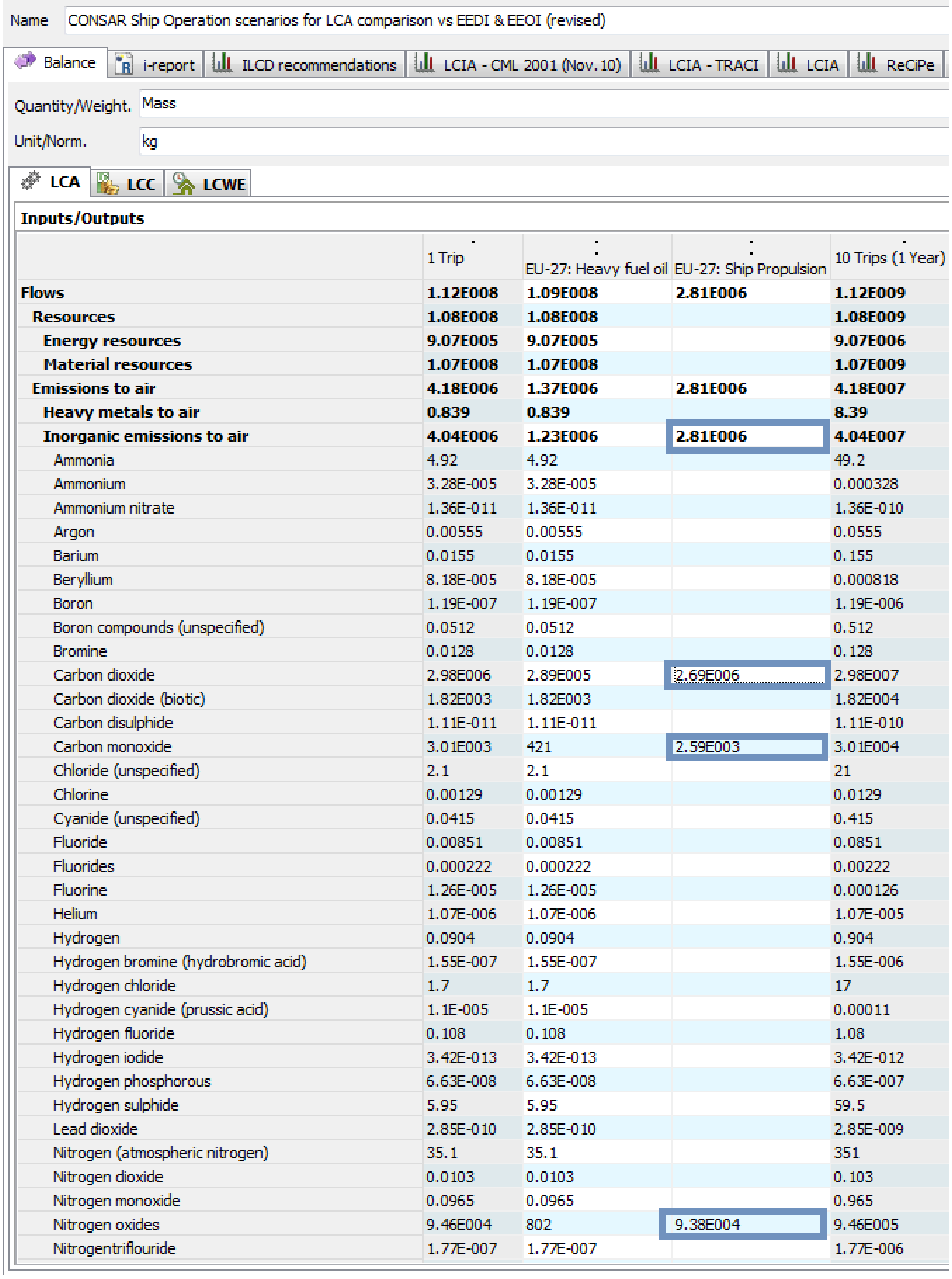
$$CO_2\ output\ _{propulsion} = 5.18E+06\ kWh \times 520\ {}^{g}/_{kWh} = 2.69E+06\ kg$$

$$CO\ output\ _{propulsion} = 5.18E+06\ kWh \times 0.5\ {}^{g}/_{kWh} = 2.59E+03\ kg$$

$$NO_x\ output\ _{propulsion} = 5.18E+06\ kWh \times 18.1\ {}^{g}/_{kWh} = 9.38E+04\ kg$$

Figure 9.0.5 encompasses the above results for the ship propulsion and generation process, while additionally displaying contributing results from the HFO production at refinery process. These last are obtained –as mentioned previously–, through the original definition of the process, while driven by the scale and requirement of HFO.

The above figures can be found in Table 4.12: Mass balance, Bulk carrier vessel operational phase – Relevant emissions to air – Absolute values (kg), while aggregate results are included in Table 4.11: Mass balance, Bulk carrier vessel operational phase – Emissions to air – Absolute values (kg) – 1 trip vs. 10 trips (1 year) results.



Name: CONSAR Ship Operation scenarios for LCA comparison vs EEDI & EEOI (revised)

