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Life cycle modeling of a wind powered car carrier

An assessment of cost and greenhouse gas emissions

Master's thesis in Maritime Management

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Gothenburg, Sweden 2020

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Master's Thesis 2020:NN
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Cover: wPCC visualization.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2020

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Abstract

Emissions leading to global warming must be addressed by all industries and IMO has set a goal to reduce annual GHG emissions from international shipping by at least 50% by 2050. Possible pathways to achieve this are selecting a less carbon intensive fuel, reducing the average speed, or by reducing fuel consumption by applying fuel saving technologies. This thesis investigates all three concepts as applied to an ocean-going car carrier and applies two methodologies, LCA and LCC, to investigate the potential gains of wind propulsion. To determine and compare the performance of wind propulsion to ships using only renewable fuels, a ship without sails fuelled by LNG is used as a baseline. Total GHG emissions as well as annual and total cost of ownership is significantly reduced by combining free and abundant wind with modern ship construction. Using a preliminary performance routing in the North Atlantic, the wind powered car carrier can reduce fuel consumption by 80% compared to a ship without sails using the same hull. Although the addition of a wind propulsion system comes at a higher initial investment cost and increased GHG emissions from construction and scrapping, the reduction in fuel consumption creates significant financial and environmental gains. Of the investigated fuel options (LBG, BioMeOH and LNG), only the BioMeOH fuelled ship has life cycle GHG emissions reductions in the same range as the wind powered car carrier (using LNG), but with significantly higher operational cost. LBG is only marginally better than LNG from a short-term perspective (GWP_{20}) and comes at a considerably higher cost of averting GHG emissions than BioMeOH because it emit at least three times as much GHGs. Only the wind powered car carrier offers a negative abatement cost of averting GHG emissions.

Keywords: Sustainable shipping, LCA, LCC, abatement cost, climate impact, wind propulsion system, alternative fuel, wPCC, marine transportation.

Acknowledgements

First and foremost we would like to express our sincerest gratitude to our supervisors at SSPA: Karolina Malmek for taking us in at SSPA and introducing us to the wPCC project; and Joanne Ellis for important academic structure and helpful remarks when we experienced low tides.

Secondly, we would like to applaud the entire research department at SSPA. Not least because the strategic office space we were given next to the coffee machine that supported us with countless cups of coffee but mainly for the opportunity to ask anyone questions.

Finally, from Chalmers' maritime research department, thank you Selma Brynolf for being stern with us, never sparing us of valuable input and criticism to our work, enticing us to go beyond what we ever imagined ourselves capable of.

May you all have fair winds and fallowing seas.

Tobias Olsson & Josef Carlsson, Gothenburg, June 2020

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Abbreviations

Methodological

DCF	Discounted cash flow
EIA	Envionmental impact assessment
ERA	Environmental risk assessment
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
MCDA	Multi criteria decision analysis
SWOT-analysis	Strengths, weaknesses, opportunities and threats analysis
TOC	Total ownership cost
TRL	Technology readiness level

Fuels, emissions and chemical compounds

BioMeOH	Renewable methanol
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon oxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalents, addressing both 20 year and 100 years time horizon
CO_2eq_{100}	Carbon dioxide equivalents with a 100 year time horizon
CO_2eq_{20}	Carbon dioxide equivalents with a 20 year time horizon
GHG	Greenhouse gas
GWP	Global warming potential
GWP_{100}	Global warming potential 100 year factor
GWP_{20}	Global warming potential 20 year factor
H_2S	Hydrogen sulfide
HFO	Heavy fuel oil
LBG	Liquefied biogas

LNG	Liquefied natural gas
MGO	Marine gas oil
N_2O	Nitrous oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
PM	Particulate matter
SO_x	Sulphur oxides

Technical

DE	Diesel electric
DF	Dual fuel
DM	Diesel mechanical
IC	Internal combustion
ME	Main engine
SFOC	Specific fuel oil consumption
SLOC	Specific lube oil consumption
wPCC	Wind powered car carrier
WPS	Wind propulsion system, the system components used to harness the wind for propulsion (i.e sail & rigg component)

Other

EC	European Commissions
ELCD	European reference Life Cycle Database
EU	European Union
ICCT	International Council on Clean Transportation
IEA	International Energy Association
ILCD	The International Reference Life Cycle Data System
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JAMDA	Japan Marine Machinery Development Association
JRC	EU Joint Research Centre
MEPC	Marine Environmental Protection Committee
OECD	Organisation for Economic Co-operation and Development
UN	United Nations

1
Introduction

1.1 Background

Current ship emissions contributed to about 2-3% of global anthropogenic CO_2 emissions and the world fleet carried as much as 90% of global trade by volume [6, 7]. Depending on future development, CO_2 emissions from ships could however rise by 50-250% by the year 2050 [8, 6, 7]. The main fuels in shipping today are heavy fuel oil (HFO) and marine gas oil (MGO) which emit greenhouse gases (GHG) together with nitrogen oxides (NO_x), sulphur oxides (SO_x) and particle matter (PM) upon combustion [9, 8]. Due to the related climate and environmental impact of these emissions there is an urgent need to reduce them [9].

On a global level, the International Maritime Organization (IMO) has since 2018 adopted two important goals on CO_2 emissions in shipping, both referring to 2008 as a base. First, to reduce CO_2 emissions per transport work by 40% by 2030 and 70% by 2050 and secondly to reduce total amount of GHG emissions emitted by international shipping by 50% by 2050 while attempting to phase them out completely [10]. On a regional level, the European Commission (EC) has set targets to reduce European GHG emissions by at least 40% by 2030, compared to 1990's level, and full climate neutrality by 2050 [11]. The Swedish Parliament's climate policy framework of 2017 aims for net zero GHG emissions by 2045 and an 85% reduction of emissions from activities in Sweden compared to 1990's level [12]. International shipping is however not included in these stringent regulations from the EC and Swedish Parliament because of its global nature. For international shipping the EC recognizes that a reduction of 40% to 50% is necessary in the EU by 2050 compared to 2005's levels [13]. To avoid distortion in market competition, the EC also recognizes in the same white paper the need for global cooperation and a level playing field where all actors unite their efforts under common rules. It is the IMO who has this power and base their targets for GHG emissions on the Paris Agreement's goals by recognizing the need for technological innovation and alternative sources of fuel and energy [10]. The industry has responded with its own initiatives such as the *Poseidon Principles* to guide banks providing funding to ship owners and the *Getting to Zero Coalition by 2030* to develop zero emission technology on deep-sea routes [14, 15].

An understanding of the contributing factors to total GHG emissions can be gained through studying equation 1.1 below [9]. The first term describes the size of the global economy as Gross Domestic Product (GDP). The second term describes a key historical driver linked to GDP – economic intensity as transport work. Third term is the energy consumed to produce transport work – energy efficiency. The fourth and last term is the amount of GHG emissions connected with the energy carrier used to transport goods – GHG intensity [9]. Future projections estimate global GDP to almost double in the coming 30 years[1] and to meet future environmental goals, three solutions to decrease total GHG emissions while maintaining GDP can be derived from equation 1.1. A general speed reduction to improve transport work because fuel consumption increases exponentially with speed; investing in technology to increase energy efficiency; and switching to a less GHG intensive source of energy. A combination of these measures will increase the likelihood of reaching environmental goals [16].

$$Total\ GHG\ emissions = GDP \times \frac{Transport\ work}{GDP} \times \frac{Energy}{Transport\ work} \times \frac{GHG\ emission}{Energy} \tag{1.1}$$

For thousands of years sailing has been the main method of transporting goods. In the 1800's, ships using a combination of sails and propeller were introduced on a large scale. The combination enabled ships to transport goods faster and more reliably. Technological development eventually made the sails go out of fashion in the merchant fleet [17, 18]. Recent trends have however questioned this development because harnessing the abundant power found in wind addresses the much-needed increase in energy efficiency. Although the potential of abating GHG emissions by using wind ranges from 10-60%, its uptake has been small due to barriers in the relative immatureness of technology as well as the risks perceived by operators and shipowners [16, 19].

A modern vessel fitted with a wind propulsion system[2] requires a conventional propulsion system to be effective in all weather conditions. The fuels that can be used for propulsion today have a large variety of characteristics ranging from technical performance, availability and cost to environmental impact. Selection of a fuel is further complicated because of the rankings individual stakeholders have on their priority [20]. Recently there has been an uptake of LNG and methanol but there is also the possibility of using ammonia, hydrogen and biofuels [8]. Each option has a set of disadvantages and advantages but the latter three suffer from either immature technology or are limited by fuel supply and infrastructure in the coming years [16, 21]. Fuels with a lower GHG intensity than HFO and MDO are however part of the solution to reduce total GHG emissions and must be implemented to meet future environmental goals.

Starting in 2019, Wallenius Marine received the coordinating role of a three-year development project of a wind powered car carrier (wPCC) collaborating with SSPA

[1]OECD: From 53,747,620 Million USD in 2020 to 93,465,100 Million USD in 2050 `https://doi.org/10.1787/d927bc18-en`

[2]With wind propulsion system we associate the system components used to harness the wind for propulsion (i.e sail & rigg components) (WPS) excluding propulsion from an engine. The complete system (engine and sails) is referred to as propulsion system.

Sweden and KTH Royal Institute of Technology. In an effort to decarbonize the maritime industry, the project aims to once again introduce wind as a primary source of energy to propel ships [22]. The project is anticipated to reduce emissions by 90% and is purposely designed to use wind propulsion as a main propulsion system [23]. If this ambition is to be fulfilled more research may have to be conducted to establish comparable results. The relevant research found can't be compared accurately because it mainly focuses on cases with other wind propulsion technologies [24, 25, 19] or retrofitted vessels that use model routes not applicable to the wPCC project [26, 27, 28].

Starting off in the remarks about slow uptake in using wind mentioned above by Balcombe et al. [16] and Rehmatulla, Parker, Smith & Sulgis [19], this thesis attempts to assess the environmental impact and costs of this novel technique on the wPCC. This will be done through a modular framework that combines life cycle assessment (LCA) and life cycle cost (LCC) analysis, developed by Chatzinikolauo & Ventikos [29] in an effort to clarify the potential of wind propulsion to risk adverse operators and shipowners.

1.2 Aim and objective

The overreaching aim of this thesis is to assess the environmental impact and cost associated with wind propulsion in shipping. The objective related to this aim is to develop a life cycle model over the environmental impacts and costs.

1.3 Research question

To reach the objectives, the following research questions will be answered:

1. How does the total Greenhouse warming potential (GWP) of the wPCC's propulsion system compare to ships using only renewable or fossil fuel?
2. How does the total ownership cost of the wPCC propulsion system compare to a ship achieving the same climate impact using a renewable fuel?
3. What is the abatement cost of reducing GHGs with the wPCC or a renewable fuel compared to a ship using fossil fuel?

1.4 Demarcations

The scope of the study is limited to direct emissions of the most significant GHGs: carbon dioxide (CO_2); methane (CH_4); and nitrous oxide (N_2O) [9]. Emissions of sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM) etc. are treated in relation to meeting compulsory environmental regulations, further elaborated in section 3.4 on page 20. Carbon monoxide (CO) is also omitted as it has an indirect greenhouse effect [30]. Specific limitations and assumptions concerning the methods and data applied in this thesis are presented in Chapter 4 on page 33 where an in depth understanding of why is also presented.

2
Method

The workflow of the thesis is illustrated in figure 2.1. It moves from left to right and starts with a literature review of existing research, moves towards the creation of a model and ends with the result where the speed of the ships is the parameter being changed and the costs of fuel and installation of the WPS are subject to sensitivity analysis. In total, three fuels are modelled: LNG, LBG and BioMeOH.

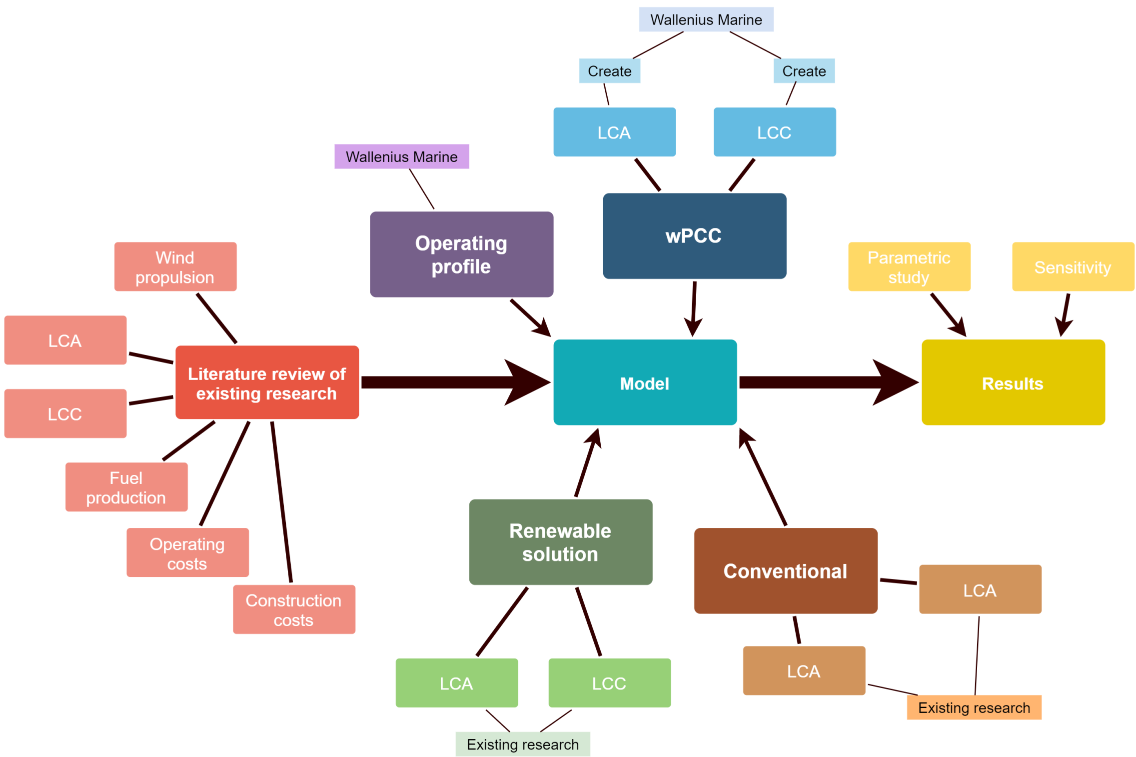

Figure 2.1: Workflow and main sources of data in the thesis.

An initial literature review is conducted to form knowledge synthesis of current regulations, the methods used in this study, energy carriers and to identify the technical frontier of wind propulsion; most of which can be found in chapter 3. The literature review generally consists of books, articles published in academic journals and reports from institutions and government agencies. Chalmers' own library held a large portion of books, e-books and articles by the university's own researchers. Furthermore, through the library's extended databases (e.g. Swedish Institute of Standards, Scopus and Regs4Ships) search words consisting of "wind propulsion", "marine transport", "LCA", "LCC", "propulsion" and "emissions" is used.

Google scholar and google search is used to find reports by regulators and industry publications.

The creation of a model is a process of combining data sourced from the literature review and stakeholder inputs by integrating them into the modular framework consisting of both LCAs and LCCs. The Goal and Scope, including key assumptions, limitations and system boundaries, are found in chapter 4.

Estimates of the wPCC and its preliminary performance are supplied by Wallenius Marine. Using these inputs, an operational profile is constructed to determine consumption where a propulsion layout is created based on Wärtsilä's current engine program. During the construction of the model a literature review method best described as snowballing is used to fill gaps in the framework of the model. For example, one article leads to another or data that is missing is sourced as more and more iterations are done to create a full inventory of emissions and costs. Additionally, some environmental data has been sourced from the European reference Life Cycle Database 3 (ELCD) database using the computer program OpenLCA. The work is presented in chapter 5.

To compare the the total GWP of the wPCC's propulsion system over the ship's life to a ship using a renewable fuel the thesis will develop an LCA of the wind propulsion system on the wPCC to quantify its emissions. Because the wPCC is purpose-built to maximize a wind propulsion system, existing research does not provide already compiled data to cover the scale of this unique project. Validity of the data surrounding the wPCC is largely dependent on inputs from stakeholders in the project (SSPA, Wallenius Marine, KTH).

In order to compare the total ownership cost of the wPCC to a ship achieving the same climate impact using a renewable fuel the thesis is required to develop LCAs for the propulsion system of the alternative solutions using renewable fuels. Furthermore, LCCs of both the wPCC and the alternative solutions are needed to be able to compare the costs of the different pathways to reduce GHGs. The bulk of the data required will be sourced from existing research, manufacture's manuals and to a smaller extent from stakeholders in the wPCC project. For the abatement cost to be determined the thesis will additionally develop an LCA and LCC of a conventional ship using LNG as a baseline to compare against. Results of the LCAs and LCCs can be found in section 6.1 and section 6.2 respectively. By combining the data produced in the LCAs and LCCs the abatement cost is calculated, found in section 6.3.

3

Theory

3.1 Shipping and climate change

Estimating future emissions from shipping is difficult and while they appear to have plateaued in recent years, projections towards 2050 point towards an absolute increase in the coming 30 years. One of the most influential and comprehensive reports of emissions from shipping is IMO's GHG study, last issued in 2014 [7], an analysis based on data from between 2007 and 2012. It shows that the highest amount of CO_2 equivalent emissions with a 100 year time horizon (CO_2e_{100}) was reported in 2008 at 1 157 million tonnes of CO_2e_{100} and levelled out at an average of 1 015 million tonnes CO_2e_{100} the following years. The result is significant because the second GHG study by IMO [31] established that fuel consumption increased dramatically by about 86% from 1990 to 2007. Looking further back in time, a historically increasing trend can be seen since the 1950's [32, 33]. Data collected by the International Council of Clean Transport (ICCT) over the years 2012 to 2015 again shows an increase of fuel consumption in international shipping (291 to 298 million tonnes), albeit still at a lower total emission than in the record year of 2008 [6]. Furthermore, the ICCT also note a 7% increase in transport supply measured as dead weight tonnage per nautical mile (DWT-nm) during the same three-year period but that increases in energy efficiency has been more than offset by the corresponding increase in activity. Criticism of the IMO's projections of 50-250% increases in emissions by 2050 is pointed out by the independent research and consultancy organisation CE Delft [34] in a study commissioned by Baltic and International Maritime Council, BIMCO by using the latest available data applied to the same methodology. With the more recent data, emissions are still projected to rise with a level of 20-120% compared to 2010's level. The lower estimated increase of emissions compared to IMO's estimation is mostly attributed to lower GDP growth and economic activity in line with the Organisation for Economic Co-operation and Development's (OECD) projections. Going even further and de-coupling GDP with transport work after 2030, growth estimations of CO_2 emissions from shipping are projected to rise even less [35].

In any case, minimizing the increase of future emissions is not enough. On the contrary, emissions must be reduced in total instead of continuously rising. According to IPCC Assessment Report 5 [4], a reduction of total global emissions of 41-72% by the year 2050 makes it likely to maintain a global average temperature increase below 2 degrees Celsius compared to pre-industrial levels. This would correspond with a CO_2 concentration range of 430 to 480 ppm in the atmosphere and work well with the goals of the Paris Agreement adopted in 2015. A decrease of CO_2 emissions of less than 50% leading to a corresponding CO_2 concentration range of 530-580 ppm adds one more degree to the projection and instead makes it likely to stay below 3 degrees. However, the IPCC stresses that unique and already threatened systems are already at risk of disappearing. Every additional increase of temperature will put more stress on the eco-systems not yet threatened.

IMO tackles marine pollution through the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978, commonly abbreviated MARPOL [36]. In Annex VI emissions to air are listed together with the two main tools to curb CO_2 emissions: Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). While both came into force on January 1st 2013 and are applicable to all ships above 400 Gross Tonnes (GT), only new-builds delivered after June 2015 must adhere to the former. The EEDI is incrementally tightened every five years and forces a more efficient design in a non-prescriptive way. Ship-owners may choose whichever technique they want as long as they reach the targets and are issued a certificate of compliance. Most large ships must by January 1st 2025 reach a reduction level of 30% compared to a reference line set by the IMO. In contrast to this long-term approach, the SEEMP is a ship-specific and mandatory management system all ships above 400 GT must develop. It allows ships to systematically track consumption and identify areas suitable for energy efficiency improvements. While most of them are of an operational measure, guidelines from the Marine Environment Protection Committee (MEPC) [37] do mention wind assistance and other renewable sources of energy such as photovoltaic panels. Started on 31st of December 2018, ships above 5 000 GT must also report their fuel consumption, distance travelled and hours underway to IMO's Data Collection System (DCS) as part of the SEEMP. However, neither the EEDI or SEEMP is projected to result in any absolute reductions in CO_2 emissions by 2050 despite increases in efficiency, largely due to the increased growth in transport work in the coming decades [38]. Furthermore, research have also shown that the SEEMP lacks crucial steps to fulfil a Plan-Do-Check-Cycle essential for improvements found in other standards aiming to improve efficiency [39]. It is a fair assessment to say that the available tools may not provide enough support to reach IMO's reduction targets by themselves without further strengthening in the coming years.

As previously described in the introduction, there are three main solutions to decrease total GHG emissions while maintaining GDP that may be derived from equation 1.1. The three main solutions are a general speed reduction, increase energy efficiency and switching to a less GHG intensive source of energy. To increase the understanding of these solutions the following sections will present the underlying theory needed to assess the work in this thesis.

3.2 Ship propulsion systems

T. Andersson describes vessel propulsion in *Maskinlära för Sjöpersonal* [40] in the following way. The resistance that must be overcome in order to propel a vessel forward and its ability to do so depends on a number of factors such as the vessel's form and size. Resistance can be divided into two categories, *frictional resistance* and *residual resistance*. The frictional resistance depends on the fluid slip over the hull while the residual resistance depends on mainly the wave resistance. The total resistance varies roughly with the square of the ships speed through water. This means that when the speed is increased by 20% the resistance increases by 44% [40]. Adding to this only a certain amount of engine power used to drive the propeller axle will result in speed through water. The so called propeller efficiency depends on the type of vessel and varies between 50% and 80%. This results in the relationship between the propulsion power that will increase with the third power when total resistance increases with the square. This in turn means when increasing the speed with 20% the engine power needs to increase with 73% [40].

The propeller efficiency and total resistance through water applies to all motor driven vessels with a propeller. Vessels under sail can disregard the propeller efficiency when sailing but are subject to the wind pattern where it is to sail instead. By reviewing Pilot charts it is possible to get a general understanding of the prevailing winds in an area, storm paths, temperature, shoals, positions of rocks and other information useful to navigators. As for the North Atlantic the wind pattern is more or less clockwise and therefore it is easiest to cross from west to east along a northern route while a southern route is easiest in the opposite direction [41]. If making a crossing through the middle of the rotary system the wind tends to be light and variable [41]. This is not always the case since a series of depressions commonly move from west to east that have their own wind system rotating anticlockwise [41]. The general current effecting the North Atlantic is the Gulf Stream which in a similar way as the wind travels from the Gulf of Mexico to Northern Europe, gradually weakening. These factors, among others give different verdicts on preferred routes depending on if the vessel is under sail or steaming with the engine. Generally speaking, the need of adjusting the route South (and increasing the distance) when travelling Westwards and the sensitivity to depressions aren't as imminent when steaming with an engine as when under sail. The optimal route, as in the shortest distance between New York and Plymouth when crossing West to East, is following a great circle route closer to the North compared to the South, necessary to avoid the middle of the rotary system [41].

3.2.1 Engines, efficiency and drive trains

There are different types of engines used to propel ships. Mainly within shipping, Internal Combustion (IC) Diesel cycle engines are used [40]. In this case, Diesel should not be confused with the fuel of the same name, rather it describes how the fuel is ignited and should be compared to Otto cycle engines. Furthermore, engines can be either two stroke or four stroke, referring to the cycle the engine uses to complete each combustion [42]. Four stroke engines are faster rotating engines with a Revolutions Per Minute (rpm) of above 600 compared to a two stroke engine that is below 240 rpm [40]. A peculiarity are the modern Duel Fuel (DF) engines, capable or utilizing both gaseous fuels and liquid fuels, in either a Diesel cycle or Otto cycle, delivered as two stroke or four stroke engines. When switching from a traditional liquid fuel such as MGO or HFO to gaseous fuels, such as LNG, most commonly the four stroke engines also changes from a Diesel cycle to an Otto cycle. To ignite the gaseous fuel a small amount of pilot fuel, usually MGO, is injected prior to the piston reaching the top dead centre [43]. The absolute majority of all DF engines are of a low pressure type meaning that the gaseous fuel is injected into the cylinder before any combustion takes place when the pressure inside the combustion chamber is low. This is followed by the injection of the pilot fuel that ignites the fuel mixture, the pressure and temperature rises and power is produced through combustion. A problem associated with this technique is that if some of the gaseous fuel mixture is trapped in small crevices, such as between cylinder wall and piston crown, and is left unburnt thus escaping with the exhaust leading to one of the sources of the dreadful methane slip. Of the some 485 ships equipped with IC DF engines, only about 90 are equipped with engines of a newer technology capable of avoiding this condition but these are limited to slow speed, two stroke engines. In other words, the problem of methane slip is more than likely to persist because of limited supply of the newer engines, especially for ships that are not suitable for two stroke engines unless technology takes a great leap forward [44].

The efficiency of an engine and drive train is how efficient it transfers the fuel's energy content to mechanical work used to propel a ship forward. Usually this varies between 38-49% [40] but can be as low as 35% for the high-speed four stoke engines or above 50% for the most efficient two stroke, low speed engines [45]. The rest of the energy content is lost through heat, for example in engine cooling water and engine exhausts, or through propeller cavitation [40]. Efficiency, often denoted with the letter n, is expressed as a percentage in equation 3.1 below.

$$Efficiency = \frac{Useful\ Output}{Total\ Input} \times 100\% \tag{3.1}$$

An electric propulsion system, often called Diesel Electric propulsion (DE), is a system consisting of prime movers, for example one or more engines of various sizes, connected to generators that in turn supply electric power to a common grid. Electric propulsion motors connected to the propeller, hotel loads for accommodation and cranes among other consumers all draw power from the common grid, offering a high level of flexibility depending on load conditions [46, 45]. Comparably in a mechanical propulsion system, often called Diesel Mechanical (DM), the prime movers mechanically transfer power to the propeller. This layout may very well be complemented with a gearbox, a clutch and an electric generator [45]. A drive train is the set up of these two systems, from transmission gearboxes, generators, electric grids and shafts to the propeller. Naturally, it can be set up in different ways to optimize efficiency [46]. Under most circumstances, the DM layout has a higher total efficiency than the DE layout albeit at the cost of reduced flexibility to optimize the load of the prime movers. It is also the case that two stroke engines are almost always used in a DM layout while the four stroke engines are capable of both [45].

