A. Karanasios

The effects of upcoming emission regulations on the selection of suitable prime mover combinations for the future harbour/terminal Rotortug

-A decision-support tool-

TU Delft

KOTUG

The effects of upcoming emission regulations on the selection of suitable prime mover combinations for the future harbour/terminal Rotortug

-A decision support tool-

By

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TU Delft

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Preface

This thesis is the final assignment of the MSc in Marine Technology at the Faculty of 3ME, Delft University of Technology. The track I followed during my studies was the Ship Design, Production and Operation with Shipping Management as a specialization.

The work outlined in this report was conducted in collaboration with Kotug International BV. The final deliverables were the MS thesis report and a decision-support tool. It was from the beginning of my studies at TU my intention to combine technical with business-related disciplines. For this reason, I decided to find a subject which would combine techno-economic aspects. Fortunately, I applied to Kotug International B.V. I would like to express my gratitude to Koos Smoor for providing me the possibility to work on a project related to sustainability and aligned with my objective. He believed in me and granted the green light to move forward with developing a decision-support tool. Hopefully, my work can be used and provide valuable insight into future options for Rotortugs fleet.

A. Karanasios

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Acknowledgements

During the project period I accepted a work offer, thus I had to combine working with studying at my free time. I devoted a lot of time and energy on finalizing this thesis and I am glad for managing to conclude it.

I am grateful for the people who supported me throughout this period. First and foremost, I want to thank Despoina for believing in me and making sacrifices throughout the research process until its completion. Next, my family who never doubted that I will graduate and their endless support and love. Special thanks to George Karras for all his support. In times of difficulties he was always there to pick up the phone, hear me out and motivate me to continue on.

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Last, I would also like to thank ir Marinus Jansen for his instructions and valuable comments. I am grateful for all insightful suggestions about the application of various methods as well as the ideas for expansion of certain modules of this thesis with additional factors.

Abstract

Nowadays the interest for environmental issues is steadily gaining ground. Inescapably, the shipping industry, is also called to contribute its fair share towards the reduction of air pollution. Harbour tugboats need to comply both with international but also with local exhaust air emission regulations, which are anticipated to become more stringent in the future. Kotug, is interested to proactively explore suitable powering solutions, which can be applied at its Rotortugs' newbuilding scheme, to comply with upcoming regulations of the intended port of operation. The goal of this thesis is to develop a decision-support tool to facilitate the selection process between alternative prime mover combinations, based on what is needed in terms of operation while considering technical challenges, environmental performance and economic returns. The effect of a variety of promising alternative fuels matched with suitable prime movers was investigated for the period 2018-2033, which was set as the study's time horizon. LNG, Methanol, Biodiesel and DME were assessed as feasible solutions. The first two were associated with gas-burning engines, whereas the rest were associated with conventional 4-stroke compression ignition engines, similar to the ones already installed in the existing Rotortugs running on MGO. The environmental performance differs substantially to a conventional prime mover running on MGO. However, to adhere to future stricter regulations in certain sea areas, additional after-treatment systems are necessary. Research indicated three post-treatment solutions are the most effective in limiting the majority of the combustion-related emissions; Selective catalytic reduction, diesel particulate filter and oxidation catalysts. The total environmental fingerprint of a vessel can be however assessed only under the context of its propulsion configuration layout. The operational profile of a tugboat is highly variable, allowing room for the exploitation of different drivetrains than the traditional diesel-direct layout, which could lead in benefits mainly in terms of fuel efficiency and maintenance savings. Three drivetrains were selected; a diesel-electric and two hybrid, based on AC and DC topology. Before deciding to invest on a future boat a ship-owner is expected to be eager to comprehend the cost-related issues between alternatives. Moreover, the already proven design of the diesel-direct Rotortug, complemented by the necessary after-treatment technologies, makes sense to be the first option to consider, provided it complies with the anticipated regulations. This option is considered the baseline case. It is reasonable to compare all other options against the baseline case. To this end, a decision framework based on a techno-economic evaluation is proposed for supporting ship-owners to take informative decisions on investment considerations; Three objectives were set; economic performance, environmental performance and cost-effectiveness. To quantify economic performance a comparative TCO analysis was implemented, while for environmental performance the emission output of alternatives is compared. Last, cost-effectiveness adds valuable insight into how good money are allocated towards emission reduction targets and provides a methodology to compete for funding from a regulatory authority. Two case studies are presented that demonstrate the utility of these methods and enhance the understanding of the impact of decisive factors in decision-making. It is concluded that the proposed decision-support tool enables decision-support at an early-stage; nonetheless can still be improved, by incorporating additional factors and expanding certain modules with more details.

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List of Abbreviations

Abbreviation	Meaning
AE	Auxiliary Engines
AFE	Active Front End
ART	Advanced Rotortug
AUS	Aqueous Urea Solution
BAU	Business-As-Usual
BC	Black Carbon
BMS	Battery Management System
C_4H_6	Butadiene
C_6H_6	Benzene
C_8H_{18}	Gasoline
CAPEX	Capital Expenses
CE	Cost-Effectiveness
CFCs	Chlorofluorocarbons
CH_2O	Formaldehyde
CH_3CHO	Acetaldehyde
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CSI	Clean Shipping Index
DCS	Data Collection System
DDP	Diesel-Direct Propulsion
DEP	Diesel-Electric Propulsion
DME	Dimethyl Ether
DoD	Depth of Discharge
DPF	Diesel Particulate Filter
ECA	Emission Control Areas
EEDI	Energy Efficiency Design Index
EGR	Exhaust Gas Recirculation
EGS	Exhaust Gas Scrubbers
EMS	Energy Management System
EPA	Environmental Protection Agency
ESI	Environmental Shipping Index
EU	European Union
F-gases	Fluorinated gases
FPP	Fixed Pitch Propellers
GA	General Arrangement
GHG	Greenhouse Gases
GRA	Grey Relational Analysis
GT	Gross Tonnage

GWP	Global Warming Potential
H_2O	Water
HC	Hydrocarbons
HFO	Heavy Fuel Oil
IAPP	International Air Pollution Prevention
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
IRR	Internal Rate Of Return
ISO	International Standard Organisation
LBSI	Lean-Burn Spark-Ignited
LCA	Life Cycle Assessment
LED	Light Emitting Diode
LH_2	Liquid Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPDF	Low Pressure Dual-Fuel Engines
LPG	Liquefied Petroleum Gas
M/G	Motor/ Generators
MAC	Marginal Abatement Cost
MADM	Multiple Attribute Decision Making
MARPOL	International Convention for the Prevention of Pollution from Ships
MBM	Market-Based Measures
MCD	Marine Control Drive
MDO	Marine Diesel Oil
ME	Marine Engine
MGO	Marine Gas Oil
MOC	Methane Oxidation Catalyst
MRV	Mozambique Rovuma Venture
MSB	Main Switchboard
N_2	Nitrogen
N_2O	Nitrous Oxide
NECAs	NO_x Emission Control Areas
NMC	Nickel Manganese Cobalt
NMHC	Non-Methane Hydrocarbon
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
NPV	Net Present Value
NRLM	Nonroad, Locomotive And Marine Diesel
NRMM	Non-Road Mobile Machinery
O_2	Oxygen
OGV	Ocean Going Vessel
OPEX	Operational Expenses
OxiCat	Oxidation Catalyst
PM	Particulate Matter

PMS	Power Management System
PN	Particle Number
ppm	parts per million
PTI	Power Take In
PTO	Power Take Out
RLNG	Rovuma LNG
rpm	Round per minute
RT	Rotortug
SCR	Selective Catalytic Reduction
SECAs	Sox Emission Control Areas
SEEMP	Ship Energy Efficiency Management Plan
SEF	Specific Emission Factor
SFC	Specific Fuel Consumption
SO_2	Sulphur Dioxide
SO_3	Sulphur Trioxide
SOC	State of Charge
SO_x	Sulphur Oxides
TCO	Total Cost of Ownership
TCS	Total Cost for Society
THC	Total Hydrocarbons
TTP	Tank-To-Propeller
UC	Urea Consumption
ULSD	Ultra Low Sulphur Diesel
USA	United States Of America
USD	United States Dollars
VECS	Vapour Emission Control System
VFD	Variable Frequency Drive
VOC	Volatile Organic Compounds
VSD	Variable Speed Drive
WTP	Well-To-Propeller

List of Symbols

Romans Variables	Description	Unit
A	absolute resulting value of the cumulative comparative net free cash flow at the end of period Y	-
Aaftertr	acquisition cost for the installed after-treatment systems	USD ($)
Aeng	acquisition cost for both the main and auxiliary engines	USD ($)
Aeq	acquisition cost for the associated drivetrain machinery equipment	USD ($)
AF	cost of fuel	USD ($)
AGEN	cost of auxiliary engines	USD ($)
AME	cost of main engines	USD ($)
Atank	acquisition cost for the installed fuel and urea tanks	USD ($)
AUT	cost of urea tanks	USD ($)
bat.life	expected battery lifespan	years
C	purchase cost	$/kW or $/m3 or $
Ca	Cost function	USD ($)
Caft-treat	cost of after-treatment systems	USD ($)
CAUX,E	cost of auxiliary engines	USD ($)
Cbat	cost of batteries	USD ($)
CF	nominal (free) cash outflow	USD ($)
CM/E	cost of main engines	USD ($)
Cum ev	cumulative number of events happening until the investigated calendar year	-
Cα	calculated cost function	USD ($)
$CE_{cand,airpol}$	cost-effectiveness per air pollutant for each candidate	Kg/$
DCF	discounted cash flow, expressed in net present value	USD ($)
Duration	mode's duration	hours/year
E	number of events per year	
$E_{Bas,air\,poll}$	Emission Reduction for the baseline configuration (base) for the investigated air pollutant (air pol)	(%)
$(E_{x,y})_{base,air\,poll}$	emission output of the examined air pollutant for the baseline configuration	Kg/day or Kg/ year

$(E_{x,y})_{cand,air poll}$	emission output of the examined air pollutant for the investigated candidate	Kg/day or Kg/ year
$(E_{x,y})_{cold-iron}$	Cold ironing emission output	Kg/day or Kg/ year
EC	energy consumption	kWh/day
EF	daily energy consumption	kWh/day
endurance	emission factor	-
Eng(LF)	endurance	-
Enginerated power	loading condition of the engine	%
Engoutput,z	rated power of the engine	kW
EO	output of the engine y	kW
$Equipment_{rated\ power}$	rated power for operation of the equipment	kW
$ER_{cand,air,poll}$	total Emission Reduction per investigated candidate (cand) per year for the air pollutant (air. poll)	%
Ext_{NPV}	external costs cash outflow	USD ($)
FC	fuel consumption	tons/day or tons/year
FP	fuel price	USD ($)/ton
i	operating mode	-
LHV	lower heating value	MJ/kg
M	molecular weight	-
m	the user-defined economic-analysis horizon	years
m	number of mission profile's modes	-
$\dot{m}A$ and $\dot{m}B$	fuel consumptions	m^3/h
n	economic-life	years
P	external cost factor for all exhaust air pollutants	USD ($) /kilos
$P_{(B,aux,req)}$	required brake power for electric needs.	kW
$P_{(B,prop,req)}$	required brake power for propulsion	kW
$P_{(B,req)}$	required brake power	kW
P_B	main engine brake power	kW
$P_{B,aux,req}$	auxiliary engine brake power	kW
Pe	maintenance schedule stage cost per event	USD ($) /event
P_{el}	electrical power demand	kW
Pp	engine power to the thruster's propeller	kW
q	inflation rate	%
q	number of the equipment's maintenance schedule stages (k)	-
q	number of installed prime movers for the investigated candidate	-

	configuration	
r	discount rate	%
RH_{Eng}	engine's running hours	hours/ day
RH_{SCR}	operating time of the SCR system	hours/day
RR	Rank Reciprocal	-
Run hours	running hours of the relevant plant equipment	hours/year
$SEF_{x,y}$	specific emission factor	gr/kWh.
SFC	specific fuel consumption	gr/kWh
$Tank_{capacity}$	Tank capacity	m^3
UC	urea consumption	tons/year
UP	urea price	USD ($) /ton
urea rate	Urea rate	litres/MWh
V	tank volume	m^3
w_j	weightage of criteria j	-
x_c	carbon content of the fuel	-
x_s	sulphur content of the fuel	-
Y	time period before the cumulative comparative net free cash flow becomes positive	years

Greek Variables	**Description**	**Unit**
$\gamma(x_{oj},x_{ij})$	grey relational coefficient	-
$\Gamma(x_o,x_i)$	grey relational grade	-
Δ	cost differential between the candidate propulsion configuration and the baseline case	-
$\Delta_{i,j}$	incremental values	-
$\eta_{(el\ dis)}$	electric distribution efficiency	%
$\eta_{AC\ SB}$	AC switchboard efficiency	%
η_{clutch}	losses in the clutch	%
η_e	thermal efficiency	%
η_{EM}	electric motors efficiency	%
η_{gen}	generator's nominal efficiency	%
η_{JB}	the connecting cable socket (Shore supply JB) efficiency	%
η_{shaft}	shaft line efficiency	%
η_{TF}	power transformer efficiency	%
η_{TRM}	propulsion transmission efficiency	%
η_{VFD}	frequency converter (VFD) efficiency	%
$\eta_{Z\text{-}drive}$	Z-drive gear box efficiency	%
$\gamma(x_{oj},x_{ij})$	grey relational coefficient	-

1 Introduction

This introductory chapter provides an overview of the subject of this research. First, the background for this research is discussed, in order for the reader to realise the rationale for this study. Then the research objectives are clarified, followed by the methodology and the scope of this research. Finally, the structure of the thesis report is outlined, indicating to the reader how the report is organised.

1.1 Background

Exhaust air emissions such as Carbon Dioxide (CO_2), Sulphur Oxides (SO_x), Nitrogen Oxides (NO_x) and Particulate Matter (PM) and other greenhouse gases are considered a well-documented problem, which concerns both the scientific community and the humanity. Although most of the conversations are focused on the greenhouse gas emissions, an area in which the shipping industry is considered having a relatively small contribution, because it is responsible for relatively low greenhouse gas emission per volume of transported material, it is playing a bigger part on the emission contribution of other gaseous emission, such as NO_x, SO_x and PM. Even though tugs, within the shipping industry, are a small contributor, accounting less than 20 per cent of overall shipping it is the geographical location that they operate that deems them dangerous. Tugs typically operate in ports, which are located in or near big cities, thus their exhaust air emissions, especially NO_x and PM, are affecting directly a significant percentage of population. Until recently, little was done to address this problem or take measures towards the reduction of those harmful exhaust emissions, neither by governments nor by the industry.

Nowadays, the interest for all environmental issues, but especially the climate change is increasing. More and more, companies are seeing sustainability as an economic opportunity. Kotug International B.V. (Kotug) is a company, with embedded in its business strategy to be a forerunner in sustainability and innovation. Kotug is towage operator, offering towage services in a variety of markets on a global scale, including services in ports and at sea as well as in the salvage, offshore and dredging industry. In developed countries the attention for the environment has already taken gigantic dimensions, and in the rest of the word it is emerging. Kotug is a company that aims at operating worldwide and willing to expand their fleet. The vision of Kotug is becoming a "leading" company, a term which can best be stipulated not so by being the biggest company but more to be reckoned with as a service minded, innovative and socially mature organization. Indicative examples of Kotug's sustainability strategy are the use of cold ironing in all ports applicable, installation of LED lighting on its fleet, preparation of the Inventory of Hazardous Materials on each of its vessels, use of washable filters and bunkering only low-sulphur MGO fuel.

The fundamental action for limiting the exhaust emissions is the introduction of emission regulations. Specifically, in shipping such regulations are set internationally by the International Maritime Organization (IMO) but also locally by countries. Currently, the enforced regulations targeting the shipping industry are very lenient, allowing either the change-over of the fuel when entering Emission Control Areas (ECA) or demanding from manufacturers the tuning of engines' combustion process. However, the upcoming regulations are envisaged to become more stringent in the future. Then, for meeting the stricter emission limits, adjustments are required in the powering configuration (e.g. in the design of prime movers used either as main or auxiliary engines, in the design of fuel systems, in the incorporation of energy storage devices) or by applying after-treatment systems which will further reduce the emission output per engine.

Another important aspect is the scarcity of fossil fuels and the development of fuel prices. Fuel costs are widely recognized as the biggest contributor of a vessel's operating costs, while price development is uncertain, provided that no viable alternatives for fossil resources are available. Incentives are given from many countries for a transition to sustainable energy sources, and alternatives for the future are already investigated. Regulating authorities are granting subsidies and other benefits making it financially interesting to invest in proven sustainable technologies. Kotug has already exploited the opportunity of gaining access to funds supporting sustainable technologies, by converting one of its conventional tugs (RT Adriaan) to hybrid, making Kotug one of the first companies in the world to acquire a hybrid tugboat under class (Lloyds Register). The addition of a hybrid propulsion power plant further enhances the vessel's performance and operational capabilities while providing increased efficiency and emission reduction.

Kotug wants to establish that as a company will continue being an innovative early adopter, which provides at the same time competitive and sustainable towage services to the maritime industry and remains in truck with their vision and company mission.

1.2 Thesis Objective

The main objective of this study is the investigation of prime mover combinations in which Kotug should invest in the near future (2018-2033) concerning their Rotortugs' fleet renewal program. The future Rotortugs should comply with the upcoming regulations with respect to the exhaust emissions produced in the harbours and terminals, which Kotug is expected to operate. In this scope, a decision-support tool should be designed; tool which aims to facilitate the selection process between alternative prime mover combinations based on what is needed in terms of operation whilst considering technical challenges, environmental performance and economic returns.

To accomplish the primary objective of this thesis a list of sub-objectives have been created.

1) Specify the marine related exhaust air pollutants originating from tugboats
2) Investigate the current and future emission regulations at the envisaged sea areas of operation
3) Determine the most promising prime mover combinations that would allow future Rotortugs to comply with the anticipated emission regulations
4) Determine the applied methodology of the decision-support tool
5) Develop and validate the decision-support tool

1.3 Scope of Work

Kotug's strategy is the replacement of current tugs deployed on ports around the world providing harbour/terminal towage services with Rotortugs, which is the trademark of its fleet. For this reason, this research is narrowed down to only one type of tug, the Rotortug. The future Rotortugs should have less fuel consumption and produce less exhaust emissions, in order to comply with the upcoming emission regulations, with the ultimate goal being zero exhaust emissions. The timespan of the research is the period 2018-2033. For this period a limited number of alternative fuels, which are considered as promising and matured enough, are examined. For the selected fuels, the most suitable prime mover to be used is chosen. The focus is set strictly on harbour/terminal towing, so no offshore or deep-sea towing is looked at. Moreover, only the newbuildings scheme will be examined, because retrofitting the new technologies is considered economically not advantageous. The future Rotortugs are expected to operate worldwide, with the exception of China, Korea, Japan, India, the Arctic and the Antarctica under the considered time period.

The availability of different energy sources and the maturity of the associated prime movers are researched, so that the most promising for application on tugs are selected. The emission's regulatory regime within the intended areas of operation is looked at, so that the effects for the compliance of existing and candidate prime movers with future requirements are determined. This analysis reveals which prime mover combinations are the most promising to consider, but also the after-treatment technologies which should complement those prime movers for attaining the foreseeable more stringent emission limits.

A baseline propulsion configuration layout, against which the candidate configuration layouts are compared is selected, according to the regulation regime applied on the examined timeframe and the area of intended operation. The combination of 4-stroke compression ignition engines, combusting Marine Gas Oil (MGO) or Ultra Low Sulphur Diesel (ULSD) with or without the use of appropriate after-treatment technologies, so that in the short-term the emission regulations are satisfied, is considered the base case inside the decision-support tool.

The selection of the most suitable concept layout is affected by the operational profile, the functional requirements that the future Rotortug should attain and the objectives defined by the user. The final selection is going to be based on the results of a techno-economic analysis. Therefore, an appropriate methodology to perform the comparison between the different candidate concept layouts is determined. An analysis on the increase of the cost of acquisition and operation of the additional equipment installed on the candidate concept layouts is carried out, so that a proper cost comparison between them can follow up. The techno-economic evaluation chosen is one pertaining in the comparative life-cycle analysis methods and is conducted on a ship-owner perspective. The proposed candidates are ranked based on three distinct objectives; the first is based on cost-related (financial) terms, the second on environmental performance terms (emission reduction potential) and the third is based on cost-effectiveness, which is a combination of the two previous objectives.

For the examined timeframe the development of fuel prices, the availability of the bunkering infrastructure, financial parameters and technology projections will have a central role in the decision process. These developments are attempted to be addressed in the proposed decision-support tool. However, no robust set of scenarios for the future are developed. This in itself is worth a study, as they require a great amount of data and information as backup. Because no concrete set of scenarios is given, no concrete strategic advice is given either. Nonetheless, possible implications for and possible reactions of Kotug are discussed in the final section of this thesis.

The main limitations of the study, considering the thesis objective and the project’s time limit, are listed below.

1) The target’s vessel design parameters, including the exterior and interior dimension constraints will remain unaltered. It is assumed that the current design of the Rotortug can accommodate the candidate prime movers and the considered drivetrain associated machinery equipment. Both the constraints of fitting the additional equipment in the given machinery space, as well as the effect in hydrodynamic efficiency (resistance) are ignored.
2) The implications of the use of different propeller types, such as Controllable Pitch Propeller (CPP), void propellers or azipods, or altering the dimensions of the existing propellers, as well as the complex issues of engine-propeller coupling are not investigated.
3) Factors such as operator’s ability to control a tugboat arranged on different propulsion configuration, as to ensure optimum vessel performance or the operator’s behaviour in vessel operation will not be addressed. Equivalent vessel performance to a conventional Rotortug is assumed.
4) Marine engineering innovations that are already being applied for improving the performance of existing propulsion configurations are not considered, other measures that increase the sustainability of a tug, next generation innovations (unmanned, autonomous) and ways of improving the fuel quality for reducing the emissions lie also outside the scope of this report.
5) The effect of dynamic performance or else the transient response of prime movers, with respect to fuel consumption and emission output is also not accounted, due to the choice of developing a static calculation model based on a steady-state instead of a time-domain simulation.
6) Complying with safety standards, rules and class regulations when altering the prime movers or integrating additional machinery equipment inside a different drivetrain layout are not studied

1.4 Report Structure

The Master thesis report consists of Chapters 1 to 7 and Appendices A to F.

Chapter 1 provides the research background, the objective, the scope of work and the outline of the report.

Chapter 2 outlines the legislative regime covering harmful exhaust air emissions in the envisaged areas of operation and presents the established compliance measures. Finally, a brief description of other measures implemented for addressing the emission problem are discussed and the chapter concludes with the future outlook.

Chapter 3 explores the emission reduction measures available, while emphasizing in the contribution of alternative fuels for addressing the emission problem. The practice which Kotug follows currently for complying with emission regulations is then presented. Next, this chapter deals with the selection of the alternative fuels along with their associated prime movers. Finally, the most promising after-treatment technologies, to supplement the selected prime movers, in order to meet the forthcoming emission limits are presented.

Chapter 4 firstly reviews the reference vessel’s propulsion configuration. Then the proposed alternative concept layouts are presented and their benefit potential compared to the conventional propulsion configuration is reasoned.

Chapter 5 provides a description of the decision-support tool developed. The functional requirements, the objectives and the interface of the tool are presented. Then the design methodology, consisting of two parts, a technical and an economic part, is explained in detail and the underlying assumptions are clarified.

Chapter 6 presents the two indicative case studies selected; one for harbour and one for terminal mission. An analysis of the results with the intention of validating the proper function of the developed decision-support tool is performed followed by a sensitivity analysis.

In the final Chapter 7, conclusions are drawn and future improvements are recommended.

In the Appendices section the reader can find details concerning the theoretical background and complementary material accompanying the derivations and assumptions made in this thesis report.