Quantity/Weight.: Mass

Unit/Norm.: kg

Inputs/Outputs

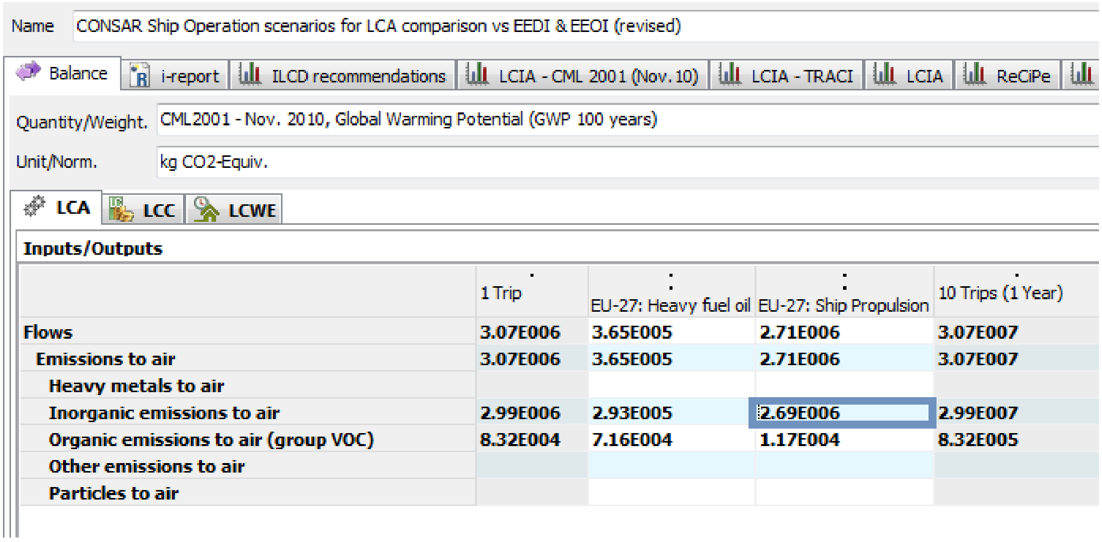
	1 Trip	EU-27: Heavy fuel oil	EU-27: Ship Propulsion	10 Trips (1 Year)
Flows	**1.12E008**	**1.09E008**	**2.81E006**	**1.12E009**
Resources	**1.08E008**	**1.08E008**		**1.08E009**
Energy resources	**9.07E005**	**9.07E005**		**9.07E006**
Material resources	**1.07E008**	**1.07E008**		**1.07E009**
Emissions to air	**4.18E006**	**1.37E006**	**2.81E006**	**4.18E007**
Heavy metals to air	**0.839**	**0.839**		**8.39**
Inorganic emissions to air	**4.04E006**	**1.23E006**	**2.81E006**	**4.04E007**
Ammonia	4.92	4.92		49.2
Ammonium	3.28E-005	3.28E-005		0.000328
Ammonium nitrate	1.36E-011	1.36E-011		1.36E-010
Argon	0.00555	0.00555		0.0555
Barium	0.0155	0.0155		0.155
Beryllium	8.18E-005	8.18E-005		0.000818
Boron	1.19E-007	1.19E-007		1.19E-006
Boron compounds (unspecified)	0.0512	0.0512		0.512
Bromine	0.0128	0.0128		0.128
Carbon dioxide	2.98E006	2.89E005	2.69E006	2.98E007
Carbon dioxide (biotic)	1.82E003	1.82E003		1.82E004
Carbon disulphide	1.11E-011	1.11E-011		1.11E-010
Carbon monoxide	3.01E003	421	2.59E003	3.01E004
Chloride (unspecified)	2.1	2.1		21
Chlorine	0.00129	0.00129		0.0129
Cyanide (unspecified)	0.0415	0.0415		0.415
Fluoride	0.00851	0.00851		0.0851
Fluorides	0.000222	0.000222		0.00222
Fluorine	1.26E-005	1.26E-005		0.000126
Helium	1.07E-006	1.07E-006		1.07E-005
Hydrogen	0.0904	0.0904		0.904
Hydrogen bromine (hydrobromic acid)	1.55E-007	1.55E-007		1.55E-006
Hydrogen chloride	1.7	1.7		17
Hydrogen cyanide (prussic acid)	1.1E-005	1.1E-005		0.00011
Hydrogen fluoride	0.108	0.108		1.08
Hydrogen iodide	3.42E-013	3.42E-013		3.42E-012
Hydrogen phosphorous	6.63E-008	6.63E-008		6.63E-007
Hydrogen sulphide	5.95	5.95		59.5
Lead dioxide	2.85E-010	2.85E-010		2.85E-009
Nitrogen (atmospheric nitrogen)	35.1	35.1		351
Nitrogen dioxide	0.0103	0.0103		0.103
Nitrogen monoxide	0.0965	0.0965		0.965
Nitrogen oxides	9.46E004	802	9.38E004	9.46E005
Nitrogentriflouride	1.77E-007	1.77E-007		1.77E-006

Figure 9.0.5: Partial screenshot of mass balance results for emissions to air flows, CONSAR vessel

GWP results

Lastly, Global Warming Potential (GWP) results are calculated as explained on Section 3.3.3 (notes on impact assessment and carbon accounting), granting relevance to the substances that have a warming potential relative to that of carbon dioxide, and additionally adding weight to this potential by using a scale procured through using CO_2 as a reference.

Figure 9.0.6 portrays a screenshot of the balance view within the GaBi software, including GWP results for the CONSAR vessel under the 1-trip and 10 trips categories. The figure additionally shows two different contributions coming from the above-mentioned processes. It is clear that the result obtained for CO_2 emissions under the ship propulsion process is the most relevant for the GWP score. These results are additionally included in Table 4.13.



Name: CONSAR Ship Operation scenarios for LCA comparison vs EEDI & EEOI (revised)

Quantity/Weight: CML2001 - Nov. 2010, Global Warming Potential (GWP 100 years)

Unit/Norm.: kg CO2-Equiv.

Inputs/Outputs

	1 Trip	EU-27: Heavy fuel oil	EU-27: Ship Propulsion	10 Trips (1 Year)
Flows	**3.07E006**	**3.65E005**	**2.71E006**	**3.07E007**
Emissions to air	**3.07E006**	**3.65E005**	**2.71E006**	**3.07E007**
Heavy metals to air				
Inorganic emissions to air	**2.99E006**	**2.93E005**	**2.69E006**	**2.99E007**
Organic emissions to air (group VOC)	**8.32E004**	**7.16E004**	**1.17E004**	**8.32E005**
Other emissions to air				
Particles to air				

Figure 9.0.6: Screenshot of GWP results for CONSAR vessel

Appendix D: Case studies additional information

D.1 ASTANDER case vessel main engines, accommodation facilities, and vessel speed and voyage particulars

Table 9.0.1: Ro-Ro passenger vessel main engine particulars

Type	Sulzer 4 x 16ZAV40S, 4 strokes, single acting
Output	MCR: 11,520 kW (x4) at 500 rpm
Machinery overview	
Main engines	4 oil engines, w/ clutches, flexible couplings and single reduction geared to screw shafts driving 2 CP propellers at 147 rpm
Total power	MCR 48,000 kW
Auxiliary generators	2 x 1,680 kW 440V 60Hz A.C. 3 x 1,600 kW 440V 60Hz A.C.
Thrusters	2 thrusters (f) 1000 kW (1360 hp) 1 thruster (a) 1400 kW (1903 hp)

Table 9.0.2: Ro-Ro passenger vessel speed and accommodation capacities

Speed, trial maximum	31.00 knots
Speed, service	28.00 knots
Accommodation	
Total capacity	850 passengers + 500 cars
Single cabins	265