3.2.2 Installed power and EEDI

There are mainly two methods to determine the minimum required installed power on a ship. The first is based on the performance of the hull and the power required to reach a certain speed by overcoming the associated frictional and residual resistance. Combining the aforementioned with total efficiency of the drive train and the minimum required installed power is obtained. The second method is based on adhering to compliance rules relating to EEDI, such as those presented by the MEPC, a part of IMO. EEDI is a regulatory measure agreed upon by the member states of IMO in 2008 as one of two measures to address the shipping sector's GHG emissions [9]. This concept has already been introduced in section 3.1 on page 7. Equation 3.2 gives a general understanding of what the EEDI represents. Because energy consumption is linked to the square of speed increase, the easiest way to comply with the index is by reducing speed, hence reducing installed engine power. To maintain maneuverability in adverse weather conditions and ensure that safe navigation is maintained, MEPC developed a set of guidelines [47] to avoid propulsive power being undersized, relating to the engines' Maximum Continious Rating (MCR), usually 85% of their maximum output. Equation 3.3 represents how to maintain compliance with EEDI if opting for reduced installed power. The formula presented is based on dead weight tonnage (DWT), i.e. the difference between the ship's actual displacement when fully loaded and the lightship weight of the ship. Simply put, the ship's cargo carrying capacity [42]. Factors a and b are determined by the ship type.

$$EEDI = \frac{Total\ CO_2\ emissions\ produced\ onboard}{Transport\ work} \tag{3.2}$$

$$Minimum\ power\ line\ value\ @\ MCR = a \times (DWT) + b \tag{3.3}$$

3.3 Tools to assess the performance of different measures

Depending on how performance is defined and what constraints are used, the outcome may differ. For example, if the primary goal is to reduce emissions the costs might spiral out of control. On the other hand, if you only look at costs, total emissions may increase. Furthermore, without a systems perspective there is the risk that problems are shifted from one place to another but the overall gains are none or the benefit is only partly favourable.

Besides the environmental impacts and cost issues, there are also other considerations to be made that differ among stakeholders within shipping. The considerations can be categorized into main criteria i.e. technical, environmental, social and economic. There are also other criteria i.e. logistics, safety, security, public opinion, ethics and political and strategic aspects that can be taken into consideration. In a recent study by Hansson et al. [20] this was put to the test for a selected group of maritime stakeholders in Sweden regarding alternative fuels. It was found that the most important technical criteria for the selected group is reliable fuel supply. As for economic criteria it is the most important criteria that the aforementioned stakeholders valued highest when choosing between economic, social, technical and environmental criteria. The most important economic criterion in the whole group is the fuel price when choosing between operational cost, fuel price and investment cost for propulsion. When the environmental criteria is considered in the same study, by choosing from climate change, health impact and acidification, climate change is the most important in all groups except engine manufacturers who value health impact higher.

As shown above, choosing the right fuel is a complex matter. There are several tools and methods possible to use to make a decision when considering the best option [9]. One method is to analyse a fuel after what solution is the most consensual and optimal for a group of stakeholders considering preferences and interests with a method called multi-criteria decision analysis, MCDA [48]. This is an approach used in the aforementioned study by Hanson et al. [20]. A method with another approach that can be used if the environmental impact of a product's life cycle is of interest is life cycle assessment (LCA) which assesses the whole life cycle of a product or service. In an evaluation of marine fuels, Brynolf [5] describes it as appropriate to address questions related to the life cycle environmental performance but less appropriate for addressing other aspects of fuel choice. These aspects can be maintenance, infrastructure requirements, fuel prices and fuel availability which are not included in an LCA. For instance an LCA does not assess the fuel choice in regard to the best outcome if an accident resulting in a fuel spill would occur. This is an example of a question an LCA cannot answer but that can be answered by using other methods such as Environmental impact assessment (EIA) or Environmental risk assessment (ERA).

3.3.1 Life cycle assessment (LCA)

LCA is described as an internationally standardized, structured and comprehensive method that quantifies all relevant consumed resources, emissions and related environmental, health impacts and resource depletion issues that are associated with a product or service [1]. ISO 14040:2006 [49] defines an LCA as an iterative four phase study consisting of a goal and scope, inventory analysis, impact assessment, and interpretation of results. An understanding of the concept can be made by studying figure 3.1 [49]. However, the ISO standard does not address social and economic impacts [49]. There are two ISO standards available: ISO 14040:2006 and 14044:2006. The former is an introduction and sets out the principles of an LCA while the latter sets out the requirements [49, 50].

The first step, defining a goal and scope, sets the boundaries of how much the study encompasses and is therefore of utmost importance. In the goal the intended application is stated together with the reasons for carrying out the study. It should also state the intended audience and whether the results are to be used in comparative assertions for public use [49]. It may be viewed as where the question: "Who wants to know what, about what and for what reason?" is answered. The scope

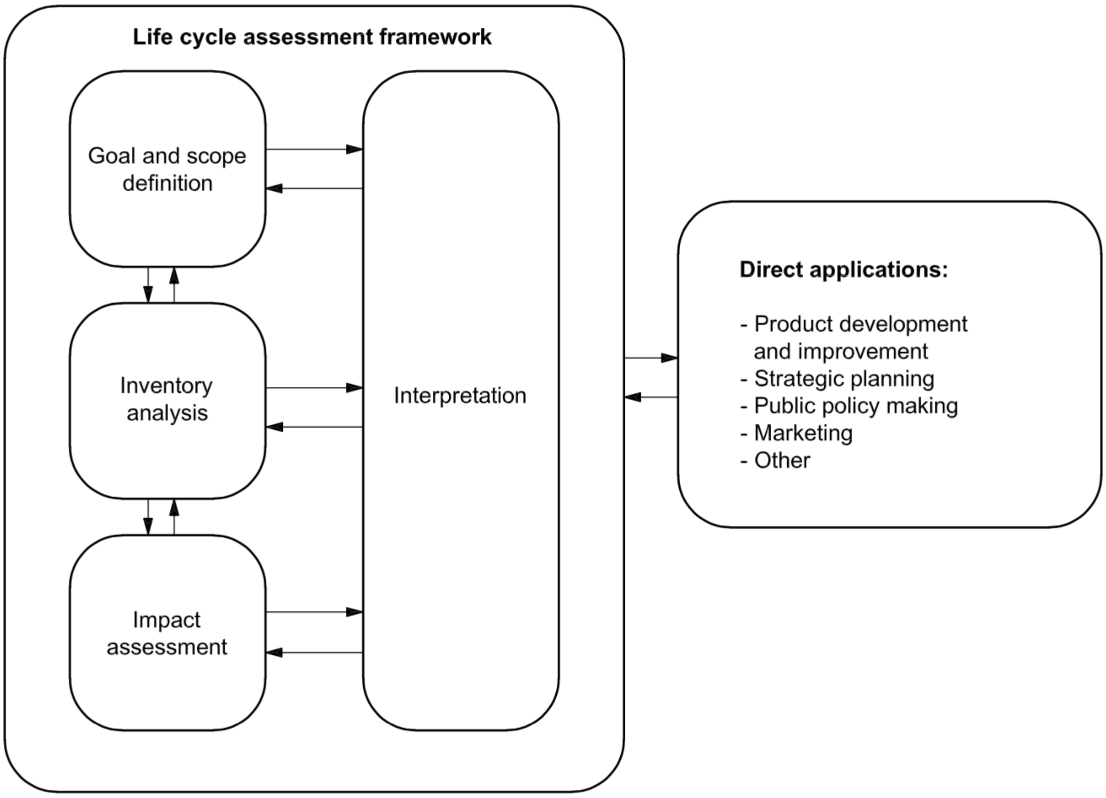

Figure 3.1: Phases of an LCA as defined in ISO 14040:2006.

may on the other hand answer the question "Which options to model?". It consists of a description of the product system and function of it, for example performance characteristics. A functional unit is defined to guide the assessment. It describes the function of the product system studied in the LCA, it is quantitative and is used as a basis for calculation. An example would be 1 m^2 of painted wall that lasts 15 years or 1 ton of cargo transported 1 km with a ship. The functional unit serves to make the assessed product or service comparable to other product or services [2].

Furthermore, as described in ISO 14040:2006 [50], the scope includes system boundaries of what to include and exclude in the study. Boundaries consider cut-off-points, product system, geography and time horizon. With clear boundaries in place an inventory of materials and processes can be formulated. From this reasoning it may be understood that a change in the scope and the subsequent boundaries could result in a different inventory, hence producing different results. A description of impact categories included, such as human health, climate impact, toxicity and eutrophication followed by which method of allocating each compound to one of the aforementioned categories should also be included. The scope ends with a description of the type of interpretation made. Data requirements as well as the quality of data should also be stated along with limitations and assumptions made. If any value choices and optional elements have been used as well as type of critical review, if any, and the type and format of the report required for the study [50]. To make an accurate assessment of the study, transparency is very important [51], thereby concluding the provisions of the initial plan for conducting the life cycle inventory phase of an LCA [50].

The second step of an LCA involves compiling inputs and outputs for each process in the life cycle and sum them across the whole system in an inventory analysis. In this step flow diagrams are constructed of all activities in the modelled system, data is collected for all identified activities in the flow and calculation of inputs and outputs are conducted. According to ISO 14044:2006 [50] this step should include the drawing of unspecific process flow diagrams that outline all the unit processes to be modelled, and should include:

- their interrelationships;
- description of each unit process in detail with respect to factors influencing inputs and outputs;
- listing of flows and relevant data for operating conditions associated with each unit process;
- developing a list that specifies the units used;
- describing the data collection and calculation techniques needed for all data;
- providing instructions to document clearly any special cases, irregularities or other items associated with the data provided.

As an example, after establishing a flowchart, the component's inputs and outputs are determined. One component may consist of 100 tonnes steel and 1 tonne concrete, the emissions per unit (i.e. 1 kg steel and 1 kg concrete) is then collected from a source which can be 1800g CO_2 and 9 g CH_4 for 1 kg steel and this multiplied with amount of material. This gives the inventory result - the total amount of emissions.

Moving on to the third step of an LCA, impact assessment, the aim is to evaluate and assign an environmental impact based on the results of the inventory analysis. This is done by associating the results with different environmental impact categories and category indicators, thereby attempting to understand the impacts beyond a long list of mere emission data points [50]. By converting and categorizing emissions into comparable units, such as ozone depletion, climate impact, eutrophication, acidification etc., midpoint impact categories are established. For example, climate change may be measured as GWP [2]. Each impact category can be converted into end-points, or areas of protection (damage areas), commonly limited to human health, ecosystem quality and natural resources [2]. An example of the relationship between inventory, mid-points and end-points is illustrated in figure 3.2. It is possible to go even further and (among other optional features) assign a weighted score using different weighting methods and by doing so being able to compare different impacts with each other [2]. According to ISO 14040:2006 [50] the life cycle impact phase must include:

- a selection of impact categories, category indicators and characterization models;
- an assignment of Life cycle inventory (LCI) results to the selected impact categories (classification);
- a calculation of category indicator results (characterization).

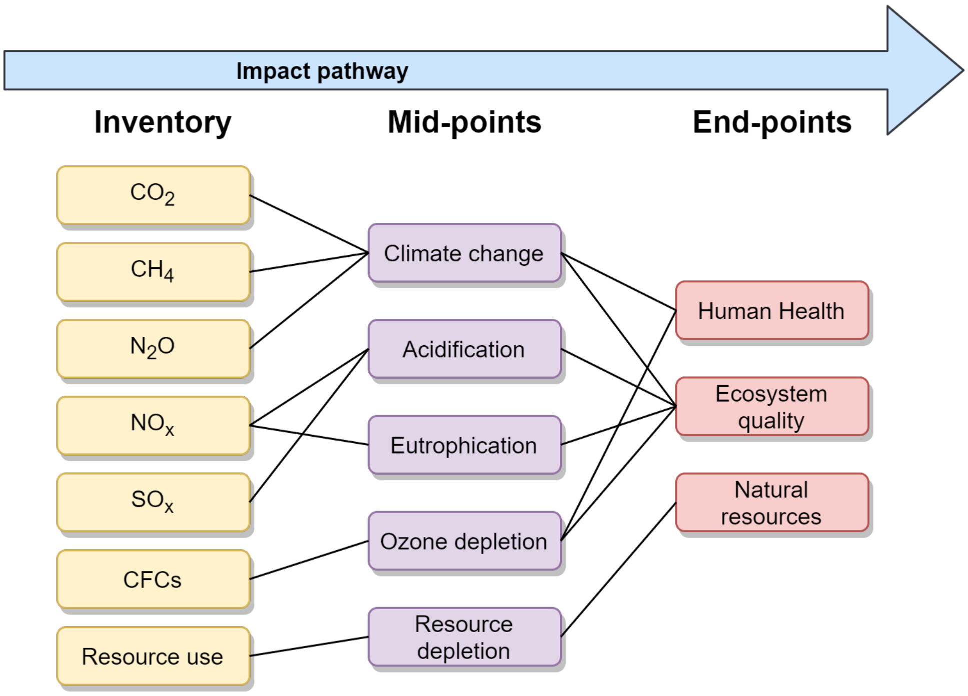

Figure 3.2: An example of impact pathways of the LCA inventory to support the interpretation, adapted from ILCD Handbook [1] and Baumann & Tillman [2].

In the fourth and last step of the LCA, an interpretation of the results is made. It should identify significant issues, evaluate completeness of the system and impacts, check sensitivity for large variations in results when varying inputs and evaluate consistency of the modeling and methodological choices made [2]. It should also contain statements of conclusion, limitations and recommendations [50]. Going back to figure 3.1 and keeping the iterative nature of an LCA in mind, it should be stressed that after each completed stage including this fourth and last, it is important to make sure that the goal and scope is still applicable. If not, it needs to be adjusted accordingly [50].

A simplified way to describe the LCA concept is expressed by Jeong et al. [52] in equation 3.4. Here the total amount of environmental impact (Ei_t) is the result of multiplying the quantity (Q) of the specific pollutants from the LCA modules in a ship's life cycle phases with their respective normalization factor (F) for the pollutant. This makes it possible to evaluate each life cycle phase's contribution to the selected environmental categories [53]. An impact factor that can be used for greenhouse gases is GWP from IPCC (table 3.1), listing those that contribute to radiative forcing, which causes climate change. Using the aforementioned equation and table results in carbon dioxide equivalents (CO_2eqi) measured in grams, kilograms or tonnes.

$$Ei_t = \sum Q \times F \tag{3.4}$$

To summarize the total life cycle environmental impact (ET) equation 3.5 can be used where the environmental impact of each phase of the life cycle is summarized. Starting from installation (EI), continuing with maintenance (EM), operation (EO) and finishing with end of life emissions ($EEOL$).

$$ET = \sum_{i=1}^{n} EI + \sum_{i=1}^{n} EM + \sum_{i=1}^{n} EO + \sum_{i=1}^{n} EEOL \tag{3.5}$$

A fundamental aspect of an LCA is the data quality and level of detail in the life cycle inventory. When conducting an assessment on the life cycle of a product system in an early design phase the level of detail and the available data is sometimes uncertain because the final product may change compared to the assessed scope. In order to still obtain meaningful statements of a future product system it is possible to conduct a screening LCA by using easily available or estimated data [51]. ISO 14040:2006 does not mention screening LCA but The ILCD Handbook developed by European Commissions Joint Research Centre, JRC, describes it only implicitly as the first iterative step of an LCA [1]. JRC also states that screening LCAs generally do not comply with ISO 14044:2006 [1]. As the organisation *PRé* describes screening LCA it is suitable to use for internal communication purposes, decision-making and business to business communication [54]. Further they describe it as helpful to identify ‘hotspots’ in a product’s life cycle, areas easy to improve, and to understand where more information is necessary.

3.3.1.1 Impact category global warming

As for global warming, the included compounds related to carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halogenated hydrocarbons. The last of which are mainly related to the use of refrigerants, not combustion, and the contribution from shipping is small [9]. Although they are different compounds, they have the potential to trap heat in the atmosphere. Figure 3.3 describes the steps in how emissions of GHGs contribute to atmospheric concentration which causes radiative forcing, leading to climate change and damage. To account for the respective compound’s potential to trap heat in the atmosphere it is common to normalize them to CO_2 equivalents to represent their respective GWP. The GWP is accounted for over different time intervals, typically 20, 100 and 500 years. In table 3.1 the characterization factors for converting CO_2, CH_4, N_2O to CO_2 equivalents of 20 years and 100 years can be found, represented by their ability to cause radiative forcing measured in W/m^2. Table 3.1 shows the variation in GWP depending on what interval of time is used. To address what GWP interval should be used ICCT [44] concluded in their report on LNG as a marine fuel that in the short term LNG offers no reduction of GHGs by stating:

> “Using a 20 year GWP, which better reflects the urgency of reducing GHGs to meet the climate goals of the International Maritime Organization (IMO), and factoring in higher upstream emissions for all systems and crankcase emissions for low-pressure systems, there is no climate benefit from using LNG, regardless of the engine technology.”

To understand why this is important it must be mentioned that LNG is currently promoted as a future ship fuel [9, 44]. This is mainly because of its lower sulphur content, lower carbon content and reduced NO_x emissions where LNG complies with current regulations [5] in Emission Control Areas (ECA) and Sulphur Emission Control Areas (SECA), listed in MARPOL. LNG has been used as a fuel by LNG carriers since the 50's and currently there are about 500 such ships in operation [44]. However, other ship types have also begun opting for this fuel with 137 of these in operation, 136 on order and 135 being prepared for conversion [44].

Table 3.1: Global warming potential factors from IPCC [4]

	$\mathbf{GWP_{20}}$	$\mathbf{GWP_{100}}$
CO_2	1	1
CH_4	84	28
N_2O	264	265

Figure 3.3: The relationship between emissions of GHGs and radiative forcing leading to damage, adapted from Balcombe et al. 2018 [3]

3.3.2 Life cycle costing (LCC)

Similar to the cradle-to-grave perspective of an LCA, the LCC accounts for all anticipated costs during the product or system's lifetime. It is described by John Vail Farr and Isaac Faber [55] in the following manner. In its most basic form, life cycle costs are the initial and future expenses ranging from early research and design to scrapping, depending on the system boundaries. It also serves as a reminder to avoid becoming fixated on technical performance and omitting downstream costs in the future. Financial aspects must be considered for a successful outcome and in this case, increased uptake of the new technology could signal success. There exist two main methods in creating an LCC; top-down and bottom-up. The former relies on using analogies to historical costs of similar products or parametric relationships of the project's goal. The latter technique, bottom-up, uses work breakdown structure from components and assembled parts to construct a complete architecture – an engineering build-up methodology. While the latter is the most accurate it is also the most time-consuming but sometimes not possible because of a project's early development phase. To develop the total ownership cost (TOC) both methods can be combined to reach a result by scaling up engineering methodology based on experience [55].

LCC is also described by Niekamp et al. [56] and how to apply it to an industrial asset. This is the method used by Jeong et al. [52] to account for the costs of a ship's life cycle, expressed in equation 3.6. The total life cycle costs (CT) are the result of summarizing initial construction costs (CI), maintenance costs (CM), operational costs (CO) and finally costs associated with the end of life ($CEOL$), for example recycling and disposal costs where applicable [56].

$$CT = \sum_{i=1}^{n} CI + \sum_{i=1}^{n} CM + \sum_{i=1}^{n} CO + \sum_{i=1}^{n} CEOL \tag{3.6}$$

The most similar concept to LCC was initially developed in 1978 by Blanchard and further fine tuned in 1998 by Blanchard & Fabrycky [57]. Since then several guidelines describing LCCs have been developed and a selection is presented below[57].

- ISO 15686-5 Buildings and constructed assets – Service life planning – Part 5: Life-cycle costing (2017)
- EN 16627 Sustainability of construction works – Assessment of economic performance of buildings – Calculation methods (2015)
- IEC 60300-3-3 - Dependability management – Part 3-3: Application guide – Life cycle costing (2017)

It can be observed that the construction industry has developed extensive and detailed LCC standard practices like ISO 15686-5[58] and EN 16627[59]. These are more detailed and applicable for the construction of buildings compared to the standard developed by IEC (60300-3-3), which covers all applications but is more general[60]. This need not mean that other industries lack in progress since other financial tools may be used to account for all anticipated costs during the product or system's lifetime.

3.3.2.1 Discounted cash flow

To improve the LCC calculation and make the future cash flows comparable to current value of money it is possible to apply a discounted cash flow model like net present value [61, 56, 57]. Discounted cash flow is a model widely used in capital budgeting that focuses on projects' cash inflows and outflows, taking into account the time value of money [61]. It is generally understood that the value of one dollar today is greater than one received dollar in the future [61]. One discounted cash flow model used for this is net present value which sums up the present values of all expected future cash flows associated with the project and subtract the initial investment. Present value can be expressed as done below in equation 3.7 presented by Horngren et al. [61] where the amount payed or received is S in n periods with the interest rate of $i\%$. There are also predetermined tables to use to retrieve a factor possible to use instead of this equation [61, 55]. Needless to say, there are also functions in Excel for this purpose [55].

$$PV = S \frac{1}{(1+i)^n} \tag{3.7}$$

Regarding the interest rate or discount rate, that it also can be called [55], the rate used is dependant on the company and often the required rate of return is used for this purpose together with an inflation component [60]. In this, the aforementioned standards differentiate from reach other, the ISO 15686-5 establishes a range of values from 0 to 4% while EN 16627 adopts a 3% discount rate that can be integrated by using supplementary calculations [57]. Horngren et al. [61] have examples where the discount rate for investments in business organizations exceed 8% but also states that applying a too high rate could be misleading to represent future costs. The discount rate is generally subject to the sensitivity analysis among others [57]. Generally the standards suggest using real cost (considering inflation as described in IEC 60300-3-3) compared to nominal costs [57].

A consequence of using a high discount rate is that it favours projects with a low initial investment cost and a high future operating and maintenance cost. Regarding a ship where the primary cost driver is fuel and maintenance, the time value effect on future costs may be misleading. If the discount rate for operational and maintenance costs reflects the opportunity cost of investing the money elsewhere, it implies that the operation can be terminated and the money spent on something else with a higher yield. It is therefore questionable to use a high discount rate for future operation and maintenance costs for an asset like a ship with a long life cycle unless it can easily be scrapped and money used for something else. Nor does it reflect the uncertainties connected with fuel costs and supply, especially those from a fossil source. If anything, emitting fossil carbon into the atmosphere should be considered risky, which should give it a low discount rate, based on the assumption that states and non-state actors, like IMO, are trying to reduce fossil carbon emissions.

3.3.2.2 Annualized investments

Investments and installation costs in the construction phase off a ships life cycle can, given the nature of the investment being very large, be written of (or depreciated) over the life time of the ship [18]. The following equation 3.8 can be used to account for a series of uniform payments (A) conducted over a period of time (n) (i.e. life cycle or shorter) that will recover the initial investment (P) at an interest rate (i) [55]. This is particularly useful when estimating the annualized investment cost to account for the capital cost of the investment, depreciated over the life cycle of the investment, based on the assumption that the interest rate and discount rate are equal [62, 63, 64].

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{3.8}$$

3.3.3 Existing applications of LCA and LCC

In a comparative LCA of liquefied natural gas and three other fossil fuels as marine fuels by Bengtsson, et al. [65] it is highlighted that there is a need for LCA when evaluating the environmental impact of a fuel change. Bengtsson et al. found that gas-to-liquid fuels has the highest global warming potential over the whole life cycle. Regarding life cycle cost, assessments have been done by the maritime consultancy firm SSPA for a new Swedish ice breaker where they compare two propulsion system concepts [66]. It is also possible to combine LCA and LCC as done in recent research where Byongug Jeong, et al. [52] illustrate how batteries can make a short-sea ferry more cost-effective and emit less GHGs over its life-cycle. They were also able to determine the most cost-effective propulsion layout for an offshore tug by varying the number of engines installed. Their layout is based on a modular framework developed by Chatzinikolaou & Ventikos [29] and is illustrated in figure 4.2 on page 37. Also Louise Laumann Kjær, et al. [67] demonstrate how combining an LCA and LCC can be a helpful tool in sustainable decision making by studying ships engaged in tanker trade. Combining both LCA and LCC in a wider setting and applying it to several technologies allows for cost comparisons and evaluation of cost effectiveness - emission abatement cost. Equation 3.9 produces a result indicating the cost of averting emissions compared to a baseline. It follows from the equation that an expensive measure which only reduces emissions marginally comes at a high abatement cost. Naturally, a low cost measure with the same emission reduction has a lower abatement cost. It may even be so that the cost of implementation is very low and the resulting aversion of emissions are so great that the abatement cost is negative.

$$Abatement\ cost = \frac{LCC_{New} - LCC_{Baseline}}{LCA_{Baseline} - LCA_{New}} \tag{3.9}$$

In the work by Eide et al. [68], the abatement cost of reducing CO_2 with 25 different measures is estimated over 20 years (2010 to 2030) compared to a baseline of no reduction. By quantifying costs and emissions, they show that a 33% reduction is possible at a marginal abatement cost of USD 0 per tonne. In a similar but more recent study, Schwartz et al. [69] conclude that a 50% reduction of CO_2 is possible in shipping at a profit. They attribute their improved results compared to Eide et al. to development in technologies and decreased costs since 2010.

It might appear inconceivable at first that an implementation which can be done at a profit isn't realized. Sorrell, Sleich, O'Malley & Sue [70] attributes the energy efficiency gap to three sometimes overlapping reasons to why. Briefly summarized they relate to economic and market issues where information is distributed imperfectly and hidden costs and risks act as a barrier. Secondly, there may be a behavioural barrier where there simply doesn't exist enough time to make rational decisions or the information is not perceived as reliable. Lastly, the organization itself might not prioritize energy efficiency or the energy efficiency manager doesn't have the authority needed to complete the task.