2 Marine air emissions

The following chapter will summarize the current and future legislative framework targeting marine emissions originating from tugboats. Rotortugs, as harbour vessels, have to comply not only with international but with local regulations as well. To this end, an overview of the main international and regional regulations targeting each specific marine air pollutant will be provided. Apart from the legislative framework, voluntary or other compulsory measures introduced for mitigating the effects of exhaust air emission from ships will briefly be discussed. Finally, a look in the evolvement of exhaust air regulations and incentives affecting the tug industry in the next 15 years is attempted.

2.1 Marine air pollution prevention measures

The problem of air pollution, since the 1960s, is well documented. A brief summary on the air pollution problem is presented in Appendix A. The origin, the formation mechanisms and the harmful effects of all primary air pollutants associated with shipping is also presented. More information on the differences between the primary air pollutants and the contribution of shipping to the problem, with the emphasis placed in the impact of shipping emissions in ports are also included in this appendix. In short exhaust air pollutants are categorized into two groups, fuel related, comprising of SO_x and CO_2 and combustion process related emissions, comprising of NO_x, CO, HC/VOC and PM. A certain trade-off exists between NO_x emissions and the rest of the cylinder process related pollutants, known as “diesel dilemma”. NO_x emissions show a reverse trend to CO, PM and HC/VOC. Specifically, when the peak temperature inside a diesel engine is increasing NO_x emissions increase, while the rest of the aforementioned pollutant’s emissions decrease. On the other hand, when the peak temperature is decreasing, it leads to less NO_x emission but to higher emissions for the rest.

In response to the impacts of air pollution on human health and climate change, regulations were introduced for the prevention of air pollution. The instrument responsible for regulating air pollution caused by international shipping is the International Convention for the Prevention of Pollution from Ships (MARPOL), enacted by the International Maritime Organisation (IMO). This convention targets various aspects of environmental pollution caused by ships. “MARPOL Annex VI” specifically addresses both Greenhouse Gas (GHG) and Non-GHG exhaust gas emissions.

The enforcement of the regulations adopted by the IMO are dependent on the governments of the country members. After ratification of an IMO convention from the parliament of a country member, the relevant convention becomes part of its own national law. It is the flag states responsibility to enforce the legislation on ships in their registries. In most cases, a classification society, acting on behalf of the flag State will do the survey. Currently 90 out of 172 country members of the IMO have ratified and are enforcing the environmental regulations on international shipping enacted by IMO through the MARPOL Annex VI. However, vessels need to comply additionally with the enforced national legislation, depending on the flag they sail; however, it is not anticipated for a flag state to have more stringent regulations, because the ship-owner can change the ship’s flag, going to a more convenient one. It must not be overlooked, that a flag state depends on maximizing the fleet sailing under its flag, due to dependency of its tax incomes.

Local authorities are also capable of setting complementary requirements associated with emission reduction targets. As an example, port authorities often have in place rules for vessels berthing on the port, like the type of vessel or necessitating the shut-down of all engines and getting power from the shore. In this case, harbour police is ensuring that the rules are enforced, on behalf of the port authorities. Some ports or local authorities are going one step further, establishing market-based incentives with the goal of reinforcing the total emission abatement. A harbour tugboat is directly affected by those emission reduction incentives.

2.1.1 Legislation

The future Rotortugs are expected to operate in harbours and terminals worldwide under the considered time period. It is outside the scope of this thesis to do a thorough investigation in the national or local regulations, which complement international regulations, for each country worldwide. For this reason, the regulation regime established at regional level is examined, only for the main areas of interest for Kotug. The main areas that Kotug is focusing to operate in the future are Europe, United States of America, Canada and Australia. For these areas the additional existing regional regulations are discussed in section 2.1.1.2. For all other regions it is assumed that IMO MARPOL Annex VI regulations are applied. In fact, all IMO country members and the ones joining in the future will eventually ratify the MARPOL Annex VI. The International regulations and the major anticipated regional regulations, with which the newly built Rotortugs will have to comply, are discussed below.

2.1.1.1 International Regulations [IMO MARPOL]

2.1.1.1.1 GHG emissions

To tackle GHG emissions, in 2011 the IMO adopted an amendment to Annex VI to include two new policy mechanisms: the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). Both mechanisms are already effective and apply for vessels bigger than 400 tonnes GT. The (EEDI) is an index of the average efficiency of ships built between a specific timespan. EEDI is calculated for an individual ship. It is expressed as the ratio of CO_2 emitted over the transportation work carried out. EEDI's purpose is setting a benchmark for CO_2 emission level for new ships. In the upcoming years, based on the EEDI development, there will be a progressive reduction CO_2 level for vessels to comply with, as outlined in Figure 2-1 below. However, currently EEDI is not applicable for tugs, since its formula is based on the cargo-capacity of the vessel. In its place, for application in tugs, a relevant formula that takes into account the tow pull capacity should be developed. The SEEMP is a certificate all boats should keep on-board, that illustrates the fuel efficiency of the vessel and is used to monitor the effects of possible operational changes. Hence, it is required by tugs to retain a SEEMP on-board.

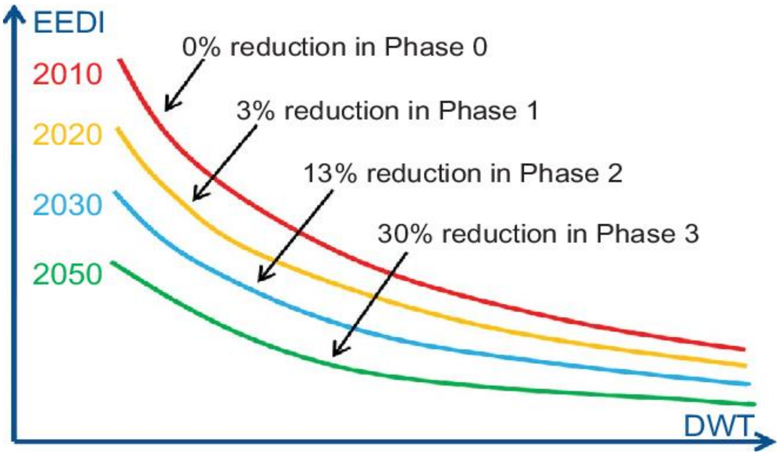


Figure 2-1: CO2 Reduction from EEDI Baseline [google]

Apart from the aforementioned regulations, IMO Data Collection System (DCS) has been already in force from early 2019, applicable only to ships above 5,000 GT. DCS is a fuel consumption data collection system. The objective for this monitoring system is to set the basis, on which a final agreement on targets and complementary measures for mitigating CO_2 emissions can be reached on future MEPC policy debate. Although tugs will not have to comply with this regulation, OGV's affected are estimated to account for almost the 85% of CO_2 emissions from international shipping [1, 2]. Finally, specifically for substances contributing to the depletion of ozone layer, a separate regulation is incorporated in MARPOL Annex VI body. Regulation 12 prohibits ozone-depleting substances emission or installations containing halons and chlorofluorocarbons (CFCs).

2.1.1.1.2 Non-GHG Emissions

Non-GHG emissions are also regulated by MARPOL Annex VI. This Annex sets emissions standards to limit air pollution from the respected pollutants, as outlined in Table 2-1 below.

Table 2-1: Relevant MARPOL Annex VI regulation with regard to the non-GHG air pollutant regulated

Pollutant	**Relevant MARPOL ANNEX VI regulation**
SO_x	Regulation 14
NO_x	Regulation 13
HC/VOC	Regulation 15
PM	No regulations (indirectly by Reg. 14)

Regarding SO_x emissions, Regulation 14 sets limits on the sulphur content of bunker fuels depending on the area of operation. The limit is expressed in terms of % [m/m]. Specifically, certain areas are established, called SO_x Emission Control Areas (SECAs). In those areas the limits are stricter than the rest of the world. The bunkers' sulphur content is progressively expected to decrease based on the year and the area of operation, as illustrated in Figure 2-2. The current sulphur limit for operations outside SECA areas is 3.5 %, but is going to drop to 0.5 % on 1 January 2020 [3]. For SECAs, the sulphur limit is currently 0.1 % and is not expected to be altered in the following years. For ships willing to use fuels with higher sulphur content than the specified, MARPOL Annex VI Regulation 4 provides the alternative of using an approved after-treatment technology instead. For the time being, if scrubbers are used, then SO_x emissions are restricted to a maximum of 6 g/kWh (as SO_2), a limit considered to attain the same reductions in sulphur emissions, as limiting the amount of sulphur using compliant fuel [4]

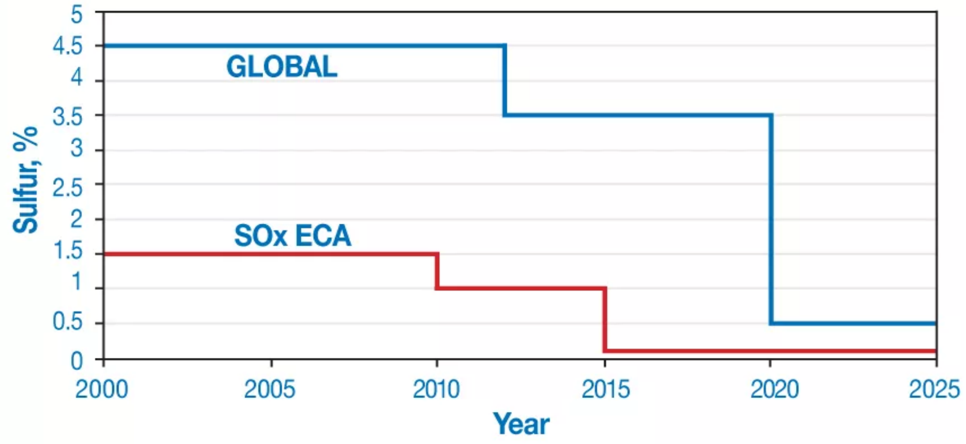


Figure 2-2: MARPOL Annex VI SOx Content Limits [IMO]

Currently, SECAs have been applied in the North Sea, the English Channel, the Baltic Sea, around the coastlines of North America and in the United States controlled part of the Caribbean Sea.[5]

Nitrogen oxide emissions are addressed at Regulation 13. Regarding new ships, the regulation applies to all marine diesel engines, with a power output bigger than 130 kW, to be installed. All ships apart from vessels used for emergency operations should comply with the regulation depending on the construction date of the ship thresholds (IMO Tiers) at which they are established, as highlighted in Table 2-2.

Table 2-2: NOx Emissions Limits and Tier calculations [IMO]

IMO Tier	Ship Construction Date	NOx Limit, g/kWh		
		n < 130	***130 ≤ n < 2000***	**n ≥ 2000**
Tier I	2000	17	45 · n-0.2	9.8
Tier II	2011	14.4	44 · n-0.23	7.7
Tier III	2016†	3.4	9 · n-0.2	2
† In NOx Emission Control Areas (Tier II standards apply outside ECAs).				

The applicable NO_x emission limit for each Tier is a function of the rated engine speed (rpm), as shown in Figure 2-3.

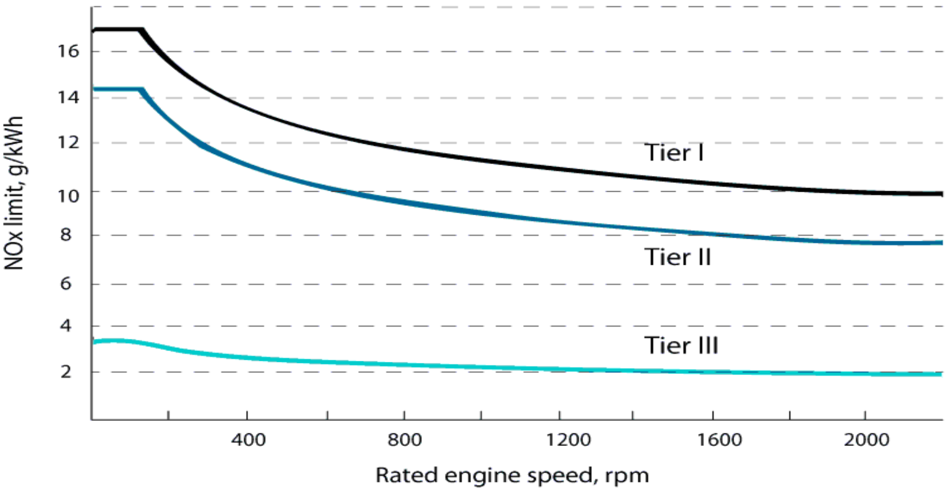


Figure 2-3: MARPOL Annex VI NOx Emisssion Limits [IMO]

Similar to SECA's, certain areas are also designated as NO_x Emission Control Areas (NECAs). Specifically, the already designated SECA's, North American coastlines and the US Caribbean Sea have been designated NECA's as well. When sailing inside these areas stricter limits are imposed. IMO replaced both SECA and NECA terms with ECA (Emission Control Area), covering both SO_x and NO_x emissions. After 2021, Tier III NO_x emission limits will apply in the North Sea and the Baltic Sea as well, designating those seas as ECA's. All ships built after January 1st of 2016 are required to comply with Tier III standards when sailing inside designated ECAs, while, when sailing outside, they must comply with IMO Tier II standards [6]. It is important to point out though that there is a basic distinction between compliance with SO_x and NO_x regulations when sailing inside an ECA area. Ships sailing inside an ECA always have to attain the relevant SO_x limit, while NO_x limits apply only to newly-build vessels [7]. This means that if a vessel is constructed prior to the designation of an area as ECA, then it does not have to attain IMO Tier III standards. In the case of harbour tugs, which are intended to operate in ports and are not expected to travel long distances, they are designed to comply with the regulations applied in the country, where the port belongs. Inside ECA's the reduction potential of NO_x emissions is estimated to be around 70%. Table 2-3 shows the already designated ECAs with their effective dates.

Table 2-3: Emissions and Effective Dates and for ECAs [based on IMO]

ECA	Included emissions / Effective date
Baltic Sea	SO_x : 2005 ; NO_x : 2021
North Sea & English channel	SO_x : 2006 ; NO_x : 2021
North American	SO_x & NO_x : 2012
US Caribbean Sea	SO_x & NO_x : 2014

Regarding particle emissions, there are still no regulations that are directed neither for port vessels nor for OGVs. These emissions are considered to be indirectly regulated by Regulation 14. The reason is that research has shown a correlation between the sulphur content of the fuel and the mass emissions of particles. Precisely, low-sulphur marine distillate fuels are emitting fewer particles than residual fuels [8].

HC/VOC, are addressed in Regulation 15. Under this regulation, the loading procedure of tankers at terminal is regulated. In particular, all crude oil tankers are supposed to implement and use an effective VOC management plan and install on-board a Vapour Emission Control System (VECS), in order to control VOC emissions.[5] Since, this regulation applies only to tankers, it is not applicable for tugs.

So far CO emissions are not regulated at all.

2.1.1.2 Domestic Regulations

Ships that are operating or allowed to enter into a country's territorial waters are obliged to comply with the existing national regulations, which may complement or overlap the existing international regulations. The main areas that Kotug is intending to operate in the future are Europe, the United States of America (USA), Canada and Australia. The USA, Canada, Australia and most of the European countries are already IMO members, which have ratified MARPOL Annex VI convention. However, additional regional regulations, usually stricter could exist. Thus, for tugs designed to operate in these areas, all applicable regulations have to be taken into consideration. Hereafter, the additional existing regional regulations are discussed, with the focus set strictly on the regulations affecting harbour tugboats.

2.1.1.2.1 Europe

In Europe, at regional level, the European Union (EU) regulation regime is worth investigating. Next to the international authorities the European Commission provides also legislation for air pollution, for ships that enter their territorial waters. EU laws are enforced through fines on vessels that sail on seas within its borders. Outside its border the enforcement lies on IMO. In domestic level, the regulation regime in the rest of countries belonging in Europe, as a continent, has not been investigated. However, it is reasonable to assume that the emission regulation regime established in EU is stricter than each individual non-EU member country's national regime. Non-EU member countries, which have ratified IMO MARPOL Annex VI convention, will be subject only to that laws.

The most important regulation is the Directive 2012/33/EU, known as EU low-sulphur Directive. Under this directive all ships, irrespective of flag, type, age or tonnage, when at berth or anchored in EU ports, as well as in-land waterway vessels are obliged to burn marine fuel with a sulphur content not exceeding 0.1 per cent by mass. This applies to all engines or equipment (e.g. boilers) burning all types of marine fuel. However, an exception is granted for ships at berth that use shore-side electricity (i.e., cold ironing) or an approved after-treatment technology is employed. [4] Besides this, worth noting is that a sulphur limit for marine distillates sold in the EU territory is in place. Specifically for Marine Gas oil (MGO) and Marine Diesel Oil (MDO) the limits are 0.1 % and 1.5 % sulphur content by mass respectively.[9] Furthermore, EU is planning to align legislation with MARPOL Annex VI standards in the future with the purpose of limiting the greenhouse emissions even further. To accomplish the alignment a set of dedicated measures; the so called "Sustainable Waterborne Transport Toolbox" is promoted. Measures planned will promote the use of alternative fuels and "green ship technology", while funding for the development of "green transport infrastructure" will be granted. [10]

At the European Union level, there is an additional legislation regime, the so-called Non-Road Mobile Machinery (NRMM), which regulates all off-road engines emissions. Regulation (EU) 2016/1628 sets requirements regarding NO_x, THC, CO and PM emissions, expressed as mass of emissions per engine work (g/kWh), that apply to ships on inland waterways.[11] Harbour/terminal tugs operating in EU ports have to comply with this regulation regime. The permitted emission standards are a function of the keel-laying date of the vessel and the category of the engine. The engines are divided in categories based on the cylinder displacement and the engine power. Specifically, for newbuildings, EU Stage IIIA regulation applies until 2019, after which Stage V regulation is phasing in. EU Stage V regulation apart from setting stricter limits, will also limit the number of particles (PN) emitted, in addition to the size of emitted PM. [9, 12] . It is stressed that in EU Stage V regulations a limit in CH_4 emissions originating from gas-burning engines with a power output over 19kW is included for the first time. That limit is not a dedicated direct limit in methane, it is contemplated via the total hydrocarbons emitted. The regulation standards can be found in Appendix D.5.

2.1.1.2.2 United States

In the USA, the Environmental Protection Agency (EPA) is responsible for setting the emission standards. The US EPA has implemented MARPOL Annex VI in its national legislation. However, domestically EPA has established in 2000 marine engine standards, which are applicable to either US or foreign-flag vessels while operating in their territorial waters. In short, commercial marine engines are classified into three (3) categories, based on their displacement volume; Category 1: under 5 litres; Category 2: 5 to under 30 litres; and Category 3: 30 litres and above.[13] Then, depending on cylinder displacement and engine power they are allocated into subcategories. Similar to IMO's MARPOL Annex VI Regulation 13, each subdivision has Tiers of reducing emission limits, as highlighted in Figure 2-4. The basic difference between IMO and EPA lies in the fact that IMO limits only NO_x emissions, while EPA regulates also PM, CO and NMHC/VOC emissions. Moreover, EPA Tier 4 is aligned with IMO Tier III standards, concerning NO_x emissions

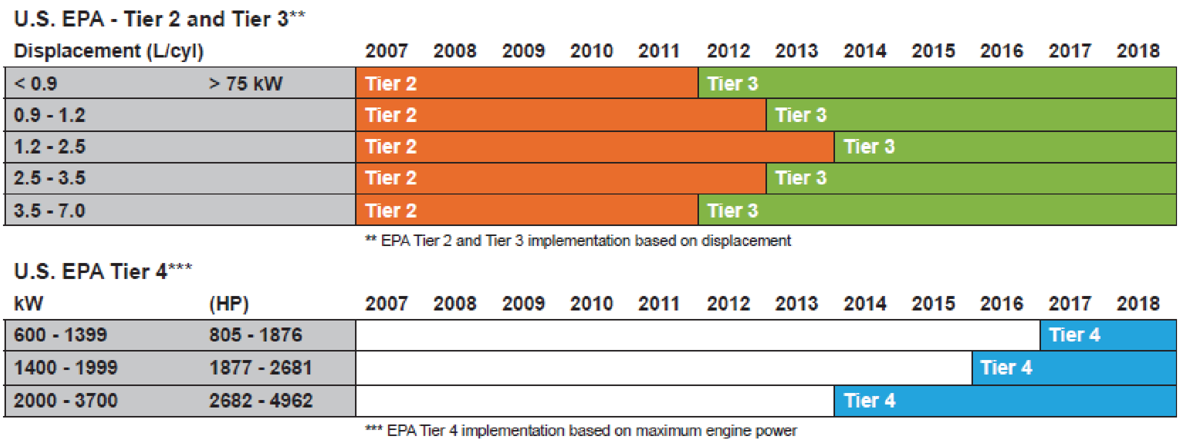


Figure 2-4: US EPA Tier implementation timetable [J. Herdzik]

Tugboats propulsion and auxiliary engines are either Category 1 or Category 2. Harbour tugboats are mostly equipped with Category 1 engines, while some of the larger assist tugs and most oceangoing tugboats are equipped with Category 2 engines.[14] US EPA Tier 4 emission requirements started phasing in January 2014, therefore all new engines with brake power greater than 600 kW must meet EPA Tier 4 standards by October 2017, while engines less than 600 kW must meet EPA Tier 3 standards. [15]

Finally, similarly to the EU legislation regime, after 2014 EPA established a sulphur limit applying in all marine distillate diesel, designated as Nonroad, Locomotive and Marine Diesel (NRLM), fuels sold in the US territory. Under EPA 40 CFR Part 80 Subpart I "Sulfur limits for marine diesel fuel" regulation the limit has been set at 15 ppm, considerably lower than the 1000ppm limit imposed in the EU and inside IMO ECA areas, in order to promote the use of Ultra Low Sulphur Diesel (ULSD) fuels or the use of abatement emission methods, as an equivalent to attain the same reductions in sulphur emissions. [13, 16] Such abatement methods would most commonly involve the installation of a scrubber system, but that would apply to OGVs. For tugboats, with limited space available, this regulation mandates the bunkering of ULSD fuel.

Not only that but two critical differences also appear between the EPA and the EU imposed standards with regard to particle and hydrocarbon emissions. Specifically, with regards to the imposed limit on

- hydrocarbons, EPA standards are imposing a limit only to the NMHC emissions excluding methane, irrespectively of the engine and/or fuel type. On the other hand, EU standards are not excluding CH_4 by limiting the THC, as discussed previously.
- particles, EU Stage V regulations, in contrast to EPA regulations, introduce an additional limit on the number of particles of $1x10^{12}$ #/kWh for all engines above 300kW, irrespectively of the combustion fuel or their type (constant/variable-speed or propulsion/auxiliary use), which phase in beginning of 2020, apart from the set limit on particle mass.

Kotug is planning to enter the United States market through making alliances with domestic companies, by forming a joint venture. Therefore, Rotortugs operating in the area will need to sail under the US flag. Since, EPA Tier limits will apply to domestically operated engines it means that Rotortugs will have to comply with EPA rules, instead of IMO's rules and thus comply with the 15 ppm sulphur limit provision. Detailed information about EPA Tier emission limits can be found in Appendix D.5.

2.1.1.2.3 Canada

From 2013, ships sailing or operating in Canadian territorial waters have to comply with MARPOL Annex VI Regulations. However, from 2016 Category 2 engines, according to EPA's classification system, on vessels sailing under the Canadian flag should comply with U.S. EPA requirements or hold a certificate issued by another country, which is considered equivalent. IMO's requirements apply for the rest. Engines on vessels with keel-laying date in 2017, are exempted from IMO Tier III provision, if the combined propulsion power is less than 750 kW. [15]

2.1.1.2.4 Australia

Ships sailing or operating in Australian territorial waters have to comply with MARPOL Annex VI Regulations.