Table 9.0.3: Ro-Ro passenger vessel operational profile

Frequent route	North of Spain to South of UK, and back
Trip details	3 trips per week, 1 day trip duration
Lay-up periods	Recommended every 2.5 years

D.2 ASTANDER case vessel engine specification, alternative engine option particulars, and assumed emission factors

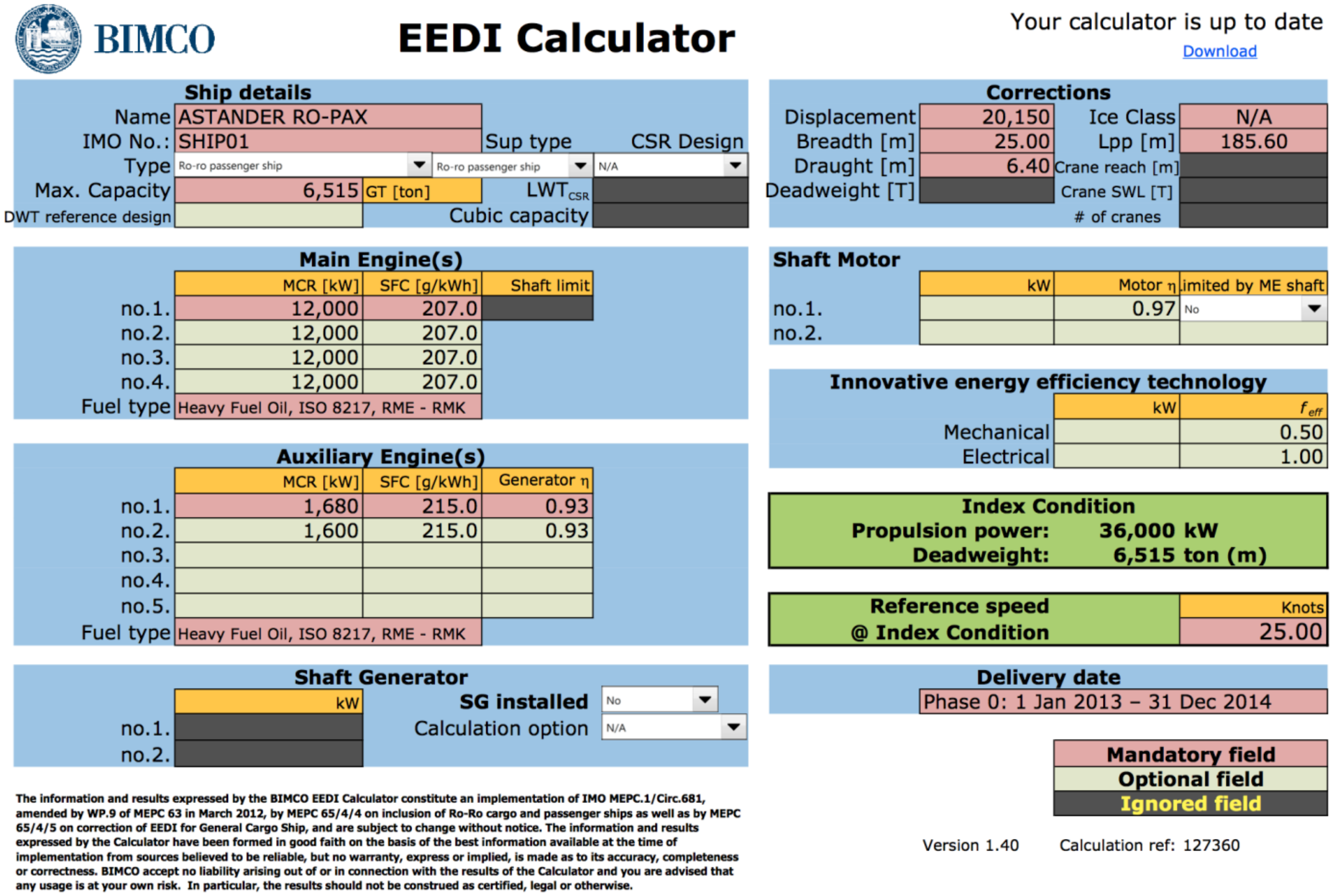
Table 9.0.4: Specification of Sulzer 16ZA40S diesel engine

Manufacturer	Sulzer Diesel France
Engine model	16ZAV40S
Cylinder bore	400 mm
Cylinder stroke	560 mm
Speed	500 rpm
BMP	24.56 bar at MCR
Number of strokes	Four
Number of cylinders	16 in V arrangement
Nominal power of diesel engine	11520 kW (720 kW/cyl.) at MCR

Table 9.0.5: Average SFC and emission factors for medium speed diesel engines, as adapted from Johnsen and Fet (1998)

Diesel (HFO 1.0 wt. % S)	Material consumption	207 g/kWh
NO_x	Inorganic emissions to air	16.7 g/kWh
CO	Inorganic emissions to air	0.36 g/kWh
Hydrocarbons	Emissions to air	0.19 g/kWh
CO_2	Inorganic emissions to air	671 g/kWh
SO_2	Inorganic emissions to air	4.2 g/kWh

D.3 Additional ASTANDER case vessel EEDI results, including screenshot of BIMCO (2011) calculator inputs and list of parameters



EEDI Calculator

Your calculator is up to date

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Ship details

Name: ASTANDER RO-PAX
IMO No.: SHIP01
Type: Ro-ro passenger ship
Sup type: Ro-ro passenger ship
CSR Design: N/A
Max. Capacity: 6,515 GT [ton]
LWT_{CSR}:
DWT reference design:
Cubic capacity:

Corrections

Displacement	20,150	Ice Class	N/A
Breadth [m]	25.00	Lpp [m]	185.60
Draught [m]	6.40	Crane reach [m]	
Deadweight [T]		Crane SWL [T]	
		# of cranes	

Main Engine(s)

	MCR [kW]	SFC [g/kWh]	Shaft limit
no.1.	12,000	207.0	
no.2.	12,000	207.0	
no.3.	12,000	207.0	
no.4.	12,000	207.0	

Fuel type: Heavy Fuel Oil, ISO 8217, RME - RMK

Shaft Motor

	kW	Motor η	Limited by ME shaft
no.1.		0.97	No
no.2.			