3.4 Alternative fuels as a measure to reduce climate impact

As briefly discussed in the introduction, the amount of GHG emissions is connected to the energy carrier and how it is utilised in a prime mover to convert the energy carrier to work. When referring to energy carrier it is here considered to be the compound or phenomenon that carries the energy in a fuel. An example is methane which is the energy carrier in both liquefied natural gas (LNG) and liquefied biogas (LBG). Fuel is a general term to describe the substance used to convert energy into movement. In this thesis a primary energy source is referred to as fuel only after its been processed and refined, ready to be used. Primary energy sources are considered the unrefined sources of energy found in nature, examples of these can be crude oil, natural gas, coal, biomass, solar, wind, hydro and nuclear. These primary sources can be refined to produce different energy carriers. For example, biomass can be used to produce a variety of different energy carriers such as hydrogen, methane, methanol, renewable diesel etc. Crude oil can too be refined into a variety of fuels.

Depending on which process is used to create the final energy carrier and type (renewable or fossil), energy consumption during production as well as environmental impact varies [9]. This is important to keep in mind while choosing an energy carrier as the production can account for a higher environmental impact than the combustion of the fuel [9]. Table 3.2 lists seven candidates for marine fuels where the first three are conventional fossil fuels in use today (HFO, MGO and LNG) followed by LBG produced from agricultural residue (LBG_{ar}), LBG produced from willow (LBG_w), a short rotation energy crop, methanol produced from natural gas ($MeOH_{ng}$) and methanol produced from the same short rotation energy crop ($MeOH_w$). The shifting of emissions can be observed in the same table where the emissions from renewable fuels are zero or close to zero at combustion (tank-to-propeller) but emit more than fossil fuels in production (well-to-tank). Therefore when accounting for the environmental impact of a fuel it is important to consider a systems perspective of the whole life cycle, from the extraction of primary energy sources, processing and transport to the final use on-board [65]. This has been further illustrated by combining the factors in table 3.1 with the total life cycle emissions of a selection of marine fuels found in table 3.2, thereby making it is possible to compare the individual fuels' total GWP, presented in table 3.3.

When referring to environmental impact, there are different categories that can be taken into consideration when choosing energy carrier and primary energy source. Recently, emissions to air have received the most attention, regulated in MARPOL Annex VI, pertaining the impact categories global warming, health, acidification and euthrophication [9]. The last three impact categories relate to emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) and may be attributed to acidification, both on land and at sea. They also contribute to the formation of particles which are related to adverse health effects [71]. Moreover, NO_x emissions also contribute to both eutrophication and formation of ground level ozone which has an adverse impact on human health and plants [9]. While there exist several different methods (i.e. ReCiPe, Eco indicator 99, CML 2010 and TRACI) to account for the strength and impact category of an emitted substance, this thesis is only looking at global warming and is using the impact factor from IPCC, hence other methods are not further elaborated.

Table 3.2: Fuel emissions to air from a selection of marine fuels, well-to-propeller, by Brynolf et al. [5]

	HFO	MGO	LNG	LBG_{ar}	LBG_w	$MeOH_{ng}$	$MeOH_w$
Emissions to air from well-to-tank [g/MJ fuel]							
CO_2	6.7	7.1	8.3	25	27	20	17
CH_4	0.072	0.078	0.033	0.17	0.18	0.011	0.042
N_2O	1.6E-4	1.7E-4	1.7E-4	2.8E-4	3.3E-4	2.9E-4	2.2E-4
Emissions to air from tank-to-propeller [g/MJ fuel]							
CO_2	77	73	54	0	0	69	0
CH_4	4.5E-4	4.5E-4	0.63	0.79	0.79	0	0
N_2O	3.5E-3	3.5E-3	0	0	0	0	0
Total emissions to air from well-to-propeller [g/MJ fuel]							
CO_2	83.7	80.1	62.3	25	27	89	17
CH_4	0.07	0.08	0.66	0.96	0.97	0.01	0.04
N_2O	3.66E-03	3.67E-03	1.70E-04	2.80E-04	3.30E-04	2.90E-04	2.20E-04

Table 3.3: Total CO_2e emissions to air from well to propeller for a selection of marine fuels when applying GWP, synthesized from Brynolf et al. [5] and IPCC [4]

Total GHG emissions when applying GWP [g/MJ fuel]

	HFO	MGO	LNG	LBG_{ar}	LBG_w	$MeOH_{ng}$	$MeOH_w$
CO_2e_{20}	90.8	87.7	118.0	105.7	108.6	90.0	20.6
CO_2e_{100}	86.7	83.3	80.9	52.0	54.2	89.4	18.2

3.4.1 Methane

The energy carrier methane consists of the molecule CH_4 and is the main component in the fuel LNG and LBG [9, 72]. It may potentially reduce CO_2 emissions by as much as 15-30% due to its lower carbon content compared to traditional fuels [65, 73, 72]. Emissions other than CO_2 are after combustion also drastically reduced and are compliant with IMO Tier III rules for NO_x and the strict SO_x rules imposed in Emission Control Areas without the need for exhaust after treatment [5, 74, 73, 72]. The main drawback of using methane as an energy carrier are the emissions of methane during extraction, processing, transport and combustion – methane slip. A methane slip of about 2% over a lifecycle cancels out the benefits of the lower carbon content compared to HFO when measuring GWP and at an even lower rate when compared to MGO [65]. When factoring in engine load, the methane slip is dramatically increased if operating at lower loads [44, 72] or when the engine is tuned to minimize NO_x emissions [72].

To effectively handle methane, it may be kept and transported in a liquid state which is the preferred and most cost-effective method for long-distances [9]. While this method reduces its volume by a factor of 600, it must be cooled to a temperature of -162 degrees Celsius, incurring both a cost of cooling and the need for insulated special tanks to prevent heat from penetrating the tank causing the liquid to boil-off [74, 73, 75]. Compared to traditional fuels, the volumetric energy density of liquified methane is still roughly half [76]. This requires tanks to be twice as large [16], sometimes up to four times as large [76], to contain the same amount of energy as traditional liquid fuels when including clearance limits and the extra equipment needed to feed the fuel to the engines. However, the resulting loss of cargo capacity may range from 0-4% depending on the vessel type, size, and location of fuel arrangements [9]. For full scale implementation, new infrastructure is also needed, able to handle the cryogenic liquid and bunkering of ships. This is a factor that is especially important when assessing the over-all gains of switching to a new fuel [44].

3.4.1.1 Fossil liquified methane (LNG)

Natural gas is found in impermeable rock foundations underground and can be extracted as a primary product or as a biproduct from oil extraction [77]. Identified reserves are estimated to last for up to 600 years but how much of it that is economically feasible to extract depend on how much those reserves cost to extract and what the market is willing to pay, ultimately making the reserves larger than the resources considered available [77]. In its liquified state and produced from natural gas, the energy carrier methane is referred to as LNG.

According to the BP Statistical Review of World Energy (2019) [78], the recent years have seen a surge in production of natural gas with the USA's accounting for 21.5% (832 billion m^3), surpassing the Russian Federation. The largest producer in the middle east is Qatar (excluding Iran) and in Europe, Norway. While EU consumes 14.3% of the world production, it only accounts for 6.5% of the production making the region a large net importer with Qatar being its largest source of import.

In figures from ICCT, global shipping consumed an estimated 298 million tonnes of fuel in 2015, slightly more than IEA's estimate (265 million tonnes) and of those, less than 3% was LNG [6]. With the global fleet of LNG powered vessels projected to almost double in the year 2020 compared to 2015 [44], it is a fair assessment that the LNG consumption will follow a similar pattern of increase. Given the global capacity to produce LNG, DNV GL concludes that it would be theoretically possible for the entire global fleet to switch to LNG today but that it would require massive investments [8]. However, to the year 2050, the global liquefication capacity is estimated to triple but with total demand levelling out in the coming years and maintaining the same output in the same period [79].

There exists three ways to bunker a ship: truck-to-ship; ship-to-ship; or terminal-to-ship via pipeline [74]. Investment cost, flexibility to deliver, and capacity generally follow in the same order as they are written. For example truck-to-ship has the lowest investment cost and can be done almost anywhere compared to a dedicated pipeline which requires new pipes to be laid and only works on the quay where it is installed but with a capacity surpassing both truck-to-ship and ship-to-ship [74]. Infrastructure is still limited compared to traditional fuels but has increased rapidly with several bunker vessels on order worldwide [8]. The Swedish flagged LNG bunker ship Coralius covers Skagerrak and the North Sea area and has a capacity of 5 800 m^3 [80]. In the Amsterdam-Rotterdam-Antwerp and Zeebrugge area there are currently four bunker vessels operating with capacities ranging from 1 480 m^3 to 6 500 m^3, with at least one more planned [81]. Each facility, including nearby Le Havre, offers truck-to-ship bunkering with Rotterdam, the largest reception facility, planning major expansions to meet demand. Around the continental European coast there are several reception facilities, including Great Britain. The North American east coast has several large plants but bunkering infrastructure is limited to Florida's east coast where there are two bunker vessels in operation and one on order [81].

3.4.1.2 Renewable liquified methane (LBG)

Depending on the feedstock used there are mainly two methods available to produce bio methane; thermochemical conversion and biochemical conversion [82]. The former relies on high temperatures and a limited air supply resulting in gasification of the feedstock and is well-suited for lignocellulosic biomaterials such as wood. The latter technique uses fermentation and anaerobic digestion and is best suited for sugar-based and starch-based materials like corn and sugar crops. With the biochemical conversion, the resulting methane composition ranges from 50-75%, depending on the feedstock, with the remainder being mostly CO_2 and a small portion of Hydrogen sulfide, H_2S [83]. Hence, the gas must be upgraded to reach the same standard as natural gas. Other feedstocks suitable for this method are sewage sludge, municipal solid waste, food waste, animal waste and even lignocellulosic biomaterials. However, the latter produces a residue after the anaerobic digestion that may be further treated through thermochemical conversion to fully utilize the carbon content of the feed stock [83] and therefore anaerobic digestion is not the most suitable technique for this feedstock [84].

A comprehensive study by Scarlat, Dallemand and Fahl[1] states that Europe is the largest producer of biological gas, followed by the USA, accounting for over 50% of the world production. The production method is almost exclusively limited to anaerobic digestion of manure, agricultural waste, wastewater treatment, energy crops and land-fill gas recovery. An overwhelming majority of this production (2015 figures) is used to generate electricity and heat with less than 9% being upgraded to meet the same standard as natural gas and injected into the common gas grid. Most noteworthy is however that there is enough unused feedstock to increase the production tenfold and ultimately meet 5% of the EU's consumption of natural gas [85].

In 2015, a total of 160 million nm^3 of the European-produced biomethane was used by road transport [85], i.e. not destined for electricity and heat production, representing an energy content of 6 PJ, sold as compressed biogas (CBG). This should be contrasted to shipping's estimated worldwide consumption of LNG representing an energy content below 380 PJ for the same year [6]. The comparison is interesting

[1] Scarlat et al. differentiates between biogas, the raw gas obtained from anaerobic digestion, and biological methane which is biogas upgraded to meet the same standard as natural gas, the latter which this thesis refers to as LBG in its liquified state.

because it means that the gas produced can be upgraded to meet the same standards as natural gas and after liquification use the same infrastructure for bunkering and distribution as LNG uses to fuel ships [86, 75].

One of the most controversial aspects of biofuels is the use of energy crops that competes with food production by occupying farm land [84, 85]. For example, sugar beets, maize or grain could be grown as a feedstock for fuel production rather than used for food purposes. Similarly, other crops such as willow trees which are not suitable for consumption for either people or animals may displace food production by occupying farm land. EU has addressed this concern in Directive 2015/1513 by limiting the use of agricultural land used for energy crops to 7% of the total energy production by 2020 [87]. The core difference between first and second generation of biofuels is the source of the feedstock where the second generation uses a sustainable source not competing with land use or food crops [88]. Ultimately, EU's policy change may open up the door for the second generation of biofuels relying on thermochemical conversion, such as gasification, to fill the gap with lignocellulosic feedstocks such as wood and forest residues, still a largely unproven technology compared to anaerobic digestion [84, 85].

3.4.2 Methanol

The chemical composition of methanol is CH_3OH, although often only written as MeOH. It is colourless, has the simplest structure of all alcohols, maintains as a liquid but is flammable under normal ambient conditions [89]. The most common and economic way to produce methanol is through indirect conversion of methane by breaking it up into synthetic gas (syngas) and reacting the parts over a catalyst together with carbon monoxide to create a liquid [90].

In 2015, the world's first methanol conversion of marine engines took place on the 2001 built passenger ferry Stena Germanica in traffic between Gothenburg and Kiel. Operational experience from the conversion of the existing four-stroke engines has been positive but highlighted that the required safety arrangements for using a volatile fuel, such as double walled pipes and location of high-pressure pumps, can be optimally placed on a new-build compared to a retrofit [91]. Going beyond minor teething problems, in 2019 the oil and chemical tankers Mari Jone and Mari Boyle operated by Marinvest had each clocked 10 000 hours of successful operation on their respective main engine [92]. Together with five more ships, they are a fleet of first-of-its kind tankers using a specially designed two-stroke engine from MAN B&W capable of using methanol as a fuel [93].

Although the conversion of Stena Germanica was capable of reducing SO_x emissions by 99%, it came close but did not meet the strictest NO_x emission levels new ships must comply with [89]. However, this was not part of the scope because the engines were delivered before 2000, the starting point of IMO's NO_x regulation [91]. Similarly, the two-stroke MAN B&W engine was not able to meet the strictest NO_x emissions during testing with simple in-cylinder modification, such as delaying the exhaust valve timing [94]. However, a technique that blends water into the methanol has been tested successfully to comply with NO_x emissions regulations without the need of exhaust after treatment on the aforementioned tanker fleet [95]. Albeit, the mixture induces a fuel penalty but it is still more cost-efficient than other techniques [96]. Both methanol and methane have a considerably lower flash point than traditional fuels but the former does not have to be kept in cryogenic tanks resulting in lower operational and construction costs [89] and given development in NO_x reduction, neither will it require exhaust after treatment.

3.4.2.1 Fossil methanol

While methanol can be produced from a range of different sources the resulting product is the same. Today, the majority of methanol production is done through fossil natural gas but there is also the possibility to employ a more expensive technique and use coal as a feedstock, practised in China for example [89]. Methanol is widely used in the chemical industry with an existing infrastructure [89] and among internationally shipped commodities, methanol ranks among the top five [97]. Regarding the location of methanol refineries, it is usually most cost-effective to produce it close to the feedstock and then transport the methanol rather than transporting the feedstock to a methanol plant closer to the end use [89, 98].

3.4.2.2 Renewable methanol (BioMeOH)

In a compilation of 18 studies by Heyne, Grahn and Sprei [82], the sustainable potential to produce biomass ranges from 25 to 1548 EJ/year in 2050, with an emphasis around 100-200 EJ/year. If all that were converted into methanol it would amount to 60-120 EJ assuming a conversion rate of 60%, widely surpassing shipping's current total need for energy. On average, Swedish biomass has the potential to produce 144 PJ of methanol [99], using the same conversion rate. However, with plants either mothballed, cancelled or still waiting for investments [100], the only reliable producer today in Sweden is a newly commissioned plant in Mönsterås [101] with a planned annual capacity of 0,0001 PJ (5 000 tonnes) [99]. Overall, the global production of renewable methanol, excluding Sweden, is currently around 100 000 tonnes (0,044 PJ) with the largest plants operating in the Netherlands (BioMCN) followed by Canada (Enerkem) and Iceland (Carbon Recycling International) [102].

If opting for methanol as the way forward to reduce the gasses causing radiative forcing, it must be understood that using methanol as a fuel produced from a fossil source will under most circumstances have a slightly higher GWP than HFO and MGO. There is of course the odd exception of using otherwise wasted CO_2 from a nearby plant that might contest this [103]. Nevertheless, in the 100-year perspective fossil methanol will always have a higher GWP than both LNG and LBG. However, in the 20-year perspective fossil methanol will have a lower GWP due to the impact of methane slip from LNG and LBG. Accordingly, it is crucial to make the transition to renewable methanol to achieve a sustainable reduction of GHG-related emissions, as seen in table 3.3.

3.5 Wind propulsion as a measure to reduce climate impact

With the growing amount of pressure on the shipping industry to reduce emissions, wind propulsion offers not only more certainty in complying with future emission's regulation but also economic and energy security against volatility on the fuel markets [104]. Before sailing cargo ships were replaced in the beginning of the 20^{th} century, speed records were set with total voyage averages of 5-6 knots between Australia and Europe (~100 days) and with daily averages of 16 knots [105]. Today a typical transit time from Australia to Europe can be between 30 and 54 days [106]. On transatlantic voyages, speed records of 9.6 knots (12 days) between Liverpool, UK and Boston, US are reported for sailing cargo ships [107]. This can be compared to today when transit times from Southampton, UK to Halifax, US can be between 9 and 10 days for conventional ships [108].

Today there exists an increasing number of 30 wind propulsion technology providers and projects [109]. They can be divided into categories from Flettner rotors, Kite sail, soft and hard sail variations to turbines and hull form variants. The range of fuel savings that can be delivered is estimated to 10-30% for retrofits and up to 50-60% for new builds with wind propulsion technology [104, 110]. A distinction between these two ways of applying wind technology for propulsion can be useful to make in order to increase the understanding of the degree of wind propulsion used for propulsion. The retrofitted vessel that makes use of wind propulsion technology may only be able to achieve a certain amount of fuel savings as it may not serve as a satisfactory vessel to sail. The new built vessel may have a larger possibility to be designed for the task and in a satisfactory way to sail which enables it to achieve a larger fuel savings. The first case can be defined as *wind assisted propulsion* while the latter *wind propulsion*. Something that contradicts this definition is that it may not be the way a vessel is designed that defines the degree of wind propulsion used for propulsion but may vary greatly from trip to trip. The following section will review a selection of both wind assisted propulsion and wind propulsion technology available today.

3.5.1 Flettner rotors

The Flettner rotor technology utilises the Magnus effect when wind passes over vertically revolving cylinders [104, 111]. The Magnus effect or force can be observed in many sports as it makes balls spin in a curve but also creates the lift force that propels the ship forward[111]. An engine makes the cylinder rotate and is the only controlled parameter, when the power consumed to rotate the cylinder is higher than the power contribution the rotation is stopped [111]. This technology was developed in the 1920s by Anton Flettner and was used on a number of ships, for example on 3 000 DWT, M/V Barbara delivered 1926 [104, 112]. Although installed and tested on a number of ships it never could compete against diesel and steam at the time. Due to the shipping crisis in the 1980s and in present time this technology has gained new attention as focus has shifted towards alternatives to fossil fuels [111].

The possible issues related to this technology is that the rotors take up deck space and are likely to increase overall height of the ship[111]. The height issue has been dealt with by US-based Magnuss, that have developed a retractable telescopic rotor system[104]. The vessels utilising this technology today range from Ro-Pax vessel M/S Viking Grace (6 107 DWT), RoRo vessel M/S Estraden (9 700 DWT) to the bulk carrier M/V Fehn Pollux (4 200 DWT) and tanker M/T Maersk Pelican (109 647 DWT).

3.5.2 Kite sail

The kite technology is a rather new technology developed in the early 2000's which harnesses the wind with the help of a kite connected with a line to the bow of the vessel pulling it forward [113, 109]. Traut et al. describe the kite system as an automated wing that flies in a circular pattern at a high altitude where the wind is often greater [111]. The kite makes use of the force called *lift* similar to wings, foils and sails. If the wind conditions become unfavourable the system hauls in the kite and stores it on deck. The most ideal case of wind is in tail wind conditions and as the kite does not need any deck space since it is flown in front of the ship[111]. Further the kite delivers a large amount of power in the aforementioned study but only within a narrow range of direction which make its performance much more sensitive to wind direction and speed. As the kite can be stowed away it does not add to the ships maximum dimensions which the Flettner rotor does. In 2008, M/S Beluga Skysails, a heavy lifting vessel of 9 821 DWT used a kite sail system between Bremerhaven, Germany to Guanta, Venezuela with successful results [114]. Although efforts are made to find ships utilising this technology today, it could not be confirmed if the ships that formerly had the system installed [109] still have it in use.

3.5.3 Rigged Sails

In this category sails that are rigged on masts that are a part of the superstructure of the vessel and similar to kites make use of the force called lift. The rigged sails are divided into the subcategories soft and hard sails depending on the stiffness of the material the sails are composed of, similar to other studies evaluating wind propulsion technology [109, 24].

3.5.3.1 Soft Sails

A soft sail system that recently has gained attention is the Dynarig system and is evaluated at an extent [27, 115, 109]. It has three masts of which all are rotatable and have sails that retract into the mast and has currently only been installed on the 90 metre super yacht Maltese Falcon built in 1990[104]. The same system has been proposed on a cargo vessel project named Ecoliner of 8 000 dwt by the same designer Dykstra Naval Architects[116]. The soft sail system are similar to the traditional sails and share characteristics although the soft sail system developed included in this category are mainly more automated than the square rigged vessels that mainly operate as training vessels today. Issues with this system that can be mentioned is that it is less efficient upwind [27] and generally adds to the dimensions of the vessel similar to Flettner rotors. Other soft sail systems that can be mentioned but not further investigated are Seagate Sails, Neoline, Autares system, Pinta rigs and the Indosail [104].

3.5.3.2 Hard Sails

There are a number of different studies performed on different hard sail systems that evaluates performance [24, 26, 27, 25, 109]. Atkinson et al. [24] review a broad range of issues regarding use of rigid sails on ships encompassing previous research studies, journal articles and operational experiences. The review is a SWOT-analysis that focuses on rigid sails assisting the main engine and not on ships where sails are the primary source of propulsion. Two rigid sail systems that are brought to light are the JAMDA from the 1980s and Walker WingSail which is evaluated in 1986. The most significant issues possible to hinder the progression of this technology that are presented in the study are: safety concerns; design limitations; economic and business considerations; and operational issues[24]. For safety concerns handling in adverse conditions is pointed out, for design limitations this relates to retrofitting the system on existing structure. As for economic and business considerations, this aims at up-front costs, return on investment periods and operating costs. Further on this topic, it is pointed out that it is important that the technology is competitive against other fuel and emission reduction technologies even when fuel prices are relatively low. Regarding the operational issues this relates to ongoing maintenance requirements and the performance of rigid sails under varying operational and weather conditions. As for current ships utilising this technology that are in commercial operation there is only one found, MV Ankie of Jan van Dam Shipping, which was installed with Econowind Ventifoils in early 2020 and therefore it may be to early to retrieve meaningful operational results[117]. Other projects and systems that can be mentioned are 84 000 DWT bulker Wind Challenger, Oceanfoil, S/V Orcelle and the wPCC project further presented in section 4.1 [104, 118].

3.5.4 Fuel savings possible with wind propulsion technology

To create an understanding of current and previous wind propulsion projects' fuel saving performance a screening is presented in table 3.4. It lists studies previously presented in this section together with more fuel saving estimates. The table should be interpreted with care since the method used in the studies to estimate fuel savings may vary greatly.

Lu & Ringsberg [27] does a comprehensive study on Flettner rotors, soft and hard sails. The study is a simulation where an Aframax oil tanker (70,000-120,000 DWT) is equipped with one of the technologies and simulated over two different Atlantic routes with the same transit time. Their results are shown to be 5.6 to 8.9% fuel savings compared to a vessel without sails. The flettner rotor has the overall greatest fuel saving in this study followed by the hard sail technology wingsail and the soft sail technology Dynarig. This study is close to the estimates produced by the company Norsepower that report 5-8.2% annual fuel savings on M/S Estraden and M/T

Maersk Pelican. On the other hand Schmidt reports 22.9% fuel savings but this is during a single voyage between The Netherlands and Portugal[119]. Further Lu & Ringsberg conclude that the fuel savings depend on a large number of factors and that a simulation model is important to determine which technology to choose for a specific ship and route [27].

The detailed study of Traut et al. [111] compare Flettner rotors and kite propulsive power contribution over 5 routes with a typical ship serving the route in a simulation. The results show that for some ships and routes tested had more power contribution by kite than by flettner rotors. The results show fuel savings of between 3-32% depending on route, ship and direction of the voyage. This agrees with estimates of Schlaak et al. [120] also presented in the aforementioned study. The case study of Naaijen can also be mentioned to have close estimates although it is more simple[113]. In the study by Traut et al. only one rotor is used in the simulation but it is anticipated that with three rotors installed over half of the power required by the main engine can be provided by the rotors under typical slow steaming conditions. This may also with advantage be compared in the light of the aforementioned reported fuel savings of M/S Estraden and M/T Maersk Pelican. Furthermore, the integration of the conventional propulsion machinery and the kite is however not taken into account and this may be important as the fuel consumption varies with the propulsion power output[7]. Adding to this, the study does not consider variations in the ships route or speed over voyage as it follows an existing route and does not deviate to benefit from better wind conditions[7].

Atkinson et al. [24] review the hard sail systems JAMDA from the 1980s and Walker WingSail which is evaluated in 1986. The first system reports fuel savings of 10% to over 30% and the latter an average of 8% with up to 15–20% logged on vessels in operation. With these fuel savings it is concluded that if rigid sails were again fitted to ocean-going powered ships, significant reductions in fuel oil consumption and airborne emissions could be achieved. In the remaining six reports the range of fuel savings reported is between 5% and 50% [25, 26, 27, 109, 121, 122].

Maybe it is not possible to draw the conclusion what wind propulsion technology is best but maybe rather the question to answer is what technology is the most suitable for a vessel type and what potential it has in line with the conclusion of Lu & Ringsberg[27]. For this to be done more specific research is needed.