2.1.1.3 Other controls

Policy makers by internalizing the external costs of air pollution might enforce a series of measures which could be combined with incentives to the end-users, in order to reduce the abatement costs due to air pollution impacts. For this reason, in some regions, emissions are also controlled by taxes and incentives. Local authorities are often developing various market-based incentives to accomplish further emission reductions. Especially ports themselves are in the forefront by implementing policy initiatives that are either facilitating the transition to upcoming more stringent regulations or act complementary to the regulations. Those ports are providing incentives targeting primarily OGV's approaching, usually by imposing a fuel switch over procedure, from residual fuels to distillates, or speed reductions. The benefits are lower port tariffs. Examples of ports offering differentiated port dues, are the port of Vancouver and the ports belonging in the Norwegian and Sweden territory targeting sulphur and nitrogen dioxide emissions. The way that various ports are introducing differentiated port dues is usually based on indexes, like the Environmental Shipping Index[1] and the

[1] Environmental Shipping Index (ESI) – an index used for scoring OGV's regarding their environmental performance. The intension of the index is to measure both OGV's air pollutants emissions and energy efficiency. Then it can be used from ports to reward "green" ships or by ship owners as a tool for fleet bench-marking 17. WPCI, *Environmental Ship Index ESI*. 2017. 18. Lam, J.S.L. and T. Notteboom, *The greening of ports: a comparison of port management tools used by leading ports in Asia and Europe.* Transport Reviews, 2014. **34**(2): p. 169-189.

Clean Shipping Index[2]. [20] Furthermore, in some cases OGV's while at berth are obliged to use the existing shore power facilities. Cold ironing might be a core strategy for other type of ships, anchored at ports in the future.

2.1.2 Compliance

Check of compliance and enforcement measures require reliable reports that document compliance (e.g. use of technology) as well as demonstrating compliance by periodic inspections and surveys. The compliance according to the provisions of IMO MARPOL Annex VI for the regulations applicable to tugs is going to be discussed next.

2.1.2.1 CO_2 compliance

Concerning CO_2 emissions, a SEEMP certificate, as explained in section 2.1.1.1 should be retained on-board at all times.

2.1.2.2 SO_x compliance

Concerning SO_x emissions, ship operators are required to keep samples of the fuel on-board. These samples are subject of a verification procedure by an authorized representative, in accordance with a test method (ISO 8754:2003), as described in the "Fuel Verification Procedure for MARPOL Annex VI Fuel Oil Samples" in the appendix VI of MARPOL Annex VI.

2.1.2.3 NO_x compliance

Each ship demonstrates compliance with the NO_x regulation, if granted an International Air Pollution Prevention (IAPP) certificate. The Certificate is issued, after a survey performed by the flag State or a classification society acting on behalf of the responsible authority. This certificate is subject to renewal every five (5) years. The certification process is done in accordance with the requirements set in IMO's NOx Technical Code 2008. This code requires all marine engines installed on-board to be accompanied by their distinct Technical File. This file contains information concerning the specifications and allowable setting values for all the engine's components affecting NO_x emissions and must be kept on-board. The verification process, for issuing the IAPP Certificate, includes by carrying out measurements to determine in service compliance, after installation. The testing procedure is performed according to ISO 8178 test cycles, found in Appendix D.6. [21] Vessels should comply at all times. For this reason, in periodic inspections compliance is determined either by checking that all equipment components show correspondence with the ones specified in the Technical File or by carrying out measurements.

2.1.2.4 PM, CO, HC/VOC compliance

The rest of the primary air pollutants are not regulated. Therefore, no compliance procedure exists.

The enforcement of the regulations in countries that have not adopted the IMO convention, is following similar principles. It is outside the scope of this thesis to delve into an extensive comparison of compliance procedures followed in different parts of the world. It should be mentioned though, that in general in many countries, including the United States the verification testing is done based on an equivalent test cycle to ISO 8178. Moreover, in Europe the majority of countries have ratified IMO MARPOL Annex VI convention, therefore compliance is demonstrated according to the convention's requirements. For, this reason in this thesis, the compliance with the relevant regulation will be determined based on the ISO 8178 specifications. Elaboration on the testing principles are provided in Appendix D.6.

[2] Clean Shipping Index (CSI) – a tool developed for cargo-carrying ships. It can be used either for fleet bench-marking; it measures a ships environmental performance or as a marketing aid in the selection process between potential ship operators looking for "green" ships in the market. 19. CSI. 2017.

2.2 Future outlook

In the future, air pollution by shipping will continue to be regulated. International aviation and shipping are the only transport modes that non-GHG emissions have increased since 1990.[22] According to future scenario studies, presented in the Third IMO GHG study (2014), maritime CO_2, NO_x and CH_4 emissions are expected to grow while PM and SO_x emissions are expected to decline by 2050. Specifically, CO_2 emissions are expected to grow by between 50 percent and 250 percent. NOx emissions are predicted to increase at a lower rate than CO_2 emissions, because new Tier III compatible engines will replace the old ones. CH_4 emissions are also going to increase rapidly, as a result of the anticipated increase in the use of Liquefied Natural Gas (LNG) as combustion fuel in marine gas engines. On the other hand, emissions of particulate matter and sulphurous oxides are projected to decline until 2050, as a result of the substitution of residual fuels by distillates.[23]

Researchers agree on the necessity to slow down the predicted rise of GHG emissions, to keep the global temperature rise below 2 degrees C, the target set by the Paris Agreement. Thus, there is a need for stricter regulations and perhaps even the introduction of other measures to ensure achieving the goal. Furthermore, as explained in Appendix A.2.2 ports will concentrate their efforts mainly in the decrease of NO_x and PM emissions, which are directly affecting the health of the local population. Hence, harbour tugs are going to be the target of future more stringent air pollutant regulations but also incentives. Next, a summary of the anticipated evolvement of regulations will be attempted focusing on the implications on tug operations.

2.2.1 Regulations

Taking into consideration that new standards are phasing in the upcoming years, both at international and domestic level, as discussed in the previous section, it is assumed that a change in regulations is not so probable in the next 5 years at least. However, it is reasonable to assume that given the fact that regulations at an international level are more lenient than regional regulations enforced in the two most developed continents of the world, complemented by the fact that certain exhaust air pollutants are not directly regulated, favours the hypothesis that regulations will be reformed in the foreseeable future. Finally, it is safe to assume that emission regulations in other countries, where such legislative regime is not already in place, will be introduced at least at the level imposed by IMO MARPOL Annex VI convention. It is not improbable to even align with either the US or EU regulations.

For greenhouse gases, the problem has not yet been resolved. Even though it is generally recognized that shipping accounts for about 2.2 percent of the total greenhouse emission volume, under the climate change context, further reduction policies are expected to continue being discussed internationally.

Regarding CO_2 emissions, the most important measure concerning tugs would be an amendment to EEDI so that it can be applied to non-transport vessels as well. Compared to its contribution to climate shipping sector's, because of its market global warming effect, CH_4 emissions have received little attention at international level. In European on-highway regulations, EU5 and EU6, a methane limitation has already been introduced for gas engines.[24] Furthermore, in Canada, methane is actively addressed in greenhouse gas reduction (policies and regulations) in Alberta and British Colombia. In the U.S climate change is referred to in regulation in Alaska and Texas and recently in a new regulation in Colorado.[25] Methane limits will be for the first time imposed on off-road machinery equipment in EU through EU Stage V standards, phasing in 2019. The set limits are targeting indirectly methane originating from gas-burning engines, by limiting the THC. A general consensus is reached between engine manufacturers that the imposed limit is rather lenient. Most engine manufacturers claim that the methane limit would be easily attained only with primary measures; engine modification methods (see section 3.1). To this end, the THC limit for gas engines, in EU regulations is expected to become stricter, but probably not before extensive demonstration of gas-engine emission performance is performed. US is anticipated that would also introduce a limit for methane, as gas-engine uptake is enhanced, probably by setting a dedicated limit for CH_4. To conclude, methane emissions could potentially pose a problem, in view of the anticipated increase of

LNG use in marine engines. It is the natural step to expect methane emissions from marine engines in the future to be regulated at both international and domestic level worldwide.

Regarding non-greenhouse gases, shipping has a significant contribution to the total volume of anthropogenic air pollution. Authorities are expected to intensify their effort for further emission reductions.

The regulation of SO_x emissions targeting international shipping in comparison to land-based sources is still weaker. In Europe, for instance the maximum limit in sulphur content for diesel is 10 ppm [0.0010% m/m]. For comparison, the limit inside ECA's for marine diesel is set at 1000 ppm [0.10 % m/m], 100 times bigger than the road limit. However, at least for the next 15 years, which is the time horizon under study, it is not anticipated to regulate a smaller sulphur limit for marine diesel fuels. There is already doubt on the ability of the bunkering industry meeting the demand for low-sulphur fuel after 2020, when the global sulphur cap phases in. The most probable scenario for lowering SO_x emissions from shipping overall, is to establish more ECA's. Eventually, the global limit might follow a stepwise reduction to the current ECA limit. Nonetheless, a differentiated sulphur cap might be established for domestic shipping. A stricter limit of 15 ppm, as mandated by EPA Nonroad Diesel Equipment Regulatory Program, might be imposed to marine distillates intended for use in domestic vessels. This means that harbour crafts may have to bunker ULSD or be equipped with suitable after-treatment technologies. Anyhow, stricter sulphur limits should be expected in the future.

NO_x emission are also considered weak. The problem is that new Tier III regulations, even though they limit substantially NO_x emissions, 75% compared to Tier II, are only applying inside established ECAs and target specifically newbuildings. This means that existing vessels will continue to produce significant quantities of NO_x. Another issue is that ships which have to comply with current Tier III regulations are the ones constructed after the date that area effectively became an ECA. This means that a considerable time between the date of adoption until the amendment becomes enforceable passes. This can be fixed if the adoption date is chosen as an effective date. Apart from that, the extension or introduction of new ECAs would contribute to greater NO_x reductions However, eventually a global approach, bringing NOx limits down to Tier III levels should be expected. Due to the detrimental effect of NO_x emissions in ports, local authorities might establish differentiated emission limits targeting certain type of ships. In such case a probable scenario would be that all harbour vessels will have to comply with IMO Tier III limits.

So far PM emissions are not directly regulated in MARPOL Annex VI. Standards have been included though in EPA and EU inland waterways legislation. Specifically, in the newer version of EU inland regulations (EU Stage V) phasing in 2019, additional quantitative emission standards on particle emissions have been included. Quantitative standards have long been introduced for on-road engines, i.e the so-called Euro standards for trucks. Special consideration might be placed in limiting Black Carbon (BC) emissions. "Black Carbon is a component of PM mass, which is dependent on the combustion source". [26] Black Carbon is an important contributor to climate change. Black Carbon emissions when in contact with ice are colouring it black. This means that ice is melting faster because it absorbs more of the sun's energy. The melting of snow in the Arctic is a global concern, because it affects the climate change. To conclude, it is expected that IMO will consider adopting eventually regulations limiting PM, and probably the emission limits will be set both for the particle mass and the number of particles.

CO and NMHC/VOC emissions are not directly regulated in MARPOL Annex VI either. CO and HC/VOC emission levels are considered low, in the range of 0.1 to 0.3 g/kWh.[27] Therefore, in international level efforts are concentrated in reducing the other pollutants. NMHC and CO limits have already been established both in EPA Tier 3 and EU Stage IIIA standards from 2012. Taking into account that new standards are phasing in the upcoming years at regional level, as discussed in the previous section, it is assumed that a change in regulations in US or EU is not so probable for these specific combustion-related emissions in the next 15 years. However, it is reasonable to assume that in other countries domestic regulation regimes, an alignment with either the US or EU imposed standards might be attempted.

2.2.2 Other Measures

In order to accomplish greater emission reductions additional incentives or other measures are complementing existing regulations in various areas. Especially ports themselves are in the forefront by implementing policy initiatives that are either facilitating the transition to upcoming more stringent regulations or act complementary to the regulations. The aim of the incentives is to encourage the adoption of technologies or practices that show improvement in energy efficiency and emission abatement. It is outside the scope of this report to identify all options or schemes proposed. One of the most prominent measures, examined by IMO is the regulation of slow steaming for international shipping. It is estimated in various reports, that a 10% decrease in global average speed would lead to 19 per cent CO_2 savings.[12] Furthermore, in IMO, there are numerous proposals discussed for the implementation of Market-Based Measures (MBM), which are targeting international shipping. The two basic schemes are the establishment of an emission trading system or the creation of an international fund for GHG emissions.

Among the strategies considered, an indication of suggestions that could implemented and would directly affect harbour tug operations could be:

- Cold ironing necessity for ships, anchored at ports
- Regulating fuel sulphur content in the market
- Incentives given for use of low-carbon fuels
- Funding of “greener” vessels (Hybrid, Full-Electric vessels)
- Limiting greenhouse gas emissions along the supply chain
- A global emissions trading scheme
- A tax scheme for specific air pollutants (NO_x , CO_2)

The actual choice between the aforementioned choices will depend on the local governmental willingness to strengthen mitigation measures and the environmental awareness of the local population. However, the tone will be set according to the global approach decided in IMO. Examining the effects of possible market-based measures in the emission abatement potential of newly built Rotortugs lies outside the scope of this thesis. Only one emission reduction strategy is going to be considered; cold ironing. This strategy is going to be discussed in the next chapter. In this thesis, emphasis is given in the emission reductions through more-efficient engine configurations, and alternative fuels. However, the effect of internalizing the external costs of air pollution upon the cost-effectiveness of the considered alternative options is going to be explored in Chapter 6, with the intention of providing to the ship-owner a rational for contesting for funding from a port-authority.

Finally, current and possible future ECA areas are indicated in Figure 2-5. Some new ECAs in the Mediterranean Sea, Mexico[3] and Panama, Singapore, Japan, Korea, Australia, the Arctic and Antartica may enter into force in the coming years [3, 29, 30] Eventually, all coastal areas worldwide could be designated ECA areas, but this is highly unlike for the next 15 years to happen.

[3] In June 2016 at the North American Leaders Summit, a joint commitment was established to work together for finalizing and submitting to the IMO a proposal for designating Mexico as an ECA.28. EPA. *Collaboration with Mexico to Reduce Emissions from Ships*. 2107; Available from: https://www.epa.gov/international-cooperation/collaboration-mexico-reduce-emissions-ships.

Figure 2-5: Existing and Future ECAs in the World [IMO]

2.3 Conclusions

This chapter identified the main regulations, both at international and regional level, which apply to newly built tugboats. Rotortugs, as harbour vessels need to comply not only with IMO MARPOL Annex VI regulations, but also with local regulations, depending on the port of operation. It has to be noted that so far PM, CO and HC/VOC emissions are not directly regulated at international level. Nonetheless, these emissions are regulated locally; in the United States and in the European Union. Regarding GHG emissions, it is concluded that all measures regulated until now are not targeting tugboats. Efforts are concentrated mainly in decreasing NO_x and SO_x emissions. ECA areas have been designated in various parts worldwide and more could follow in the next 15 years; inside these areas stricter limits are imposed. Specifically, the limit inside ECAs for marine diesel is set at 1000 ppm [0.10 % m/m], while concerning NO_x emissions, Tier III limits must be attained. It must be highlighted though that if a vessel is constructed prior to the designation of an area as ECA, then it does not have to attain IMO Tier III standards while it still has to comply with the SO_x limit. Besides this, worth noting is that a sulphur limit for marine diesel distillates sold in the EU and the US territory are in place of 1000 ppm and 15 ppm respectively. To this end, tugs operating in EU and US harbours are directly affected. Moreover, it is the natural step to expect methane emissions from gas engines in the future to be regulated, in view of the anticipated increase of alternative fuels use in marine engines. In the next chapter, the emission reduction measures will be presented, with the focus set at the contribution of alternative fuels, when combusted on different engine concepts. Finally, apart from the legislative framework voluntary or other compulsory measures introduced for mitigating the effects of exhaust air emission from ships were briefly discussed. Cold ironing, as emission reduction strategy is going to be considered in more detail in the next chapter.

3 Energy sources and technologies

Chapter 2 introduced the steps taken to address the air pollution problem through regulations and other measures, with the focus set at tugboats. This chapter will summarize important aspects of the alternative fuels under consideration for marine use. Initially, the various emission reduction measures, introduced in the shipbuilding industry, are presented. Emphasis is given in the after-treatment technologies that can be employed in tugboats for ensuring compliance with the international but also with the upcoming more stringent regional regulations. The rationale for the need of introducing alternative fuels to address the emission problem, is provided. Following, Kotug's practice for complying with the current emission regulations is presented. Kotug is using MGO, a marine distillate fuel with low sulphur content for their entire fleet worldwide, to comply with SO_x emission regulations. Hence, in this thesis, MGO's sulphur content, serves as the limit for selecting appropriate alternative fuels. An alternative fuel has to surpass certain barriers to enter the market. The parameters that constitute an alternative fuel appropriate for use in a tugboat will be discussed, with the intention to offer a better understanding of the complexity of the selection process to the reader. The alternative fuels that satisfy a range of criteria are selected. Finally, the characteristics of the associated prime movers, burning the selected fuels, are addressed and a reference to alternative energy storage methods is made.

3.1 Emission reduction measures

Compliance with the upcoming regulations concerning the adopted and planned air emissions limits and/or market-based measures are drivers for the development of methods for reducing air emissions. The measures introduced in the shipbuilding industry, in order to reduce maritime exhaust gas emissions, can be categorized in two broad categories, technical and operational measures. Technical measures include measures improving energy efficiency and other emission-reduction strategies. Energy efficiency measures comprise of fuel saving strategies, which will consequently reduce fuel-related exhaust gases emissions. Emission-reduction strategies can target a single air pollutant or a combination of pollutants within the exhaust gases. Emission-reduction strategies are further subdivided into pre-treatment of the fuel, engine modification methods, and "end-of-pipe solutions" or "post-combustion" according to [31].

Indicative energy efficiency measures are:

1) The design of ship hulls for reduced resistance
2) Energy-saving techniques (either as appendages on hulls or waste-heat recovery)
3) The efficiency optimisation of power and propulsion systems.

The major emission-reduction strategies are:

1) Pre-treatment of the fuel
    a. The use of alternative fuels
    b. De-nitration of fuel
2) The use of after-treatment equipment ("end-of-pipe solutions)

   a. Exhaust Gas Scrubbers (EGS), or Scrubbers as they are more typically known, for SO_x
   b. Selective Catalytic Reduction (SCR) for NO_x
   c. Particle filtering for PM
   d. Oxidation catalysts for HC and CO
3) Engine modification methods
   a. Advanced combustion modifications
      i. Humidification
      ii. Water emulsion
      iii. Miller timing
   b. Exhaust Gas Recirculation (EGR) for NO_x

Operational measures include measures that are aiming at energy management techniques. The most common are:

1) Operation at reduced speed
2) Weather routing
3) Optimized hull and machinery maintenance scheduling
4) Traffic management and control systems
5) Improved fleet planning.

[27, 32-34]

In the Second IMO GHG Study (2009), emission-reduction methods targeting the primary exhaust gas pollutants are listed and the factors from which their subsequent reduction is dependent are explained. [35] has listed several of the above-mentioned methods together with their reduction potential. In Table 3-1, the reduction potential of various methods, related to their respective targeted air pollutant are presented, as compiled from the literature review conducted, including papers and feasibility studies.[11, 26, 34, 36] In order to achieve the target of ships exhaust gases emission reduction, a set of the abovementioned techniques could be applied separately or in combination.

Table 3-1: Overview of available methods for reducing emissions and their reduction potential [compiled from various sources]

<table>
<tr><th>Component</th><th>Reduction method</th><th>Potential reduction</th></tr>
<tr><td rowspan="5">NO_x</td><td>Selective catalytic reduction (SCR)</td><td>Up to 99%</td></tr>
<tr><td>Emulsification</td><td>20-25%</td></tr>
<tr><td>Humid air</td><td>70%</td></tr>
<tr><td>Engine tuning</td><td>50-60%</td></tr>
<tr><td>Exhaust gas re-circulation</td><td>10-30%</td></tr>
<tr><td rowspan="2">SO_x</td><td>Fuel Switching Process*</td><td>60-90%</td></tr>
<tr><td>Sea water scrubbing. Exhaust below water line</td><td>Up to 95%</td></tr>
<tr><td>CO_2</td><td>Energy Management</td><td>1-10%</td></tr>
<tr><td rowspan="2">PM</td><td>Electrostatic filters</td><td>Up to 85%</td></tr>
<tr><td>Diesel Particulate Filters</td><td>>90%</td></tr>
<tr><td>HC</td><td rowspan="2">Oxidation Catalysts</td><td>Up to 95%</td></tr>
<tr><td>CO</td><td>Up to 97%</td></tr>
<tr><td colspan="3">*Switching from residual fuel to distillate fuel</td></tr>
</table>

It is important to remind to the reader though the existing trade-off between HC/VOCs and CO emissions with NO_x, for NO_x targeting reduction measures, either than SCR, as stated in Chapter 2.

Specifically, they show a reverse trend; when NO_x decrease, they tend to increase. The same trade-off exists also between NO_x and PM. However, this trade-off is not anticipated to unescapably remain in the future. Further combustion related improvements in engines, could result in simultaneous improvements for some of the aforementioned emissions. [27, 37]

3.2 Kotug's compliance strategy

In this section the mainstream strategies ship-owners use to comply with IMO MARPOL Annex VI regulations are discussed. Next, Kotug's approach for complying with these regulations is presented and the next steps for compliance with the upcoming more stringent emission regulations are introduced.

3.2.1 Current situation

Traditionally marine transportation uses diesel fuels in internal combustion engines. Diesel fuels suitable for on-board use are classified based on their degree of processing. There are two basic types - residual oils and marine distillates. A third type is the intermediate fuel, which is a mixture of these two. The International Standard Organisation (ISO) has classified diesel fuels based on their related grade, as indicated in ISO 8217, and assigned them coded names. Distillate fuels start with 'DM', Intermediate with "IFO" and Residual with 'RM'. The basic differences between them are three, the density, the viscosity and the sulphur content. [4]

Table 3-2: Classification of diesel fuels according to ISO 8217

Fuel Type	Fuel Grade	Common Industrial Name	Characteristics
Distillate	DMX, DMA (called MGO)	MGO	Light distillate fuel, low viscosity, low levels of impurities
	DMB (called MDO) & DMC, DMX	MDO	heavier distillate, may contain some residual components
	ULSD	ULSD	Light distillate fuel, low viscosity, low levels of impurities, no more than 15 ppm sulphur content
Intermediate	IFO 180 - IFO 380	Intermediate fuel Oil (IFO)	Heavy fuel oil that might contain distillate fuels
Residual	RMA-RML	HFO	Residual fuel with the highest viscosity and highest levels of impurities. Individual Grades are designated by the letters A through to L and a number signifying the viscosity limit

The most common fuel used on ships today is Heavy Fuel Oil (HFO), which is considered a residual product, accounting for 80-85% of the total merchant fleet fuel consumption [33]. The emission factors of CO_2 and NO_x are considered high. HFO contains a wide range of undesirable contaminants, such as sulphur, ash and sodium. Typically, it has a sulphur content of at least 1 %. HFO does not meet the sulphur regulations without the use of after-treatment technology (scrubbers).

The most common marine distillates are Marine Diesel Oil (MDO), Marine Gas Oil (MGO), and Ultra-Low Sulphur Diesel (ULSD) all considered low-sulphur distillate oils. MDO contains lower concentrations of sulphur than HFO, but still the sulphur content by weight remains quite high at 1.0%. MGO is a distillate fuel with an even lower sulphur content than MDO, usually less than 0.1

wt% sulphur, due to the refining process. ULSD contains the lowest sulphur content compared with the other distillates, up to a maximum of 15 parts-per-million (ppm)[4]. [38] All distillate fuels do not differ substantially compared to HFO in terms of CO_2 and NO_x emission factors.