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	kW	f_{eff}
Mechanical		0.50
Electrical		1.00

Auxiliary Engine(s)

	MCR [kW]	SFC [g/kWh]	Generator η
no.1.	1,680	215.0	0.93
no.2.	1,600	215.0	0.93
no.3.			
no.4.			
no.5.			

Fuel type: Heavy Fuel Oil, ISO 8217, RME - RMK

Index Condition
Propulsion power: 36,000 kW
Deadweight: 6,515 ton (m)

Reference speed @ Index Condition: 25.00 Knots

Shaft Generator

	kW
no.1.	
no.2.	

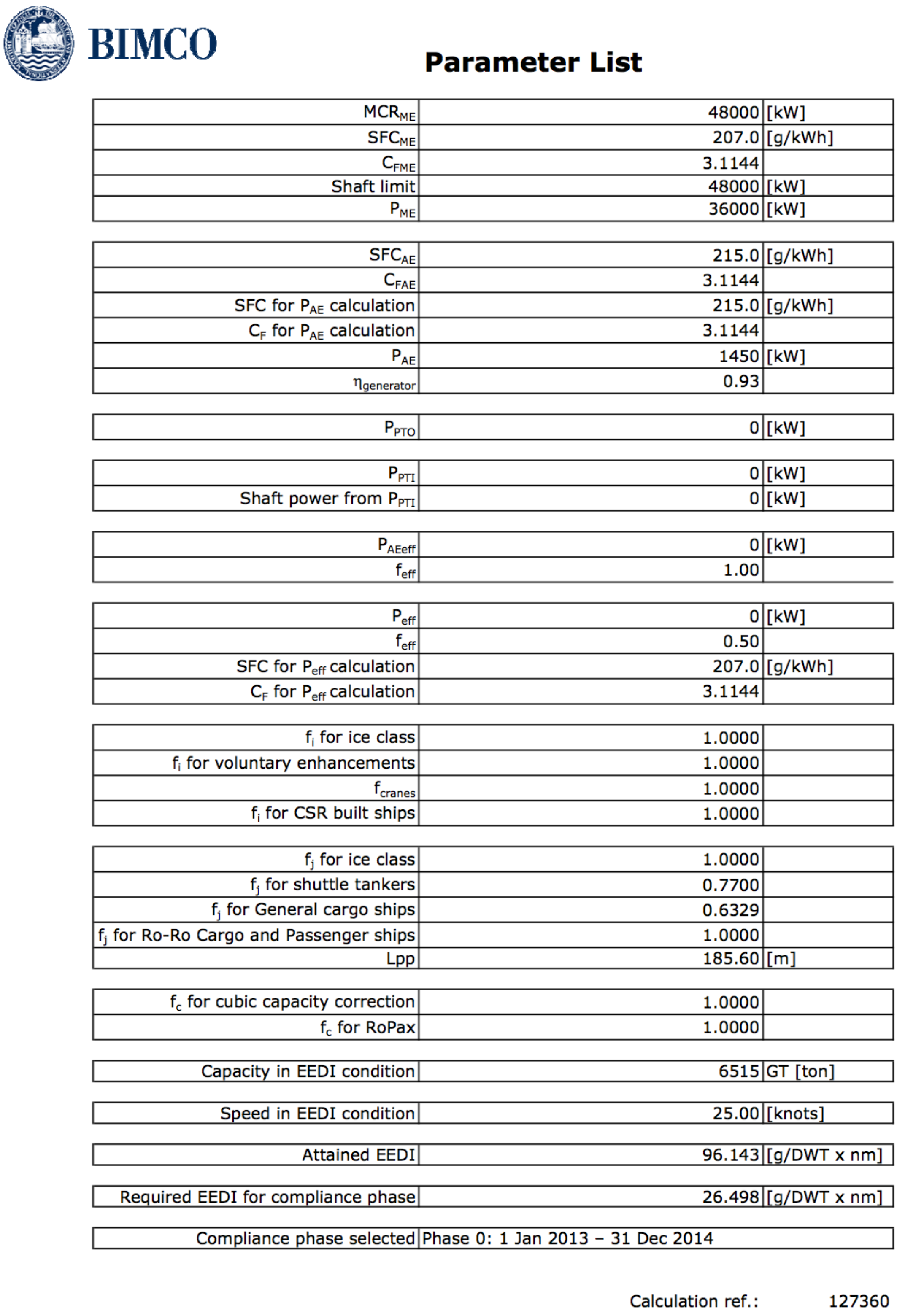
SG installed: No
Calculation option: N/A

Delivery date: Phase 0: 1 Jan 2013 – 31 Dec 2014

Mandatory field
Optional field
Ignored field

The information and results expressed by the BIMCO EEDI Calculator constitute an implementation of IMO MEPC.1/Circ.681, amended by WP.9 of MEPC 63 in March 2012, by MEPC 65/4/4 on inclusion of Ro-Ro cargo and passenger ships as well as by MEPC 65/4/5 on correction of EEDI for General Cargo Ship, and are subject to change without notice. The information and results expressed by the Calculator have been formed in good faith on the basis of the best information available at the time of implementation from sources believed to be reliable, but no warranty, express or implied, is made as to its accuracy, completeness or correctness. BIMCO accept no liability arising out of or in connection with the results of the Calculator and you are advised that any usage is at your own risk. In particular, the results should not be construed as certified, legal or otherwise.