Table 3.4: Selected projects and studies assessing wind propulsion systems

Source & Year	WPS system	Type of study	Fuel savings	Area	Vessel
Lu & Ringsberg (2019) [27]	Flettner, Soft sails, Hard sails	Simulation	5.6-8.9%	Atlantic	Aframax tanker (70 000 - 120 000 DWT)
Bouman et al (2017) [122]	Kite, Sail/wings	Review	1-50%	Worldwide	
Nelissen et al. (2016) [109]	Flettner, Soft sails, Hard sails, Kite, Turbine	Simulation	1-24%	Worldwide	6 vessels at 2 avg. speeds
Schmidt (2013) [119]	Flettner	In commercial operation	22.9% single voyage	N.Atlantic	10 500 DWT
Norsepower (2020) [123]	Flettner	In commercial operation	5% annually		9 700 DWT Ro-Ro carrier
Norsepower (2020) [124]	Flettner	In commercial operation	8.2% annually		109 647 DWT Tanker
Traut et al. (2014) [111]	Flettner and Kite	Simulation	3-32% (50% w. three rotors)	N.Atlantic, Worldwide	5 500 - 30 000 DWT
Schlaak et al. (2009) [120]	Kite	Simulation	1-36%		Multi purpose freighter
Naaijen (2007) [113]	Kite	Theoretical Case study	up to 50%		50 000 DWT Tanker
Kazuyuki et al. (2013) [26]	Hard sails	Simulation	20-30%	Pacific	180 000 DWT
Kisjes (2017) [121]	Hard sails	1:2 scale model	40%		
Yong (2019) [25]	Hard sails	Simulation	18.2%	Asia	76 000 DWT

4

Goal & Scope

4.1 Introduction to the wPCC

The Wallenius shipping companies have for almost two decades been working towards an emissions free ship. In 2005 it resulted in the ship concept ORCELLE where wind power showed great potential in reaching zero emissions. The work intensified in 2017 and resulted in a conceptual design of a wind powered car carrier using a wing rig to reduce consumption of fossil fuel [125]. The current project stretching from 2019 to 2021 aims to demonstrate a sustainable transport concept reaching IMO's target of 50% reduction of greenhouse gases before 2050. The intended result is to produce a design ready to build at shipyards that is both economically and technically feasible. The project group consists of Wallenius Marine AB, KTH Royal Institute of Technology, Chalmers University of Technology and SSPA Sweden AB [125].

More specifically, the intended result is a ship design of a Technical Readiness Level 6 (TRL), proof-of-concept, ready to build at a ship yard within 3 to 5 years. For this to be achieved it is required to use basic and applied research, risk mitigation and simulation, unconventional testing methods, aerodynamic and hydrodynamic simulation methods in addition to a new logistics solution. The development of the design is seen as deliverable as the method development, verification and validation will be made available to society and be presented to the general public, academia and industry through events, participation in conferences and publication in international journals. A free running model will be made to enable simulations that may occur during ship operation [125]. An in-depth description of the wPCC is presented in chapter 5, section 5.1 with ship particulars in table 5.1.

4.2 Goal

The goal of this study is to develop an understanding and assessment of the life cycle climate impact and cost of wind propulsion on ships. This is done by performing a screening LCA and life cycle costing investigating the propulsion system on the wPCC compared to a car carrier without sails. The intended audience are the main stakeholders in the project - Wallenius Marine and SSPA. Notwithstanding, it may also be of interest to ship owners and ship operators in general curious about the technology as well as regulating authorities, firms developing related technology and other marine consultancies.

4.3 Scope

The system studied is the propulsion of the ships serving the function of providing transport. Boundaries of the system are limited by the materials and energy used for construction, fuel and lube oil consumption during its operative years, and the final recycling (scrapping) of materials in the propulsion system. While the function of a ship and most cargo systems is transportation of cargo over a distance, for this comparative assessment where each assessed ship is considered to have the same cargo capacity and are engaged in the exact same trade route, the functional unit is the transport service of a propulsion system over 30 years, optimized for the investigated speeds and the dead weight tonnage specified in table 5.1 and section 5.1 to 5.4. A summary of modelling choices can be found in table 4.1 together with key limitations and assumptions.

Table 4.1: Summary of modelling choices of the LCA

Category	Modelling choices
Functional unit	30 year of transport service with propulsion system of a car carrier as specified in table 5.1 and section 5.1 to 5.4
Type of LCA	Allocative
Time horizon	30 years
System boundary	The whole life cycle from extraction of raw material to recycling of the engines and WPS. Capital goods used for construction of the ship and capital goods used for production of raw materials are excluded.
Geographical location	Construction (South Korea); Operation (North Atlantic); Scrapping (India)
Impact categories	Global warming potential over a 20 and 100 year time perspective (CO_2eq_{20} and CO_2eq_{100})
Speeds investigated	8.0 and 11.4 knots
Fuel chains investigated	Liquified natural gas (LNG); Liquified biogas (LBG); Methanol produced from willow (BioMeOH)
Limitations and assumptions	- Only the propulsion system is included - All ships have equal cargo capacity. - The WPS consists of steel only - Emissions from maintenance are omitted - Methanol engines (although not in production) are equal to dual fuel LNG engines except cheaper to maintain - Pilot fuel is 0.1% Sulphur MGO - Costs reflect 2020 levels by applying 2% inflation and an exchange rate of 1.1 from USD to EUR - Emissions from scrapping are allocated as 50/50% to new steel using recycled material and scrapping activity

System boundaries are presented in figure 4.1. Raw materials (metal) used in construction are from cradle-to-grave and hence also accounts for emissions from recycling. Yard work emissions from construction of the WPS is based on the present average electric grid mix in South Korea. Fuel and lube oil consumption is accounted for as the full life cycle from extraction to combustion (well-to-propeller). However, the emissions from maintenance, i.e. spare part production and transport for engine repairs and continuous maintenance of the WPS are omitted from the LCA. Emissions are based on averages and hence, an allocative approach is used. Impact of emissions (CO_2, CH_4 and N_2O) are limited to global warming potential over both a 20 and 100 year perspective, presented and normalized as CO_2 equivalents. Allocation of greenhouse gases warming potential is based on IPCC's latest figures, presented in table 3.1.

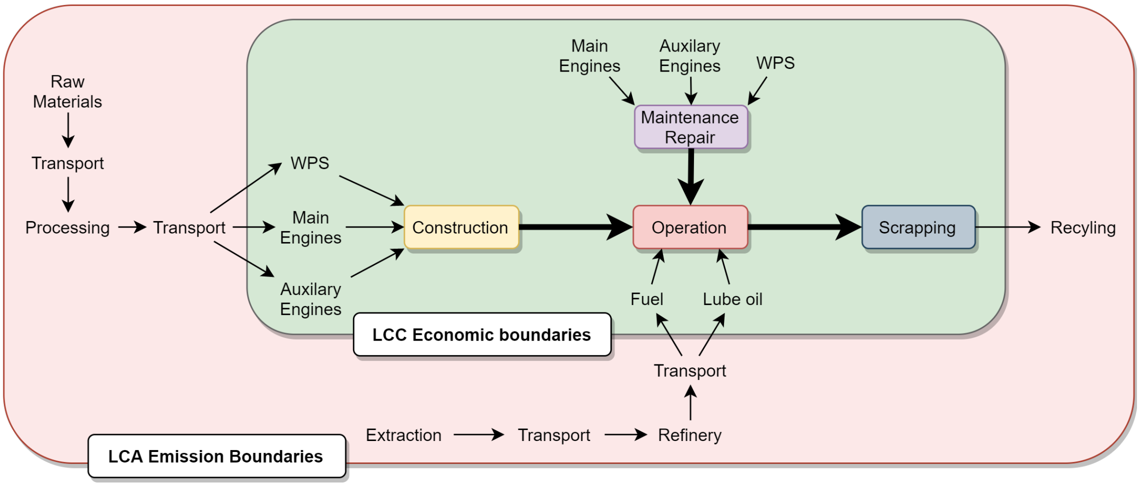

Figure 4.1: Description of the system boundaries for the LCA and the LCC. The important difference being that the LCC only accounts for the summarized direct costs of construction, operation, maintenance and scrapping and not the indirect costs of each individual step.

4.3.1 Sensitivity analysis

To understand how the input data contribute to the model output a sensitivity analysis is conducted based on a selection of factors which represent the largest uncertainty. Future cost of fuel is extremely difficult to assess, especially renewable fuels because today's production capacity is small. However, future legislation and infrastructure changes may dramatically alter their cost and competitiveness compared to traditional fossil fuels. Furthermore, the wPCC is a unique ship with its never before constructed wind propulsion system. While cost estimates have been indicated and maintenance costs suggested, it is of great interest to investigate what the impacts are if final costs are considerably higher. Finally, the wPCC is connected with a higher initial investment cost compared to the ships without sails due to the addition of a wind propulsion system, hence it is also interesting to investigate how that translates given different terms of depreciation. A list of the factors in the sensitivity analysis is found below:

- Cost of renewable fuels (high and low)
- Installation cost of WPS (high and low)
- Maintenance cost of the WPS (1% or 5% of investment)
- Borrowing cost (interest rate 3% or 8%)
- Depreciation time of the construction investment (25 years or 10 years)

4.3.2 Parametric study

In this thesis a parametric study is conducted, defined as altering a key parameter, not only changing its value to a high or low option. It is similar to a sensitivity analysis but differs in the context of the result from the variation. For example, changing speed from 8.0 knots to 11.4 knots requires a different engine configuration to maintain optimal load conditions. Moreover, changing fuel is associated with completely different emission factors directly related to the chemical composition of that fuel. It is arguably so that fuels of the same type offers some variation in emissions if for example it is sourced from two different locations (North Sea compared to Qatar) or two different feed stocks (agricultural residue compared to forest residues). However, the results are fundamentally different when altering speed or fuel type that they are kept apart from the sensitivity analysis. The two parameters changed are listed below:

- Optimal engine configuration (8.0 knots and 11.4 knots)
- Renewable fuel choice (LBG or BioMeOH)

4.3.3 Method of combining LCA and LCC

As a method to combine LCA and LCC, the ship is considered as a system based on stand-alone modules that can be removed or changed independently, illustrated in figure 4.2. This layout is based on the framework developed by Chatzinikolaou and Ventikos [29] and refined by Jeong et al. [52]. The ship system is divided into two main parts, hull and machinery (green tiles). The life cycle of each sub-system (orange tiles) is divided into phases of construction, operation, maintenance and scrapping (dashed black lines). For a comparative assessment, only the three sub-systems marked by dashed orange lines are modelled, consistent with the parts the LCAs and LCCs focuses on. By using the inputs, outputs and material flows presented in the modular system of a ship, the data is aligned and well suited for a comparison by avoiding cut-offs [67]. The content and flow of each module is presented in the inventory analysis, section 5.

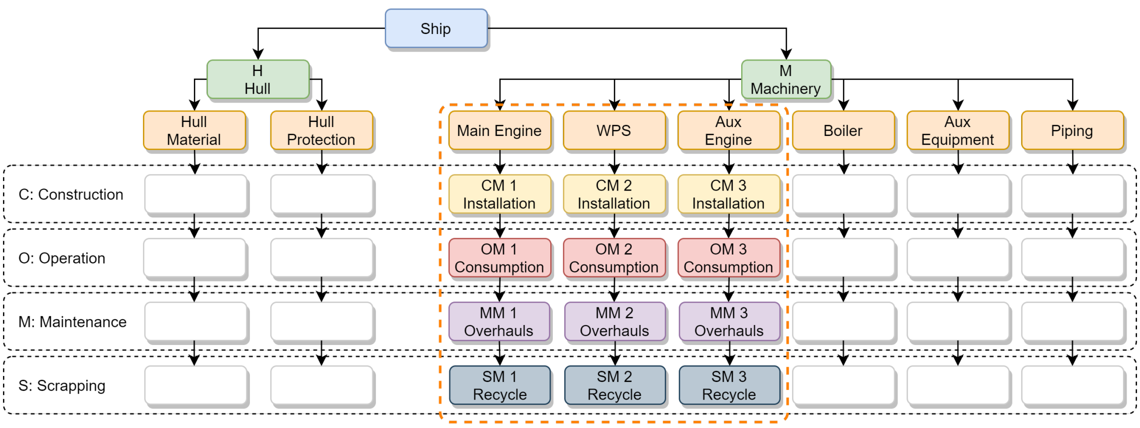

Figure 4.2: Overview of a modular system and life cycle of a ship

5

Inventory analysis

5.1 Case vessels

Three main ships form the foundation of the model: the wPCC using LNG; a conventional ship using one of two types of renewable fuel (LBG and BioMeOH); and a conventional ship using LNG. Each ship is modelled at two different design speeds, 8.0 knots and 11.4 knots but all share the same hull. Given that three different fuels are modelled, at two different speeds, and measuring environmental impact and costs for all, a total of eight models are constructed in a mathematical model, including the wPCC. Because the ships without sails only differ in type of fuel used and based on the assumption that these engines share the same capabilities regardless of fuel used, they share layouts for their respective design speeds. It is however important to remember that Wärtsilä currently doesn't have any serial production of methanol engines, hence this option is not readily available compared to regular gas engines. During the writing of this thesis, the wPCC is in a development stage and the specifics may be altered before the final hull design is finished. In this thesis a preliminary ship design is used, presented in table 5.1. In the construction of the mathematical model, these particulars are also used as constraints for the ships not fitted with sails, allowing for comparisons that are like for like.

Table 5.1: Ship particulars based on a preliminary ship design of the wPCC. Inputs are shared for all ships in the mathematical model in this thesis.

Characteristic	Value	Unit
Length	210	meters
Beam	39	meters
Draft	8.5	meters
Deadweight	13 021	tonnes
Minimum power @ MCR *	4 368	kW
Total sail area	4 000	square meters
Total sail weight	400	tonnes

**Based required minimum propulsion according to EEDI guidelines*

5.2 Performance and power demands

5.2.1 wPCC

To be able to assess the wPCC and its sailing performance, the particulars of the wPCC has been fed into a preliminary weather routing software containing wind direction and wind speed in the North Atlantic. The simulation was run by Wallenius Marine over a period corresponding to 11 years of operation. This ensures consistent results and load conditions. A major constraint in the preliminary performance routing is that if the ship cannot maintain a speed of at least 8.0 knots by sailing alone, propulsion is supplemented by support from the propeller. Generally, this happens when the wind speed drops below 2 m/s, when the direction of the wind is unfavourable, i.e. direct head wind, or when both conditions apply. Support is gradually increased as wind conditions for sailing become more and more unfavourable. Hence, maximum support from the propellers occur when the ship has a strong headwind, with loads from 900 kW and up representing less than 2% of the total time in transit. Lastly, a very interesting condition appears when giving the wPCC the opportunity to maintain an average speed of 8.0 knots instead of 11.4 knots. This is done by allowing the ship to stay idle instead of motorsailing[1] when it cannot sail, thereby reducing the demand for power even further. A small percentage to support (6%) is however added to account for extra manoeuvring to get into and maintain position, leaving total time in idle at 40%. This odd condition may be viewed as an extreme case of weather routing or at least as an opportunity to use the full potential of sailing, compared to traditional propulsion. Highlights from this data set produce the underlying input data for the wPCC. A summary is presented in table 5.2 with the distribution of energy in figure 5.1. The weighted averages are based on energy consumption in propulsion power demand increments of 100 kW each, ranging from 0 kW to a maximum of just above 1 000 kW.

Table 5.2: A summary of the data obtained from Wallenius Marine's preliminary weather performance simulation of the wPCC

Characteristic	**Value**	**Unit**
Time spent sailing (without support)	54%	-
Average speed when only sailing	14.1	knots
Average speed of the ship for all conditions	11.4	knots
Average auxiliary base load	214	kW
Max. propulsive load in adverse weather @ 8.0 knots	1 014	kW
Weighted average total load @ 11.4 knots	437	kW
Weighted average total load @ 8.0 knots	227	kW

[1]Using the engine for part of the propulsion while still utilising the WPS for part of the propusion

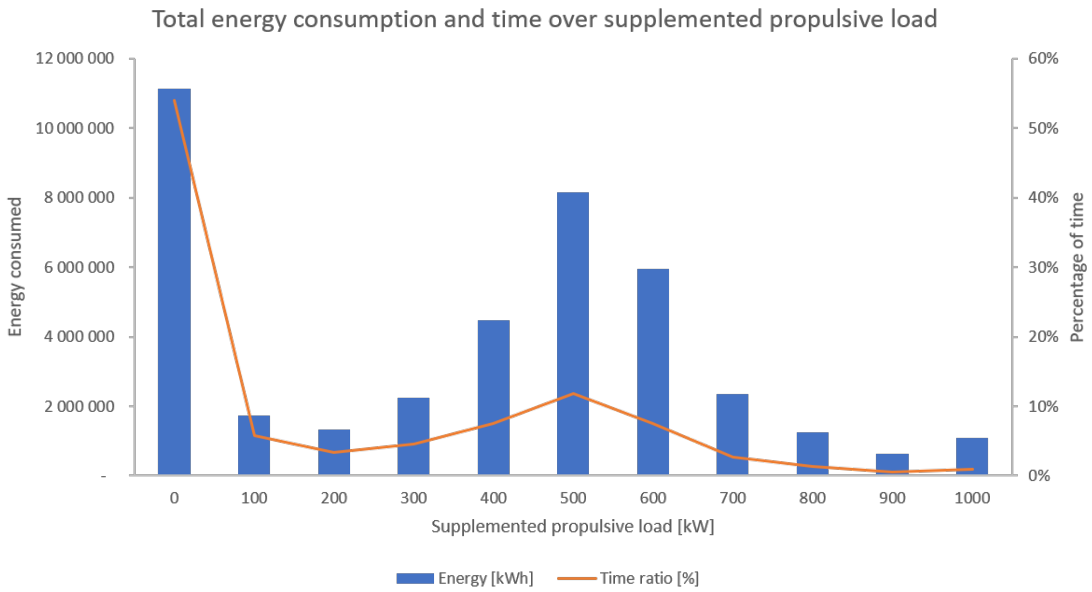

Figure 5.1: Distribution of energy and time over supplemented propulsive power in increments of 100 kW where 0 kW represents that the wPCC is sailing (54%) only consuming energy from auxiliary load (214 kW)

5.2.2 Car carriers without sails

To accurately compare the wPCC to a car carrier that does not sail, a preliminary power-speed curve was obtained from SSPA to determine the power needed for the hull at 8.0 and 11.4 knots, the wPCC's two average speeds. Figures are presented in table 5.3. An important difference between these data points and the ones used for the wPCC are that the former have not been subjected to resistance from weather.

Table 5.3: Summary of the data obtained from SSPA on hull performance

Characteristic	Value	Unit
Average propulsive load @ 11.4 knots	2 680	kW
Average propulsive load @ 8.0 knots	992	kW

5.2.3 Applying efficiency

Power, presented in table 5.2 and table 5.3, does not take any sort of losses into consideration. To accurately represent a real ship, an efficiency rate must be applied that accounts for engine losses in heat and transmissions as well as propeller. In this model that efficiency rate has been set to 0.36, a conservatively low number for four-stroke diesel-electric propulsion [45]. Furthermore, the average auxiliary load to supply electrical power to the ship has been increased to 300 kW to avoid the engine being undersized. Presented in table 5.4 are the average total power demands, with efficiency and auxiliary loads applied, as used in the mathematical model, thereby concluding each ship's average demand for power.

Table 5.4: Total power demands for each ship and speed used in the mathematical model with drive train efficiency applied

Characteristic	Value	Unit
Total efficiency	0.36	-
Average auxiliary load	300	kW
wPCC @ 8.0 knots	347	kW
wPCC @ 11.4 knots	1 211	kW
Ships without sails @ 8.0 knots	3 056	kW
Ships without sails @ 11.4 knots	7 743	kW

5.3 Engine layouts

A set of engine layouts have been developed from Wärtsilä's product guides of existing engines to match power demand for each ship and speed. These are presented in table 5.5. The power output of the engines have been selected to best match the average power demand during transit and to minimize the total installed power. An important factor relevant for the wPCC is that all engines are capable of sharing spare parts because the engines only differ by cylinder count, not cylinder size, thereby reducing the amount of spare parts needed on board. This is part true for the alternative and conventional ship also where the three smaller engines are of the exact same type. It is also worth highlighting that the 6L20DF engine at 1200 RPM is the smallest available in Wärtsilä's product line compatible with a 60 Hz generator, the most common frequency for the power grid on ships.

Table 5.5: Summary of the engine layouts for the ships at different speeds

Speed	8.0 knots			11.4 knots		
wPCC						
	Diesel-Electric			Diesel-Electric		
	Engines	RPM	Power [kW]	Engines	RPM	Power [kW]
	2 x 6L20DF	1 200	1 110	2 x 6L20DF	1 200	1 110
	2 x 9L20DF	1 200	1 665	2 x 9L20DF	1 200	1 665
	Total power: 5 550 kW			Total power: 5 550 kW		
	Total weight: 41.8 tonnes			Total weight: 41.8 tonnes		
Alternative & Conventional						
	Diesel-Electric			Diesel-Electric/Diesel-Mechanical		
	Engines	RPM	Power [kW]	Engines	RPM	Power [kW]
	1 x 8L34DF	720	3 840	1 x 8L46DF	600	9 160
	3 x 6L20DF	1 200	1 110	3 x 6L20DF	1 200	1 110
	Total power: 7 170 kW			Total power: 12 490 kW		
	Total weight: 72.2 tonnes			Total weight: 158.2 tonnes		

Two things stand out as exceptionally noteworthy at this stage. Firstly, the minimum required power according to EEDI guidelines puts a much larger requirement on installed power than what is necessary to propel the ship at a design speed of 8.0 knots. Secondly, the smallest engine in Wärtsilä's engine program is about twice as powerful as the 8.0 knots the wPCC ship requires on average, leading to a dreadfully low engine load of just above 30%. A consequence of the former peculiarity is that a diesel electric layout is preferred over a traditional drive-train because it allows the total installed power to be counted towards propulsion. With an engine layout such as the one presented in table 5.5, a compromise is struck between compliance and the most fuel effective solution by avoiding running conditions that would occur if there were only one main engine large enough to satisfy the demands of minimum propulsion power according to EEDI guidelines. This argument can be applied for both wPCC models, all 8.0 knots ships but not the 11.4 knots ships without sails. For these faster ships, it may be a better choice to use a different drive train set up because the average power requirement is significantly higher than the EEDI demands. Finally, the second item regarding the low engine load of the wPCC may only be mitigated by choosing a different mean of power generation or opting for a different engine manufacturer who specializes in smaller gas powered engines.

5.4 Operational profile

By combining the average total power demands in table 5.4 with the engine layouts in table 5.5, consumption of fuel and lube oil can be calculated, found in table 5.6. The annual time in operation is measured in days over a full year. While these do not add up to a full year, they take into account the days a ship spends doing maintenance and yard-work. The three main categories are "Transit", "Manoeuvring" and "Moored". The first, transit, represent the amount of days in a year that the ship is in transit from one port to another. The second, manoeuvring, is getting to and leaving the quay after ending transit. Lastly, the ship is moored when it is along side a quay for loading and unloading. During transit, one engine is running, best matching the average load. All engines are running during manoeuvring and when moored in port, only the smallest engine is running. Hence, the SFOC for both main fuel and pilot fuel is a product of the engine load and calculated from the engine manufacturer's product guide. Main fuel, pilot fuel and lube oil are summarized as annual consumption.

Table 5.6: Summary of operational profiles for the ships at 8.0 and 11.4 knots

Category	Transit	Manoeuv.	Moored	Total	Unit
Annual time in operation	300	10	30	340	days
wPCC - 8.0 knots (LNG)					
No. engines running	1	4	1		
Engine load	31%	32%	27%		
SFOC - Main fuel	10 027	9 970	10 246		kJ/kWh
SFOC - Pilot fuel	319	318	324		kJ/kWh
LNG consumption	1 403	241	124	1 768	tonnes
Pilot fuel consumption	52	9	5	66	tonnes
LO consumption	1 272	216	108	2 046	kg
wPCC - 11.4 knots (LNG)					
No. engines running	1	4	1		
Engine load	73%	32%	27%		
SFOC - Main fuel	8 538	9 970	10 246		kJ/kWh
SFOC - Pilot fuel	234	318	324		kJ/kWh
LNG consumption	4 166	241	124	4 531	tonnes
Pilot fuel consumption	132	9	5	147	tonnes
LO consumption	5 066	241	140	6 087	kg
Alternative and Conventional - 8.0 knots (LBG/LNG)					
No. engines running	1	4	1		
Engine load	80%	25%	27%		
SFOC - Main fuel	7 533	8 725	10 246		kJ/kWh
SFOC - Pilot fuel	101	326	324		kJ/kWh
LBG consumption	9 304	211	124	9 368	tonnes
Pilot fuel consumption	145	9	5	169	tonnes
LO consumption	14 303	281	140	14 724	kg
Alternative and Conventional - 11.4 knots (LBG/LNG)					
No. engines running	1	4	1		
Engine load	85%	14%	27%		
SFOC - Main fuel	7 542	8 117	10 246		kJ/kWh
SFOC - Pilot fuel	91	193	324		kJ/kWh
LBG consumption	23 538	196	124	23 858	tonnes
Pilot fuel consumption	331	5	5	341	tonnes
LO consumption	28 088	216	108	28 412	kg
Alternative - 8.0 knots (BioMeOH)					
No. engines running	1	4	1		
Engine load	80%	25%	27%		
SFOC - Main fuel	7 553	8 725	10 246		kJ/kWh
SFOC - Pilot fuel	101	326	324		kJ/kWh
BioMeOH consumption	23 434	531	312	24 276	tonnes
Pilot fuel consumption	145	9	5	158	tonnes
LO consumption	14 303	281	140	14 724	kg
Alternative - 11.4 knots (BioMeOH)					
No. engines running	1	4	1		
Engine load	85%	14%	27%		
SFOC - Main fuel	7 542	8 117	10 246		kJ/kWh
SFOC - Pilot fuel	91	193	324		kJ/kWh
BioMeOH consumption	59 288	494	312	60 094	tonnes
Pilot fuel consumption	331	5	5	341	tonnes
LO consumption	36 239	281	140	36 660	kg

5.5 Construction

5.5.1 CM 1 - Engines

Emissions from the construction of the engine are difficult to quantify because there are many processes involved and may be unique to the ship yard. Data compiled by Chatzinikolaou & Ventikos [29] gives a fair assessment that includes engine construction, testing, transport to the yard (125 km by road) and sea trials. All related construction emissions for the engines can be seen in figure 5.2 where the content inside the black dashed line contain all emissions by using input engine power as a proxy, as seen in yellow box CM 1.1.

Construction, transport, testing and sea trials emissions for the engines (EI_{engine}) are the summary of total installed power of the engines ($P_{engines}$) multiplied by the emission impact for each pollutant (Ei_t), expressed in equation 5.1. Note that the emissions from transport from engine factory to yard are also included with input EI_{engine} and that all emissions from module CM 1 are encapsulated by this equation. Each ship's propulsion layout is found in table 5.5 and the emissions data per installed kW is found in table 5.7.