As mentioned in section 2.1.1.1, the two basic international regulations ships have to comply with at the moment are MARPOL Annex VI regulations 13 and 14, which set limits on sulphur and nitrogen oxides emissions respectively. The mainstream strategies ship-owners use to comply with those regulations are:

As far as SO_x is concerned, two are the main strategies:

- Continue using HFO but install an "end-of-pipe solution" (scrubber)
- Use of Distillate Fuels (MGO, MDO or ULSD)

As far as NO_x is concerned, it depends whether the vessel needs to meet Tier II or Tier III standards:

- In the case of Tier II: Installation of a commercial engine combusting either residual or distillate fuels in combination with advanced combustion modifications would suffice.
- In the case of Tier III though, it would require one of the following strategies:
  - The use of a diesel engine in combination with EGR
  - The use of a diesel engine in combination with an after-treatment technology (SCR)
  - The use of an engine combusting Liquefied Natural Gas (LNG)

3.2.2 Kotug's approach

Today Kotug's entire fleet of Rotortugs is using MGO to comply both with the 0,1% wt sulphur content-limit and existing Tier II NO_x standards. As stated, the sulphur content of MGO is less than 0,1%, enabling compliance with Annex VI sulphur limits for marine fuels, while the installed diesel engines are Tier II certified. Those engines are 4-stroke high-speed compression ignition engines, and a verification for their NO_x emission performance can be found in their respective NO_x Technical File. The use of MGO as a fuel also leads to reductions in PM in exhaust gases, as a result of less sulphur content in the fuel. The range is estimated from 50% to up to about 85% compared to HFO, although the actual reduction percentage can only be verified after measurements from engine manufacturers, as highlighted in [39] report. Apart from that, MGO is a technically proven fuel with an existing infrastructure and market in all operation parts worldwide [4, 16].

However, greenhouse gases, as stated before, will remain at the same level as when using HFO and further reduction of NO_x emissions to Tier III limits will necessitate the pursue of a different strategy. Selective Catalytic Reduction (SCR) is considered by scientists the only reliable way presently, capable of achieving reduction of NO_x to Tier III limits. [16, 27, 40] This means that internal combustion engines installed in Kotug's tugboats today, cannot comply with NO_x Tier III in ECAs, without SCR after-treatment system fitted. Moreover, engines combusting MGO do not constitute an attractive choice concerning the CO_2 reduction potential either.

Since MGO is used as a fuel in Kotug's fleet, it will be considered the baseline fuel for complying with IMO MARPOL Annex VI regulations in this thesis. MGO is considered to be the fuel of the DMA grade as stated in ISO 8217. As a solution for complying with NO_x Tier II regulations, the same 4-stroke compression-ignition diesel engines running on MGO will suffice, while for complying with NO_x Tier III regulations, the use of the same Tier II certified 4-stroke compression-ignition diesel engines complemented by SCR technology will be considered as the baseline case. However, for constituting newly built Rotortugs compliant with regional regulations but also as an option for enhancing their emission reduction potential, Kotug is considering the use of alternative combustion

[4] 1 ppm = 0.0001 %[kg/kg fuel] = 0.0001 % mass base = 0.0001% wt = o.ooo1 % percent

fuels in appropriate prime movers complemented by additional after-treatment technologies targeting the rest of the combustion-related pollutants. For this reason, in the next sections the alternative fuels and their associated prime movers along with the after-treatment technologies which were considered suitable, complemented by a justification of the compatibility for use in tugboats, will be presented. It is stressed that specifically for complying with the EPA regulations, the baseline fuel will be ULSD instead of MGO, because of the imposed regulation. Apart from the lower sulphur content of 15 ppm, the rest of ULSD specifications are similar to MGO. Finally, Kotug will use shore power for its fleet of Rotortugs, in ports where cold ironing is a requirement. The environmental benefits of cold ironing are discussed in section 3.6.

3.3 Alternative fuels

There are several available alternatives to conventional diesel fuels that can be envisaged as part of the tugboats' future fuel mix. It was not the objective of this thesis to investigate all "theoretically" possible fuel alternatives for marine use. A pre-selection of alternative fuels has taken place, primarily based on the literature review. Please refer to Appendix B, for a detailed assessment of the considered alternative fuels.

*3.3.1 **Energy transition (Sustainability)***

The energy sources currently used in society are mostly non-renewable. Oil, coal, and natural gas are the three dominant fossil fuels used today, representing approximately 83 % of the global primary energy usage in 2016. [41] In the book written by [5] is stated that the dominant opinion between scientists is that "the supplies of oil and gas are expected to be seriously diminished by the middle of the twenty-first century". In [42] report different pathways for the decarbonisation of the shipping sector were assessed, so that the target set by the Paris Agreement is achieved. The findings of that report are that "most of the pathways will require a substitute for fossil fuel, because energy efficiency improvements alone will not be sufficient in the medium to longer term". This leads to a need for diversification of fuel sources, towards renewable energy alternatives. The drivers behind this transition are justified by the anticipated scarcity of fossil fuels, which will result in higher prices, the need for securing the continuously increased demand for fuel supply to meet transportation needs, and the binding legislative target for mitigation of exhaust air emissions. [43] The percentage of renewable energy sources in the future global fuel mix needs to increase, necessitating the investigation of the impact of alternative fuels for future use in the shipping industry.

3.3.2 Contribution of alternative fuels in addressing air emission problem

The emission performance of alternative fuels inside internal combustion engines will vary. As mentioned in Chapter 2, a basic distinction between fuel related and cylinder process related (or combustion related) emissions is possible. From the primary air pollutants, CO_2 and SO_x are fuel related, while the rest (CO, NO_x, PM, HC/VOC) are cylinder process related.

The introduction of alternative fuels, with lower carbon and sulphur content will address the need for reduced greenhouse gas and sulphur emissions respectively. This is because the emitted carbon-dioxide (CO_2) as well as the emitted Sulphur oxide (SO_x) are a function of the carbon content and the sulphur content in the fuel, respectively. The reduction potential of CO_2 emissions from alternative fuels could be investigated under the Well-to-Propeller (WTP) or the Tank-to-Propeller (TTP) perspective, as elaborated in Appendix B.2.1. In short, the WTP perspective considers the full fuel cycle (i.e. production, refining, distribution and consumption, while the TTP only includes the emissions produced from the combustion of fuels. In addition, the switch from high sulphur content fuels to low sulphur content fuels will help compliance with MARPOL Annex VI sulphur emission regulations.

The emitted Nitrogen-oxide (NO_x), on the other hand is dependent on the conditions under which the fuel is burnt in the engine. [27] The NO_x emission performance of alternative fuels inside internal combustion engines can vary. According to [44] the highest emission per kWh are emitted at low power. There are fuels that comply with the upcoming more stringent NO_x Tier III emission limits and others that need complementary emission reducing technology to comply.

It is acknowledged, that the amount of sulphur content in the fuel is related to the amount of PM emissions generated. Low-sulphur fuels have less PM emissions than high-sulphur ones. Therefore, the investigation of lower-sulphur content alternatives fuels, can be seen as indirectly trying to minimize PM emissions as well. However, according to the second IMO GHG study (2009), the amount of PM emissions is related mainly to the consumption of the lubricating oil used in the engines. Therefore, the way to further reduce PM emissions is by optimising combustion techniques, complemented by minimizing both the consumption of lubricating oil and the use of additives in lube oil.

Concerning CO and HC/NMVOC emissions, the combustion conditions inside the engine will determine their final emission output. Reductions can be achieved by combustion optimization techniques. However, as mentioned previously, a trade-off exists, between NO_x emission reduction accomplished through combustion modification techniques and the increase of these exhaust gases pollutants. Specifically, for CH_4 emissions, originating from gas engines, the optimization in the design of the combustion chamber is the most significant factor for reducing emission release.

To conclude, it is evident that the use of alternative fuels can contribute in the reduction of exhaust gas emissions. The parallel implementation of internal-combustion optimisation techniques from engine manufacturers will define the real reduction percentage of the exhaust gases pollutants in the end.

3.3.3 Aspects for consideration

From the Kotug's perspective, as an owner, the selection between viable options is of vital importance, because the type of alternative fuel selected will have an impact on both the environmental and the commercial performance of the future Rotortugs. Criteria used to assess the suitability of marine fuels can be divided into four broad categories: technical, economic, environmental and others, each of which contains sub-criteria, as presented in Figure 3-1.

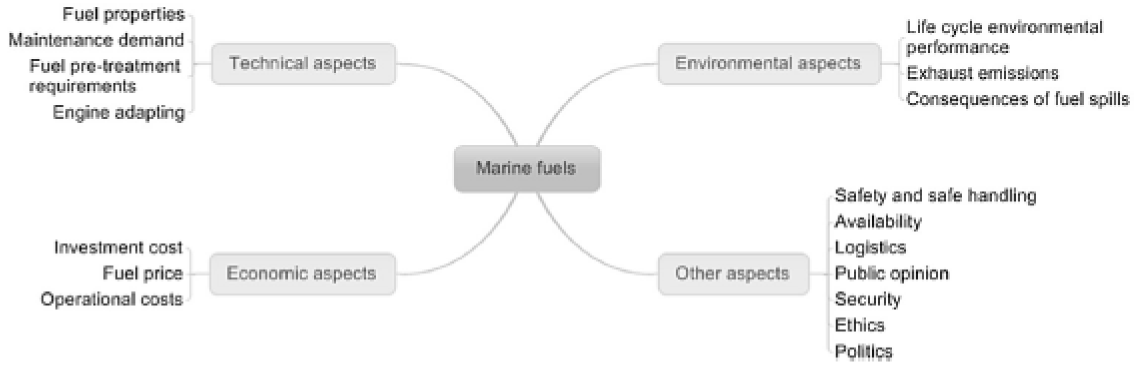


Figure 3-1: Aspects for consideration when selecting alternative fuels for marine use[Brynolf,Friedell et al. 2015 p.2/10

The main drivers for alternative fuels to constitute viable candidates are regulations, financial considerations and availability of technology. Candidate fuels should be available in the next 15 years, compatible with existing technology, compliant with current and future environmental requirements and cost-effective. For a fuel to be available, it means that there is sufficient feedstock to produce the fuel and a given market exists to match supply and demand. Logistic considerations are also important. Lack of bunkering facilities and supply chains are barriers for the introduction of alternative fuels. Moreover, new "exotic" fuels that are still under early-stage research or have not been tested on ships, are more likely to be subject to unforeseen technical issues. The fuel system in the engine rooms of ships is a complicated system, comprising of storage tanks, transferring pumps with extensive piping network, processing equipment, engines and exhaust funnels. Therefore, the operation of such systems should be feasible when introducing an alternative fuel, either by using the already existing fuel network with minor modifications or by setting up a completely new one. The fuel properties is a parameter that impacts the technical performance of the engines operating on a given fuel. Fuel properties are an indication of the quality of the fuel. Close attention should be paid specifically at the Cetane and Octane numbers. These properties represent the ignition quality for engines. [5] The energy density is another fuel property, crucial for the selection process. It provides a measure of the energy content of the fuel and is presented usually in energy per mass (MJ/kg). When the energy density is presented in energy per volume (GJ/m^3) it indicates the fuel's on-board storage demands. A higher volumetric energy density means that less storage space is needed. Especially, for tugboats, which suffer from shortage of available space, this factor is particularly important. Safety related concerns should also be addressed early. Potential health hazards to crew handling the fuel, as well as other risks (fire, explosion) should be minimized. Concerning the environmental requirements, certain minimum levels with respect to emission output must be satisfied, in order to meet the expected limits. Finally, the affordability of the candidate fuel a decisive factor for a choice decision. The cost of an alternative fuel is mainly related to the availability and the production method. Differences in price are expected according to the geographical area. [45]

3.3.4 Selection of alternative fuels

Even though a variety of different fuels are predicted to show a good environmental performance potential the analysis in this thesis is limited to only the ones that are most commonly considered today and satisfy the time span of 15 years set as research time length and show a high potential with respect to the application on tugboats. The focus was set on identifying the alternative fuels that satisfy the following criteria:

- The sulphur content of candidate fuels should be at least 0.1% (m/m) in order to meet the sulphur content-limit set by MARPOL Annex VI.
- The average weighted cycle NO_x emission value attained after combustion of the candidate fuel in its associated prime mover should be reported to be at least same as the Tier II NO_x limit.
- The alternative fuels should be available in sufficient quantities worldwide for bunkering or anticipated to be so until 2030.
- The technology should be mature enough and proven. Experiments with the use of candidate fuels should have already been conducted on-board ships (preferably tugboats)
- The use of candidate fuels does not present any major safety or environmental risks.

LNG, Biodiesel, Methanol and DME were found to satisfy the above requirements. Those fuels are either in liquid or gaseous form. Elaboration on the selection process are provided in Appendix B. In particular, information on the fuel properties, the availability, the engine compatibility and the environmental performance, both for the fuel-related (CO_2 and SO_x) and the cylinder process related (CO, NO_x, PM, HC/VOC) emissions are contained in the Appendix B.2.2. A summary of the characteristics of the candidate fuels is provided in Table 3-3. The characteristics of the baseline fuel are also included in the same table.

Table 3-3: Fuel specifications of investigated alternative fuels (compiled through literature review)

Fuel	**Density** [t/m^3]	**Energy Content (LHV)** [MJ/kg]	**Volumetric energy density** [GJ/m^3]	**Carbon content** [% m/m]	**Sulphur content** [ppm]
MGO/ULSD	0.89	43	38.3	87	1000/15
LNG	0.45	46.2	20.8	75.8	3.5
Methanol	0.792	20	15.8	37.5	0
DME	0.668	28.4	19	52.2	0
Biodiesel	0.86-0.90	37.3	32.078	77	10

In this thesis, LNG and Methanol have been associated with gas-burning engines, while Biodiesel and DME with a conventional 4-stroke medium speed compression engine. In particular, LNG is matched with both a single-gas and a dual-fuel engine, while Methanol only with a dual-fuel engine.

The deployment of a different engine technology will lead in different tank-to-propeller emissions. Emission data from various sources were collected from published sources, with the purpose of establishing the emission reduction potential of the non-GHG exhaust pollutants, for the alternative fuels under consideration, according to their associated prime mover, when compared to a 4-stroke compression-ignition engine running on MGO. Emphasis was given in studies containing data from on-board and manufacturer test-bed measurements (see Appendix B.2.2). The results are summarized in Table 3-4. Generally, emission factors are found in two formats, specific values in [g/kWh] and in [g/kg fuel]. When the emissions are given as [g/kWh], then the efficiency of the engine is incorporated, therefore comparisons between engines can be made. For the fuel-related emissions, two are the decisive parameters which will judge the final emission percentage, firstly the carbon or sulphur content of the fuel and secondly the efficiency of the engine. It must be highlighted that there were limited data regarding the cylinder process related emission performance in the literature. Especially concerning HC/VOC and CO emissions, which are not directly regulated from MARPOL Annex VI, hardly any data have been published for most of the alternative fuels under consideration. The lack of comprehensive data adds uncertainty in the emission reduction potential of the alternative fuels under examination.

3.4 Associated Prime Movers and Energy Storage Devices

The following section describes the two basic types of gas-burning engines identified through the literature review, suitable for use in harbour tugboats. The two engine concepts are Lean-Burn Spark-Ignited engines (LBSI) and Low-Pressure Dual-Fuel engines (LPDF). A brief description of the characteristics of the two gas-burning engines is presented in this section and some general remarks concerning the emission performance of gas-engines in comparison to traditional diesel compression engines. Furthermore, a reference is made to alternative energy powering devises and energy storage devices, suitable for marine use. From those devices, only batteries will be considered under the scope of this thesis. Finally, the potential benefits on emission reduction from cold ironing are discussed.

3.4.1 Gas-burning engine concepts

Alternative fuels can be combusted in two groups of internal combustion reciprocating engines; mono-fuel and dual-fuel engines. The reason behind the use of gas-burning engine types instead of conventional compression engines is the difference in auto-ignition temperature between alternative fuels (expressed by the methane number MN). Harbour tugboats need engines in the lower capacity range. These are 4-stroke, medium or high-speed engines, operating on the Otto cycle ignited by spark ignition or by pilot fuel. The two gas-burning engine concepts suitable for use in tugboats would be Lean-Burn Spark-Ignited engines (LBSI) and Low-Pressure Dual-Fuel engines (LPDF). Both concepts have been evaluated, while in operation, in a variety of ship types; tugs among them and are considered as proven technology. [46] Such engines at power bands suitable for main propulsion are available from most engine manufacturers, such as Wärtsilä, MAN B&W, Caterpillar, Mitsubishi and Rolls Royce, while for lower power bands suitable for use as gensets are still under development. [45, 47]. Ship owners tend to prefer Dual fuel engines at the moment. The reason behind this preference is primarily the flexibility to use diesel fuel in case a problem exists in the fuel (gas) network, or if there is no available fuel for bunkering in the port of operation, despite the complexity of the installation; two separate fuel systems need to be installed on the ship.

Lean-Burn Spark-Ignited engines (LBSI)

LBSI is a mono-fuel gas engine which runs on the Otto cycle concept. The auto-ignition temperature of most alternative fuels is higher than conventional diesel fuels, which means that an ignition source is needed for the combustion to be initiated. In this type of gas engines, a spark plug is used for ignition. A pre-mixed homogeneous mixture of air and fuel is introduced into the cylinders, the spark plug initiates the combustion and the flame starts propagating through the unburned fuel mixture until the combustion is complete. The air excess ratio (λ) is typically between 1.7 - 2.2, in order to achieve lower combustion temperature, and consequently lower NO_x emissions. It has been quoted that there is a risk of knocking[5] or misfiring[6] when operating at varying operating conditions, as depicted in Figure 3-2. However, there are control techniques employed at commercial engines for addressing these problems.

[5] Knocking occurs if the thermal load and combustion pressure in the cylinder increase. Then the unburned fuel mixture may ignite spontaneously prior to being reached by the propagating flame.
[6] Misfiring occurs at higher excess air ratios due to failure of the mixture to ignite

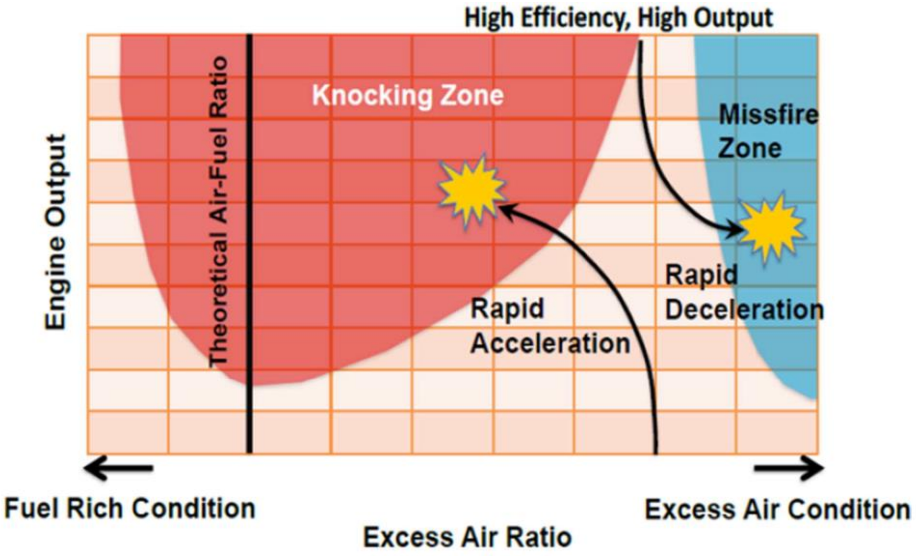


Figure 3-2: Regions of misfiring or knocking for operation of LBSI engines

Low Pressure Dual-Fuel engines (LPDF)

The Dual-fuel engines can run on two different modes. On diesel mode these engines run according to the Diesel cycle, 100% on diesel fuel, while on gas mode they run on the Otto cycle, but in contrast with LBSI engines they differ with regard to the ignition source used. Ignition is accomplished by the injection of a small amount of pilot fuel, typically diesel fuel into the cylinder. The pilot fuel is ignited from the high temperature at the end of the compression stroke, and then the flame is propagating like the LBSI engine, through the lean fuel-air mixture. Load pick-up has been cited to be slower than LBSI engines.[46, 48] Typical pilot fuel consumption level is between 1-2% of the total energy used at full load condition by the engine. In all Dual-fuel engines there is a transitional limit, depending on the manufacturer, typically, between 20 and 30% load, under which the engine runs necessarily on diesel-only mode. Dual-Fuel engines may also run on 100% liquid diesel fuel (MGO).

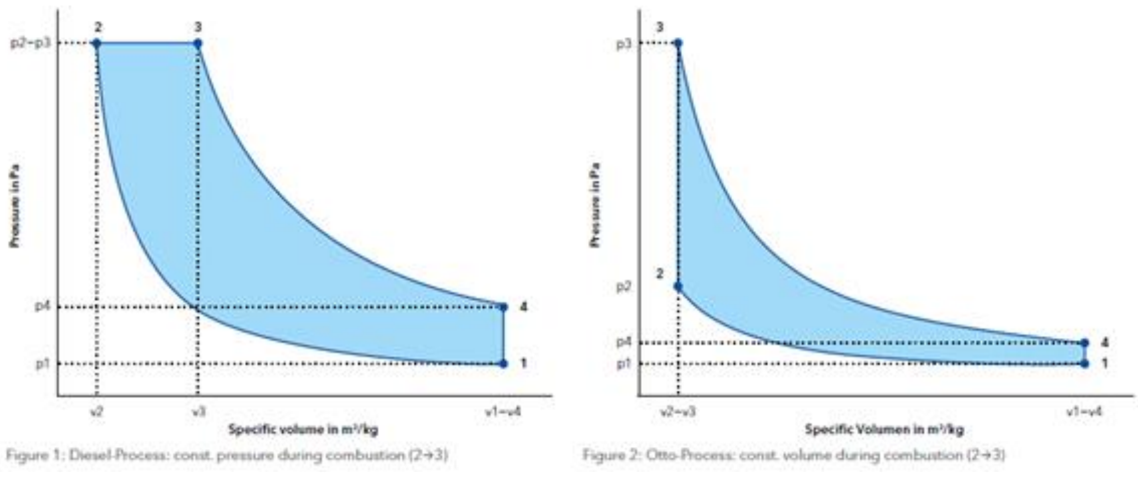


Figure 3-3: Volume-Pressure diagram of Diesel (fig.1) and Otto (fig.2) process

Performance of gas-burning engine concepts

With respect to gas-burning engines' performance certain general remarks apply. Of course, the engine performance and emission profile will depend on the fuel used (physical and chemical properties), the engine manufacturer and the operational profile of the ship.

Gas-engines are considered to have similar performance as the diesel engines. Single gas engines may even reach higher thermal efficiency than diesel engines; in high loads up to 48%-49%. Dual fuel engines show lower thermal efficiency at low to intermediate load range, while at high loads may even reach higher thermal efficiency compared to diesel engines. Maneuverability is a very important aspect, particularly regarding tugboat operation. Gas-burning engines are capable of the same torque response as the diesel engines, enabling safe vessel maneuvering.

Generally, for all engines, the emission performance differs depending on the load range. Operation on the low load range results in higher specific emissions than on the high load range. Performance measurements have shown that both engine concepts, regardless of the fuel, are showing certain trends. To begin with, the NO_x emissions achieved are lower than IMO Tier III emission limits. [49] Secondly, particulate emissions, for both engine concepts on gas mode, are lower compared to diesel engine counterparts operating in MGO by 90% at least. [46] Nonetheless, studies indicate that Otto engines cannot escape the "diesel dilemma" either. The trade-off for NO_x emissions and HC/CO emissions remains. Specifically, the leaner the fuel mixture, the less the NO_x emissions and the higher HC/CO emissions. It is reported that at medium to low load range, Otto cycle engines have higher Total Hydrocarbon (THC) emissions compared to a diesel engine running on MGO.

An overview of the emission performance of the selected fuels when combusted in their associated engine type, compared to the emission output from 4-stroke CI engines running on MGO, per exhaust air pollutant is given in Table 3-4.

Table 3-4: Overview of the emission performance of alternative fuels under evaluation, according to their associated prime mover, compared to a 4-stroke compression-ignition engine running on MGO expressed in % reduction/increase potential [compiled from various literature sources]

Fuel	**Engine Type**	**% Emissions reduction (-) / increase (+) factors compared to 4-stroke compression-ignition engines running on MGO**			
		NOx	**PM**	**HC/VOC**	**CO**
LNG	**LBSI**	-(85% to 90%)	-(95% to 99%)	+(1300 to 2100%)	+(160% to 240%)
	LPDF	-(75% to 90%)	-(95% to 98%)	+(1600% to 3550%)	+(260% to 280%)
Methanol	**LPDF**	-(30% to 50%)	-100%	≤ +400%	≤ +100
DME	**4xCI**	-35%	-100%	0 or (-)	0 or (-)
Biodiesel	**4xCI**	+(5% to 10%)	-(47% to 70%)	-(65% to 74%)	-(16% to 47%)

3.4.2 Alternative electrical power sources (Non-traditional)

Apart from the conventional 4-stroke medium-speed internal combustion reciprocating engines used for marine propulsion in harbour tugboats today, other alternative power sources could be used. Fuel cells and power sources utilising renewable energy (Wind/Solar energy) are the two most common power sources considered today.