Version 1.40 Calculation ref: 127360



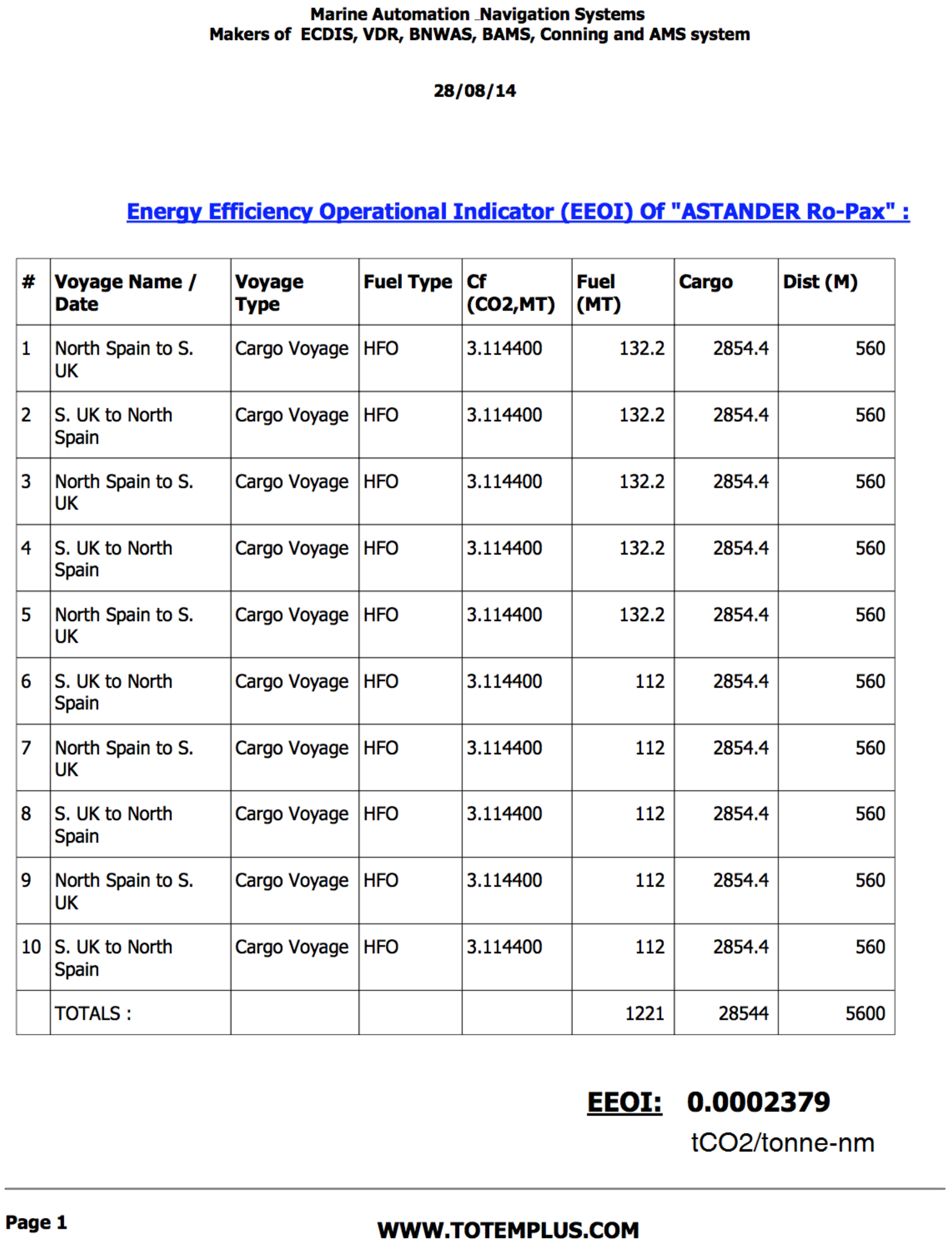
BIMCO

Parameter List

MCR_{ME}	48000	[kW]
SFC_{ME}	207.0	[g/kWh]
C_{FME}	3.1144	
Shaft limit	48000	[kW]
P_{ME}	36000	[kW]
SFC_{AE}	215.0	[g/kWh]
C_{FAE}	3.1144	
SFC for P_{AE} calculation	215.0	[g/kWh]
C_F for P_{AE} calculation	3.1144	
P_{AE}	1450	[kW]
$\eta_{generator}$	0.93	
P_{PTO}	0	[kW]
P_{PTI}	0	[kW]
Shaft power from P_{PTI}	0	[kW]
P_{AEeff}	0	[kW]
f_{eff}	1.00	
P_{eff}	0	[kW]
f_{eff}	0.50	
SFC for P_{eff} calculation	207.0	[g/kWh]
C_F for P_{eff} calculation	3.1144	
f_i for ice class	1.0000	
f_i for voluntary enhancements	1.0000	
f_{cranes}	1.0000	
f_i for CSR built ships	1.0000	
f_j for ice class	1.0000	
f_j for shuttle tankers	0.7700	
f_j for General cargo ships	0.6329	
f_j for Ro-Ro Cargo and Passenger ships	1.0000	
Lpp	185.60	[m]
f_c for cubic capacity correction	1.0000	
f_c for RoPax	1.0000	
Capacity in EEDI condition	6515	GT [ton]
Speed in EEDI condition	25.00	[knots]
Attained EEDI	96.143	[g/DWT x nm]
Required EEDI for compliance phase	26.498	[g/DWT x nm]
Compliance phase selected	Phase 0: 1 Jan 2013 – 31 Dec 2014	

Calculation ref.: 127360

D.4 ASTANDER case vessel EEOI voyage inputs and result, Totem-Plus (2012) calculator



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28/08/14

Energy Efficiency Operational Indicator (EEOI) Of "ASTANDER Ro-Pax" :

#	Voyage Name / Date	Voyage Type	Fuel Type	Cf (CO2,MT)	Fuel (MT)	Cargo	Dist (M)
1	North Spain to S. UK	Cargo Voyage	HFO	3.114400	132.2	2854.4	560
2	S. UK to North Spain	Cargo Voyage	HFO	3.114400	132.2	2854.4	560
3	North Spain to S. UK	Cargo Voyage	HFO	3.114400	132.2	2854.4	560
4	S. UK to North Spain	Cargo Voyage	HFO	3.114400	132.2	2854.4	560
5	North Spain to S. UK	Cargo Voyage	HFO	3.114400	132.2	2854.4	560
6	S. UK to North Spain	Cargo Voyage	HFO	3.114400	112	2854.4	560
7	North Spain to S. UK	Cargo Voyage	HFO	3.114400	112	2854.4	560
8	S. UK to North Spain	Cargo Voyage	HFO	3.114400	112	2854.4	560
9	North Spain to S. UK	Cargo Voyage	HFO	3.114400	112	2854.4	560
10	S. UK to North Spain	Cargo Voyage	HFO	3.114400	112	2854.4	560
	TOTALS :				1221	28544	5600

EEOI: **0.0002379**
tCO2/tonne-nm

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D.5 CONSAR case vessel main engine, hold capacities, and vessel speed and voyage particulars

Table 9.0.6: Bulk carrier main engine particulars

Type	Mitsui MAN B&W 6S60MC-C8, 2 strokes, single acting
Output	MCR: 14,280 kW (x1) at 105 rpm
Machinery overview	
Main engines	1 diesel oil engine
Total power	MCR 14,280 kW
Auxiliary generators	1 x 625 kW 440V 60Hz A.C.