Transportation cost ($Tc_{engines}$) in equation 5.2 is based on the total weight ($W_{engines}$) of the engines, a transport distance of 125 km ($D_{engines}$), multiplied by a freight cost ($C_{freight}$) of € 1 615 per tonne-km [52]. Installation cost ($Ic_{engines}$) in equation 5.3 is based on total engine power and cost per kW found in table 5.8, expressed by C_{power}. Finally, the summary of the total cost produced in module CM 1 is expressed by equation 5.4 where are parts are added up.

$$EI_{engines} = P_{engines} \times Ei_{engines} \tag{5.1}$$

$$Tc_{engines} = W_{engines} \times D_{engines} \times C_{freight} \tag{5.2}$$

$$Ic_{engines} = P_{engines} \times C_{power} \tag{5.3}$$

$$CI_{engines} = Tc_{engines} + Ic_{engines} \tag{5.4}$$

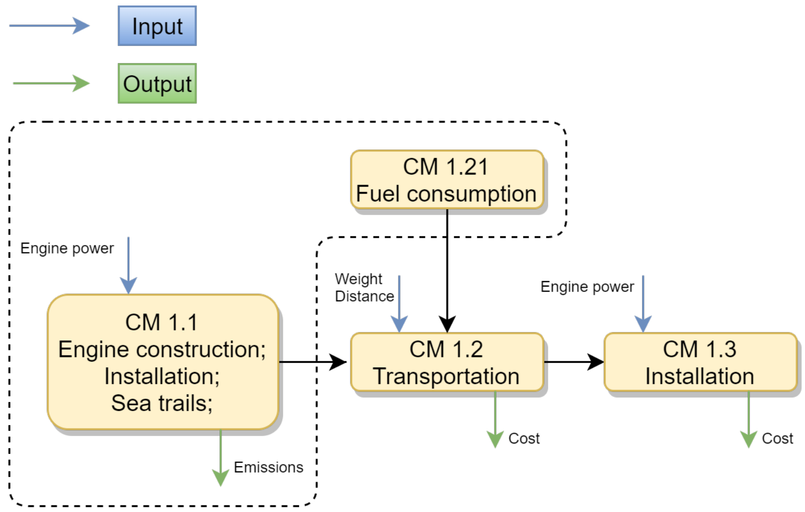

Figure 5.2: Construction Module 1 - Process flow of engine construction. The processes inside the dashed black line is covered by the input Engine power in CM 1.1

Table 5.7: Emission from engine production, steel production and steel scrapping

Activity	**CO_2**	**CH_4**	**N_2O**	**Unit**	**Source**
Engine production *	84 827	104	-	*g/kW-engine*	[29]
Steel production	1 099.5	0.72	1.69	*g/kg-steel*	[126]
Steel scrapping	1 762	196	18	*g/kg-steel*	[29]

** Includes construction, testing, transport, installation, sea trails*

Table 5.8: Data on engines costs where the average is used to determine the cost of engine alternatives, based on installed power [EUR/kW] and in 2020 prices.

	Diesel engine		**LNG engine**		**MeOH engine**	**Source**
	Low	*High*	*Low*	*High*		
	512	717	717	1024	-	[127]
	557	604	-	(1 280)*	(818)*	[89]
	-	-	614	896	-	[128]
	597	-	433	-	-	[129]
Avg.	**597**		**774**		**(818)***	

** Includes fuel tanks and other equipment and is only used for indicative purposes*

5.5.2 CM 2 - Wind propulsion system

One of the assumptions made is that the WPS is made out of steel, hence emissions from raw materials are based on steel production. It is fair to mention that in reality, the sub-system WPS is likely to comprise of a mast, a wing surface and a hydraulic system, as seen in figure 5.3. Given that the project is still in an early phase, these details, although important, are disregarded and instead an approximate weight of the installation is used as the main input to calculate emissions. Wallenius Marine indicate that the weight per mast is 100 tonnes and given that there will be four masts installed, the total weight of the WPS is 400 tonnes. The flow and inventory can be seen in figure 5.4.

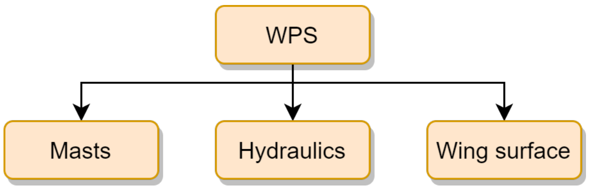

Figure 5.3: The three main parts of the WPS are substituted for the weight of the whole installation to represent total emissions

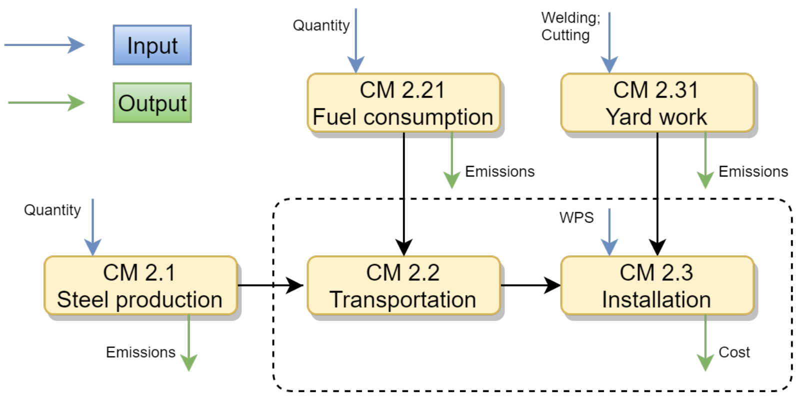

Figure 5.4: Construction Module 2 - Process flow of the WPS during construction

Steel production emissions for the WPS (EI_{WPS}) are the summary of the total weight of the WPS(W_{WPS}) multiplied by the emission impact of each pollutant (Ei_t), expressed in equation 5.5. Emissions from steel production are found in table 5.7 and represented in the yellow box CM 2.1 in figure 5.4. According to the flow used in this module, the WPS is produced from steel delivered to the yard by lorry from a steel factory located 1000 km from the yard. How the actual delivery and construction will take place is not yet established. It may very well be that the distance is shorter, that delivery is by barge or that the WPS is constructed midway at a separate factory and delivered ready to install. In any case, the flow used here may therefore be considered as a high emissions estimate.

Quantifying the emissions from transporting the WPS as well as the work associated with constructing the WPS is found in equation 5.6 and 5.7 respectively. In the former equation, the quantity of fuel (Q_{lorry}) used is based on the distance ($D_{transport}$, 1000 km), average consumption of a lorry (29.9 l/100-km [130]) and the amount of cargo shipments ($L_{shipments}$) needed to deliver all the goods based on an average capacity of a lorry (40 tonnes). Road diesel is assumed to have the same emission factors as MGO. In the latter equation, yard work emissions ($Ei_{yardwork}$) are based on data presented in table 5.9, including emissions from the electric grid listed in the same table. Each sail is constructed from steel sheets with a standard dimension, welded and cut on all sides.

Table 5.9: Measurements and construction data used in the manufacturing of one sail, including energy consumption and average emissions from the electric grid

Category	Value	Unit	Source
Sail			
Surface area of sail	1 000	m2	
Height	80	m	
Width (calcuated)	6.25	m	
Steel sheets (standard size)			[131]
Height	6 000	mm	
Width	2 400	mm	
Area	14.2	m2	
Steel sheets used (calculated)			
Width	6	pcs.	
Height	14	pcs.	
Total (rounded up)	84	pcs.	
Energy consumption			[132]
Welding	15.10	MJ/m	
Cutting	8.50	MJ/m^2	
Energy used per 1000 m^2 sail (calculated)			
Welding	36 530	MJ	
Cutting	8 500	MJ	
Emissions from electricity grid (South Korea)			[133]
CO_2	407.7	g/kWh	
CH_4	0.0052	g/kWh	
N_2O	0.0026	g/kWh	

Total cost of the WPS is one of the inputs the sensitivity analysis is focusing on. For that reason the cost of the transport is considered to be part of the total price. Hence, the content found inside the black dashed line in figure 5.4 is represented by a single input where everything is included. This means that the installation cost ($Ci_{installation}$), represented by the yellow box 2.3, may take one of two different values , namely € 8 000 000 or € 16 000 000, representing the total cost (CI_{WPS}) for the entire module.

$$Ei_{WPS} = W_{WPS} \times Ei_{steel} \tag{5.5}$$

$$Ei_{Transp.fuel} = D_{transport} \times Q_{lorry} \times L_{shipments} \times Ei_{diesel} \tag{5.6}$$

$$Ei_{yardwork} = Ei_{grid} \times (Q_{sheets} \times (H_{sheet} \times W_{sheet}) \times 2 \times Weld_{energy} + A_{sail} \times Cut_{energy}) \tag{5.7}$$

$$CI_{WPS} = Ci_{installation} \tag{5.8}$$

$$EI_{WPS} = Ei_{WPS} + Ei_{Transp.fuel} + Ei_{yardwork} \tag{5.9}$$

5.6 Operation

5.6.1 OM 1 - Engines

Moving on to the operational phase in the life cycle, the major inputs of this example are those that are consumed during running. For the engines, these are the production and consumption of fuel oil and lube oil, illustrated in Figure 5.5. Emission factors for the fuels are found in table 3.2, divided into well-to-tank (extraction, production and transport) and tank-to-propeller (combustion). Lube oil emissions are limited to CO_2 from production with an associated emission of 688.12 gCO_2 per kilo produced lube oil [134], at a price of €1 681 per tonne [52]. During normal operation, a small amount of lube oil is lost in each piston cycle, this is set to an average rate of 0.65 g/kWh [52], referred to as Specific Lube Oil Consumption (SLOC). It may vary and increase as piston rings wear but more importantly, the emissions from combustion of lube oil are part of the fuel emission factors tank-to-propeller in table 3.2. Fuel and lube oil costs are summarized in the red box OM 1.5 in figure 5.5.

Each equation of this module is dependent on quantities consumed. The module is perhaps best understood if read from CM 1.5 and in reverse order of the flow. In the operational profile, found in table 5.6, necessary data on required power (P_{load}), time ($T_{operation}$) and Specific Fuel Oil Consumption ($SFOC$) is listed. Together with Lower Heating Value (LHV_{fuel}) - the energy content of the fuel (table 5.11) - and the average efficiency (n) of the propulsion, fuel consumption can be determined, as seen in equation 5.10. An approximation of the SFOC for both main fuel and pilot fuel is done through equations 5.19 to 5.26 and stem from Wärtsilä's own product guides [135, 136, 137]. Lube oil consumption is determined in a similar fashion as fuel consumption, expressed in equation 5.11. Specifics of the engine layout can be seen in table 5.5, fuel prices are listed in table 5.10 and are assumed to include the cost of transport to the ship. Total operation costs ($CO_{operation}$) is expressed in equation 5.17 by summarizing equation 5.15 and 5.16. Lastly, total emissions from

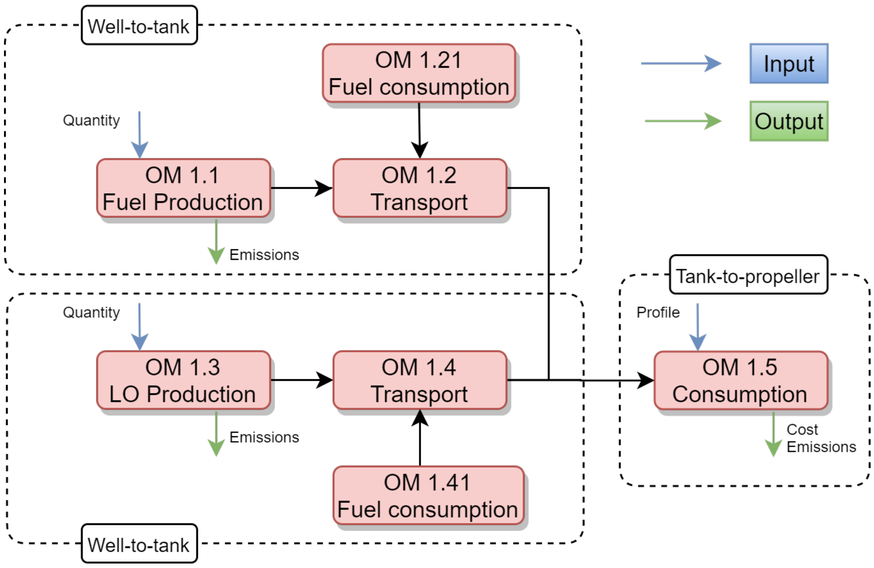

Figure 5.5: Operational Module 1 - Process flow of an engine based on the operational profile. The dashed black lines represent what is covered in well-to-tank and tank-to-propeller, respectively.

operation ($EI_{operation}$) is expressed in equation 5.18 by summarizing equation 5.12, 5.13 and 5.14.

$$Q_{fuel} = \frac{P_{load} \times T_{operation} \times SFOC}{LHV_{fuel} \times n} \tag{5.10}$$

$$Q_{lube-oil} = P_{load} \times T_{operation} \times SLOC \tag{5.11}$$

$$Ei_{fuel-production} = Q_{fuel} \times Ei_{well-to-tank} \tag{5.12}$$

$$Ei_{fuel-consumption} = Q_{fuel} \times Ei_{tank-to-propeller} \tag{5.13}$$

$$Ei_{LO-production} = Q_{lube} \times Ei_{LO-production} \tag{5.14}$$

$$Co_{fuel} = €_{fuel} \times Q_{fuel} \tag{5.15}$$

$$Co_{lube} = €_{lube-oil} \times Q_{lube-oil} \tag{5.16}$$

$$CO_{operation} = Co_{fuel} + Co_{lube} \tag{5.17}$$

$$EI_{operation} = Ei_{fuel-production} + Ei_{fuel-consumption} + Ei_{LO-production} \tag{5.18}$$

Table 5.10: Summary of fuel costs [EUR/MWh] in 2020 prices

	MGO 0,1%S	LNG	LBG		BioMeOH		Source
			Low	*High*	*Low*	*High*	
	46,2	31,9	110	170	78	-	[97] *
			11	199	33	132	[63] **
			40	120	48	112	[138] ***
Average	**46**	**32**	**54**	**163**	**53**	**122**	

** Low estimate in report for MGO and LNG*
*** Based on production costs for biogenic fuels*
**** Depending on feed stock and production method*

$$SFOC_{6L20DFMain} = 0.3364x^2 - 70.937x + 11917 \quad (5.19)$$

$$SFOC_{6L20DFPilot} = -0.0196x^2 - 0,0249x + 339.09 \quad (5.20)$$

$$SFOC_{9L20DFMain} = 0.3364x^2 - 70.937x + 11917 \quad (5.21)$$

$$SFOC_{9L20DFPilot} = -0.0196x^2 - 0.0249x + 339.09 \quad (5.22)$$

$$SFOC_{8L34DFMain} = 0.292x^2 - 64.909x + 10953 \quad (5.23)$$

$$SFOC_{8L34DFPilot} = 0.0097x^2 - 3.0786x + 284.63 \quad (5.24)$$

$$SFOC_{8L46DFMain} = 0.035x^2 - 10.204x + 8063.1 \quad (5.25)$$

$$SFOC_{8L46DFPilot} = 0.0036x^2 - 1.8151x + 218.91 \quad (5.26)$$

Table 5.11: Lower heating values of MGO, LNG/LBG and BioMeOH

Fuel	Value	Unit
MGO (pilot)	42 700	*MJ/kg*
LNG/LBG	49 600	*MJ/kg*
BioMeOH	19 700	*MJ/kg*

5.6.2 OM 2 - Wind propulsion system

Operating the WPS requires electric power. This is included in the auxiliary load and the subsequent consumption of the engines. Hence, the WPS should not be considered as emission free or not associated with any cost to operate. Rather, it is not further differentiated from the fuel and lube oil consumption in module OM 1 for generating power.

5.7 Maintenance

5.7.1 MM 1 - Engines

In a simplistic way, the maintenance cost of the engines are determined by their energy consumption. Energy consumption is again determined by the operation profile. Emissions are omitted from this module as done by Öguz et. al [139] because of impracticalities of collecting sufficient data of each spare part in combination with a negligibly small emission impact.

Nonetheless, an illustrative figure of the flow is presented in figure 5.6. Calculating the total cost of engine maintenance ($CM_{engines}$) is done through first obtaining the amount of energy consumed by multiplying fuel quantities (Q_{fuel}) with the lower heating value of the specific fuel (LHV_{fuel}) followed by multiplying it with the maintenance cost ($C_{maintenance}$) for that specific engine type (LNG/LBG or MeOH), expressed in equation 5.27. Data for the maintenance costs are found in table 5.12.

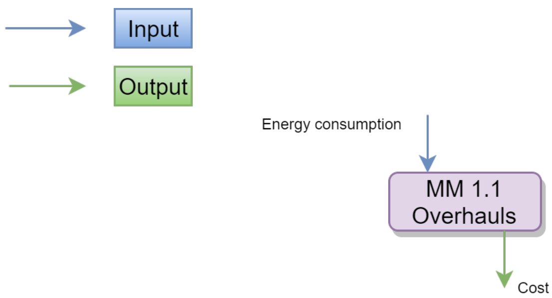

Figure 5.6: Maintenance Module 1 - Process flow of the maintenance cost of an engine as applied

$$CM_{engines} = Q_{fuel} \times LHV_{fuel} \times C_{maintenance} \tag{5.27}$$

Table 5.12: Engine maintenance costs based on energy consumption, in 2020 prices

	LNG	MeOH	Unit	Source
	5.3	-	€/MWh	[129]
	6.6	-	€/MWh	[89]
	-	4.4	€/MWh	[89]
Average	**6.0**	**4.4**		

5.7.2 MM 2 - Wind propulsion system

Maintenance cost for the WPS is based on a percentage of its installation cost. An estimation for the cost of maintenance is set to 1% based on data from Schinas & Metzger [140]. Because the WPS is a unique piece of equipment, the true maintenance cost is difficult to accurately estimate at this stage. Therefore, this cost is included in the sensitivity analysis and complemented with a high percentage of 5%. The process is illustrated in figure 5.7 and equation 5.28 represents total maintenance cost (CM_{WPS}) through input $€_{WPS}$ multiplied by percentage factor $\%_{maintenance}$.

$$CM_{WPS} = €_{WPS} \times \%_{maintenance} \tag{5.28}$$

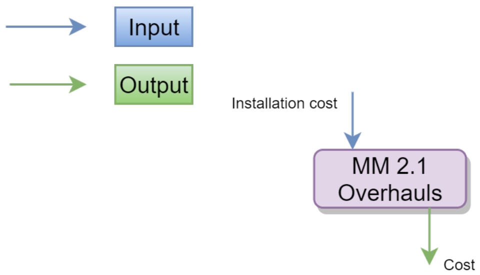

Figure 5.7: Maintenance Module 2 - Proces flow of the maintenance costs of the WPS as applied

5.8 Scrapping

5.8.1 SM 1 - Engines

Engine weight is the key factor in determining emissions and costs from scrapping, represented in figure 5.8. It is assumed that 86% of the weight is recovered [52]. This corresponds to the percentage of cast iron and steel in an engine [141], assumed to be the only recovered metal [52]. Emissions from steel recycling in India, found in table 5.7, are applied [29] with a 50% emission reduction, a method recommend by the European Commission [142] to prompt recycling of materials and reducing the need for virgin material. The bottom-up method of scaling the material composition of a smaller engine to a larger marine engine has been done previously by Oguz [139]. Total emissions from the scrapping phase of the life cycle ($ES_{engines}$) is a product of the weight of the engines ($W_{engines}$), the recoverable ratio ($R_{recovery}$), emission factors from scrapping ($Ei_{scrapping}$) and the 50% reduction, expressed in equation 5.29. Furthermore, the total income ($CS_{engines}$), expressed in equation 5.30, applies the same weight and ratio with the addition of a scrap metal price ($€_{scrap}$) of 0.0095 €/kg [52] to determine the economic benefit from selling scrap. Cast iron prices are applied, the lower of cast iron and steel. Regardless, the difference between scrap metal prices of cast iron and steel has a small impact on the overall economic outcome.

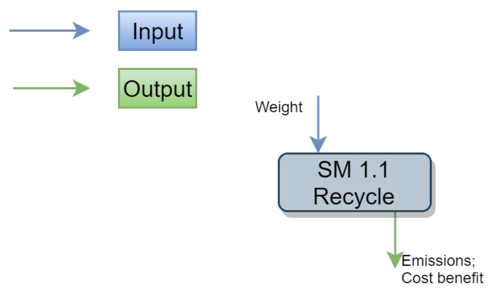

Figure 5.8: Scrapping Module 1 - Process flow of scrapping an engine as applied

$$EEOL_{engines} = W_{engines} \times R_{recovery} \times Ei_{scrapping} \times 50\% \tag{5.29}$$

$$CEOL_{engines} = W_{engines} \times R_{recovery} \times €_{scrap} \tag{5.30}$$

5.8.2 SM 2 - Wind propulsion system

The scrapping of the WPS is based on the weight of the four wing sails at 100 tonnes each. The recovery ratio of 81% is based on values used by Chatzinikolaou & Ventikos [29] where hull recovery rates for different ship types are estimated based on data from Mahindrakar et. al. [143]. According to the preceding authors [143] this value could be as low as 56% depending on the type of vessel. However, considering the screening LCA of the M/V Color Festival which uses a 95% recovery ratio [132], a high number, and also assuming that the major component of the WPS is steel sheets which are easy to recover, an 81% recovery ratio is therefore used. The emissions are accounted for in the same manner as in SM 1, by recommendation and common practice [142]. The process flow does not differ from figure 5.8 nor does the equations (5.31 and 5.32), except for the input weight being that of the WPS.

$$EEOL_{WPS} = W_{WPS} \times R_{recovery} \times Ei_{scrapping} \times 50\% \tag{5.31}$$

$$CEOL_{WPS} = W_{WPS} \times R_{recovery} \times €_{scrap} \tag{5.32}$$

5.9 Total elementary life cycle flows

Elementary flows per functional unit - 30 year of transport service with propulsion system of a car carrier - for each modelled ship and speed are presented in table 5.13.

Table 5.13: Summary of elementary flows [tonnes] at 11.4 and 8.0 knots per functional unit.

Years	Life cycle phase	CO_2		CH_4		N_2O	
wPCC (LNG)		11.4 kn	8 kn	11.4 kn	8 kn	11.4 kn	8 kn
Initial year	Construction	9.24E+02	9.24E+02	8.74E-01	8.74E-01	1.93E-02	1.93E-02
30 year period	Operation	4.23E+05	1.65E+05	4.47E+03	1.74E+03	1.20E+00	4.80E-01
30 year period	Maintenance	N/A	N/A	N/A	N/A	N/A	N/A
Final year	Scrapping	3.17E+02	3.17E+02	3.60E+01	3.60E+01	3.24E+00	3.24E+00
	Totals	4.24E+05	1.66E+05	4.51E+03	1.78E+03	4.46E+00	3.74E+00
Alternative (LBG)							
Initial year	Construction	1.06E+03	6.08E+02	1.30E+00	7.46E-01	N/A	N/A
30 year period	Operation	9.96E+05	4.05E+05	3.45E+04	1.39E+04	1.32E+01	5.40E+00
30 year period	Maintenance	N/A	N/A	N/A	N/A	N/A	N/A
Final year	Scrapping	1.20E+02	5.50E+01	1.30E+01	6.00E+00	1.22E+00	5.60E-01
	Totals	9.97E+05	4.06E+05	3.45E+04	1.39E+04	1.44E+01	5.96E+00
Alternative (Bio MeOH)							
Initial year	Construction	1.06E+03	6.08E+02	1.30E+00	7.46E-01	N/A	N/A
30 year period	Operation	6.39E+05	2.60E+05	1.53E+03	6.30E+02	9.30E+00	3.90E+00
30 year period	Maintenance	N/A	N/A	N/A	N/A	N/A	N/A
Final year	Scrapping	1.20E+02	5.50E+01	1.30E+01	6.00E+00	1.22E+00	5.60E-01
	Totals	6.40E+05	2.61E+05	1.54E+03	6.37E+02	1.05E+01	4.46E+00
Conventional (LNG)							
Initial year	Construction	1.06E+03	6.08E+02	1.30E+00	7.46E-01	N/A	N/A
30 year period	Operation	2.25E+06	9.09E+05	2.36E+04	9.54E+03	7.50E+00	3.30E+00
30 year period	Maintenance	N/A	N/A	N/A	N/A	N/A	N/A
Final year	Scrapping	1.20E+02	5.50E+01	1.30E+01	6.00E+00	1.22E+00	5.60E-01
	Totals	2.25E+06	9.10E+05	2.36E+04	9.55E+03	8.72E+00	3.86E+00

6

Impact assessment & Interpretation

6.1 Life cycle climate impact

A single impact category - climate change - is selected to assess the emission's impact on the environment. Collectively, CO_2, CH_4 and N_2O, contribute to radiative forcing by trapping heat in the atmosphere, causing an increase in global average temperature. Two characterization factors are used to determine impact, based on figures from IPCC's Assessment Report 5 on GWP for the three emission compounds. Hence, a 20-year time perspective and 100-year time perspective is presented, normalized to CO_2-equivalents.

Results from the LCA are presented in table 6.2 and 6.3 for the 11.4 knots ships and the 8.0 knots ships respectively. Together they reveal that the wPCC has the lowest amount of emissions over its life cycle when comparing CO_2eq_{100} (550 245 tonnes and 216 091 tonnes for 11.4 and 8 kn). However, in the shorter time perspective when comparing CO_2eq_{20} the wPCC is triumphed by the alternative ship using BioMeOH as a fuel (771 683 tonnes and 314 481 tonnes for BioMeOH at 11.4 and 8 kn compared to 802 110 tonnes and 315 025 tonnes for the wPCC at same average speeds). The difference in the shorter time perspective is about 4% at 11.4 knots and 0.02% at 8.0 knots compared to emitting about 20% more in the longer time perspective. Moreover, using LBG as a fuel emits between three to five times more CO_2eq than the wPCC and is only marginally better than LNG in the shorter time perspective. A significant factor to why the gaseous fuels underperform is attributed to the methane slip. Life cycle emission for all the ships at both speeds are also presented in figure 6.1, further illustrating the results.

A major reason to why the wPCC's life cycle emissions are low despite using LNG as a fuel is because it is solely propelled by its sails at least 54% of the time. This is a result of previously conducted research shared by Wallenius Marine from their preliminary performance routing. A sailing ratio of 54% may very well be probable but is dependent on what average speed is expected, or expressed in another way - at what sailing speed the engine is turned on to assist the propulsion. Part of the parametric study is to reduce the average speed to 8.0 knots, allowing the wPCC to be idle when wind conditions are unfavourable, resulting in a condition where it's waiting for weather 40% of the time, only consuming auxiliary load. This advanced case of weather routing was also met with using the propeller 6% of the time to maintain position or getting into position to be able to wait out the weather safely. Reducing the speed by some 30% reduces the average demand for power by more than 60% for the ships without sails and 70% for the wPCC. Despite the larger reduction of average power demand of the wPCC, using BioMeOH as a fuel still matches the climate impact of the wPCC in the short time perspective.