3.4.2.1 Fuel Cells

Fuel Cells are electrochemical devises which convert a fuel's chemical energy into electricity. There are several commercially available fuel cell technologies, classified by the type of electrolyte utilized. Fuel cells are attractive for use on-board vessels for two basic reasons; because of higher efficiencies compared to diesel engines and the elimination of exhaust gas emissions, when run on LH_2. [38, 44, 47]. The only by-products of a fuel cell are water and heat. Different alternative fuels, like Methanol and LNG can be combined with a fuel reformer and used in a fuel cell. In this case, emissions of exhaust gases will result. Furthermore, due to absence of moving parts, fuel cells are also very quiet in operation, significantly reducing noise and vibration on-board vessels. Various fuel cell research projects have been identified, exploring the use of several types of fuel cells on-board vessels. A complete description of these projects and the underlying fuel cell technologies can be found at [50] study. It is evident from this study that there is an upper boundary of fuel cell's power output, when an alternative fuel is used. The fuel cell, using Hydrogen, with the highest power output identified is the one installed on-board a class 212A submarine, being 306 kW, while the fuel cell with the highest power output is a 320 kW MCFC system, using LNG as a fuel, installed on-board an Offshore Supply Vessel. It is argued that in the next 15 years it is highly unlikely that the fuel cell technology is going to be capable of reaching diesel engines' power output. Moreover, high capital expense, fuel cell life expectancy and maintenance issues have been identified as drawbacks that remain to be resolved. [50] The effort is concentrated on making fuel cells technology reliable enough to complement existing power technologies. Thus, the use of fuel cells is not going to be considered as an option in this thesis.

3.4.2.2 Wind/Solar Energy power sources

While wind and solar energy power sources are widely considered as potential renewable energy sources for greenhouse gas emission reduction, this is not seen as a viable alternative for tugs. Certainly, on one hand solar panels might be used to complement energy supply dedicated for hotel loads but the energy capacity is not enough for powering purposes. On the other hand, wind kites or sails might be of use in OGV's, which could be installed, but the limited space on-board tugboats deem them ill-suited.

3.4.3 Energy storage methods

There are various methods of energy storage, such as batteries, supercapacitors and flywheels, used to complement the energy supply of vessels. The principle of energy storage devices is that energy is accumulated, stored and may be used depending on the vessel's power management. Such power sources are combined with traditional power sources to optimise the electrical needs arising from the vessel's operational profile. Both supercapacitors and flywheels are energy storage with high potential, however they are still considered maturing technologies for the marine sector and as such are excluded from further consideration.[51]. Information for both technologies can be found in the Hybrid Advisory report, prepared by ABS.

3.4.3.1 Batteries

The application of batteries in the marine sector is not something new. In the tugboat segment, several vessels have been equipped with battery systems. During the last years the lithium-ion battery is being promoted as the most reliable and suitable solution to fit the tugboat industry demands, on energy density, power density, cycle life, cold weather performance, robustness, safety and cost. [45, 51]

Batteries can be used as a second power source, in combination with a variable speed drive (VSD) electric motor. Besides simply being a power source, batteries can be put to more diversified use. If the power requirement during operation is low, the engine cannot be operated efficiently due to high emissions, regardless of the engine speed. Energy buffering is the term used to describe the underlying technique of batteries function. Specifically, the engine can operate on a higher power than required for propulsion; the excess energy supplied is stored (buffered) in the battery bank. Once the batteries are full the engine can be turned off and the low propulsion power requirement met by electric drive alone. When the batteries become depleted then the engine could be turned back on again. The engine is thus operated in stop/start cycles and while running it is operating under a substantial load, resulting in higher overall efficiency. Batteries may also be used for peak shaving; the engines could be sized so that they operate at a certain power limit constantly, while the additional power demand is met by the batteries when required. In this way, batteries are used to smooth the load variations on the generators, in cases where there is a sudden load step from the electrical load demand. With the addition of batteries on-board vessels there is also decreased need for spinning reserve; meaning that in case a generator fails, then a battery will provide the power needed until the generator is put back on operation. Finally, in cases where the load can regenerate power, such as in winches, the battery may be used to harvest the energy.

Currently the greatest concerns about using batteries are related to a low life expectancy and relatively high initial costs. It can be expected that batteries will become considerably more efficient and less expensive over the next 15 years, coupled with longer life duration. In addition, transformation losses during battery charging are decreasing significantly due to the technological improvement of charging systems. It has been predicted, that automotive quality battery prices are estimated to reach 200 $/kWh in 2023 and 160 $/kWh in 2025. [52] Marine-optimized batteries are considered costlier than automotive quality, predominantly because of safety reasons. Such batteries usually come with an integrated Battery Management System (BMS) with the purpose of monitoring the battery's proper operation and ensuring that they will not be overcharged or over-discharged. Additionally, the are also complemented by a liquid cooling system, integrated inside the battery modules, with the purpose of ensuring the battery will not suffer a thermal runaway or fire. Nevertheless, after consultation with industry experts, as years pass by the price is anticipated to drop, following the automotive batteries' cost trend, from 600 $/kWh (2018 price) to 300 $/kWh in 2033, the timespan of this thesis.

Batteries during operation are not producing any emissions. The environmental performance of batteries can be assessed only through a lifecycle point of view, which lies outside the scope of this thesis. However, it is important to highlight that when integrating batteries on-board a ship, what really matters, is the total emission output produced from the energy sources used to charge the batteries, against the same vessel's emission output without batteries, under the same operational conditions. This matter will be investigated in the following chapters. In this concern, special consideration should be given in the case a shore power connection is available. Then batteries can also be charged from the local electrical distribution grid.

3.5 After-treatment technologies

The literature review revealed certain after-treatment technologies, which are more suitable than others for application on tugboats. [11, 26, 27, 34, 53] In particular, these systems consist of a SCR for reducing NO_x emissions, a Diesel Particulate Filter (DPF) for reducing PM emissions and an Oxidation Catalyst (OxiCat) for reducing both CO and HC/VOCs emissions. These systems can be coupled together leading to combined emission reductions for all combustion-related air pollutants. The emission reduction potential for each distinct after-treatment technology considered here is summarized in Table 3-5 at the end of this section.

3.5.1 Selective Catalytic Reduction (SCR)

A SCR system is an after-treatment technology that is used to reduce nitrogen oxides by converting nitrogen oxides into nitrogen and water. This process involves the use of a catalyst for the reduction of nitrogen oxides to take place, after the injection of a reagent into the exhaust system. The most typical reducing agents used are ammonia or urea, but urea is preferable for reasons of practicality, that are listed in [30] report. The Rotortug is using 4-stroke high-speed engines, operating on MGO. For such engines SCR systems have been reported to operate successfully, over a broad range of operating conditions (down to 10% load) and exhaust temperatures, constituting it a well-proven and trustworthy technology. [16, 27, 40] The use of commercially offered SCR systems has been demonstrated to effectively achieving over 90% reduction in NO_x emissions, while it is anticipated that they could reach effectiveness of up to 98% in the thesis timespan of 15 years. Furthermore, it is considered ineffective in capturing the remaining combustion-related emissions (CO, NMHC/VOCs and PM). [34, 40, 54]. Moreover, a review commissioned by ICCT[40] concluded that the supply network for urea is considered mature enough and the distribution network over all major ports worldwide is considered developed. Concerning the influence on engine and fuel performance, the same report expects that no fuel penalty will result. Not only that but it is anticipated that engines with an SCR will be tuned for maximum fuel efficiency and rely on the after-treatment process to capture the NO_x emissions, hence an engine's fuel efficiency is anticipated to be slightly improved, on the order of 2% to 4%. Finally, ammonia slip and CO_2, two potential by-products, from the ineffective use of the SCR system are expected to constitute a manageable risk, due to advanced control strategies introduced by manufacturers. For the abovementioned reasons, it is clear that the future Rotortug using 4-stroke diesel engines with SCR after-treatment technology will comply with the NO_x Tier III standards.

According to [55] the main system components for a SCR system are :

• A pumping unit for transfer of urea solution from storage
• A urea dosing unit
• A mixing duct with urea injection point
• A reactor housing containing replaceable catalyst blocks
• A control system
• A soot/ash cleaning system.

A typical configuration for a SCR system fitted to a 4-stroke compression-ignition engine, can be illustrated in Figure 3-4 where it is seen that the reactor unit is usually placed downstream of the turbocharger.

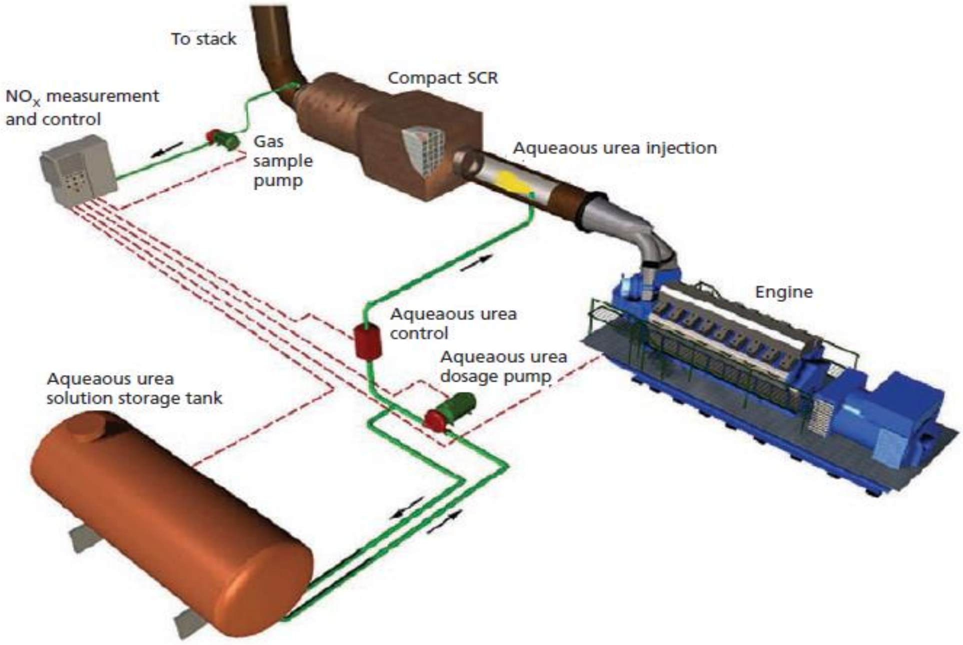


Figure 3-4: Marine SCR arrangement - four stroke medium-speed engine [LR]

3.5.2 Diesel Particulate Filter (DPF)

A DPF system is an after-treatment technology that is used to reduce particulate matter by trapping the particles in the exhaust flow. The process involves the passing of exhaust from a honeycomb structure consisting of alternate open and closed channels, where particles are trapped between the filter's open channels' semipermeable walls, allowing only gases to pass through to the plugged channels. DPFs are classified based on the method of disposing the trapped particles, known as "filter regeneration", into two (2) types: passive and active. The basic difference is that active regeneration techniques require the use of an external heat source, often on the form of a fuel burner, while passive use only the heat in the exhaust flow.

DPFs have been firstly introduced in auto-motive industry targeting both heavy and light-duty engines and are now more than a decade in use with substantial results; efficiency of more than 90% in reducing PM engine-out levels have been demonstrated. The reduction order of magnitude for particle numbers is assessed to be in the order of 3 to 4 times the number of particles upstream of the DPF filter. [56]. DPF has limited applications on harbour tugboats and other small crafts (inland vessels). It has been identified from the research conducted that DPFs have been primarily employed experimentally in tugboats operating in the ports of Los Angeles, Philadelphia and Boston in the United States and by the EU's Cleanest Ship program. However, it has found numerous applications in large yachts, mostly on auxiliary engines rather than main engines. Moreover, there are a number of feasibilities studies conducted that have illustrated the possibility of installing DPFs on marine engines.[57]. Both types of DPFs, passive and active, is understood to be suitable for installation in marine engines.

Passive filters usually are manufactured with a layer of catalyst applied to the surfaces of the filter. On such filters the particles are trapped onto the catalyst layer and are converted to carbon dioxide. As an extra benefit of the catalyst behavior is the subsequent reduction in HC and CO emissions, by converting them into carbon dioxide and water vapour. In this thesis it is assumed that a passive catalysed-based regeneration filter will be employed, due to the combined effect on combustion-related air pollutants emission reduction. Such a DPF is usually constructed either with a silicon carbide or ceramic porous material (cordierite) wall-flow filter element. The emission abatement potential is estimated to be for HC in the range of 60% - 80%, while for the CO in the range of 75% -

85%. Lastly, DPF are also considered able to effectively reduce the PN up to 99,7%. [58] The operating principle of a catalysed-based regeneration DPF can be illustrated in Figure 3-5.

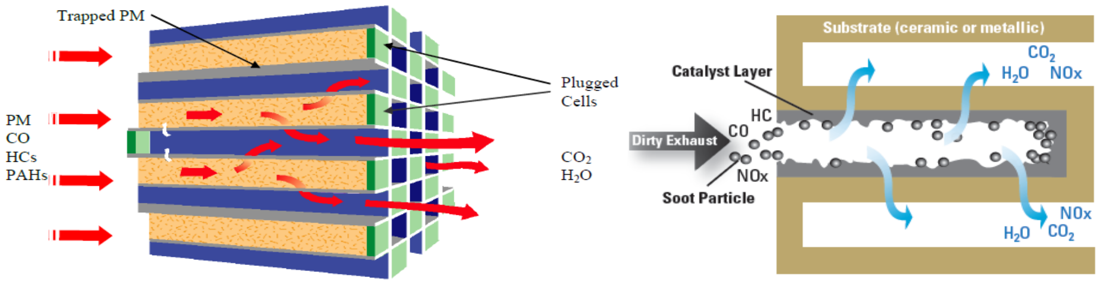


Figure 3-5: Operating principle inside a wall-flow catalysed-based regeneration DPF [google]

A DPF's efficiency is related to the sulphur content of the fuel used and the exhaust temperature. Specifically, it is regarded to be working only with fuels with less than 700 ppm sulphur content. Typical exhaust temperatures needed for regeneration are ranging from 300 ºC to 465 ºC. It is important to note that especially catalysed-based regeneration DPFs rely on the use of low sulphur content fuel for their effective operation. It has been reported that during cold-start or fully-warm conditions a decline in particle emission reduction efficiency, both in particle mass and numbers, is observed. [56]. With that in mind, the use of low-ash lube oils is proposed. The emission reduction potential of DPF for marine use, based on the demonstrated efficiency in pilot projects and the manufacturer's quoted performance metrics for state-of-the art commercial solutions, is appraised to be already in the range of over 90% and is anticipated to reach even levels of 99%, in the next 15 years; the timespan of this thesis.[26, 34] Furthermore, a slight increase in fuel consumption has been reported, on the order of 1% to 5%, attributed to the backpressure developed because of a plugged filter and the use of equipment assisting the regeneration mainly in active-type filters.[26] However, optimized commercial solutions are expected to adequately address this issue. Finally, an additional benefit of fitting a DPF is the achieved sound attenuation.

3.5.3 Oxidation Catalysts (OxiCat)

An oxidation catalyst (also called two-way catalytic converter) is an after-treatment technology that is used to reduce both NMHC/VOCs and CO emissions by converting them into carbon dioxide and water vapour. This process involves the use of a catalyst layer, within which the conversion takes place, as illustrated in Figure 3-6. Materials used for the catalyst are precious metals, usually palladium or platinum.

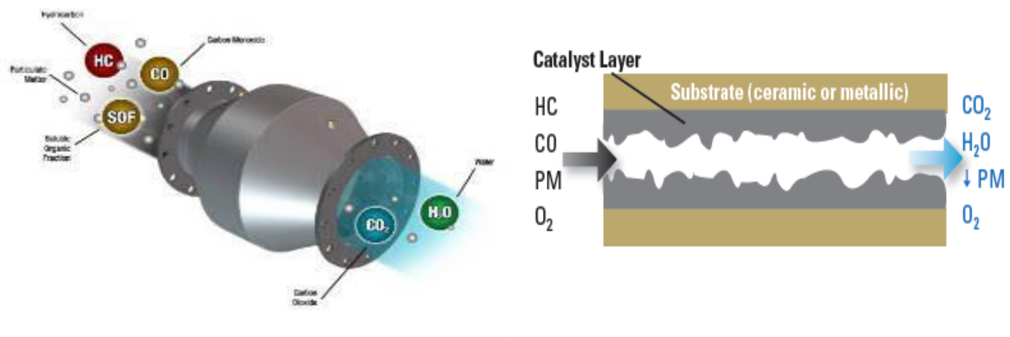


Figure 3-6: Operating principle of an oxidation catalyst [google]

Oxidation catalysts are considered a well-proven technology, having a substantial application on both on and off-road vehicles for over 30 years. This technology has been widely adopted on passenger and heavy-duty highway vehicles. Feasibility studies for evaluating the use of oxicats on vessels have been performed mainly on larger vessels; passenger ferries, with evidence that they can be safely introduced for use in the marine environment.[57]. It is estimated that the effectiveness level for NMHC and CO emissions would be in the range of 85%-95% and 85%-97% respectively.

It is highlighted though that this kind of oxicats are considered ineffective on capturing the methane-hydrocarbon (CH_4) proportion of total hydrocarbons, typically known as methane slip. At the moment, manufacturers are using primary measures for limiting the "methane slip". In case dedicated stricter CH_4 limits should apply, which implies that primary measures will not be sufficient, research has shown that a dedicated methane oxidation catalyst (MOC) would be required. Such MOC are still in development phase.[59] It has been reported that certain challenges, related to experimental catalyst's operating exhaust temperature range and the catalyst sensitivity to exhaust impurities, affecting the catalyst's long-term efficiency remain to be resolved before these catalysts can enter the market and be used in marine power plants on tugboats. [46].

Even though it is accepted that the use of oxicats will have an effect on the reduction of the soluble part of hydrocarbon species, being widely considered as an organic fraction of particulate matter, tests on compression-ignition marine diesel engines under dynamic engine operating conditions showed that the effect of an oxidation catalyst on solid PM can be considered insignificant, which verifies the results of several studies mentioned in the same paper. [56]. For this reason, in this thesis it is assumed that use of an oxicat will have no effect on the reduction of PM. Oxicats are cited to be effective also against formaldehyde byproducts emissions from gas engines running on LNG. [59] Finally, they are also considered effective on capturing the ammonia slippage originating from SCR operation. [27]

Similarly to DPFs, the efficiency of oxicats is related to the sulphur content of the fuel, with best performance rates shown on lower sulphur fuels and the exhaust temperature. Actually, fuels with a sulphur content of 500 ppm or lower are required for optimum performance.[34]. With regard to the exhaust temperature, a minimum temperature of 150 °C is required for efficient operation, which means that engines operating at idle or low-load power could result in untreated exhaust flow through the oxicat. However, manufacturers have found ways to bypass this problem, allowing efficient operation both in steady-state and transient low-load operating conditions. An additional benefit of oxicats application are the elimination of visible smoke and the characteristic odor of the exhaust gas.

3.5.4 Combined after-treatment solutions

The aforementioned technologies can be combined in pairs or all-together, in order to achieve emission reductions to their respective targeted air pollutants. An indicative example of a combined after-treatment solution, consisting of all three aforementioned systems, is shown in Figure 3-7. Combined solutions can also be integrated into the same reactor housing, thereby reducing the total footprint required for the installation; a factor which is critical especially in the case of a tugboat.

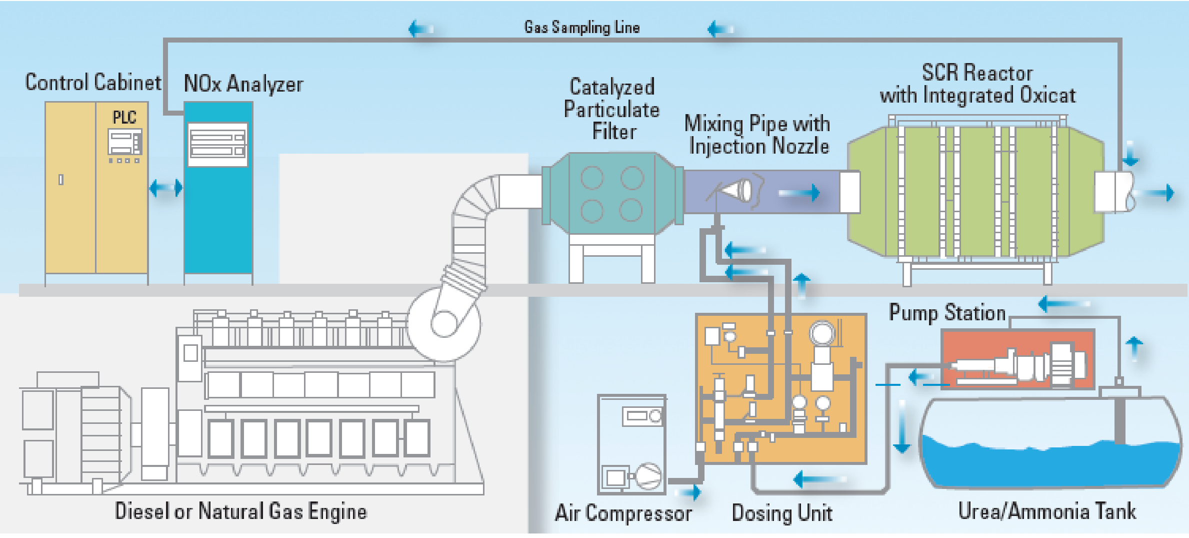


Figure 3-7: Indicative layout of the application of a combined SCR reactor with integrated oxicat and a catalysed particulate filter on a marine engine

At least one case related to tugboats, of a harbour push boat operating at the port of Los Angeles, retrofitted with a catalyzed combined DPF and SCR system has been identified. Its performance has been evaluated and the efficiency of this combined after-treatment system for reducing combustion-related emissions below US EPA Tier 4 limits for category 2 marine engines was demonstrated. [60]

The application of one or more of the above-mentioned after-treatment technologies are going to be considered in this thesis as compliance options with the more stringent upcoming regional regulations, as described in Chapter 2. The emission reduction potential for each after-treatment system when used stand-alone, is summarized in Table 3-5. Further to the after-treatment technologies discussed, dedicated ammonium or methane slip catalyst (MOC) modules could be integrated in a combined after-treatment system to control the potential excess emissions, if upcoming emission regulations come in place. It is interested to note that such systems are usually serving a dedicated engine, either for use as an auxiliary or main engine and are mounted above their respective engines; however, other configurations might be possible, relevant to the optimum exhaust piping layout of the vessel, defined after a detailed engineering analysis.

Table 3-5: After-treatment systems emission reduction percentages (compiled through literature review)

After-treatment solution	%emissions reduction (-) / increase (+)			
	HC	PM	CO	NO_x
SCR (0.1% MD)	0%	0%	0%	-(90% to 98%)
DPF	-(60% to 80%)	-(90% to 99%)	-(75% to 85%)	0%
OxiCat	-(85% to 95%)	0%	-(85% to 97%)	0%

3.6 Cold Ironing

As already mentioned in section 2.2.2, cold ironing is one of the strategies some ports are using to reduce air emissions locally. Cold ironing is the term used for powering vessels at berth using shore-based electricity. The availability of shore power plugs is still limited, while in less developed ports, they may not be available at all. Several researchers have investigated the environmental and economic potential of cold ironing with respect to the electrical distribution topologies, the power generation process and the power demand in combination with the utilisation rates for different ship types. [36, 61, 62] It has been found that the environmental benefits of cold ironing could be measured only with respect to the electricity's production methods. In cases where the electricity generation originates from renewable sources, an emission benefit for both the GHG and the Non-GHG pollutants arises.