Table 9.0.7: Bulk carrier speed and hold capacities

Speed, trial maximum	14.50 knots
Speed, service	12.00 knots
Hold capacity	
Total capacity, grain	100,300 m^3

Table 9.0.8: Bulk carrier operational profile

Frequent route	From Port Kirkenes to Port Said, and back
Trip details	10 trips per year, 484 hours trip duration

D.6 CONSAR case vessel engine specification, and assumed emission factors

Table 9.0.9: Specification of MAN B&W 6S60MC-C8 diesel engine, as adapted from MAN-Diesel (2009)

Manufacturer	MAN B&W
Engine model	6S60MC-C8
Cylinder bore	600 mm
Cylinder stroke	2.400 mm
Speed	105 rpm
BMP	20.0 bar at MCR
Number of strokes	Two
Number of cylinders	6 in line
Nominal power of diesel engine	14280 kW (2380 kW/cyl.) at MCR
Fuel consumption at 100% load	170 g/kWh
Fuel consumption at 85% load	168 g/kWh
Fuel consumption at 75% load	167 g/kWh
Fuel consumption at 50% load	170 g/kWh

Table 9.0.10: Emission factors for slow speed diesel engines, as adapted from Cooper and Gustafsson (2004) as cited by Moldanová et al. (2012)[15]

NO_x	Inorganic emissions to air	18.1 g/kWh
CO	Inorganic emissions to air	0.5 g/kWh
Hydrocarbons	Emissions to air	0.3 g/kWh
CO_2	Inorganic emissions to air	620 g/kWh
SO_2	Inorganic emissions to air	3.9 g/kWh

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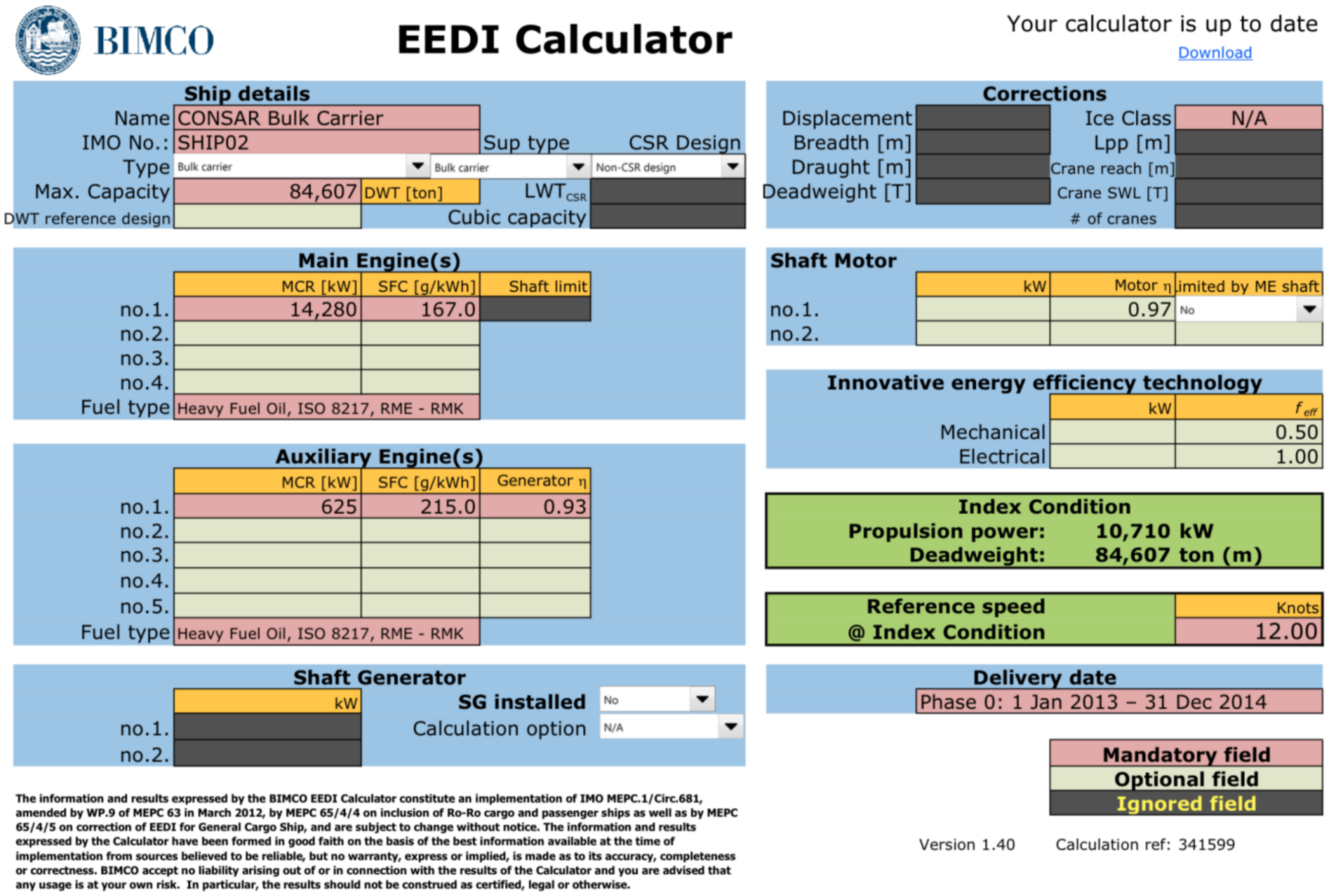
[15] Please note that the values included herein are not directly related to the engine specified in Table 9.0.9, but are meant to be utilised as a broad representation.

D.7 Additional CONSAR case vessel EEDI results, including screenshot of BIMCO (2011) calculator inputs and list of parameters



EEDI Calculator

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Ship details

Name	CONSAR Bulk Carrier		
IMO No.:	SHIP02	Sup type	CSR Design
Type	Bulk carrier	Bulk carrier	Non-CSR design
Max. Capacity	84,607	DWT [ton]	LWT$_{CSR}$
DWT reference design		Cubic capacity	

Corrections

Displacement		Ice Class	N/A
Breadth [m]		Lpp [m]	
Draught [m]		Crane reach [m]	
Deadweight [T]		Crane SWL [T]	
		# of cranes	

Main Engine(s)

	MCR [kW]	SFC [g/kWh]	Shaft limit
no.1.	14,280	167.0	
no.2.			
no.3.			
no.4.			