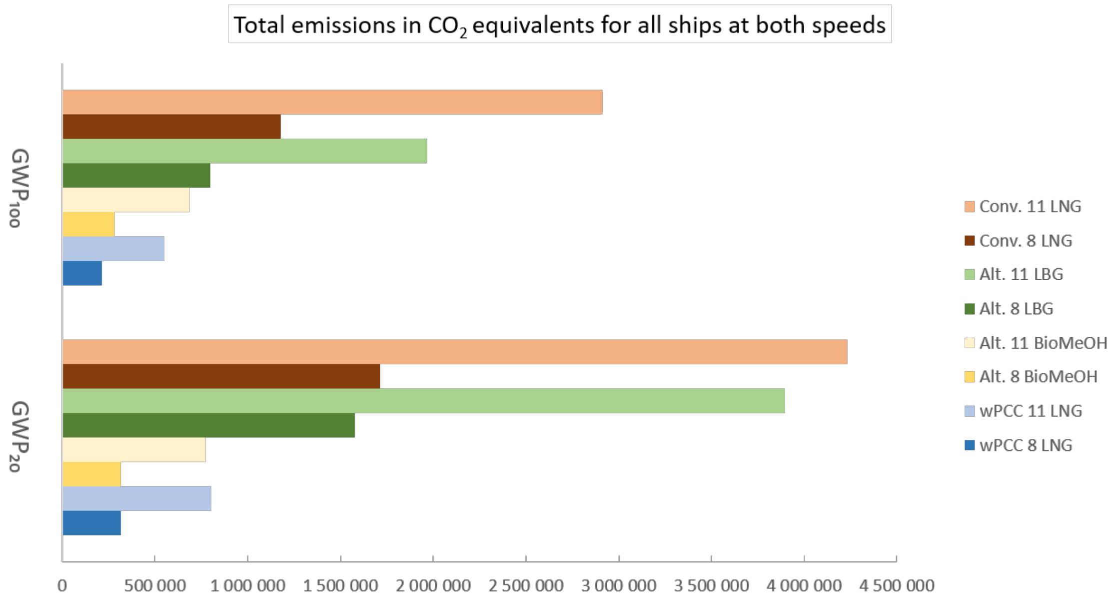

Figure 6.1: Life cycle emissions in CO_2 equivalents [tonnes] for all ships at both speeds showing the difference between measuring emissions in a short (20-years) and long (100-year) time perspective

The most dominant phase of the life cycle for all ships and speeds is during operation (table 6.2 and 6.3), accounting for more than 99% of all emissions. Proportions are largely similar in all ships but in absolute numbers the difference is significant. In table 6.1 the emissions for each part of the Operational Module (section 5.6) is listed for the non-sailing ships at 11.4 knots, displaying a clear dominance of the main fuel, making it the main driver for emissions. However, when comparing where in the fuel life cycle emissions occur, a shift up stream can be observed for the renewable fuels where a greater proportion is emitted during production (Well-to-tank) than during combustion (Tank-to-propeller), illustrated in figure 6.2. On the one hand, it cannot be stressed enough that absolute emissions from BioMeOH are by far the lowest compared to the other two fuel options. It is also notable that all emissions occurring Tank-to-propeller when using BioMeOH are those from the pilot fuel. On the other hand, the result serves as a reminder that a reduction in emissions from combustion may come with higher emissions from production as in this example.

Table 6.1: Annual life cycle emissions of the non-sailing ships at 11.4 knots

	Well-to-tank	**Tank-to-propeller**	**Total**	**Ratio**
Alternative - LBG @ 11.4 knots			CO_2eq_{20} [tonnes]	
Main fuel	49 968	78 561	128 529	99,00%
Pilot fuel	199	1 076	1 275	0,98%
Lube oil	25	-	25	0,02%
Alternative - BioMeOH @ 11.4 knots			CO_2eq_{20} [tonnes]	
Main fuel	24 371	-	24 371	94,93%
Pilot fuel	199	1 076	1 275	4,97%
Lube fuel	25	-	25	0,10%
Conventional - LNG @ 11.4 knots			CO_2eq_{20} [tonnes]	
Main fuel	13 161	126 579	139 740	99,08%
Pilot fuel	199	1 076	1 275	0,90%
Lube oil	25	-	25	0,02%

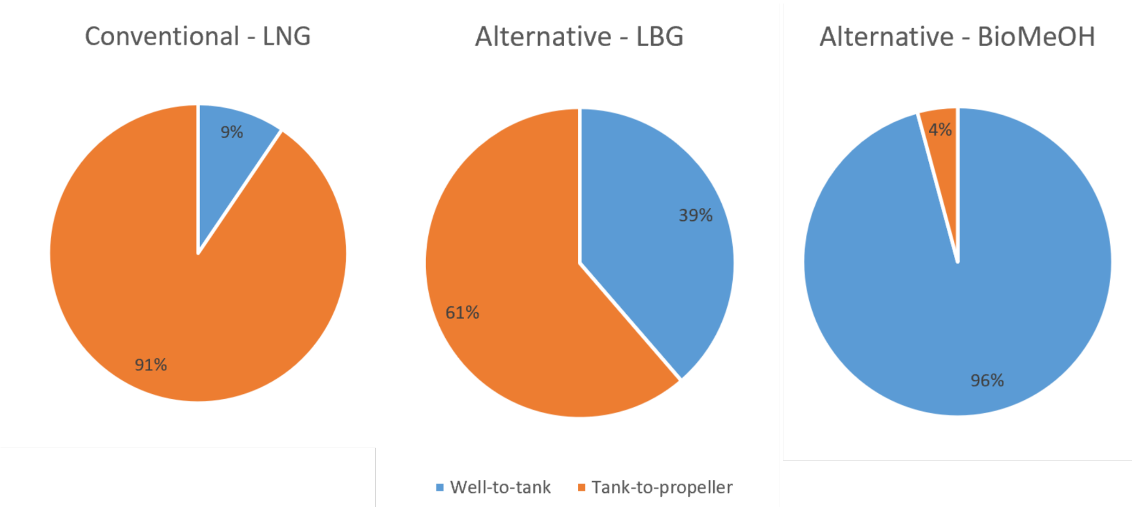

Figure 6.2: An example comparing annual well-to-propeller emission proportions (CO_2eq_{20}) for the three fuels, based on the consumption of the non-sailing ships during operation. A gradual shift to increased production emission can be seen from left to right when assessing the life cycle of the fuels.

6.1.1 LCA for 11.4 knots

When comparing the total emissions of the 11.4 knots ship presented in table 6.2, the total emissions of the wPCC is reduced five fold compared to the conventional ship, despite using the same fuel. Although the difference is attributed to a lower fuel consumption, there is still significant room for errors in the construction of the WPS attributed to its early design phase. For example, construction of the wPCC emits just less than the other non-sailing ships despite there being a significant weight difference (400 tonnes WPS compared to 158 tonnes of engines for the non-sailing 11.4 knots ships). This result is caused by how the emissions from engine construction is calculated as it includes construction, transport, testing and sea trials. Even if a similar approach would be applied based on the weight of the WPS, currently limited to construction and transport emissions, such a factor would have to amount to an increase of 1 000 for it to even come close to the conventional ship's total life cycle emissions. Finally, the heavy weight of the WPS is also the reason behind why the emissions in the scrapping phase of the wPCC is two to four times the amount of the non-sailing ship's scrapping phase.

Table 6.2: Summary of LCA 11.4 knots

Time	Life cycle phase	CO_2eq_{20} [tons]		CO_2eq_{100} [tons]	
wPCC (LNG) - 11.4 knots					
Initial year	Construction	997	0.12%	953	0.17%
30 year period	Operation	799 045	99.62%	548 210	99.63%
30 year period	Maintenance	N/A		N/A	
Final year	Scrapping	2 068	0.26%	1 082	0.20%
	Totals	802 110	100.00%	550 245	100.00%
Alternative (LBG) - 11.4 knots					
Initial year	Construction	1 169	0.03%	1096	0.06%
30 year period	Operation	3 894 890	99.95%	1963 756	99.92%
30 year period	Maintenance	N/A		N/A	
Final year	Scrapping	782	0.02%	409	0.02%
	Totals	3 896 840	100.00%	1 965 261	100.00%
Alternative (BioMeOH) - 11.4 knots					
Initial year	Construction	1 169	0.15%	1 096	0.16%
30 year period	Operation	769 732	99.75%	684 714	99.78%
30 year period	Maintenance	N/A		N/A	
Final year	Scrapping	782	0.10%	409	0.06%
	Totals	771 683	100.00%	686 218	100.00%
Conventional (LNG) - 11.4 knots					
Initial year	Construction	1 169	0.03%	1 096	0.04%
30 year period	Operation	4 231 218	99.95%	2 910 670	99.95%
30 year period	Maintenance	N/A		N/A	
Final year	Scrapping	782	0.02%	409	0.01%
	Totals	4 233 168	100.00%	2 912 174	100.00%

6.1.2 LCA for 8 knots

Presented in table 6.3 are the life cycle emissions for the ships when changing the speed from 11.4 knots to 8.0 knots, a speed reduction of 30%. Proportionality between the life cycle phases does not change to any greater extent compared to a higher speed. However, total emissions in absolute numbers are more than halved for all ships. This is a result of the correlation between speed and power and is coherent to the description presented in section 3.2. Moreover, it further strengthens the argument that fuel consumption is the main driver for emissions. Decreasing total life cycle emissions on any of the ships is still dominated by using the least carbon intensive fuel. At this speed the wPCC is only consuming 347 kW on average, of which 300 kW are designated for auxiliary load, i.e. not for propulsion. Despite this, emissions from the alternative ship using BioMeOH as a fuel is still able to match the wPCC when looking at CO_2eq_{20}.

Table 6.3: Summary of LCA 8.0 knots

Time	Life cycle phase	CO_2eq_{20} [tonnes]		CO_2eq_{100} [tonnes]	
wPCC (LNG) - 8 knots					
Initial year	Construction	997	0.32%	953	0.44%
30 year period	Operation	311 965	99.03%	214 056	99.06%
30 year period	Maintenance	N/A		N/A	
Final year	Scrapping	2068	0.66%	1082	0.50%
	Totals	315 026	100.00%	216 091	100.00%
Alternative (LBG) - 8 knots					
Initial year	Construction	671	0.04%	629	0.08%
30 year period	Operation	1 575 795	99.93%	795 531	99.90%
30 year period	Maintenance	N/A		N/A	
Final year	Scrapping	357	0.02%	187	0.02%
	Totals	1 576 819	100.00%	796 347	100.00%
Alternative (BioMeOH) - 8 knots					
Initial year	Construction	671	0.21%	629	0.22%
30 year period	Operation	313 454	99.67%	278 820	99.71%
30 year period	Maintenance	N/A		N/A	
Final year	Scrapping	357	0.11%	187	0.07%
	Totals	314 481	100.00%	279 636	100.00%
Conventional (LNG) - 8 knots					
Initial year	Construction	671	0.04%	629	0.05%
30 year period	Operation	1 711 662	99.94%	1 78 067	99.93%
30 year period	Maintenance	N/A		N/A	
Final year	Scrapping	357	0.02%	187	0.02%
	Totals	1 712 690	100.00%	1 178 883	100.00%

6.2 Life cycle cost impact

To create an overview of the economic data, three scenarios have been constructed where extremes of four ships are compared. These are summarized in table 6.4, stemming from both the sensitivity analysis and parametric study described in section 4.3.1 and section 4.3.2. A base scenario where the lowest possible cost of the wPCC is compared to the other two ships using a high cost for renewable fuel but with same slow depreciation time. The conventional ship using LNG without sails is held at a constant same fuel price as the wPCC but the depreciation follows the ships on renewable fuel. In the second scenario, the wPCC has a high construction and maintenance cost, the renewable fuel costs are high and all ships have a fast depreciation time. The third and last scenario is where the wPCC is most expensive and the other two ships have a low renewable fuel cost and a slow depreciation, mimicking the worst scenario for the wPCC but the best possible scenario for the other ships. In each scenario the annual and the total cost are presented. Total cost is interesting because it is what each ship will cost over its total life cycle. An annual cost is interesting because it represents the minimum cash-flow earnings that transport must bring in. Regardless of having a lower total cost in the end, an option resulting in a negative cash-flow is unsustainable. While income is not part of the thesis it illustrates of how different options affect the outcome. The scenarios are presented with the average speed of 11.4 knots and 8.0 knots separately. An example of the payment structure is presented in figure 6.4 where the different depreciation times are illustrated over the ships' life cycle using the highest and lowest costs of the wPCC compared to the least costly alternative without sails - LNG. An overview of the total cost of ownership at 11.4 knots and 8.0 knots can be seen in figure 6.3 and figure 6.5 respectively. The complete results are presented in tables 6.5 to 6.10 and can also be found in the appendix as whole tables (A.3, A.4 and A.5).

Table 6.4: Summary of LCC scenarios

	Base Scenario	Scenario 2	Scenario 3
wPCC - LNG			
Depreciation	Slow (25 years and 3%)	Fast (10 year and 8%)	Fast (10 year and 8%)
WPS cost	Low (8 million)	High (16 million)	High (16 million)
Fuel cost	Constant	Constant	Constant
Maintenance cost	Low (1% of purchase)	High (5% of purchase)	High (5% of purchase)
Alternative ships - LBG and BioMeOH			
Depreciation	Slow (25 years and 3%)	Fast (10 year and 8%)	Slow (25 years and 3%)
Fuel costs	High	Low	Low
Maintenance cost	Constant	Constant	Constant
Conventional ship- LNG			
Depreciation	Slow (25 years and 3%)	Fast (10 year and 8%)	Slow (25 years and 3%)
Fuel cost	Constant	Constant	Constant
Maintenance cost	Constant	Constant	Constant

6.2.1 Base scenario - 11.4 knots

The base scenario is presented in table 6.5 with the annualized total cost first and the summary of the total cost in the lower part of the table. Here, the wPCC is calculated with the lowest established cost for the WPS, an €8 000 000 initial construction cost and a 1% annual maintenance cost of the initial construction cost. Renewable fuel prices are high but all ships share the same condition for depreciation, 25 years at a rate of 3%. In the remaining five operating years of the expected 30 year life for each ship, the investment cost has been paid off and the annualized cost is reduced with the corresponding amount. It is therefore not possible to multiply the annualized total cost with the 30 operating years to calculate the total cost of ownership. Moreover, the total construction cost of the wPCC is €17 664 598, a result of adding the interest rate accumulated over the 25-year period of depreciating the WPS and the engines. While all ships except the wPCC share the same engine layout, the difference in cost among the ships is reflected by the added cost of the WPS.

Furthermore, of most significance is the operational phase, the largest cost post for all ships which is a result of the main cost driver - fuel - with prices listed in table 5.10. However, a ship without sails using the cheapest fuel (LNG) is still four times as expensive in total compared to the wPCC in this scenario. Engine maintenance is defined as €/kWh and it too contributes to the dramatically lower cost of the wPCC because of its low energy demand.

Table 6.5: Summary of LCC Base Scenario - 11.4 knots [EUR]

Time	Life cycle phase	wPCC	LBG	BioMeOH	LNG
Annualized costs base scenario - 11.4 knots					
25 years	Construction	706 584	556 967	556 967	556 967
Annually	Operation	2 088 617	53 854 693	40 370 690	10 771 659
Annually	Maintenance	453 177	1 964 924	1 452 316	1 964 924
Final year	Scrapping	-588	-272	-272	-272
Annualized total		3 247 790	56 376 312	42 379 701	13 293 278
LCC for the base scenario					
Initial year	Construction	17 664 598	13 924 175	13 924 175	13 924 175
30 year period	Operation	62 658 497	1 615 640 803	1 211 120 708	323 149 767
30 year period	Maintenance	13 595 320	58 947 721	43 569 478	58 947 721
Final year	Scrapping	-17 638	-8 163	-8 163	-8 163
Total LCC		93 900 777	1 688 504 536	1 268 614 361	396 013 500

6.2.2 Scenario 2 - 11.4 knots

In scenario 2 presented in table 6.6 the total construction cost is calculated with a faster depreciation of 10 years at a rate of 8%, a more aggressive way to pay off the loan. Hence, the annualized total cost is reduced after 10 years for all ships and only includes operation, maintenance and scrapping. The WPS has a high construction cost of €16 000 000 and a high annual maintenance cost of 5% based on the initial construction cost of the WPS. LNG and MGO prices are not varied but LBG and BioMeOH are low.

All ships except the wPCC share the same engine layout in this scenario as well but the disadvantage of the high depreciation for the wPCC is clearer, accounting for twice the annualized construction cost compared to the other ships. In this scenario, depreciation terms of the initial construction cost is the main driver for the wPCC but for the other ships, fuel and operation is still dominating. Comparing operational phases the differences are significant and the LBG is still the most expensive followed by BioMeOH and LNG (nearly half the cost of LBG). However, despite the fact that the the maintenance cost of the wPCC is set to its highest possible, it is still more favourable than the other ships. Overall, despite the wPCC being at a disadvantage, both total costs and annual costs for the wPCC are remarkably lower than for the other ships.

Table 6.6: Summary of LCC Scenario 2 - 11.4 knots [EUR]

Time	Life cycle phase	wPCC	LBG	BioMeOH	LNG
Annualized costs scenario 2 - 11.4 knots					
10 years	Construction	3 025 872	1 445 370	1 445 370	1 445 370
Annually	Operation	2 088 617	18 006 978	17 678 100	10 771 659
Annually	Maintenance	1 173 177	1 964 924	1 452 316	1 964 924
Final year	Scrapping	-588	-272	-272	-272
Annualized total		6 287 666	21 416 999	20 575 514	14 181 681
LCC for scenario 2					
Initial year	Construction	30 258 724	14 453 697	14 453 697	14 453 697
30 year period	Operation	62 658 497	540 209 331	530 342 987	323 149 767
30 year period	Maintenance	35 195 320	58 947 721	43 569 478	58 947 721
Final year	Scrapping	-17 638	-8 163	-8 163	-8 163
Total LCC		128 094 903	613 602 586	588 357 999	396 543 022

6.2.3 Scenario 3 - 11.4 knots

The following table 6.7 shows scenario 3 where the extremes are presented. The wPCC is calculated with the highest costs found and the other ships are for the lowest costs found. This means that the faster depreciation (10 year and 8%) is used for the wPCC, the highest cost of the WPS (€16 000 000) with an annual maintenance for the WPS of 5% of the initial cost of the WPS. For the other ships, the slower depreciation (25 years and 3%) is used along with the low fuel cost for LBG and BioMeOH. The application of discounted cash flow (DCF) at a rate of 3% is applied to all ships on the operation and maintenance costs, presented in the lower part of the table.

The cost in the construction phase of the wPCC is here about five times as high compared to the other ships the first ten years. Even though the depreciation terms are more beneficial for the other ships, it does not overcome the dominance of the operational phase. Regardless, the annual cost of the wPCC is half that of the LNG powered ship the first ten years and in the remaining 20 years, after the initial construction load has been paid off, the difference increases. Any ship owner who can operate an LNG powered vessel at a profit under the annual terms presented here would increase profit correspondingly. Hence, savings from reduced fuel consumption due to WPS always outperform ships without a WPS, even under the most unfavourable terms.

In lower section of table 6.7 discounted cash flow is applied to operation and maintenance phases at a rate of 3% and a reduction of the total cost for all ships can be seen. In this scenario the total cost of the wPCC is reduced by a total of 27% where as the other ships' total cost is reduced by about 34%. The decrease in cost is higher for the ships without sails because they have larger expenses occurring in the future compared to the wPCC. The technique is widely applied in capital budgeting and the higher the discount rate the larger the difference in total cost becomes. It may therefore be advisable to use this financial technique with caution when interpreting the results over long time lines and where large amounts are at stake because there is a risk that the calculation becomes overly optimistic or vice versa. Despite the fact that the wPCC is operating under its most unfavourable terms and that a higher initial investment costs tend to be disadvantageous compared to lower initial costs and higher future operating costs when using this method, the total cost of the wPCC is still lower than for any other ship. The ship using LNG is the second best option and is more than twice as expensive although down from more than three times as expensive when not applying discounted cash flow.

Table 6.7: Summary of LCC Scenario 3 - 11.4 knots [EUR]

Time	Life cycle phase	wPCC	LBG	BioMeOH	LNG
Annualized cost scenario 3 - 11.4 knots					
10 & 25 years	Construction	3 025 872	556 967	556 967	556 967
Annually	Operation	2 088 617	18 006 978	17 678 100	10 771 659
Annually	Maintenance	1 173 177	1 964 924	1 452 316	1 964 924
Final year	Scrapping	-588	-272	-272	-272
Annualized total		6 287 666	20 528 597	19 687 111	13 293 278
LCC for scenario 3					
Initial year	Construction	30 258 724	13 924 175	13 924 175	13 924 175
30 year period	Operation	62 658 497	540 209 331	530 342 987	323 149 767
30 year period	Maintenance	35 195 320	58 947 721	43 569 478	58 947 721
Final year	Scrapping	-17 638	-8 163	-8 163	-8 163
Total		128 094 903	613 073 063	587 828 477	396 013 500
LCC for scenario 3 applying discounted cash flow on operation and maintenance					
Initial year	Construction	30 258 724	13 924 175	13 924 175	13 924 175
30 year period	Operation	40 937 806	352 944 710	346 498 554	211 129 269
30 year period	Maintenance	22 994 794	38 513 378	28 466 033	38 513 378
Final year	Scrapping	-17 638	-8 163	-8 163	-8 163
Total		94 173 687	405 374 100	388 880 598	263 558 659

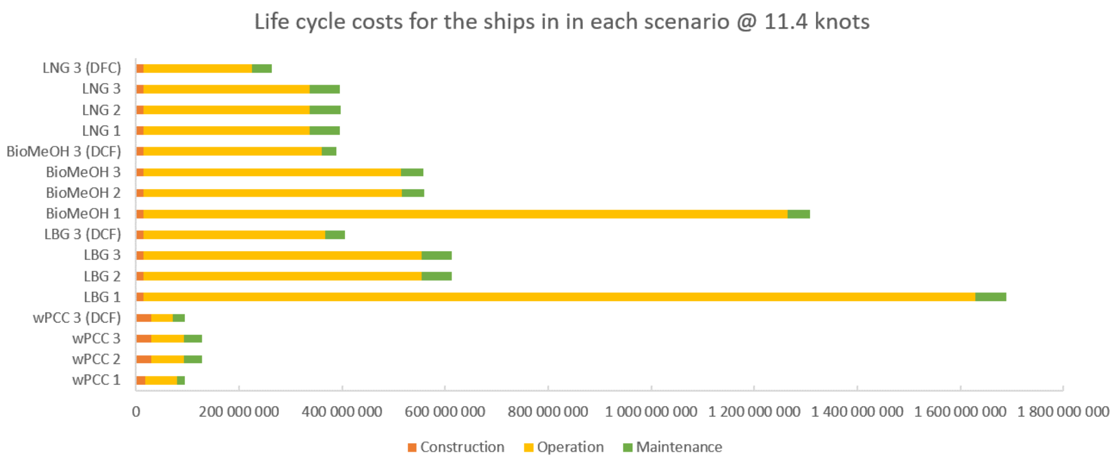

Figure 6.3: Total life cycle costs [EUR] for all the ships in each scenario at 11.4 knots, including when DCF has been applied.

6.2.4 Base scenario - 8.0 knots

The base scenario presented in table 6.8 is different from the same scenario in table 6.5 because engine layout is optimized for 8.0 knots instead of 11.4 knots. Since the wPCC is modelled to be idle when no favourable wind is present, only its smaller engine is running during that time. The other ships' engines are also optimized for the lower speed and are therefore also smaller, resulting in a significantly lower construction cost. Regarding the operation phase, the cost connected to the wPCC is still significantly lower compared to the other ships. The cost driver for the wPCC is the operation phase but the margin to the construction phase is not as large as it is for the other ships. However, this margin is larger in the 11.4 knot base scenario in table 6.5 for the wPCC. The annualized total is still considerably higher for all the ships compared to the wPCC. As for the total costs, the differences are similar to the annualized total where the operational phase is dominant for all ships but where the wPCC maintains the lowest cost.

Table 6.8: Summary of LCC Base Scenario - 8.0 knots [EUR]

Time	Life cycle phase	wPCC	LBG	BioMeOH	LNG
Annualized costs base scenario - 8 knots					
25 years	Construction	706 584	319 516	319 516	319 516
Annually	Operation	818 603	21 767 511	16 320 210	4 362 720
Annually	Maintenance	225 623	793 795	586 710	793 795
Final year	Scrapping	-588	-124	-124	-124
Annualized total		1 750 222	22 880 698	17 226 312	5 475 907
LCC Totals					
Initial year	Construction	17 664 598	7 987 906	7 987 906	7 987 906
30 year period	Operation	24 558 087	653 025 335	489 606 301	130 881 592
30 year period	Maintenance	6 768 704	23 813 847	17 601 306	23 813 847
Final year	Scrapping	-17 638	-3 726	-3 726	-3 726
Total		48 973 751	684 823 363	515 191 782	162 679 619

6.2.5 Scenario 2 - 8.0 knots

In scenario 2 presented in table 6.9 the ships have the same fast depreciation rate, renewable fuel costs are favourable but the WPS comes at a high initial investment and high annual maintenance cost. Here it is clear that the shift in depreciation makes the construction phase dominant for the wPCC while the operation phase remain dominant for the other ships. Despite making the WPS this costly, it still has the lowest annualized cost and total cost. For the first time the maintenance cost of the wPCC surpasses the other ships' and the cost of the construction is the largest total cost. Furthermore, the wPCC's previous overall large cost margin to all other ships is greatly reduced. On the one hand, it should be kept in mind that all ships are fully depreciated after 10 years and after that the annual cost of construction is disregarded. On the other hand, the same observation will again make the wPCC's annual cost much more beneficial as the majority of annualized costs lies in the construction phase.