The emission output will vary between countries and even ports, depending on the fuel mix used for electricity generation. Emission factors are usually presented in grams pollutant emitted per kWh electricity produced. Average emission factors for electricity generation in Europe, from European Commissions Shore-Side Electricity Report, are presented in Table 3-6.

Table 3-6: Average emission factors for EU25 electricity production

	NO_x	SO_x	HC/VOC	PM	CO	CO_2
Emission Factors (g/kWh)	0.35	0.46	0.02	0.03	0.0125	330

Of course, cold ironing may also have an impact in the operating cost of a vessel. Taking advantage of the shore-power electricity orders for suitable electrical infrastructure, comprising of power transformers, switchboards, control panels and cable reel systems. This means extra capital costs for a ship owner. In addition, transmission and distribution losses in the system must be considered in order to compare emissions at the point of consumption. Depending primarily in the electricity price, compared to the fuel's price per tonne used for electricity generation on-board, the average power demand and the time a tug-boat is berthed it might be appealing for the ship owner to pay for shore power or use the ship's own auxiliary equipment. An estimation on the average shore-side electricity price for European ports was made in European Commissions Shore-Side Electricity Report. It was estimated at €0.0715/kWh. A variation in this price is expected in other regions worldwide.

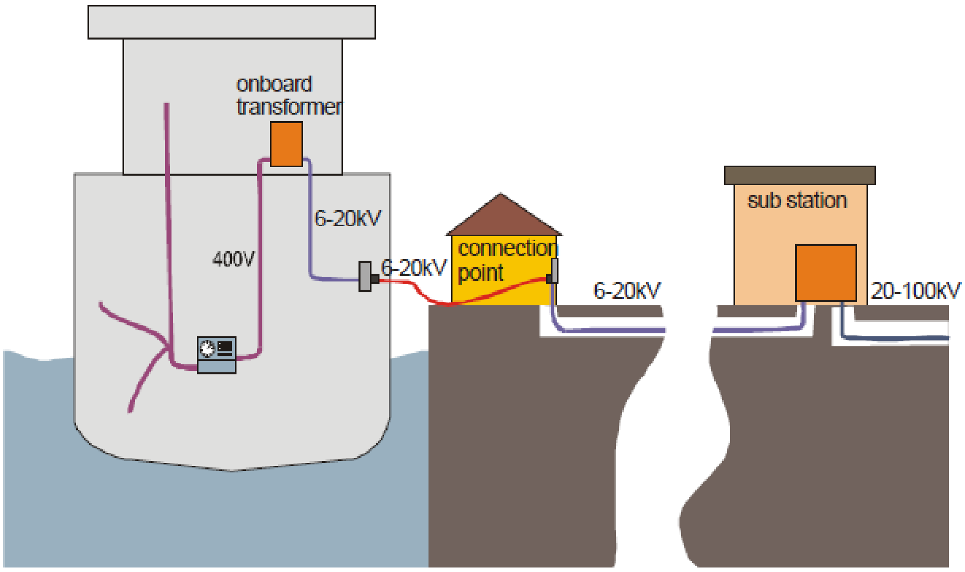


Figure 3-8: Typical OGV's shore-side power connection principle

3.7 Conclusions

In this chapter it was clarified that the use of alternative fuels can contribute in the reduction of exhaust gas emissions. Kotug's practice for complying with current IMO MARPOL Annex VI SO_x regulations is by using MGO in 4-stroke high speed internal combustion engines. Complemented by the installation of a SCR system is the strategy considered for attaining the upcoming stricter NO_x IMO Tier III limits. For compliance with more strict standards, imposed by regional regulations (EPA Tier 4, EU Stage V) further post-combustion technologies were identified and presented. Specifically, the application of a DPF and an OxiCat targeting PM emissions and both CO and HC emissions respectively. After-treatment technologies can be combined to offer a collective emission potential for combustion-related air pollutants. It must be highlighted that possible ammonia slip from use of SCR is expected, which might be addressed in future emission regulations.

An assessment of various alternative fuels, in terms of availability, compatibility with existing technology, compliance with current and future environmental requirements and cost-effectiveness, has indicated LNG, Biodiesel, Methanol and DME as feasible solutions, for use in future Rotortugs. The deployment of different engine technology leads in different tank-to-propeller emissions. LNG and Methanol, were associated with gas-burning engines. Two types of gas-burning engines were identified as suitable for use in harbour tugboats; Lean-Burn Spark-Ignited engines (LBSI) and Low Pressure Dual-Fuel engines (LPDF). LNG was matched to both engine concepts while Methanol only to LPDF. On the other hand, Biodiesel and DME are matched with a conventional 4-stroke compression ignition engine. Gas-engines are considered to have similar performance as diesel engines.

With respect to environmental performance, the distinction between fuel-related and combustion-related air pollutants is crucial. Regarding the fuel-related emissions, two are the decisive parameters which judge the emission output, the carbon or sulphur content of the fuel and the efficiency of the engine. Regarding the combustion-related emissions, the combustion conditions inside the engine determine their final emission output. Because of the unwillingness of manufacturers to provide performance data for commercial engines running on alternative fuels, the emission reduction potential in comparison with 4-stroke compression ignition engines running on MGO, for the cylinder process related emissions was specified, based on the literature review. It is noted that gas engines, like the conventional compression ignition engines, cannot escape the "diesel dilemma" either. It is also stressed that the overall environmental performance of alternative fuels in this thesis is assessed by taking into account only the tank-to-propeller emissions.

Moreover, reference was made to alternative energy powering devises and energy storage devices, suitable for marine use. In this thesis only lithium-ion batteries will be considered. It has to be highlighted that the net environmental benefit arising from the use of batteries can be assessed only through a comparison between propulsion configurations, considering the same operational profile and power management. This matter will be investigated in the following chapter. Finally, the potential benefits on emission reduction from cold ironing were discussed. It was shown that the environmental benefits of cold ironing could be measured only with respect to the electricity's production methods.

4 Candidate concept layouts

In Chapter 3 the alternative fuels with their associated prime movers for the future Rotortugs to be built, were determined. Moreover, the most promising after-treatment technologies, for installation were also determined, which could further decrease emissions, helping the newly-built Rotortugs to comply with the more stringent upcoming emission requirements. The net environmental benefit of the candidate prime mover combinations, can be assessed only in the context of the propulsion configuration line-up. The rationale behind the benefits of investigating different configurations, instead of only the traditional diesel-direct configuration is elaborated. The candidate concept layouts are divided between conventional propulsion, diesel-electric and hybrid configurations. The benefit potential of diesel-electric and hybrid configurations is discussed. It is the operational profile of the vessel though which will determine which propulsion configuration is more suitable. Thus, the importance of the operational profile will be deliberated. Firstly, an introduction of the existing Rotortugs' propulsion configuration is presented, which will serve as the baseline for comparison.

4.1 Rotortug's propulsion configuration

The reference tugboat is a Rotor class tug (Rotortug). It is an 80-tonne bollard pull tug, 32 m long tug with a maximum attaining ahead speed of 13.3 knots, which is fitted with two single drum towing winches fore and aft. For maneuvering, it has three azimuthing thrusters with fixed pitch propellers (FPP) in nozzles, two in the forward part of the vessel and one in the aft part, as can be seen in Figure 4-1. This specific type of Rotortug is also recognized in the industry as Advanced RotorTug (ART) 80-32 and is used mainly as a harbour or as a terminal tug.

Tugs that are constructed to perform harbour duty, are primarily engaged in short transits, assisting the vessels entering or leaving a port to berth/unberth respectively. The main task is towing vessels, which have limited manoeuvring ability, inside the harbour area. The denomination of "terminal" tug is used within the industry, only to differentiate a harbor tugboat in respect to a service point of view. Terminal tugs are considered harbour tugs dedicated to a specific terminal operation. Such tugs could also be employed for anti-pollution control or fire-fighting duties.

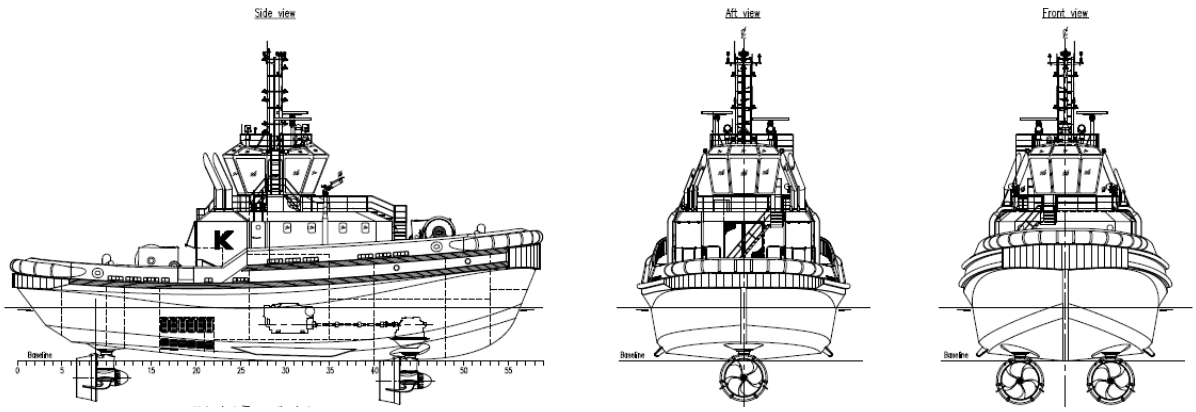


Figure 4-1: Side, aft and front view of Advanced Rotortug 80-32

The propulsion line-up, as depicted in Figure 4-2, consists of three Caterpillar 3512C main diesel engines rated at 1765kW at 1800 RPM, shafted to the Schottel 1215 Azimuthing Drives (also called Rudderpropellers) via Twin Disc Marine Control Drives (MCD) units (slipping clutches) in Z-drive formation. In this way each of the main engines propels its related shaft, and subsequently its related thruster.

For supplying the electric needs of the vessel, such as pumps, fans, lighting, HVAC, and communications the Rotortug is equipped with two Caterpillar C9 162kW diesel generator sets and one 36 kW Caterpillar C4.4 diesel generator set, serving as a harbor generator. Each of the C9 generator sets is capable of meeting the electric load demand of the vessel. The second auxiliary generator set is installed for redundancy reasons. The harbor gen set is operated, while the ship is docked, instead of one of the bigger gensets, in order to satisfy the hotel loads. The complete General Arrangement (GA) of an ART 80-32 can be found in Appendix C.1.

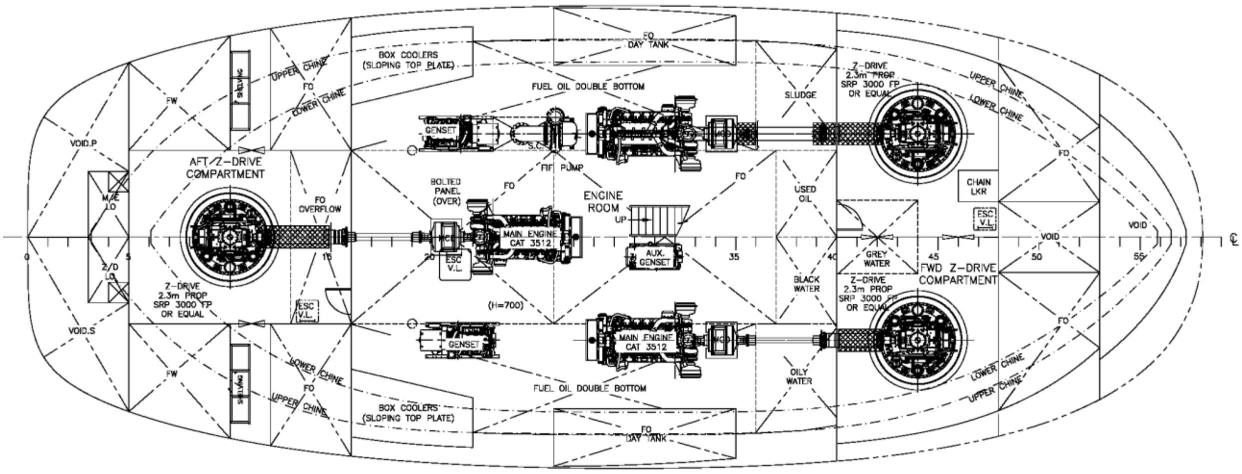


Figure 4-2: Propulsion line-up of ART 80-32 [courtesy of Kotug]

The vessel's specifications are summarized in the Table 4-1 below.

Table 4-1: Rotortug Specifications

Length	32 m
Beam	12.01 m
Draft	5.95/6.45m
Bollard Pull	80 tonnes
Speed	13.3 knots
Main Propulsion Engines	3 X Cat 3512C 1765kW @ 1800 rev/min
Auxiliary Generator Sets	2 X Cat C9 162kW 1 x Cat C4.4 36kW
Propulsors	3 x Z-drives Schottel SRP 1215 FP

This propulsion configuration pertains in the conventional propulsion configuration, known also as diesel-direct propulsion configuration (DDP) or diesel-mechanical propulsion configuration.

Propulsion power is produced solely from the main engines, while electric loads are satisfied only by the auxiliary engines. This drive train configuration, represented in the form of one-line diagram, is depicted in Figure 4-3.

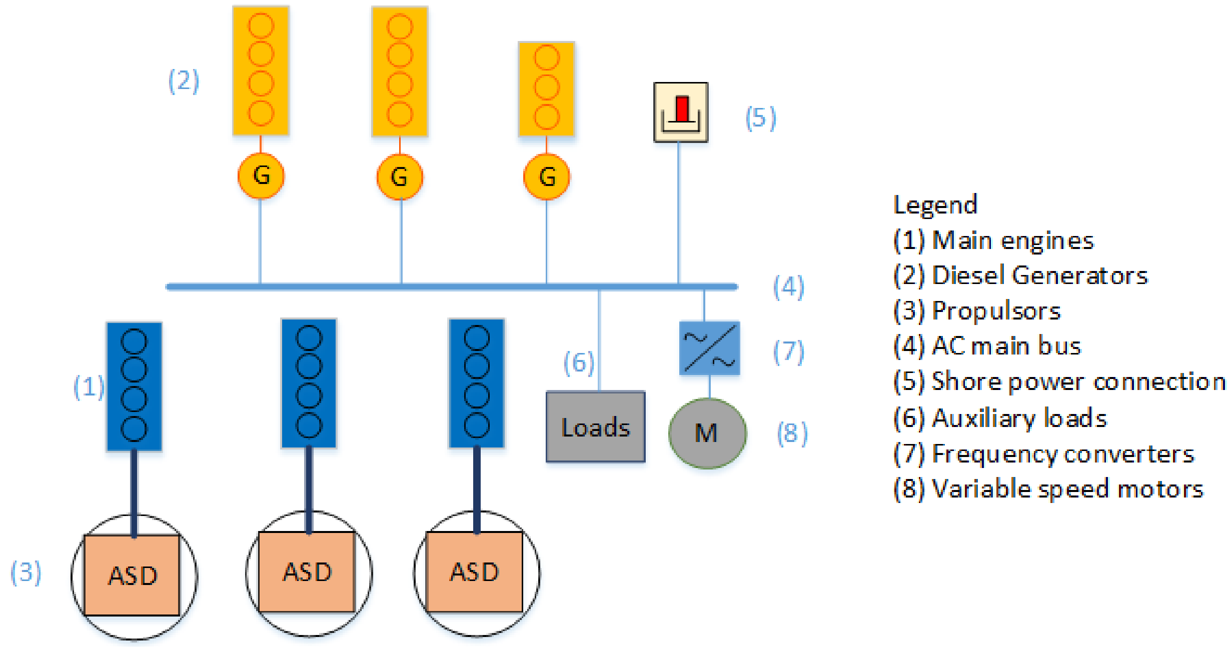


Figure 4-3: Schematic one-line diagram for diesel-direct configuration (ART80-32)

Typical weighted-average emission factors, according to ISO 8178, for the reference Rotortug's Main and Auxiliary engines, combusting MGO 0,1% [m/m], in g/kWh are presented in Table 4-2 for non-GHG pollutants. Due to confidentiality reasons the values cannot be disclosed.

Table 4-2: Typical average emission factors for 4-stroke high-speed engines installed in reference Rotortug

Engine type	**NOx**	**CO**	**HC/VOC**	**PM**
	g/kWh	**g/kWh**	**g/kWh**	**g/kWh**
Main Engine [C3512]	[redacted]	[redacted]	[redacted]	[redacted]
AUX. Eng. [C9]	[redacted]	[redacted]	[redacted]	[redacted]

The outcome of a comparison between power plant configurations can be valid only if investigated under a given operating profile.

4.2 Operational Profile

The mission of a vessel, in general in combination with the given environmental conditions will determine its operational profile. A vessel's operational profile defines the distribution of time the vessel spends operating across its power range. In the operational profile only the time when the vessel is operating is considered. Thus, time at dock is not included.

The way an operational profile is constructed is by obtaining data for the load profile by data logging sensors, fitted on the engines. These data are analysed by suitable data analysis software, and the so-called engine histograms are generated. After ensuring that the recorded data have captured the full range of vessel operations, a reliable operating profile can be generated.

The operating profile differs between harbours. It must be highlighted that an exact operating profile to be anticipated cannot be assumed with 100 per cent confidence, due to the altering environmental conditions. The ideal way for determining an operational profile is to collect data from other tugs already in service, in the intended area of operation. This process necessitates originally to operate tug vessels in that port. If not, that an affiliate company would provide the operational profile. It goes without saying that a data logging system should be in place in the first hand. Also, that if in the harbour that the company is intending to begin operating, is segmented only by competitors this task will might be proven impossible.

Kotug currently does not have in place such a data logging system in any of its Rotortugs, in operation. To this end, for the purpose of this study a representative typical operational profile, as collected from various published sources will be used. In many of those studies, data logging on harbour tugboats has been conducted for an extended period. [63-67]. In the future it is the intention of the company to equip its fleet with the necessary tools for monitoring, storing and transmitting operating data as a part of normal operations.

An exemplary load profile of a typical harbor tug fleet, as measured during vessels' lifetime operating in the ports of Los Angeles and Long Beach, in California is shown in Figure 4-4. [68]

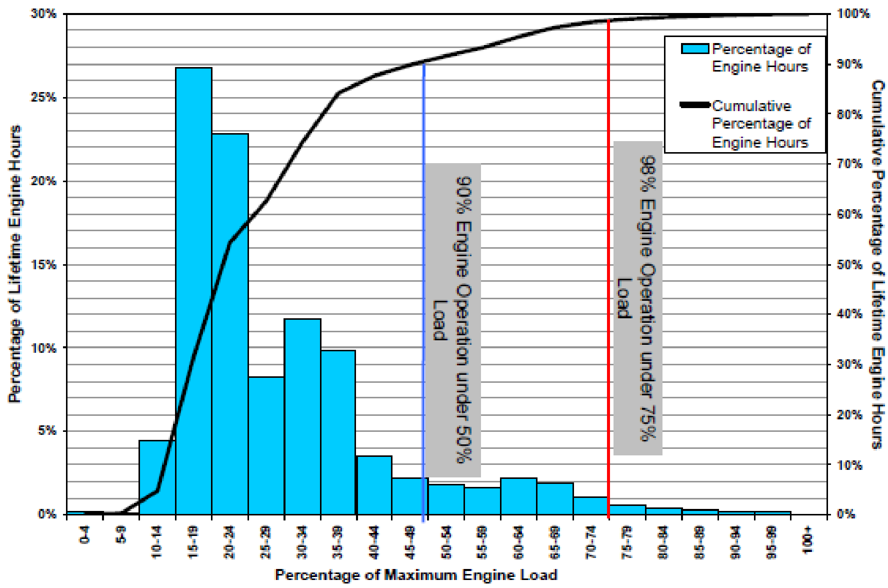


Figure 4-4: Mission profile results from data-logging of a competitor's harbour tug fleet, operating in Los Angeles and Long Beach harbours (Daniel Cavalier, 2008)

There are certain general observations, through the literature review conducted, which can be summarized in the following bullet points:

- Low engine load (<50 per cent of rated power) occurs 90 per cent of the time
- Low engine load (<10 per cent of rated engine power) occurs more than 50 per cent of time
- High engine load (>70 per cent of rated engine power) occurs less than 5 per cent of the time
- High engine load (>90 per cent of rated engine power) occurs less than 2 per cent of the time
- Maximum Engine power (Bollard pull) occurs less than 1 per cent of the time

Low load operation is clearly dominating. This means that most of the time the engines operate at, or close to idle, with some medium duty average load of 40 to 50 per cent and short high-power outputs.

The operational profile can be broken down to operating modes. A typical harbour tug's operational profile can be broken down to 3 basic operating modes; transit, loitering /or stand by and assist. Each operating mode is defined by a power demand and duration. A representative mission profile depicted in the time-domain, where one can distinguish the abovementioned operating modes would look like the following:

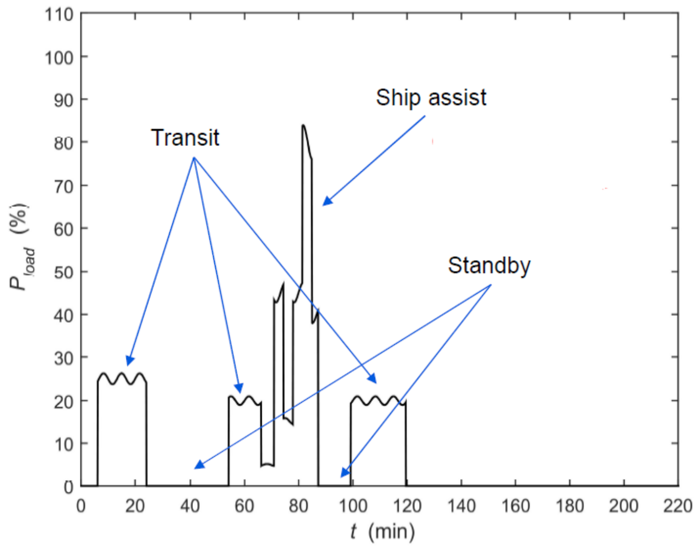


Figure 4-5: Representative time-domain mission profile of a tugboat [69]

The x-axis represents the time, while the y-axis the power demand, in percentage of total installed power, for each operating mode for a certain time period. It is evident, similarly to the previously illustrated operational profile, that for the time period investigated the tugboat spends a high percentage of time in power bands below 50 per cent, in transit and standby modes, while only a small amount of time operating at full power, at ship assist modes. The peak is when berthing, for a few minutes.

Transit

In this mode the tugboat is transiting between the berth and the target area for assisting the boat berthing or unberthing. In this mode the main engines of a tugboat will be running in a typically steady load pattern for producing the amount of thrust needed to obtain the predefined transit speed.

Standby

In this mode the tug is loitering at sea, either while waiting for the vessel to arrive at the predefined spot from where the assist operation will commence or while waiting to be notified in the radio to start pulling or pushing. The main engines are running idle, meaning that no power is delivered to the propulsors for doing work. The idle speed settings (rev/min) are low, typically varying between 25 to 35 per cent of the engine's rated rev/min, while the power settings at standby mode are between 5 to 7 per cent of the engine's rated power. These settings are however dependent on the engine manufacturer's tuning settings.

Assist

In this mode the tugboat performs the actual job, of pulling or pushing the vessel in such a manner as to safely dock or undock. In this mode the tugboat is normally experiencing extended periods of lightly loaded fluctuation pattern, while there are short peaks of high-power demand. The tugboat should be able to respond sufficiently fast to load fluctuations, depending on the condition.

As mentioned before the time that the tugboat rests at the dock is not considered part of the operational profile. However, it is worth mentioning and investigating the effect of this time on the fuel consumption and emission output. It is typical for a harbor tugboat to spend more than 50 per cent of its time annually at dock. Its main engines are off, but there is still energy demand for hoteling purposes. Thus, depending on whether the vessel will be using shore power or not, it might have a significant aggregated impact on total emissions and fuel consumption measured in annual basis.