Fuel type: Heavy Fuel Oil, ISO 8217, RME - RMK

Shaft Motor

	kW	Motor η	Limited by ME shaft
no.1.		0.97	No
no.2.			

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	kW	f_{eff}
Mechanical		0.50
Electrical		1.00

Auxiliary Engine(s)

	MCR [kW]	SFC [g/kWh]	Generator η
no.1.	625	215.0	0.93
no.2.			
no.3.			
no.4.			
no.5.			

Fuel type: Heavy Fuel Oil, ISO 8217, RME - RMK

Index Condition
Propulsion power: 10,710 kW
Deadweight: 84,607 ton (m)

Reference speed @ Index Condition: 12.00 Knots

Shaft Generator

	kW
no.1.	
no.2.	

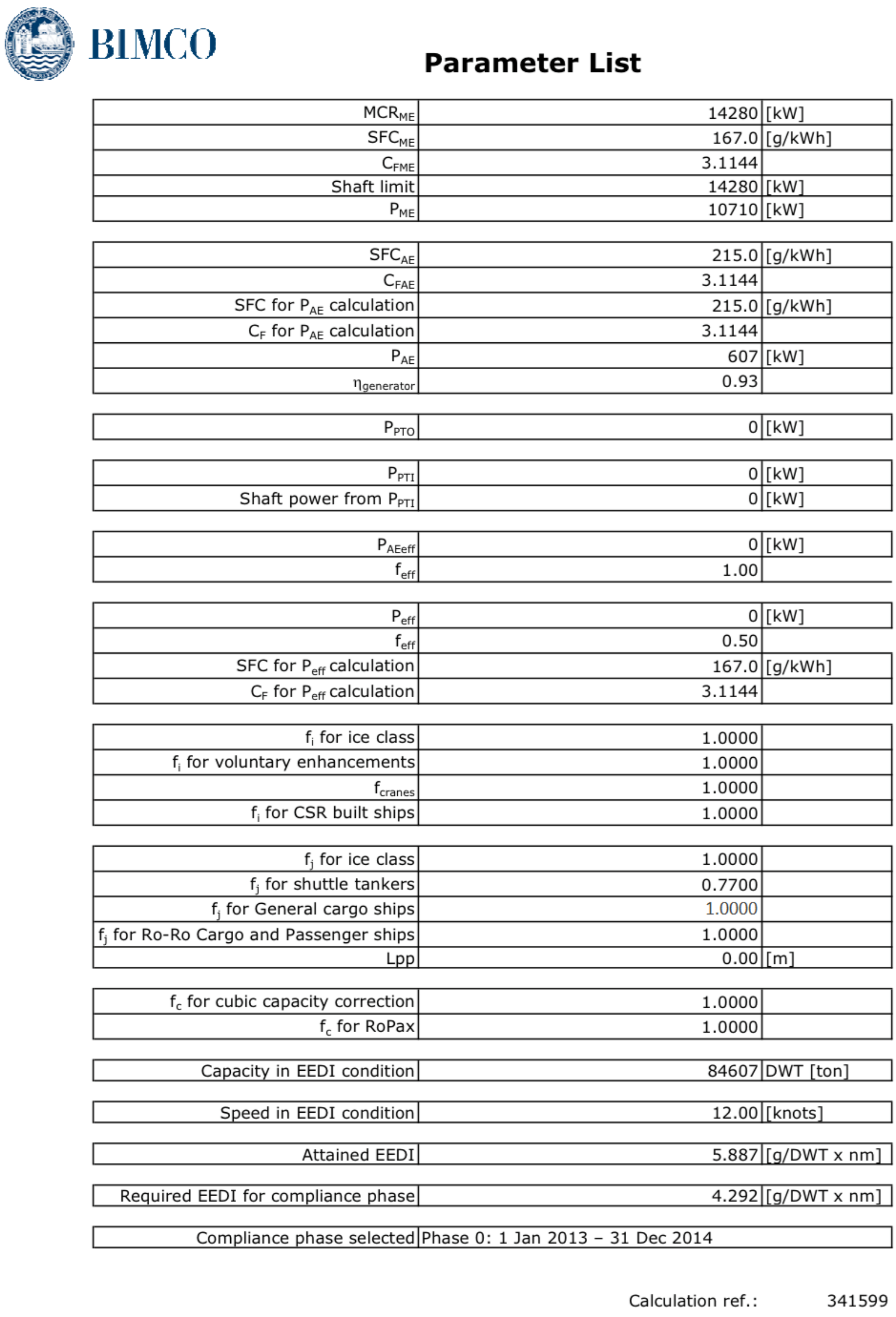
SG installed: No
Calculation option: N/A

Delivery date: Phase 0: 1 Jan 2013 – 31 Dec 2014

Mandatory field
Optional field
Ignored field

The information and results expressed by the BIMCO EEDI Calculator constitute an implementation of IMO MEPC.1/Circ.681, amended by WP.9 of MEPC 63 in March 2012, by MEPC 65/4/4 on inclusion of Ro-Ro cargo and passenger ships as well as by MEPC 65/4/5 on correction of EEDI for General Cargo Ship, and are subject to change without notice. The information and results expressed by the Calculator have been formed in good faith on the basis of the best information available at the time of implementation from sources believed to be reliable, but no warranty, express or implied, is made as to its accuracy, completeness or correctness. BIMCO accept no liability arising out of or in connection with the results of the Calculator and you are advised that any usage is at your own risk. In particular, the results should not be construed as certified, legal or otherwise.