Table 6.9: Summary of LCC Scenario 2 - 8.0 knots [EUR]

Time	Life cycle phase	wPCC	LBG	BioMeOH	LNG
Annualized costs scenario 2 - 8 knots					
10 years	Construction	3 025 872	829 168	829 168	829 168
Annually	Operation	818 603	7 285 662	7 152 801	4 362 720
Annually	Maintenance	945 623	793 795	586 710	793 795
Final year	Scrapping	-588	-124	-124	-124
Annualized total		4 789 511	8 908 500	8 568 555	5 985 558
LCC Totals					
Initial year	Construction	30 258 724	8 291 678	8 291 678	8 291 678
30 year period	Operation	24 558 087	218 569 854	214 584 024	130 881 592
30 year period	Maintenance	28 368 704	23 813 847	17 601 306	23 813 847
Final year	Scrapping	-17 638	-3 726	-3 726	-3 726
Total		83 167 877	250 671 653	240 473 282	162 983 391

6.2.6 Scenario 3 - 8.0 knots

Table 6.10 shows scenario 3 where the extremes are presented for all ships at 8.0 knots. Comparably, in scenario 3 for 11.4 knots, the construction phase of the annualized costs of the wPCC were 5 times higher than the other ships. This number has increased and is now roughly 10 times higher for the wPCC and is clearly the cost driver for the first ten years. The large difference is attributed to the reduced engine size where the cost of the engines are based on €/kW installed. While the wPCC too has a lower demand for power due to the reduced speed, its engine layout doesn't change. However, fuel consumption for all ships without sails are still the main cost driver and are between 5 and 9 times higher than the wPCC. Regarding total costs, the wPCC still has the lowest cost and that the second cheapest option is still twice as expensive although matching the wPCC's annual costs closely. Regardless, it should be borne in mind that the wPCC will be fully repaid after 10 years and thereafter the spread will again increase.

When applying discounted cash flow to this scenario there is a reduction similar to the reduction for scenario 3 at 11.4 knots. Naturally, the reduction is larger for the ships without sails because they have higher operating and maintenance costs occurring in the future.

Table 6.10: Summary of LCC Scenario 3 - 8.0 knots [EUR]

Time	Life cycle phase	wPCC	LBG	BioMeOH	LNG
Annualized cost scenario 3 - 8.0 knots					
10 & 25 years	Construction	3 025 872	319 516	319 516	319 516
Annually	Operation	818 603	7 285 662	7 152 801	4 362 720
Annually	Maintenance	945 623	793 795	586 710	793 795
Final year	Scrapping	-588	-588	-124	-124
Annualized total		4 789 511	8 398 849	8 058 903	5 475 907
LCC Totals					
Initial year	Construction	30 258 724	7 987 906	7 987 906	7 987 906
30 year period	Operation	24 558 087	218 569 854	214 584 024	130 881 592
30 year period	Maintenance	28 368 704	23 813 847	17 601 306	23 813 847
Final year	Scrapping	-17 638	-3 726	-3 726	-3 726
Total		83 167 877	250 367 881	240 169 510	162 679 619
LCC Totals applying discounted cash flow on operation and maintenance					
Initial year	Construction	30 258 724	7 987 906	7 987 906	7 987 906
30 year period	Operation	16 044 978	142 802 187	140 198 052	85 511 232
30 year period	Maintenance	18 534 637	15 558 730	11 499 779	15 558 730
Final year	Scrapping	-17 638	-3 726	-3 726	-3 726
Total		64 820 701	166 347 288	159 682 012	109 054 143

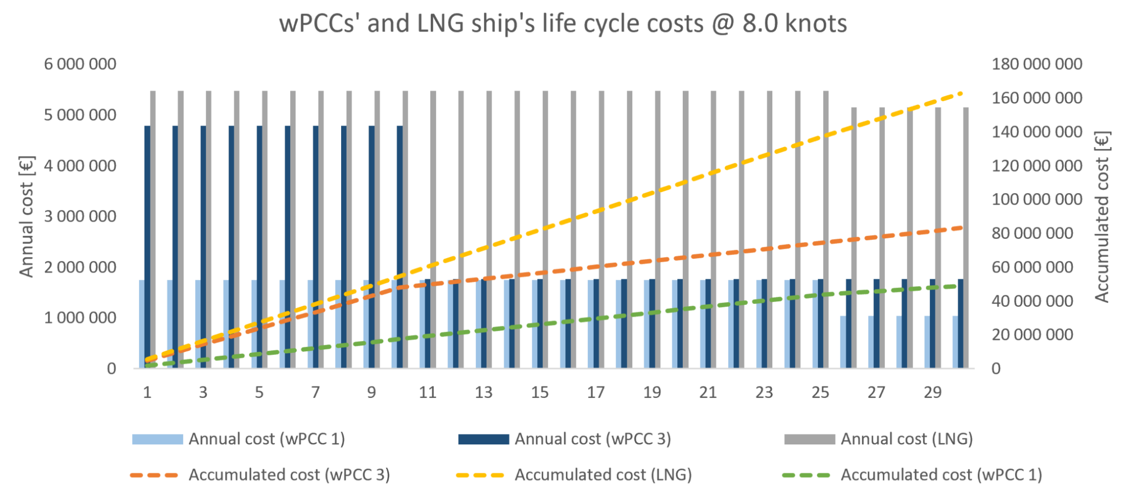

Figure 6.4: The payment structure of different depreciation times, comparing the highest and the lowest costs of the wPCC with the least costly ship without sails (LNG scenario 3 without DCF) at 8.0 knots. Plotting both annual costs (left axis) and accumulated costs (right axis) over their 30-year life cycle, a decrease of the annual cost can be seen in either year 10 or year 25.

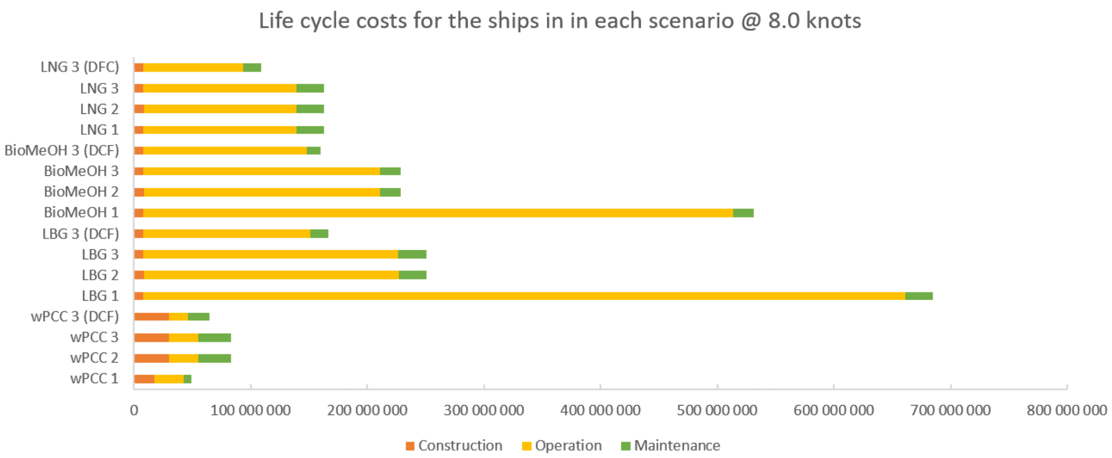

Figure 6.5: Total life cycle costs [EUR] for all the ships in each scenario at 8.0 knots, including scenario 3 when DCF has been applied.

6.3 Abatement cost

A distribution of the environmental and economic data is presented in figures 6.6 and 6.7, for 8.0 knots and 11.4 knots respectively. Only the base scenario and the third scenario have been plotted for the ships, representing the spread between the highest and lowest economic values (horizontally) and the spread between CO_2eq_{20} and CO_2eq_{100} emissions (laterally). As a reference and baseline, the base scenario for the conventional ship using LNG is also plotted at its lowest total cost. The most attractive location in the figures is in the lower left quadrant, where both costs and emissions are minimized yet retaining the same performance. This is quadrant where the wPCC is located. Differences in proportions of both emissions and costs between the ships are largely similar when comparing the two speeds, they do however vary in absolute numbers where the faster ships have higher total costs and higher total emissions. It further illustrates the dominance of fuel choice as both the main emissions driver and main cost driver over the life cycle.

The spread in cost and emissions have a large impact on the abatement cost, presented in table 6.11. Applying the ship without sails using LNG as the baseline to calculate the cost of avoiding emissions (equation 3.9), the wPCC exhibits a negative abatement cost for all its cases (from EUR -128 to -57 per averted tonne CO_2eq).

Table 6.11: Summary of high and low abatement costs using the least costly conventional LNG ship as a baseline without applying DCF.

Case	**€/CO_2eq_{20}**		**€/CO_2eq_{100}**	
	8.0 knots	11.4 knots	8.0 knots	11.4 knots
wPCC 1	-81	-88	-118	-128
wPCC 3	-57	-78	-83	-113
Alt. LBG 1	3 843	3 843	1 365	1 365
Alt. LBG 3	645	645	229	229
Alt. BioMeOH 1	252	252	392	392
Alt. BioMeOH 3	55	55	86	86

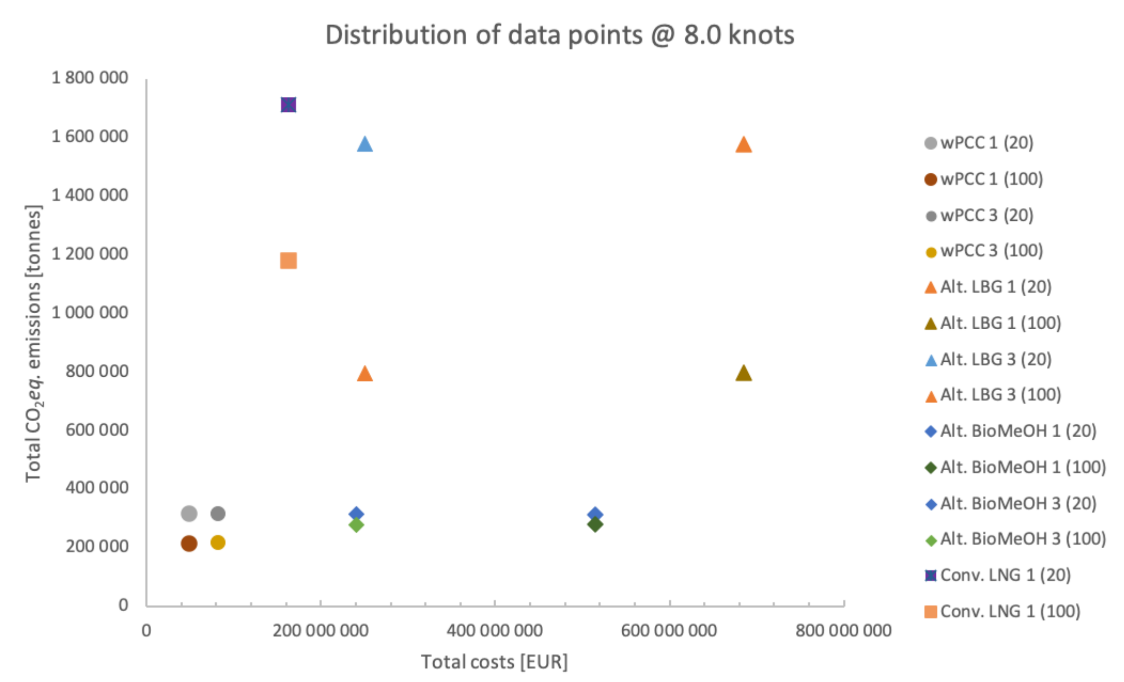

Figure 6.6: Distribution of LCA and LCC data points for the 8.0 knots ships

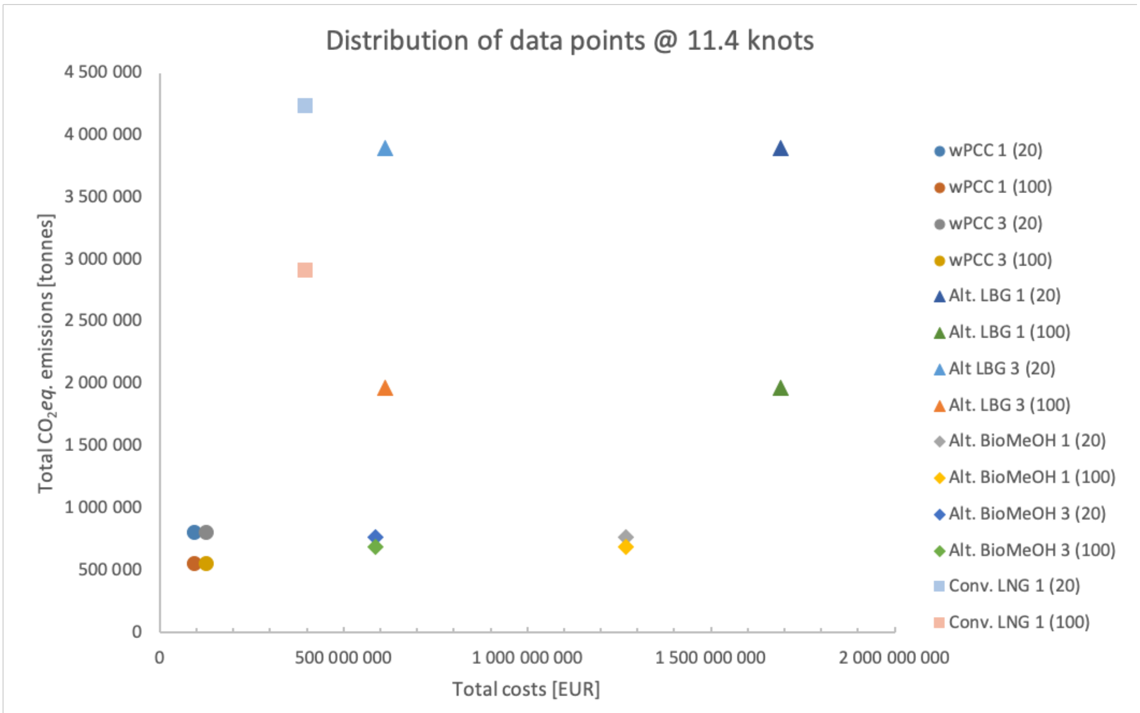

Figure 6.7: Distribution of LCA and LCC data points for the 11.4 knots ships

7

Discussion

7.1 Climate impact

A screening LCA have been done in this thesis meaning that the results are best suited for internal communication, sharing between businesses or for early decision-making. Early results of this kind are suitable for highlighting the phases of the life cycle requiring more attention and inventory flows where more information is needed or to identify areas easy to improve. The results presented are an outline of the assessed options and their key differences, based on a model which can be adjusted and complemented as more detailed data emerges.

The functional unit is an essential part of an LCA as it defines the outcome of the LCA because all inventory flows are calculated in relation to this. In this thesis it is defined as 30 year of transport service with the propulsion system of a car carrier. The choice of functional unit is connected to the early design phase of the wPCC where design speed, cargo capacity and final design of the WPS support structure is not completed. A different approach would have been to use cargo capacity and adjust it to match the extra space a WPS or any other propulsion option is likely to occupy and thereby relate all flows to transport work (tonne-mile). The approach is used by Brynolf et al. [144] to compare marine fuels, applying the functional unit of 1 tonne of cargo transported 1 kilometer with a ro-ro vessel. Transport work makes it possible to compare different modes of transport and base a decision on how much resources are used per transported unit, in other words, efficiency. Comparably, transport service offers information on moving goods from one place or another without explicitly stating how efficiently the work was carried out. While the parameters to calculate transport work can be estimated for the wPCC, they stem from preliminary data of an early design stage and the resulting figure would include a large portion of uncertainty. There is a large risk that the output would not represent the final product because of the added assumptions. Hence, transport service is selected as the appropriate functional unit to facilitate decision making and set direction rather than settling details, corresponding with the intention of a screening.

By assessing each phase in a life cycle the applied method makes it possible to identify where the largest impact is found. Each life cycle phase can broken down further to find critical factors and highlight areas of potential improvement, a point which is made by Brynolf [5]. This is recognised in this thesis, where the operational phase and choice of fuel holds the largest climate impact, mirrored in previously presented work by Magerholm & Johnsen and Chatzinikolaou & Ventikos [132, 29]. Among the results of Magerholm & Johnsen, there are processes and phases in the life cycle that are more important than others but with consideration to different impact categories than climate change. Their work establish that the impact categories human toxicology and acidification is where the assessed ship M/V Color Festival has the largest impact, which are not among the impact categories investigated in this thesis. Had this thesis included more impact categories, it is unlikely that it would alter the dominance of the operational phase and fuel choice given that the scope is limited to the propulsion system only. Rather, an addition would highlight more critical factors and areas which can be improved based on the choices made in the scope.

It is always the case that data collection can be improved and more accurate figures used. During the work with the thesis it has been challenging to make a representative picture of the complete life cycle. Regarding the completeness of the impact assessment the only evaluated gases have been CO_2, CH_4 and N_2O, no other GHGs have been accounted for. While there are other GHGs present in shipping, they are mostly unrelated to combustion. An addition of halogenated hydrocarbons may bear a significance to a ship using large amounts of refrigerants but not to a car carrier where cargo does not have to be cooled.

Regarding the construction phase, due to the early design stage the level of details of the WPS are significantly blurry. As previously described in section 5.5.2 the WPS consists of 400 tonnes steel and the emissions connected to this. A potential improvement to the detail could be made by adding masts, dedicated hydraulic components, including hydraulic oil and electrical consumption to power the hydraulic system, as applicable to all life cycle phases. Figure 5.3 on page 47 represents a more ideal level of detail. A consequence of the current way of calculating the emissions is, other than the large uncertainty, that the current method may be considered as a low estimate. Although the masts and hydraulics are unaccounted for, it seems unlikely that such an addition can be compared to the life cycle emissions of the conventional LNG ship emitting more than five times as much in total.

Furthermore, the construction phase of the engines includes engine testing, transport, installation emissions and sea trials. A similar approach has not been integrated in the WPS construction. It is reasonable to believe that there are long sea trials involved with commissioning of the wPCC where at least a similar amount of fuel is used (also in the installation). The data used for the engines are however based in installed power (kW) and are not easily translated for installation of fixed wings (based on weight). This itself probably has a low significance as the operational phases for the ships without sails are considerably larger but it does make the comparison between wPCC and the ships without sails unfair in this regard.

Moving on to the operational phase, when regional environmental aspects of fuel emissions are considered it must be mentioned that the emissions from fuels may vary depending on starting point of the raw material extraction [144, 8]. The fuel emissions data used for the LNG is based on fuel distributed from Norway which gives 5% lower GHG emissions than if it were distributed from Qatar according to the work of Brynolf[5]. In the aforementioned dissertation by Brynolf, LBG from both willow (LBG_w) and waste residues from agriculture waste, manure and organic municipal waste are listed (LBG_{ar})[5]. This thesis is using LBG_w because it represents the second generation of biofuels by applying the gasification route using a wood feedstock. The choice is based on this process being similar to the use of forest residues not suitable for timber production nor the paper pulp industry. To upgrade the biogas and remove impurities a cryogenic technology is applied in in the model presented in the aforementioned dissertation. The resulting product is modelled to be 100% pure CH_4 which is reflected as higher methane slip compared to a lower purity gas of say 95% methane, where the remaining part is otherwise made up of other hydrocarbons present in natural gas. If carefully studying the complete elementary flow in the same dissertation, this is reflected in the emission factors of LNG compared to LBG by the presence of other hydrocarbons in the emissions [5]. While the use of dedicated energy crops, such as short rotation energy forest, may not be the future of biofuels given EU directive 2015/1513, it still serves as a benchmark for using wood. When the gasification route is used to produce methanol from wood, emissions are however considerably higher than using black liquor as a feed stock, citing data from JRC's Well-to-wheel study [145], leaving ample room for future improvements in renewable methanol production.

The thesis investigates the climate impact of using a wind propulsion system under the circumstances specified in section 4.3. It would have been appropriate and beneficial for the thesis to conduct a sensitivity analysis by varying emissions similar to what is done extensively on the financial part. More precisely, emissions occurring in the fuels' life cycle could have been varied to test how methane slip contribute to the overall emissions. As methane is a large contributor of the investigated GHGs the outcome of a lower or higher emissions factor would show how it would effect the end result. This is an error in this thesis which results in reducing the reliability of the results. The data which is used for OM1 is sourced from Brynolf [5] with the main issues listed below:

- Data from Northern Europe or Europe is used regarding raw material acquisition and fuel production. A ship may bunker in other ports where the fuel price is more beneficial, affecting the emission factors.
- The limited sources regarding bio fuels have issues with discrepancy between assessments of the same fuel. This is a result of the current biofuels production mainly occurs on pilot scale.
- Combustion data is as far as possible gathered from actual measurements but as secondary data due to the scope of work. If this was not possible the data was estimated based on discussions with industry representatives or from studies of road transportation or both.
- Methane slip from gas and dual fuel engines has significant effect on the climate impact (LNG and LBG). In the data used the methane slip for LNG is modelled at 3.3 wt.% of which 0.2 wt.% comes from well to tank. Regarding LBG the methane slip is modelled at a total of 4.8 wt.% of which 0.9 wt.% comes from well to tank. Both are presented in table 3.2.

Furthermore, in the operation phase module OM 1.3, lube oil production does not include CH_4 and N_2O. Also, the data is accounted for from cradle to gate, excluding transport to the ship. It is however considered that these emissions are so small that the effect of omitting these are minimal.

It should also be stressed that the climate impact of the maintenance phase has not been accounted for. As described in section 5.7.1 on page 52 the emissions are omitted based on the same assumption made by Öguz et. al [139] who assumes a negligible small GHG emission impact of the maintenance phase. According to Magerholm & Johnsen [132], maintenance emissions of most interest are noise pollution and discharges to water, e.g. from paint effluent, oil spills and heavy metals. All of which are related to impact categories not covered in this thesis. The result of the method currently applied is that comparisons are only made based on construction, operation and scrapping. A potential improvement that could be made to strengthen the results given the impact categories used in this thesis is by adding details of spare parts through access to more data from engine parts producers. However, because the same method is applied identically to all ships a difference would be found in the wPCC because of the addition of the WPS. A similar addition about the necessary maintenance and overhauls to the WPS, a component which is still being developed, would also create a more accurate estimate albeit with a small overall difference.

Regarding the scrapping phase the allocation of scrapping emissions can be mentioned. The method used here is recommended by the European Commission [142] which allocates a 50% benefit of the recycled material to the current product and 50% to the new product. This method is also used and supported in the work by Chatzinikolaou & Ventikos [29] and Magerholm & Johnsen [132]. There are other methods of allocating scrapping emission namely 0:100 approach - end-of-life recycling and 100:0 approach - avoided burden or recycled content [146, 147]. These methods have both advantages and disadvantages [147]. It is understood that the 50:50 method goes half way between the two methods [148] and is supported in the Commission's recommendation. Regardless of choice, the scrapping phase represents a maximum 0.2% of the total GHG emissions which means any choice of method has a small impact.

A regional environmental aspect to consider regarding the scrapping is that it is selected to be done in India which is one of the largest ship scrapping nations in the world. This selection is also used by Chatzinikolaou & Ventikos [29] and is assumed to be representative of a possible scenario today. This may not be the case in the future due to actions like the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (Hong Kong Convention) established by IMO which is designed to put an end to dangerous scrapping practices in South Asia [9]. The Hong Kong convention is not yet mandatory but covers life phases of a ship and preparedness of it as to facilitate safe and environmentally sound recycling [149]. Emissions from scrapping activities makes up for less than 0.5% of the investigated ships' life cycle emissions and consequently it is a small source of uncertainty.

7.1.1 Environmental results discussion

The benefit of WPS allows the wPCC to reduce fuel consumption by 80% when modelled in voyages crossing the North Atlantic. Fuel consumption is interesting from an environmental perspective because it is the main driver of emissions. A previous screening of wind technologies is presented in table 3.4 on page 31 where a simulation by Traut et al. [111] exhibits the highest fuel savings from wind technologies of up to 50%. They achieve their result by allowing a general cargo ship of 5 500 DWT fitted with three Flettner rotors to transit at 8.8 knots from the Swedish west coast to the British east coast, using historical weather statistics as input. However, the authors acknowledges that the ship is using traditional shipping routes and if it were allowed to deviate and maximize wind conditions the results would have been more favourable. Comparably, the wPCC is purpose built to use wind and able to use a route where the WPS can be maximized while maintaining an average speed in approximately the same range, indicating the potential fuel savings may be higher for individual ships and routes.

Under the conditions presented the wPCC exceed Wallenius' goal of a transport concept able to meet IMO's annual GHG reduction target of at least 50% by 2050 [125]. It is even possible to achieve the reduction with a fossil fuel because of the significantly lowered fuel consumption. The result is somewhat contradicting the conclusion of Balcombe et al. [16] who's stating that wind technology in combination with LNG or LBG must be combined with several more measures (including slow steaming) to reach IMO's goal. Their results are modelled on global fleet where renewables, which includes wind power, may offer up to 32% of carbon reduction. As indicated in this thesis, wind power may offer much larger savings on individual ships and routes. Nonetheless, their results also point toward BioMeOH and other Bio-liquids (e.g. straight vegetable oil, hydrotreated vegetable oil, fatty acid methylester) as having a 100% likelihood of achieving a 50% reduction of GHG emissions. However, only BioMeOH in combination with three other measures can meet an 80% reduction in GHG emissions with a 100% likelihood. The speeds investigated in this thesis may be regarded as slow steaming and in combination with BioMeOH plus a a more efficient hull design the reduction in carbon emissions is around the 80% mark, close to the estimation of the aforementioned study.

In the sensitivity analysis there is a focus on the financial variables while no environmental variables are subject to variation. Although the engine layout is optimised for the average speeds in the parametric study, and therefore environmental impact variables like fuel consumption is changed, this cannot be exchanged for a sensitivity analysis on the emission factors used as input in the model. The input data used for calculating the environmental impact of the operational phase is based upon one study by Brynolf [5]. The consequence of this is that it is not determined how a variation in emission data affects the overall impact on GWP. Because the operational phase is the largest contributor of GHGs for all ships (see table 5.13, page 55) in the thesis it would have been an appropriate element to conduct a sensitivity analysis on. Time constraint is the main reason for this deficiency. A future study where more iterations and data is used would solidify the climate impact of the fuel choice.

7.2 Financial impact

The financial concept *Total cost of ownership*, TCO, or *Total ownership cost*, TOC, is closely related to LCC and may even be interchangeable as it is used here. While TOC is mainly used in the private sector and looks at the part of the cost that burdens the organisation, LCC is used more frequently in the public sector and can be used to quantify the costs that are closely related but outside the organisation [150].