4.3 Reasoning behind alternative propulsion configurations investigation

The conventional propulsion configuration was for decades the preferred configuration for tugboats, if not the only one considered. Such tugboats are mainly equipped with medium or high speed 4-stroke diesel engines, depending on the attained bollard pull. Rotortugs are fitted with high speed 4-stroke diesel engines. High-speed are generally more compact and less expensive than medium-speed engines. These engines are efficient mainly in the power range of 80 to 100% MCR. When operating in lower power bands, they are considered inefficient in terms of specific fuel consumption (SFC) as well as in terms of emission output (Specific Emission Factor : SEF) [68].

The SFC of an engine is a function of engine speed and delivered power. It is usually depicted as a sum of contour lines, like in Figure 4-6. A typical graph of the SFC trend of a medium speed 4-stroke diesel engine is shown in Figure 4-7. The same pattern is also observed for high-speed 4-stroke diesel engines.

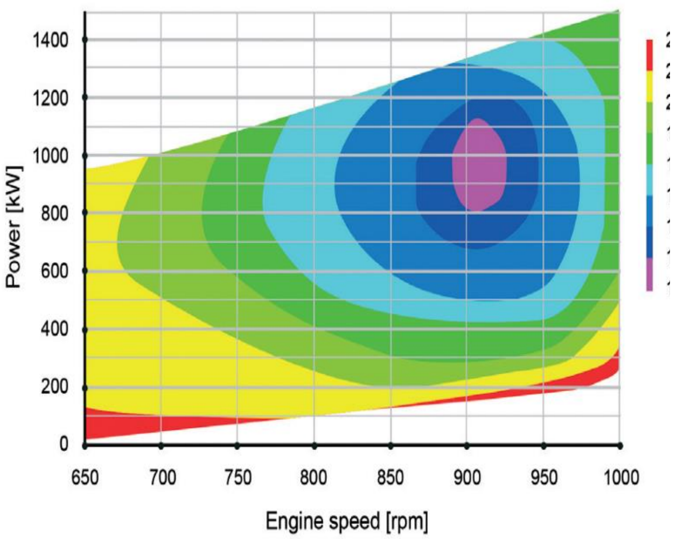


Figure 4-6: Consumption map (SFC in g/kWh) of a typical medium-speed diesel engine [ITS 2015]

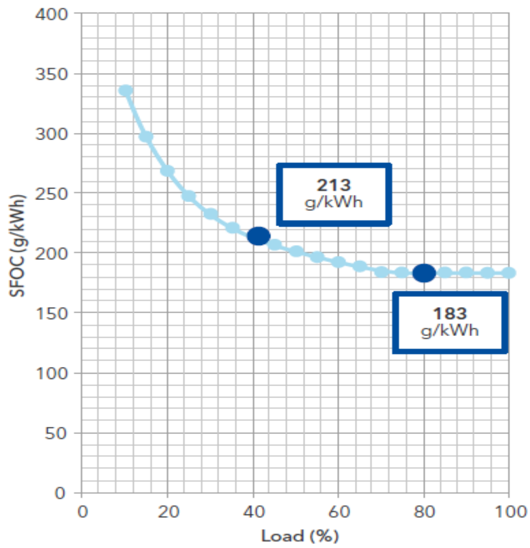


Figure 4-7: Specific fuel consumption vs load for a typical medium-speed 4-stroke diesel engine [DNV, 2010]

Especially regarding harmful NO_x emissions, which lot of focus is placed on minimizing them, a rising trend with both lower engine speeds and lower engine loads is apparent. Based on manufacturers' data, for such diesel engines to remain within Tier II limits, they need to be either loaded beyond 60 per cent, regardless of speed or run on speeds to at least 80 per cent, regardless of load. In addition, when running close to idle speed, they are emitting about 75 per cent more NO_x pollution per unit of energy produced than when running at an optimal load point. Additionally, extended periods of lightly loaded running accelerate engine wear in several important ways. Lightly-loaded running increases the risk of cylinder bore glazing, which in turn further increases pollutant emissions and decreases performance. [70]

As described in the foregoing section, a harbour tugboat uses more than 90 per cent of its power for less than 5 per cent of the time. It actually spends about 75 per cent of its lifetime in operations where it needs less than 35 per cent of its power (see Figure 4-4). In a conventional propulsion configuration, the main engines are kept running in all operating modes, irrespectively of the load condition. Main Engines are turned off only when the tugboat is docked or anchored. This means that for a DDP configuration, the main engines would operate most of their lifetime on sub-optimum power range.

One could reach to the conclusion that tugboats, with a diesel-direct configuration, are not optimised for both low power and full power ratings. The basic principle behind the design of the propulsion architecture of a tugboat until recently, was achieving the maximum Bollard pull, set as a design requirement. The way to do so, was by selecting engines that would produce the maximum power to attain the set Bollard pull (contractual requirement). However, day to day tug operation would rarely need the installed power. During transit operations the engine load is predictable, may even be considered stable, but during assist operations it fluctuates from low to peak. The installed main engines should be able to respond to a high-power demand at short notice. It is during transient behaviour that diesel engines have been proven highly reliable with short response times. Not only that but diesel engines after so many years which are tested in real-time conditions have been improved significantly and are commonly regarded reliable for the shipping industry. In addition, regarding investment consideration, the capital expenses for a diesel engine, even though still high is considered decent. To conclude, diesel-direct configuration is considered the dominant option for harbour tugboats because of three main factors; reliability, power availability and capital expenses. [71]

In recent years it has become a common practise in towing business to evaluate the towing services, apart from the Bollard pull requirement in terms of energy efficiency, by taking into consideration the fuel consumption. Not only this, but nowadays the focus is shifted also in becoming environmentally friendly. Owning a tugboat which could prove less emitting than the competition could prove a significant advantage, especially if it is combined with a port's strategy to lower its overall emission activity profile.

4.4 Alternative Propulsion Configurations

With the intention of reducing the ecological footprint of the future Rotortug, after consultation with the company's management and external consultants (Rotortug Ltd) it was decided to investigate a finite number of candidate configuration solutions, taking into consideration the limitations of the study, as listed in section 1.3. All variants are expected to show gains either at the efficiency of the vessel, or the emission reduction, in some cases also for both. An improvement is anticipated especially when altering the drivetrain configuration, due to the subsequent engine load increase in most of the operating modes, leading to a more effective use of the installed engines for the complete duty profile, in comparison to the conventional layout.

The focus of this thesis has been set from the beginning in the type of fuel and its associated prime mover, when combined under preset drivetrain configurations. Principally, the prime movers as presented in the previous chapter are considered for use as main engines. The auxiliary engines have been decided to remain fixed-speed diesel engines. In this context, three power plant principles are considered; conventional, diesel-electric and hybrid. For both the conventional and hybrid configurations five (5) alternative powering options are investigated, while for diesel-electric only one (1). An extensive review on different variants of each of the aforementioned concept layouts, applied in various ships, with emphasis on the control strategy employed in each case is presented at [72]

Four important points should be noted. First, with regard to the objectives of the thesis, altering the design criterion (maximum bollard pull) for a harbour tugboat does not constitute an option. The proposed candidates will still need to produce the maximum power to contemplate the set Bollard pull requirement. Second, an Energy Management System (EMS) is developed according to a rule-based strategy, which differentiates depending the propulsion configuration. The power management principle, under the context of operating modes, for each propulsion configuration is presented in Appendix C.3. Third, a shore connection is fitted in all propulsion architectures which allows for total shutdown of engines and generators during waiting periods alongside a quay, in cases it is provided by the harbour facilities. Fourth, a variety of after-treatment technologies, as discussed in section 3.5, namely SCR, OxiCat and DPF will supplement separately or in combinations each of the candidate configurations if deemed necessary for complying with the emission regulations in the intended port of operation.

4.4.1 Conventional with other prime movers

As discussed, the conventional propulsion configuration has been the dominant propulsion configuration for the majority of tugboats. Tugboats with such a propulsion configuration are cheap to build and reliable. In the previous chapter, the effect of different prime movers and their potential emission benefit, when combusting alternative fuels has been argued. It is only logical to investigate the influence of replacing diesel engines by such prime movers, when combined under the same proven conventional line-up. It is anticipated that the differences on fuel consumption and emission output of those prime movers, in comparison to diesel engines, will have a combined effect when investigated under the whole operational profile spectrum, which could prove adequate for complying with the upcoming emission regulations.

4.4.1.1 Description of Candidate concept layout

Based on the selected prime movers, as concluded from Chapter 3, there are five (5) variations, which will be investigated:

Table 4-3: List of conventional configuration candidates

Scenario	Engine Type	Fuel
CONV S1	LBSI	LNG
CONV S2	LPDF	LNG
CONV S3	LPDF	Methanol
CONV S4	4*CI	Biodiesel
CONV S5	4*CI	DME

Where:

S1: LNG burnt in Low Pressure Dual Fuel (LPDF) Engine
S2: LNG burnt in Lean-Burn Spark Ignited (LBSI) Single Gas Engine
S3: Methanol burnt in LPDF
S4: Biodiesel burnt in 4-stroke Compression Ignition Engine (4*CI)
S5: Dimethyl Ether burnt in 4*CI

The main engines will be mechanically coupled to the Z-drives powering the Rudderpropellers. Hotel and auxiliary electric loads are satisfied by the same diesel gensets, as the baseline configuration; two Caterpillar C9 162kW and one 36 kW Caterpillar C4.4 diesel generator set, serving as a harbor generator. Likewise, each of the C9 generator sets can meet the electric load demand of the vessel. The second auxiliary generator set is installed for redundancy reasons. The harbor gen set is operated, while the ship is docked, instead of one of the bigger gensets, in order to satisfy the hotel loads. The drive train configuration, represented in the form of one-line diagram, is illustrated in Figure 4-8

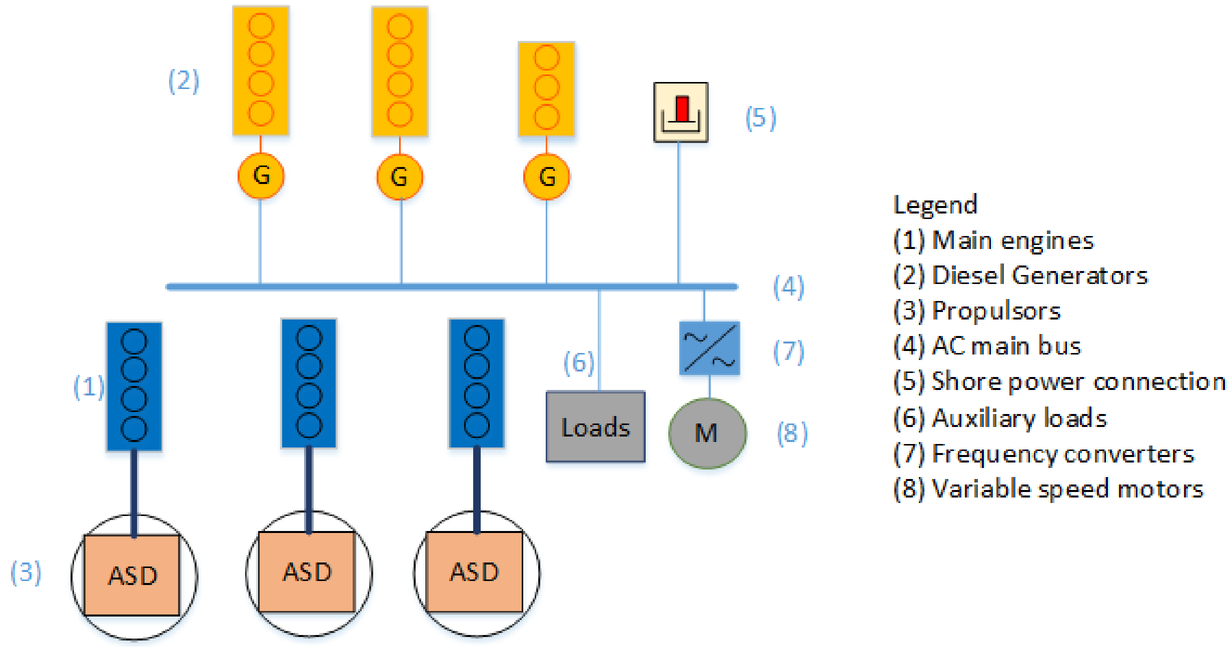


Figure 4-8: Schematic one-line diagram for conventional propulsion configuration

In a mechanical propulsion configuration, the control strategy employed when fixed pitch propellers are used, is typically based on the governor speed control. The governor regulates the engine's speed, by controlling the fuel supply rate. Without a governor an engine would not be able to attain a stable idling speed and it would also be prone to overspeed. The power management principle is presented in Appendix C.3.1.

4.4.2 Diesel-Electric

A diesel-electric system is considered an electric propulsion system, because electrical power is used both for propulsion, auxiliary and hoteling needs. In a diesel-electric propulsion configuration, mechanical power from the prime movers, usually medium or high-speed 4-stroke diesel engines for tugboats, is converted into electrical and then distributed to all consumers. There is no need for any additional auxiliary generator sets.

In a typical diesel-electric propulsion configuration, like the one under consideration in this thesis, the prime movers are usually constant speed 4-stroke diesel engines driving alternate current (AC) gensets, providing a fixed output frequency. An electrical motor shafted usually on a gearbox or connected directly to the propellers shaft, is driving its associated propulsor. The energy produced is fed to the electric motors through the Main Switchboard (MSB), based on either an AC or DC topology, a transformer depending on the voltage of the electrical bus and a power converter. There are a lot of variations concerning the propulsion motors to be used, depending on the power application; conventionally, ac induction motors, dc motors or ac synchronous motors are used. Modern approaches are also favoring permanent magnet motors, which are considered to have a higher efficiency at low revolutions per minute [73]. Depending on the chosen motor, energy is delivered through variable frequency or voltage converters.

In this thesis AC induction motors, are chosen as propulsion motors, connected directly to their associated propellers' shaft. The energy produced is fed to the electric motors through a low voltage AC MSB and a frequency converter, also known as variable frequency drive (VFD).

Electric propulsion is very popular among certain vessel types. It is widely used in special purpose vessels, like offshore support and construction support vessels as well as in floating drilling rigs. Diesel-electric configurations are mostly found in ships that employ dynamic positioning or ice-going capabilities. Moreover, it is widely used on passenger vessels and cruise ships.[74] On a pure electric generation plant, the energy is produced by generator sets, but can also be supplemented with energy storage systems.

4.4.2.1 Benefit potential

The key advantages of electrification are the flexibility, redundancy in power capacity and improved engine loading. Flexibility is offered mainly due to three reasons. Firstly, the elimination of long shafts and clutches connecting the prime movers with the propellers and secondly the subsequent eradication of fixing the prime mover in a certain position, in-line of the thrusters' shafting. Lastly, due to the absence of additional generator sets, there is the potential for space gain, which can be allocated to other uses. As already said, the extensive low-load operation in tugs causes their main engines to run very inefficiently. By detaching a propeller from a main engine and fitting a propulsion motor instead, the engine operation becomes independent of the propeller speed, hence the propulsion speed. Instead the engine operation is dependent on the load demand, which enables the optimisation of the engine operation based on the anticipated load rather than the propeller speed. The capability of installing multiple generator sets which could be programmed to start automatically and run in parallel, responding to the load demand offers both redundancy in power capacity, especially considering the response to engine failure situations as well as the potential for improved loading. It is important to be highlighted that in a diesel-electric configuration is not mandatory to install equally sized engines. The installation of different size engines can contribute in better matching of the anticipated load demand. When the load is low, one or more engines can be shut down to maximize the load on the engines still running. Although a prime mover can still be lightly-loaded, in the cases that the propulsion load is low, by choosing the number and capacity of the running engines it may provide the means to improve the efficiency.

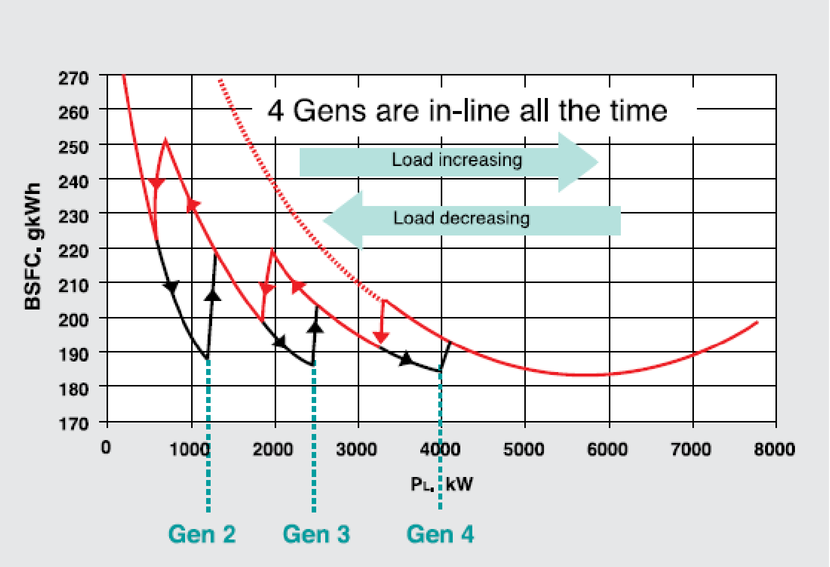


Figure 4-9: Fuel consumption per kWh of produced energy

In Figure 4-9 is illustrated for a typical four (4) diesel generator set installation, the effect of starting or stopping the diesel engines, acting as prime movers, on fuel consumption, with regard to the load demand. It is evident from that graph by observing the red dotted line, that if only one engine, capable of satisfying the load demand was installed instead of 4 equal power smaller engines then the fuel consumption per kWh of produced energy would be substantially higher. Depending on the selection of the prime movers, there would be different SFC curves and thus different potential for efficiency improvement.

Whether a diesel-electric propulsion configuration would provide the wanted gain in efficiency is an issue, which requires a case study considering the efficiency losses of energy transformation.

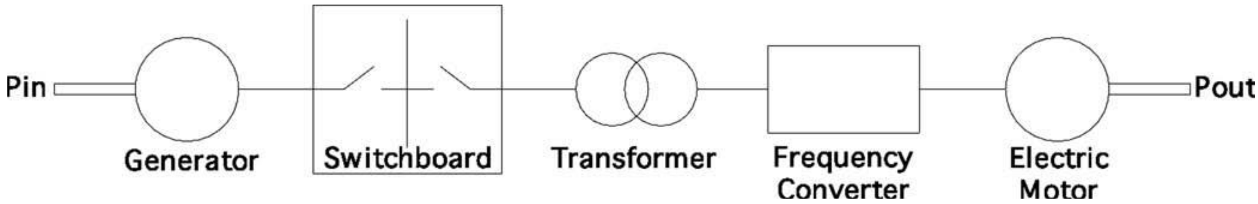


Figure 4-10: Chain of transmission losses in a typical high voltage diesel-electric propulsion configuration

In Figure 4-10 the transmission losses of each component between the production of electric energy from the generator and final distribution to the propeller shaft is displayed, for a typical high voltage diesel-electric configuration. It has been cited that power losses are in the range of 8-11 percent, in contrast to a diesel-mechanical propulsion configuration, which are in the range of 4-6 percent.[75, 76] Despite the conversion losses, still a net benefit in fuel consumption can be achieved compared to a traditional tug, set up on a conventional line-up. This will be dictated though, by the exact operational profile of the tugboat, under consideration and the Power Management System (PMS) of the generators.

Another benefit of diesel-electric propulsion is an electric motor's ability to provide torque margins close to 100 per cent even at very low speed, while maintaining wide margins throughout the full speed range. This means, that diesel-electric systems have high torque available in all operating conditions, thus the system can respond very fast. This will provide an added benefit on manoeuvrability. An example of the torque limits of a diesel engine compared to those of an electric motor is illustrated at Figure 4-11 below. It is evident that, at 50 per cent propeller speed the electric motor has eight times as much torque available for acceleration.

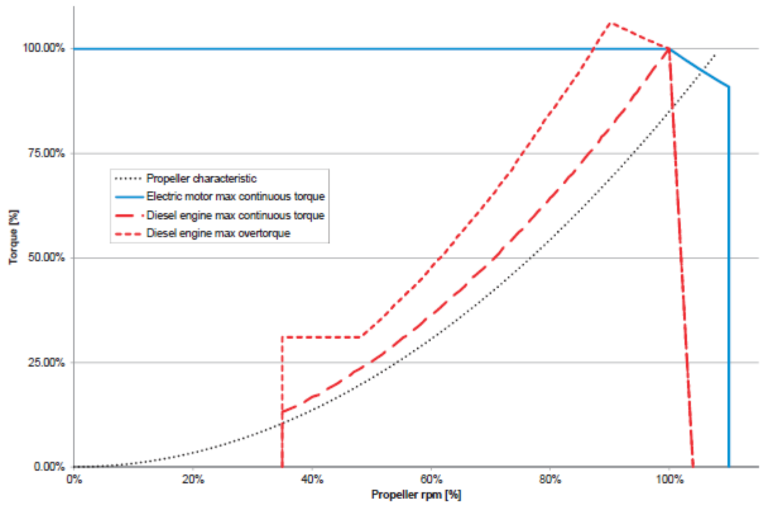


Figure 4-11: torque limits comparison between an electric motor and a diesel engine

4.4.2.2 Description of Candidate concept layout

For the scope of this thesis, only one case for electrification for the target vessel was chosen for investigation, the diesel-electric configuration, set up on an AC topology. The power plant considered uses a 60 Hz AC MSB distribution network. The power plant consists of four (4) Caterpillar 3512C 1432kW diesel generators, one Caterpillar C18 465kW diesel generator and one C9 200kW all running at 1800 rpm are supplying the electric power. Three variable speed induction electric propulsion motors in line with frequency converters are connected directly to the Z- drive formation Rudderpropellers. In this way each of the ac induction motors propels its related shaft, and subsequently its related thruster. The diesel-electric propulsion architecture under investigation is depicted in Figure 4-12.

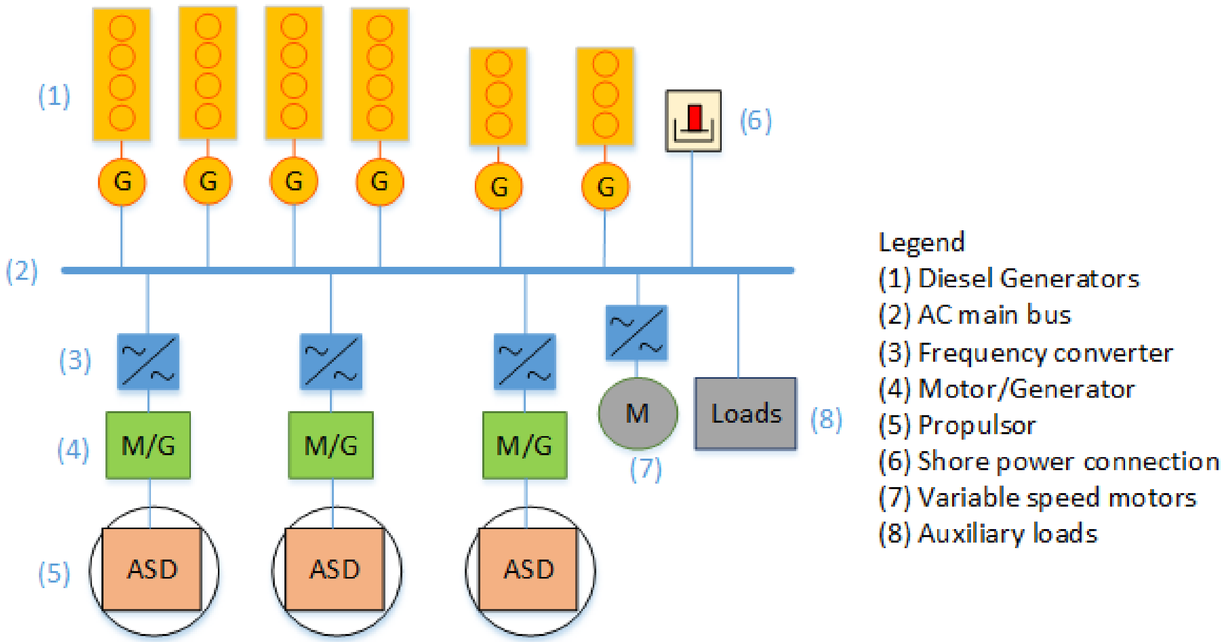


Figure 4-12: Schematic one-line diagram of diesel-electric propulsion configuration

The power distribution on such a configuration is different than of a conventional configuration. Power is provided for all systems, including propulsion, hotel and ancillaries from the gensets. Based on the power sharing strategy, the generators are automatically started up and run in parallel in order to match the load demand, while at the same time ensuring that the online engines' load is kept within their efficient operating range, as far as practicable. The EMS philosophy is discussed in Appendix 0, under the context of the established operating modes. This algorithm is by no means optimized; optimisation is a complex process which lies outside the scope of this thesis. It must be noted though that most energy management strategies already applied in vessels are also simple rule-based strategies, typically developed based on past operations experience.