Version 1.40 Calculation ref: 341599



BIMCO

Parameter List

MCR_{ME}	14280	[kW]
SFC_{ME}	167.0	[g/kWh]
C_{FME}	3.1144	
Shaft limit	14280	[kW]
P_{ME}	10710	[kW]

SFC_{AE}	215.0	[g/kWh]
C_{FAE}	3.1144	
SFC for P_{AE} calculation	215.0	[g/kWh]
C_F for P_{AE} calculation	3.1144	
P_{AE}	607	[kW]
$\eta_{generator}$	0.93	

P_{PTO}	0	[kW]

P_{PTI}	0	[kW]
Shaft power from P_{PTI}	0	[kW]

P_{AEeff}	0	[kW]
f_{eff}	1.00	

P_{eff}	0	[kW]
f_{eff}	0.50	
SFC for P_{eff} calculation	167.0	[g/kWh]
C_F for P_{eff} calculation	3.1144	

f_i for ice class	1.0000
f_i for voluntary enhancements	1.0000
f_{cranes}	1.0000
f_i for CSR built ships	1.0000

f_j for ice class	1.0000	
f_j for shuttle tankers	0.7700	
f_j for General cargo ships	1.0000	
f_j for Ro-Ro Cargo and Passenger ships	1.0000	
Lpp	0.00	[m]

f_c for cubic capacity correction	1.0000
f_c for RoPax	1.0000

Capacity in EEDI condition	84607	DWT [ton]

Speed in EEDI condition	12.00	[knots]

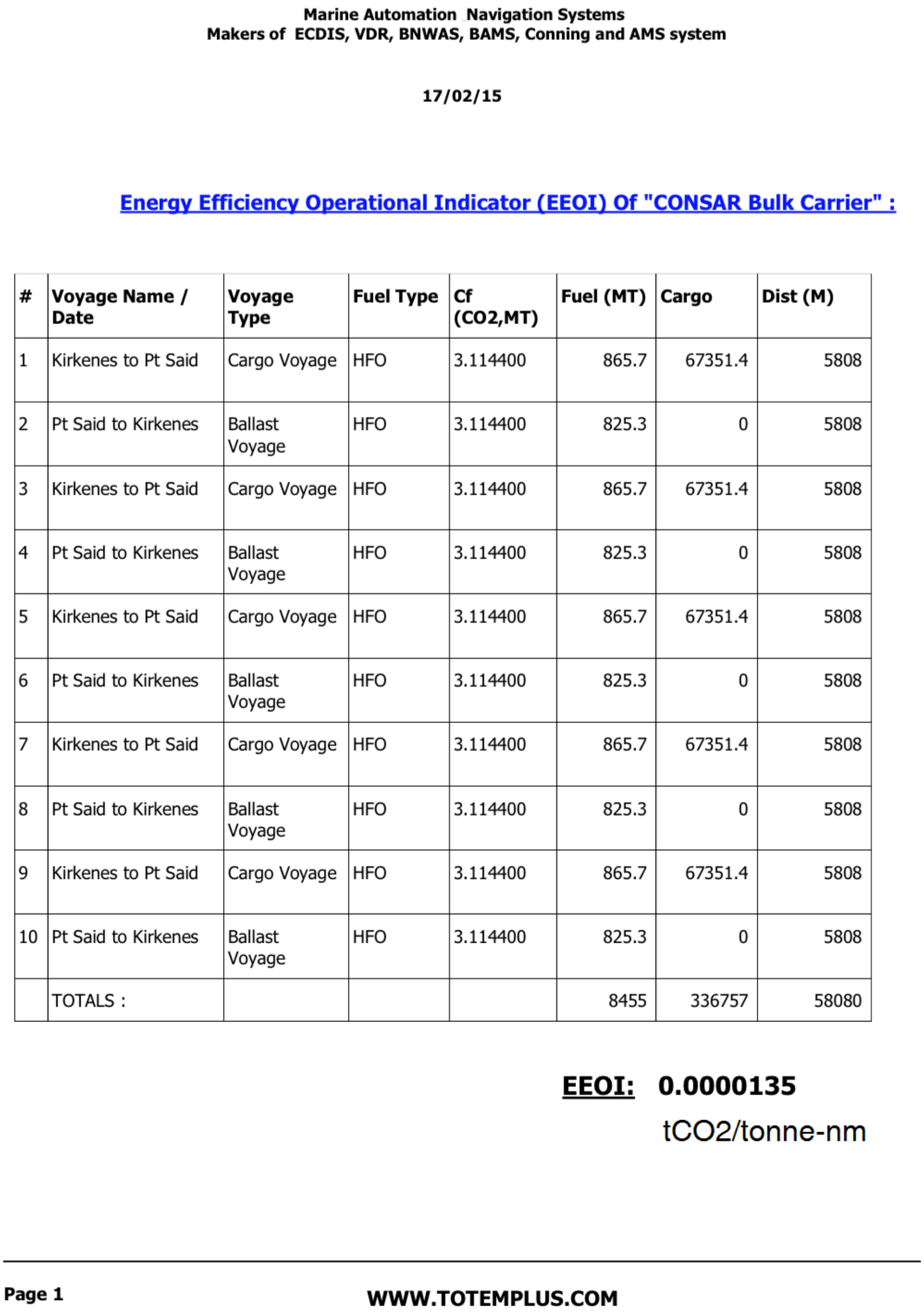
Attained EEDI	5.887	[g/DWT x nm]

Required EEDI for compliance phase	4.292	[g/DWT x nm]

Compliance phase selected	Phase 0: 1 Jan 2013 – 31 Dec 2014

Calculation ref.: 341599

D.8 CONSAR case vessel EEOI voyage inputs and result, Totem-Plus (2012) calculator



Marine Automation Navigation Systems
Makers of ECDIS, VDR, BNWAS, BAMS, Conning and AMS system

17/02/15

Energy Efficiency Operational Indicator (EEOI) Of "CONSAR Bulk Carrier" :

#	Voyage Name / Date	Voyage Type	Fuel Type	Cf (CO2,MT)	Fuel (MT)	Cargo	Dist (M)
1	Kirkenes to Pt Said	Cargo Voyage	HFO	3.114400	865.7	67351.4	5808
2	Pt Said to Kirkenes	Ballast Voyage	HFO	3.114400	825.3	0	5808
3	Kirkenes to Pt Said	Cargo Voyage	HFO	3.114400	865.7	67351.4	5808
4	Pt Said to Kirkenes	Ballast Voyage	HFO	3.114400	825.3	0	5808
5	Kirkenes to Pt Said	Cargo Voyage	HFO	3.114400	865.7	67351.4	5808
6	Pt Said to Kirkenes	Ballast Voyage	HFO	3.114400	825.3	0	5808
7	Kirkenes to Pt Said	Cargo Voyage	HFO	3.114400	865.7	67351.4	5808
8	Pt Said to Kirkenes	Ballast Voyage	HFO	3.114400	825.3	0	5808
9	Kirkenes to Pt Said	Cargo Voyage	HFO	3.114400	865.7	67351.4	5808
10	Pt Said to Kirkenes	Ballast Voyage	HFO	3.114400	825.3	0	5808
	TOTALS :				8455	336757	58080

EEOI: **0.0000135**
tCO2/tonne-nm

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Notes