An LCC is similar to an LCA because both are based on a holistic perspective. It is limited by the scope and the results should be weighed against how well it corresponds to those limitations. In this thesis the LCC best reflects the perspective of a ship owner investing in an available technology. While an LCC may include more than what it is covered here, for example costs for development and sea trials, the results should reflect those added parts. Therefore an LCC of the same product may have different outcomes depending on the goal and scope. A similar scope on life cycle costs as in this thesis is applied by Jeong et al. [52] with the difference that the time value of money is not included and that maintenance costs are calculated differently. Similarly to this thesis the operational costs is the dominating part in the ships' life cycle. More importantly, Evangelou et al. [151] highlights that the required data to perform an LCC may be limited and hard to acquire cheaply when there is a limited amount of time and reliable calculations are a priority. Ultimately, there may exist a difference in LCCs but the over all result should still be in the same order of magnitude if similar limitation has been applied.

Adding four 80 metre masts will call for structural reinforcements diminishing cargo capacity to some extent compared to a conventional ship. Compared to wind assisting technologies which can be retrofitted with a minimum of lost cargo space such as kites, Flettner rotors and smaller sails, the assumption made that all ships in this thesis have equal cargo capacity can be questioned. As mentioned previously in section 7.1, with a known cargo capacity adjusted for the propulsion option for each ship it would be possible to evaluate the efficiency of the transport mode of choice. Although the aforementioned section relates to the environmental aspect the issue is similar in the financial aspect adding to the uncertainty. Similarly the result is aimed to set direction rather than detail.

Today there exists large two-stroke methanol engines, retrofitted medium speed four-stroke engines and even a conversion of a smaller high speed four-stroke engine in a pilot boat [152]. A price indication for methanol engines was found in a report by Ellis & Tanneberger [89] where an LNG powered engine including surrounding equipment is almost 50% more expensive than a methanol powered dito (see table 5.8 on page 46). Hence, the construction cost of the ship powered by methanol in this thesis could be regarded as an estimated high cost because it is assumed to be equal to the LNG engines.

In the operational phase, fuel price has a large influence on the outcome of the LCC and is difficult to estimate, therefore it is subject to the sensitivity analysis. Prices of fossil fuels can be establish using historical data, as done by Winnes et al. [97], because they are sold in large quantities world wide or even traded as commodities. In general, renewable fuels does not have the same transparency, hence production costs are used in this thesis to establish their respective cost. The two sources for production costs is a compilation of biogenic fuels found in literature between 2010 and 2016 [63] and a recent study of current production costs in 2020 [138]. An average of low and high costs of the renewable fuels are calculated and used in the sensitivity analysis. A consequence of the low price estimate may be that the renewable fuel prices are optimistically calculated because it doesn't cover the cost of distribution.

A data gap possible to consider in the operation phase is that no costs have been added for personnel training to operate the WPS. When a new technology emerges it cannot be ruled out that there are additional costs in training personnel to handle the technology safely and efficiently. This has not been accounted for in the modelled LCC. Although personnel training is not included in the cost of other ships, it is fair to mention that a WPS deviates significantly from a normal propulsion layout and will require additional training.

The maintenance costs for the ships without sails are solely based on the energy consumption of the engines as described in section 5.7 on page 52. This is a top down approach. However, with a bottom up approach of collecting data for each spare part and when it is scheduled for replacement or overhaul, more detail could have been applied to the model. This affect the wPCC to a lesser degree because the cost of the WPS is accounted for as a percentage of the installation cost. Nonetheless, the maintenance cost of the WPS does not relate to the usage of the system in the same way energy consumption does for the engines. This difference in calculating the maintenance cost is unavoidable but still seems fair to use. Another point is that the maintenance cost could benefit with the application of a factor to increase costs to account for ageing of equipment during its life cycle for all ships.

Most ships' life cycle ends with scrapping and this phase has the lowest impact on the life cycle cost and is nearly negligible. Data is sourced from only one place, stemming from current scrap prices in Europe while the ships are modelled to be recycled in India. Hence, the income from scrapping is most likely high but the overall impact from scrap sales does not make much difference.

Discounted cash flow is applied in scenario 3 (table 6.7 and 6.10 on pages 65 and 68) to compare present values at a discount rate of 3%. The selection can be seen from a business perspective as low rate. It is however matching recommendations in the ISO and EN standard which ranges from no application (0%) to 4%. In the work of Jeong et al. DCF is not applied and only compares nominal costs [52].Comparably, Schwartz et al. [69] applies a rate of 4% and Eide et al. [68] applies a rate of 5%. A tendency that can be observed in this thesis is that the option with high investment cost and low future cost is benefited less than the alternatives with low investment cost and future high cost.

Furthermore, it may be worth mentioning what it means to change the borrowing cost and depreciation time as this is varied in the scenarios. Depending on what perspective is chosen regarding the investment cost - societal or private - the outcome is different. In a societal perspective risks are viewed in a longer time perspective while the opposite applies for a private perspective. This implies that a lower rate of interest for borrowing money may be applied over a longer investment lifetime (normally equal to the assets lifetime) and can be used to calculate the annual cost of investment for societal investments. For private investors decisions are mainly driven by economic benefits and risks may be viewed in a much shorter perspective. The rate of interest used to reflect a private investment in this thesis is 8% which is close to 7.5% used in the work by Yaramenka et al. [62]. The societal rate of interest used is 3% and similar to 4% used in the aforementioned work. It can be added that the purpose of the slight adjustment of these interest rates is to increase the difference of the results, making the societal and private perspective more clear but not unreasonable. As for the chosen depreciation time of 25 years which is shorter than the 30 year life cycle it is motivated by completing the investment well before it is time for its disposal. As for the 10 year private depreciation time it is in line with the aforementioned work by Yaramenka et al.

7.2.1 Financial results discussion

The addition of a WPS makes the initial investment cost for the wPCC higher in all scenarios. Regardless, the annual cost of the wPCC is lower because there is a reduction in fuel consumption combined with the investment being depreciated over time.

Consequences of the early design phase has a significant influence in the wPCC's construction and maintenance costs and little is known or can be confirmed at this time, hence best estimates are applied to preliminary data. The addition of a WPS is the primary difference between the wPCC and the other ships, accounting for twice the total construction cost of the wPCC compared to the other ships.

In the construction phase of the WPS, the cost used is the upper limit indicated by Wallenius Marine. This is then doubled in the scenarios 2 and 3. There is a risk that it still may not be enough for a unique product. To deal with this problem it may instead be better to ask the question how much the WPS has to cost to match a conventional vessel. In all scenarios except for an extreme (see scenario 3 for 8.0 knots in table 6.10 on page 68 when discounted cash flow is applied) the WPS base cost of €8 000 000 can at least be increased up to four times to match the ships without sails.

Fuel is shown in this thesis to be a main cost driver. When looking at a complete conventional ship without sails, e.g. not just the propulsion system, it makes up as much as 50% of the operating cost and is the main determinant for voyage cost [18]. Given that LNG is a fuel that is both competitive in price and emissions compared to traditional fuels, it follows that an increased uptake is likely to continue. Moreover, if it is possible to use the same infrastructure and engines and switch to renewable methane in the future it makes even more sense. However, a gradual switch from LNG to LBG would require an increase in production to cover both the existing use of biogas and the need for ships. All of which may be possible given there is a potential to increase production [85, 153]. This is a similarity shared by fossil and renewable methanol with the added downsides of the current renewable methanol production is more limited, and that there needs to be a leap in engine development capable of using the fuel (see section 3.4.2, page 25). Two advantages of using BioMeOH compared to the other renewable fuels investigated is first that the cost of engine construction including surrounding equipment and maintenance is lower compared to engines burning a gaseous fuel (see table 5.8, page 46) and secondly that BioMeOH production costs appears to be lower (see table 5.10, page 51).

Formulating a financial strategy for a ship may therefore very well include a great deal of choices in propulsion and power generation. A dual fuel engine is capable of using two different types of fuel. Compared to a conventional diesel engine they are more expensive but offers partial redundancy to whatever fuel option is most cost efficient. A choice must still be made in regard to weather it should use a gas, methanol or a range of other options in combination with a traditional liquid fuel, although they can be converted to either depending on what becomes available in the future [154]. A different path is to use wind propulsion and reduce fuel consumption. The financial results presented in this thesis makes a compelling argument for a future strategy including wind propulsion to reduce fuel consumption as a starting point.

It may be so that the investment cost still is seen as the main obstacle for investing in green technology. For example, Rehmatulla et al. mentions estimations of the investment can be more than twice of that assumed in the modelling [19]. Adding to this point the benefit from the fuel savings may not be accrued to the owner who invests in the technology but rather to the charterer of the ship and hence there is no incitement for the investment. This is an example of a split incentive known to be found in shipping [19, 155]. There are many different forms of split incentive but the most common arises in a time charter agreement where fuel costs and the charter rate is borne by the charterer and and a large part of the operating costs are borne by the ship owner or operator. This principal-agent problem is also found in the the construction sector between tenant and landlord [19]. Split incentives is far from the only factor that potential investors and decision makers must explore further to increase uptake of new green technology as contractual and financial obstacles remain that hinder the fulfilment of IMO's goal on annual GHG reduction.

7.3 Abatement cost

Abatement cost may be described as an index of relative performance more than a method itself. More specifically, in this thesis it is a combination of cost savings and emission reductions. The underlying methods (here, LCA and LCC) are guided by the design of the study, i.e. the goal and scope where definitions, assumptions and limitations are found. It is imperative to have the design of a study in mind and be vigilant to differences when comparing studies because the methods applied to produce abatement costs are seldom identical. Not least, the selection of baseline to compare against has a huge impact on reduction potential, something Bouman et al. [122] brings up as a source of uncertainty in their review of 150 studies on technologies to reduce GHGs. Moreover, any shortcomings in the results of the previous assessments are transferred to the abatement costs. Hence, it is important to understand where there are assumptions, limitations and possible gaps when interpreting the abatement costs. These are however highlighted in the previous sections (7.1 and 7.2).

In the study produced by Eide et al. [68] there are four main differences compared to this thesis. First, the baseline they compare against are the total emissions of the global fleet (with a few exceptions) over 20 years, taking into account scrapping of old tonnage and implementation of new and more energy efficient tonnage. Hence it paints a more dynamic picture of the abatement cost than in this thesis where the ships' annual emissions remain static over their respective 30-year life cycle. The difference in application makes the abatement cost more beneficial for the ships early in Eide's study compared to ships being introduced later because the baseline shifts, ultimately affecting the average abatement cost. Secondly, there is a difference in which emissions are measured. Where this thesis uses the impact category climate change and categorize CO_2, N_2O and CH_2 according to their respective potential to trap heat in the atmospere, Eide et al. does not look beyond emissions of CO_2, omitting the other two. Thirdly, Eide et al. convert all future costs to present value at a discount rate of 5%. Fourth, merely emissions from the operational phase in the life cycle of the ship has been accounted for. Emissions from construction and scrapping are omitted. In summary, Eide et al. produces a dynamic average for a fleet and a range of emission reduction options while this thesis produces an average for one ship type in a specific geographic location, size and category of ship but accounting for each ship's whole life cycle and more than CO_2.

In a most recent study by Schwartz et al. [69] from 2020, similar differences are observed when calculating the abatement cost of reduction technologies. For example, only CO_2 is included, emissions from construction and scrapping are omitted, present value is applied to future costs, the selection of data consists of a (short sea shipping) fleet rather than one ship and the baseline stems from historical data of the same fleet being continuously renewed.

7.3.1 Results discussion

Where Eide et al. [68] attributes sails and fixed wings to a significantly higher cost, more than $100 per averted tonne CO_2, Schwartz et al. [69] does however come closer at € -36.20 in their projections compared to this thesis. Most likely, the improved results of the wPCC has its origins in being a ship purpose built to use wind as main propulsion. It is further exacerbated by applying the technology to a single ship on a route where the technology can maximize its potential. The result is however penalised because the baseline the wPCC is compared against is an LNG powered ship which in the other studies is regarded as less carbon intensive option to begin with, compared to traditional fuels. Moreover, the two studies only regard the emissions from operating ships, measured in CO_2. While only using the operational phase as a proxy for a ship's total life cycle impact on climate is a small source of uncertainty, the omission of GWP in favour of only CO_2 fails to capture the impact CH_4 and N_2O has, possibly constituting a far greater source of uncertainty.

The small environmental gain from using LBG comes at the highest abatement cost when the price of renewable methane is high and measured over the 20-year perspective where emission from LNG and LBG does not diverge to any greater extent. Over a 100-year perspective the prospects of averting emissions using LBG are better but it is only when the supply of LBG is connected with a low price that it becomes an option in the same order of magnitude as the other options. Regardless, the fuel best suited to compete with wind powered propulsion, both environmentally and economically, is renewable methanol.

7.4 Future research

A result open to further exploration is the low average energy consumption of the wPCC. Only a small portion of available techniques and fuels have been investigated, all of which are using traditional drivetrains and internal combustion engines. Part of the thesis required the average power demand to be established. Continuing to build on those findings but applying non-conventional power generation layouts could make the wPCC both more cost effective and have a smaller environmental impact.

A major shortcoming to the results presented is the lack of a sensitivity analysis on the emission factors of the fuels investigated. The consequence is that there is a large uncertainty surrounding the environmental impact of the ships which is also carried over into the abatement cost calculations. A future study would greatly benefit from incorporating more studies and data on for example the effect of using different amounts of methane slip.

As details of the wPCC starts coming together a functional unit better describing transport work can be applied. Such an addition would better describe the environmental gain of the ship in relation to its function and would make it comparable to other ships and other modes of transport.

Data can always be improved and in the model created in this thesis more impact categories can be included to create a more comprehensive understanding of the environmental impact. Moreover, research aimed at collecting new data on maintenance costs of a WPS would increase reliability. Comparably, internal combustion engines have been widely researched in relation to a WPS and new data would make an important contribution as more and more details become available on how a WPS is constructed.

8
Conclusion

How does the total GWP of the wPCC's propulsion system compare to ships using only renewable or fossil fuel?

Total GHG emissions of the wPCC's propulsion system over its life cycle compared to a ship with the same hull using fossil fuel (LNG) are reduced by more than 81% CO_2eq_{20} and CO_2eq_{100}. The main driver for emissions is fuel consumption for all ships modelled. By using a WPS the total fuel consumption is reduced by more than 80% annually. More than 99% of emissions occur during the operational phase for all ships. Despite the additional emissions from constructing and scrapping the WPS, they do not make any significant addition to the total life cycle emissions. Replacement of parts and continuous maintenance of the propulsion system have been omitted. Given the small impact energy consumption and material production have in the construction phase and scrapping phase, the omission of maintenance emissions would not change the weight of the operational phase to any significant degree.

It is possible to reach similar reduction in climate impact on a car carrier without sails. This is possible when using a fuel with significantly lower life cycle climate impact compared to the additional fuel used on the wPCC. It was in this study shown to be possible with renewable methanol (BioMeOH).

How does the total ownership cost of the wPCC's propulsion system compare to a ship achieving the same climate impact using a renewable fuel?

This thesis produces several different total ownership costs by using scenarios to evaluate the sensitivity of data used. The total ownership cost for the wPCC's propulsion system ranges between € 48.9 millions and € 128.1 millions. The cost of a ship using BioMeOH and reaches a similar climate impact ranges between € 159.7 millions and € 1 268.6 millions. In scenario 3 for 8.0 knots when discounted cash flow is been applied and conditions are most favourable to the ships without sails, the ship using BioMeOH is 2.5 times as expensive as the wPCC which is operating under its most unfavourable conditions. In the same scenario the ship using LBG is 2.6 times more expensive but with a climate impact at least five times as high. Furthermore, this is also the scenario where the LNG ship and wPCC is closest in total ownership cost and differs by 68% in favour of the wPCC. Without applying discounted cash flow the ship using BioMeOH is at least three times as expensive as the wPCC.

In general, the main cost driver is fuel for all ships. Only on two occasions is this different and it occurs in scenario 2 and 3 for the wPCC at 8.0 knots. Furthermore, the consequence of doubling the cost of the WPS is evaluated in scenarios 2 and 3 as a sensitivity analysis since the wPCC is in an early design phase and it is found that the cost of the wPCC is still lower in comparison to the other ships without sail. Except for in the most extreme scenario the WPS base cost (€ 8 000 000) can be increased with a factor of 4 to match the ships without sail.

What is the abatement cost of reducing GHGs with the wPCC or a renewable fuel compared to a ship using fossil fuel?

Using abatement cost as a metric allows emission abatement options to be compared to find the most cost effective solution. Based on a preliminary performance routing over the North Atlantic, the wPCC offers the possibility to reduce GHG emissions at a negative cost. The second best option is switching to renewable methanol (BioMeOH), displaying similar total GHG emissions as the wPCC. However, because the fuel is more expensive than LNG it comes at a significantly higher abatement cost. Renewable methane (LBG) comes at a much higher abatement cost. The main reason why LBG cannot match the former fuel is because it does not reduce GHG emissions to the same extent, yet it retains a similar price. However, the data has not been tested for sensitivity by decreasing methane slip, a major reason to the gaseous fuel's high climate impact.

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A
Appendix 1

Table A.1: Summary of elementary flows at 11.4 and 8 knots [tonnes]

Years	**Life cycle phase**	**CO_2**		**CH_4**		**N_2O**	
wPCC (LNG)		11.4 kn	8 kn	11.4 kn	8 kn	11.4 kn	8 kn
Initial year	Construction	9.24E+02	9.24E+02	8.74E-01	8.74E-01	1.93E-02	1.93E-02
30 year period	Operation	4.23E+05	1.65E+05	4.47E+03	1.74E+03	1.20E+00	4.80E-01
30 year period	Maintenance	N/A	N/A	N/A	N/A	N/A	N/A
Final year	Scrapping	3.17E+02	3.17E+02	3.60E+01	3.60E+01	3.24E+00	3.24E+00
	Totals	4.24E+05	1.66E+05	4.51E+03	1.78E+03	4.46E+00	3.74E+00
Alternative (LBG)							
Initial year	Construction	1.06E+03	6.08E+02	1.30E+00	7.46E-01	N/A	N/A
30 year period	Operation	9.96E+05	4.05E+05	3.45E+04	1.39E+04	1.32E+01	5.40E+00
30 year period	Maintenance	N/A	N/A	N/A	N/A	N/A	N/A
Final year	Scrapping	1.20E+02	5.50E+01	1.30E+01	6.00E+00	1.22E+00	5.60E-01
	Totals	9.97E+05	4.06E+05	3.45E+04	1.39E+04	1.44E+01	5.96E+00
Alternative (Bio MeOH)							
Initial year	Construction	1.06E+03	6.08E+02	1.30E+00	7.46E-01	N/A	N/A
30 year period	Operation	6.39E+05	2.60E+05	1.53E+03	6.30E+02	9.30E+00	3.90E+00
30 year period	Maintenance	N/A	N/A	N/A	N/A	N/A	N/A
Final year	Scrapping	1.20E+02	5.50E+01	1.30E+01	6.00E+00	1.22E+00	5.60E-01
	Totals	6.40E+05	2.61E+05	1.54E+03	6.37E+02	1.05E+01	4.46E+00
Conventional (LNG)							
Initial year	Construction	1.06E+03	6.08E+02	1.30E+00	7.46E-01	N/A	N/A
30 year period	Operation	2.25E+06	9.09E+05	2.36E+04	9.54E+03	7.50E+00	3.30E+00
30 year period	Maintenance	N/A	N/A	N/A	N/A	N/A	N/A
Final year	Scrapping	1.20E+02	5.50E+01	1.30E+01	6.00E+00	1.22E+00	5.60E-01
	Totals	2.25E+06	9.10E+05	2.36E+04	9.55E+03	8.72E+00	3.86E+00

Table A.2: Single data inputs

Module	Data	Reference
CM	Emissions from road transport are based on lorry transport and a diesel consumption of 29.9 litre fuel/100 km	[130]
CM	Each lorry transport has a cargo capacity of about 40 tonnes and emissions of CO_2, CH_4 and N_2O are the same as those of MGO in table 3.2	
CM	Transport distance from factory to yard for the engines - 125 km	[29]
CM	Transport distance from factory to yard for steel used in the WPS - 1 000 km	
CM	Cost of transport - € 1.615 per tonne-km	[52]
CM	Cost of the WPS is based on an early indicative price from Wallenius Marine of €8 000 000, for sensitivity purposes, this has also been doubled.	
MM	Cost of maintaining the WPS is based on the above mentioned total installation cost of the WPS, given as an annual cost of either 1% or 5%, for sensitivity purposes	[140]
OM	Emission factors from lube oil production, 688.12 g CO_2/kg - lube oil	[134]
OM	Specific Fuel Oil Combustion (SFOC) formulas are based on Wärtsilä's product guides and can be found in equation 5.19 to 5.26 for each engine	[137, 136, 135]
OM	Specific Lube Oil Consumption (SLOC) is held constant at 0.65 g/kWh for all engines	
OM	Cost of lube oil - € 1 681 per tonne	[52]
SM	Economic benefit for recycling is based on a recovery rate of 86% and 81% for engines and WPS respectively	[52]
SM	Average steel scrap price 0.095 €/kg	[52]

Table A.3: Base Scenario - 11.4 and 8 knots [EUR]

Time	Life cycle phase	wPCC		LBG		Bio-MeOH		LNG	
Annualized costs		11.4 kn	8 kn	11.4 kn	8 kn	11.4 kn	8 kn	11.4 kn	8 kn
25 years	Construction	706 584	706 584	556 967	319 516	556 967	319 516	556 967	319 516
Annually	Operation	2 088 617	818 603	53 854 693	21 767 511	40 370 690	16 320 210	10 771 659	4 362 720
Annually	Maintenance	453 177	225 623	1 964 924	793 795	1 452 316	586 710	1 964 924	793 795
Final year	Scrapping	-588	-588	-272	-124	-272	-124	-272	-124
Annualized total		3 248 378	1 750 222	56 376 312	22 880 698	42 379 701	17 226 312	13 293 278	5 475 907
LCC for the base scenario									
Initial year	Construction	17 664 598	17 664 598	13 924 175	7 987 906	13 924 175	7 987 906	13 924 175	7 987 906
30 year period	Operation	62 658 497	24 558 087	1 615 640 803	653 025 335	1 211 120 708	489 606 301	323 149 767	130 881 592
30 year period	Maintenance	13 595 320	6 768 704	58 947 721	23 813 847	43 569 478	17 601 306	58 947 721	23 813 847
Final year	Scrapping	-17 638	-17 638	-8 163	-3 726	-8 163	-3 726	-8 163	-3 726
Total LCC		93 900 777	48 973 751	1 688 504 536	531 135 108	1 268 614 361	515 191 782	396 013 500	162 679 619

Table A.4: Scenario 2 - 11.4 and 8 knots [EUR]

Time	Life cycle phase	wPCC		LBG		Bio-MeOH		LNG	
Annualized costs		11.4 kn	8 kn	11.4 kn	8 kn	11.4 kn	8 kn	11.4 kn	8 kn
10 years	Construction	3 025 872	3 025 872	1 445 370	829 168	1 445 370	829 168	1 445 370	829 168
Annually	Operation	2 088 617	818 603	18 006 978	7 285 662	17 678 100	7 152 801	10 771 659	4 362 720
Annually	Maintenance	1 173 177	945 623	1 964 924	793 795	1 452 316	586 710	1 964 924	793 795
Final year	Scrapping	-588	-588	-272	-124	-272	-124	-272	-124
Annualized total		6 287 666	4 789 511	21 416 999	8 908 500	20 575 514	8 568 555	14 181 681	5 985 558
LCC for scenario 2									
Initial year	Construction	30 258 724	30 258 724	14 453 697	8 291 678	14 453 697	8 291 678	14 453 697	8 291 678
30 year period	Operation	62 658 497	24 558 087	540 209 331	218 569 854	530 342 987	214 584 024	323 149 767	130 881 592
30 year period	Maintenance	35 195 320	28 368 704	58 947 721	23 813 847	43 569 478	17 601 306	58 947 721	23 813 847
Final year	Scrapping	-17 638	-17 638	-8 163	-3 726	-8 163	-3 726	-8 163	-3 726
Total LCC		128 094 903	83 167 877	613 602 586	228 515 792	588 357 999	240 473 282	396 543 022	162 983 391

Table A.5: Scenario 3 - 11.4 and 8 knots [EUR]

Time	**Life cycle phase**	**wPCC**		**LBG**		**Bio-MeOH**		**LNG**	
Annualized cost		11.4 kn	8 kn	11.4 kn	8 kn	11.4 kn	8 kn	11.4 kn	8 kn
10 & 25 years	Construction	3 025 872	3 025 872	556 967	319 516	556 967	319 516	556 967	319 516
Annually	Operation	2 088 617	818 603	18 006 978	7 285 662	17 678 100	7 152 801	10 771 659	4 362 720
Annually	Maintenance	1 173 177	945 623	1 964 924	793 795	1 452 316	586 710	1 964 924	793 795
Final year	Scrapping	-588	-588	-272	-588	-272	-124	-272	-124
Annualized total		6 287 666	4 789 511	20 528 597	8 398 849	19 687 111	8 058 903	13 293 278	5 475 907
LCC Totals									
Initial year	Construction	30 258 724	30 258 724	13 924 175	7 987 906	13 924 175	7 987 906	13 924 175	7 987 906
30 year period	Operation	62 658 497	24 558 087	540 209 331	218 569 854	530 342 987	214 584 024	323 149 767	130 881 592
30 year period	Maintenance	35 195 320	28 368 704	58 947 721	23 813 847	43 569 478	17 601 306	58 947 721	23 813 847
Final year	Scrapping	-17 638	-17 638	-8 163	-3 726	-8 163	-3 726	-8 163	-3 726
Total		128 094 903	83 167 877	613 073 063	250 367 881	587 828 477	240 169 510	396 013 500	162 679 619
LCC Totals applying discounted cash flow on operation and maintenance									
Initial year	Construction	30 258 724	30 258 724	13 924 175	7 987 906	13 924 175	7 987 906	13 924 175	7 987 906
30 year period	Operation	40 937 806	16 044 978	352 944 710	142 802 187	346 498 554	140 198 052	211 129 269	85 511 232
30 year period	Maintenance	22 994 794	18 534 637	38 513 378	15 558 730	28 466 033	11 499 779	38 513 378	15 558 730
Final year	Scrapping	-17 638	-17 638	-8 163	-3 726	-8 163	-3 726	-8 163	-3 726
Total		94 173 687	64 820 701	405 374 100	166 347 288	388 880 598	159 682 012	263 558 659	109 054 143