For tugs, the major advantage of a diesel-electric propulsion; maximization of engine loading on online diesel engines may not be enough to counteract the transmission losses due to electrical conversion to mechanical power. Not only that but the space available for equipment is not abundant on a tugboat; rather the opposite, space is restricted. Thus, another of the main advantages of a diesel-electric power-plant; flexibility of placing generators at convenient places is lost. Considering also the capital cost and the extra weight of the additional electrical equipment are limiting factors pushing for investigating a different more-suited for tugboats power-plant architecture. The interest is placed in hybrid propulsion systems, as will be explained in the following section.

4.4.3 Hybrid

A hybrid propulsion architecture can consist of multiple propulsion engines, generator sets and electric propulsion motors. It may further be supplemented by energy storage technologies. Depending on the combination of components various solutions can be implemented. Hybrid architectures exist that consist only of mechanical components for providing the necessary propulsion power. Those architectures are known as mechanical-mechanical. The most common is the so called "father and son" concept, where two different size engines are connected to a gearbox. Then the necessary thrust to the propulsor is delivered via a single shaft output. In highly load demanding operating modes both engines (father and son) are running, while in lower only the smaller one (son) is used. Such layouts have been satisfactorily applied in anchor handling tugboats.

Architectures which consist of both mechanical and electrical components, for delivering thrust to a propulsor are known as electro-mechanical layouts. As in a conventional configuration the connection of a main engine with its associated thruster via a clutch and a shaft line occurs. However, an electric motor (e-motor) is introduced in the drive train, able to deliver a fraction of the maximum torque to the thruster in conjunction with the main engine or stand-alone. When the electric motor is delivering propulsion power, it is working in “motoring” mode. In most cases these motors can also absorb power from the main engine, depending on the mode of operation and deliver power to the auxiliary network, thus working in “generating” mode. Those e-motors are also known as motor/generators (M/G). Please refer to Appendix C.2 for more information. In those cases where the main engines and the e-motors are providing propulsion power via a gearbox, those electro-mechanical layouts are denoted “hybrid parallel”, while when the main engines and the e-motors are coupled in-line to the propeller shaft they are denoted “hybrid series”.

Hybrid systems have been successfully introduced in submarines, where diesel-direct propulsion is used for sailing, while when submerged they are electrically propelled. Throughout the decades, hybrid concept layouts have been applied in numerous vessel types, especially in the offshore segment. Currently a variety of hybrid concepts, operated by many companies all around the world, are available for tugboats, all to show improvement in terms of fuel consumption and emission performance.

4.4.3.1 Benefit potential

With a hybrid power-plant the ability to use a combination of electro-mechanical components, depending on the operating mode offers the potential for optimizing the total transmission loses in each operating mode, leading to a better total efficiency for the whole mission profile, even though additional equipment is introduced. In this way the advantages of both the conventional and electric power plant principles can be utilized. To this regard, the relative performance of the power sources used should be taken into account. Specifically, during low loading operation, the main engines can be switched off, providing electric power generated by the auxiliary engines or energy storage devices. Even though the electrical losses will be higher they could be offset by the more efficient operation of smaller diesel generators instead of the bigger main engines. In loitering conditions for instance, eliminating the idling operation of the engines will increase the fuel savings. In addition, during mid and high loading operations the main engines can constantly run inside their efficient power range, by enabling the e-motor to absorb power from the main engines for generating electric power and feeding it into the vessel’s electricity grid. Especially, during bollard pull conditions, depending on the sizing of the main engines the clear advantage of mechanical propulsion over electrical propulsion in terms of transmission efficiency will be fully utilized.

Again, like the diesel-electric configuration, the exact benefit potential will be dictated by the choice of powering components, their integration within the drivetrain line-up and the energy management system developed for their operation control. Better utilization of the power components will also lead to better operating and maintenance costs, in comparison to a conventional layout. The integration of energy storage technologies; in particular batteries, increases the fuel and emission savings potential even further, as explained in section 3.4.3.

4.4.3.2 Description of Candidate concept layouts

In this thesis two hybrid options have been considered as candidates, both pertaining in the series hybrid layout. The first option is utilizing an AC distribution electrical network, while the other one a main DC bus bar and a secondary AC distribution network supplemented by batteries. More information on the differences between AC and DC distribution network topologies can be found in Appendix C.2. Below the one-line diagrams for the candidate configurations are illustrated.

With the focus set at ensuring additional redundancy by providing to the operator the way to propel the tugboat in 100 per cent non-hybrid mode of operation it was decided not to downsize the main engines, but to keep the same three Caterpillar 3512C main engines, as in the conventional configuration. Thus for both candidates, three Caterpillar 3512C rated at 1765kW running at 1800 rpm were selected. These drive via the Twin Disc MCD slipping clutches the Rudderpropellers. The MCD slipping clutches will operate in the same manner they do on the conventional Rotortug, when the main engines are powering the thrusters.

Two Caterpillar diesel generator sets, a C9 rated at 200kW and a C18 rated at 450kW, will provide electric power for propulsion and hotel services. The electricity generated is fed via inverters (VFDs) into its thruster's dedicated electric motor. The e-motors are mounted in the shaft between the slipping clutch and the rudder propellers, as depicted in Figure 4-13. The motor/generators function on PTI mode; in particular the e-motors will function either as motors, providing propulsive power to the thrusters, or as passive elements on the propulsion shaft, allowing the main engines to propel the vessel. However, these motors will not work on a "boost" mode, since the main engines are capable of meeting the maximum bollard pull requirement. In addition, those motor/generators will also operate in PTO mode, in some operating modes. The EMS philosophy is described in Appendix C.3.3.

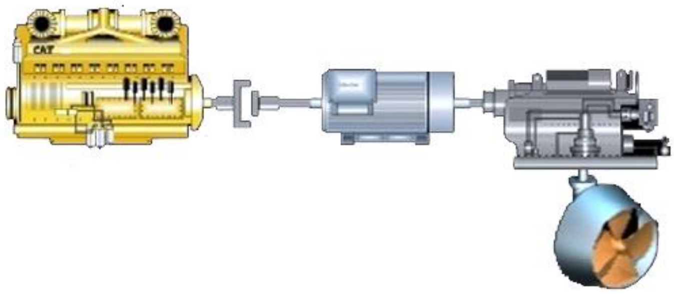


Figure 4-13: Series hybrid propulsion line-up of ART80-32

Therefore, particularly for the hybrid versions, the option of keeping the same main engines as the conventional drivetrain will also be examined. In addition, the effect of substituting the prime movers is investigated. Therefore, the following five (5) variations for both hybrid architectures are examined:

Table 4-4: List of hybrid propulsion configuration candidates

Scenario	**Engine Type**	**Fuel**
HYBRID S1	LBSI	LNG
HYBRID S2	LPDF	LNG
HYBRID S3	LPDF	Methanol
HYBRID S4	4*CI	Biodiesel
HYBRID S5	4*CI	DME

4.4.3.3 Hybrid with AC electrical network

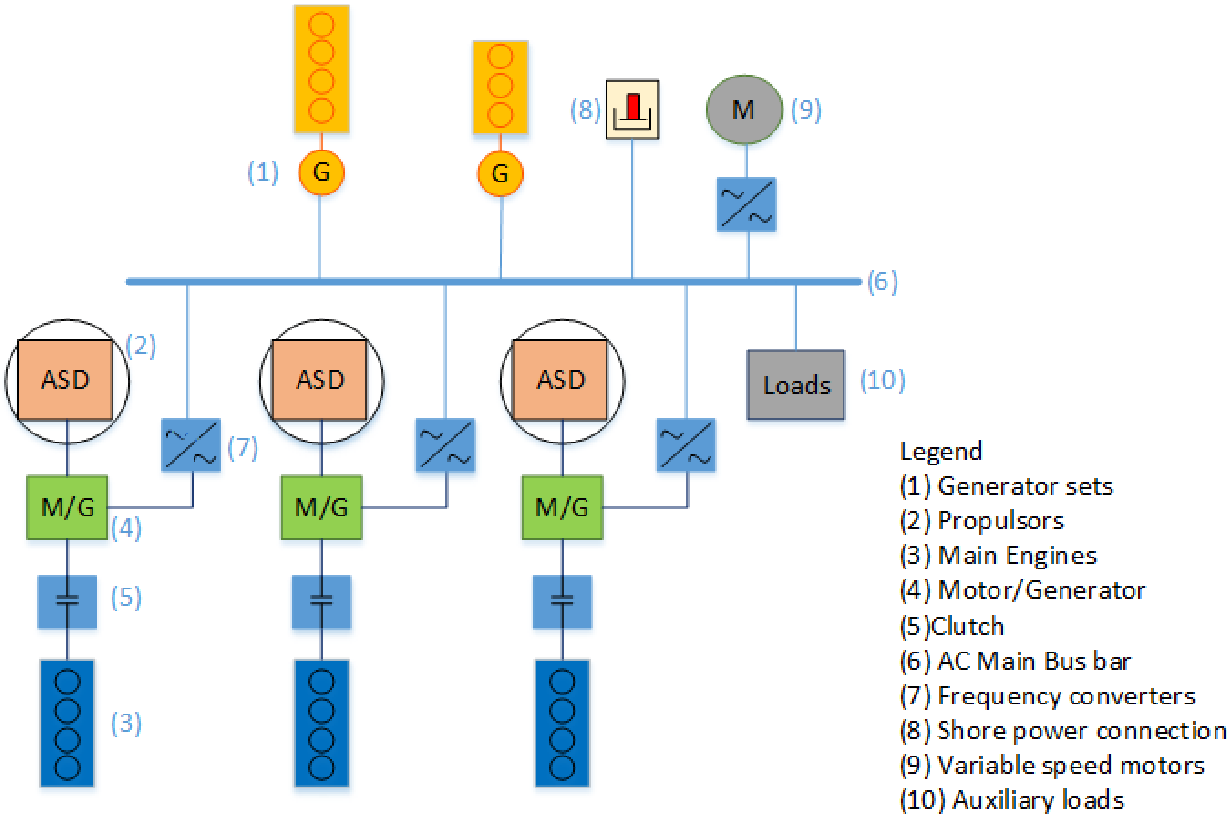


Figure 4-14: Schematic one-line diagram of hybrid propulsion configuration based on AC distribution network

4.4.3.4 Hybrid with DC electrical network

In this thesis only one DC distribution concept will be investigated consisting of two fixed speed generator sets. The same two generator sets as in the hybrid candidate based solely on an AC network are kept. In particular, the bigger C18 engine will connect directly to the AC bus bar, while the smaller C9 engine is able to connect both to the main DC and AC bus bar through a change-over contactor. The main DC bus is supported by two Active Front End (AFE) converters, one fed from the AC switchboard (which in turn is supported by the 200kW generator) and one fed from the 450kW auxiliary generator. Either one or both generators can be used to support the DC bus. In addition, the integration of battery banks to the DC main switchboard is also examined. The focus is primarily set on efficiency gain due to energy transformation losses reduction in comparison to an AC distribution network, as well as fuel and emission reduction potential of integrating batteries. In contrast to the hybrid with AC bus bar additional DC/AC and DC/DC converters are introduced to the drive train. A layout of the proposed candidate configuration represented as a one-line diagram is illustrated in Figure 4-15

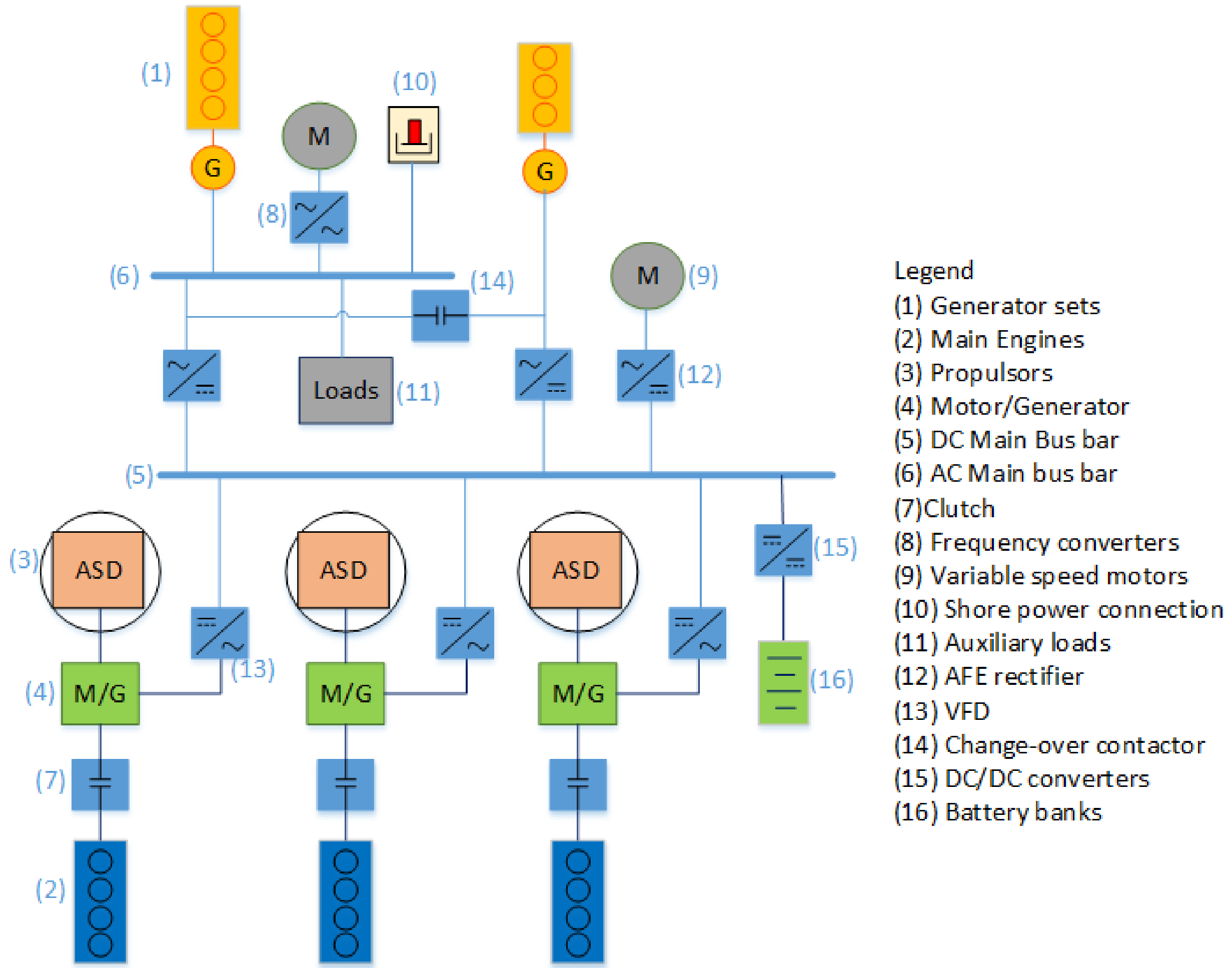


Figure 4-15: Schematic one-line diagram of hybrid propulsion configuration based on a main DC distribution network

4.5 Conclusion

In this chapter it was shown that tugboats have a highly variable operational profile, consisting of extensive low-load operation with short-periods of peak power consumption. From analysing a typical tugboat's operational profile, it was concluded that it can be broken down in three basic operating modes; transit, loitering /or standby and assist. Apart from those operating modes, great significance should also be placed in the fact that tugboats remain almost 50 percent of annual operating hours docked. The conventional power plant principle is well-established within the industry and will remain for years to come. However, because such tugboats are built with big main engines capable of providing the necessary torque in bollard pull conditions, means that they run inefficiently for most of the time. Thus, the potential for efficiency improvements in terms of fuel consumption and emission reduction exists. The potential benefits of electrification of tugboats for addressing this issue was elaborated and two different concept layouts were presented; diesel-electric and hybrid series. In particular, two variants of the hybrid series configuration were decided to be further investigated, one set up on AC distribution network topology and the other one on DC supplemented by battery banks. In total, three power plant principles are considered; conventional, diesel-electric and hybrid series. For the conventional five (5) alternative powering options are investigated. For the hybrid six (6), one (1) based on the same main engines combusting MGO, as the conventional drivetrain and five (5) alternative powering options. Lastly, for diesel-electric only one (1). In total eighteen (18) variants. These variants will be compared against the baseline configuration in terms of fuel consumption and emission output. It must be highlighted that the final outcome of a comparison between power plant configurations on fuel consumption and emission savings will be dictated both by the transmission losses for each operating mode, when examined throughout the complete mission profile but also by the power management strategy employed. The decision of conducting a steady-state analysis imposes limitations, mainly on the inability to account the effect of transient load behavior and exploiting the full potential of integrating batteries on the hybrid power plant. In the next chapter the design methodology of the decision-making tool will be presented.

5 Description of the decision-support tool

In this chapter firstly a brief description of the purpose of this tool is given accompanied by a brief overview of the tool's design philosophy. The decision support tool is designed in Microsoft Excel®. Next, all vital input data required for the tool to function are listed, along with the information contained in the database. The evaluation of the alternative candidate propulsion configuration variants is conducted based on technical and economic aspects. The tool is developed on the basis of interconnected modules, which would yield the final output. Each block is explained in detail accompanied by the mathematical representation of the followed procedure, and its related assumptions, enhancing the reader's level of understanding with respect to the decision-making methodology. All important aspects discussed in the previous chapters are now integrated inside their relevant block and all blocks combined form the complete model.

5.1 Purpose and overview of the tool

The objective of this work is to develop a computer-based tool to appraise the compliance of alternative propulsion configuration concepts for the upcoming more stringent emission regulations. The tool is envisaged to support Kotug International in the investigation and assessment of alternative propulsion configurations for their future newbuilding program scheme and is supposed to serve as a decision support tool.

Within Kotug International, Microsoft Excel® is widely used, in contrast to other programming platforms, which are specifically developed for engineers and scientists. Thus, it was decided to develop the model solely in Microsoft Excel®. The functional requirements of the tool are listed in Appendix D.1.

The model consists of several interlinked spreadsheets. In numerous spreadsheets coding has been written in VBA, which runs in the background. The output of the tool is a list of the viable candidates ranked in terms of the chosen criterion, as will be elaborated below, accompanied by a series of diagrams, used as visual aids to illustrate the effect of various parameters in the performance of the alternatives when compared against the baseline case. The main blocks and the flow of information between them is outlined in Figure 5-1 below.

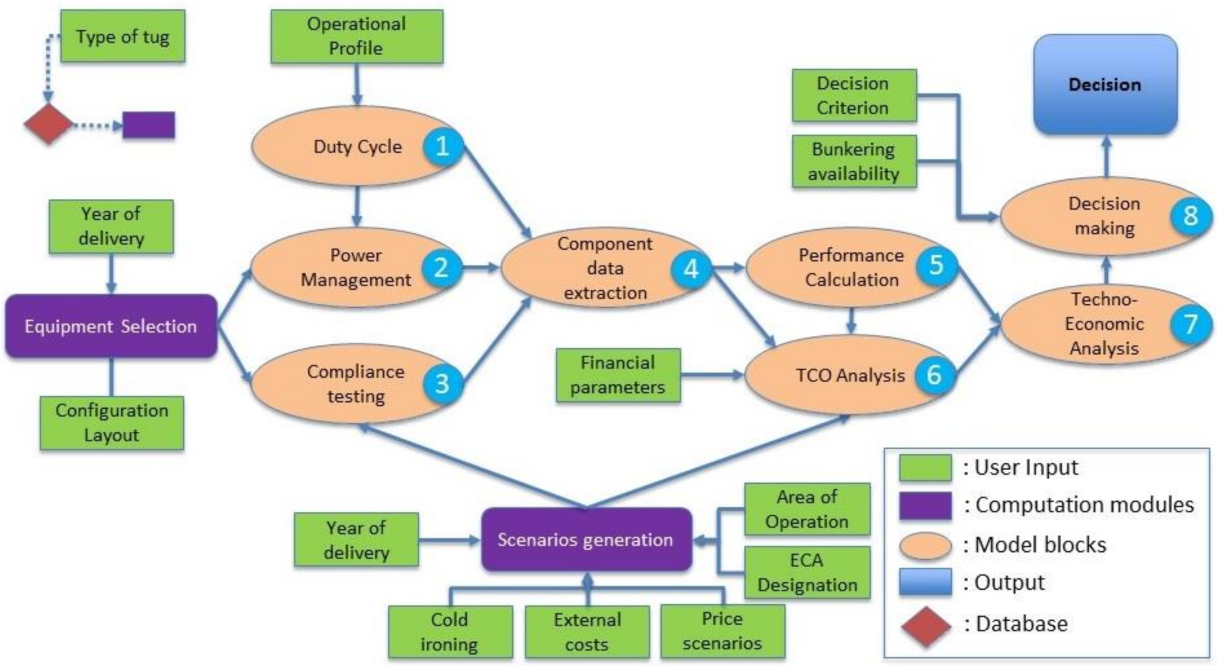


Figure 5-1: Overview of the decision-support tool (flow line)

The user inserts the "user input" data in the Input interface spreadsheet, when starting the tool. These data, depicted in green blocks, are represented in this schematic in way of the modules, where they are used for further computations. The calculation process consists of eight (8) modules (model blocks), depicted in salmon-pink, each representing an underlying spreadsheet where the calculations are performed, according to either user data inputs, depicted in green or output data of "computation" modules, depicted in purple. The arrows are outlining the process flow. The computation modules interact with the database in order to extract the necessary data, according to the user input. Finally, "Output" is the user interface spreadsheet, where the results of the decision-support tool are displayed. All the spreadsheets will be explained in the next sections, along with the basic assumptions made.

5.2 Input

The Input spreadsheet is the interface where the user should either fill in directly the data input variables or choose them between predefined options. The user will be asked to specify the following input data:

1) Region of operation / Country of Operation / Port of operation

The user, with the purpose of selecting the intended area of operation, which will determine the applicable emission regulation regime, is provided with the option to select the region, the country and the port of intended operation, out of the pre-set data entries. Each area entails a list of regions, each region a number of countries and each country a number of ports. The user after making a selection in one of the three aforementioned fields, is presented only with a list of feasible options, relevant to his/her choice, in the remaining fields. Further explanations on the classification followed concerning the regions, countries and ports are provided in section 5.3.1.

2) Year of delivery

The user must select the year of delivery of the newly built Rotortug. It is assumed that the keel laying date is also the year of delivery. This is an important assumption, since the applicable regulations regime is defined based on the keel laying date. The user has the option of selecting a year from 2018-2033, the time period which is considered for the scope of the thesis. The choice of year is attempted to capture the progress of technology (engines, after-treatment systems and batteries), by impacting three (3) parameters; the emission performance of the examined engine types running on alternative fuels, the emission reduction potential of after-treatment systems and the battery's cost and life expectancy.

3) Decision criterion

The decision-making methodology may be conducted upon three (3) distinct decision criteria. The choice is between

a) Environmental performance
b) Economic performance
c) Cost-effectiveness

Depending on the decision criterion selected initially, different valuation metrics are used, as explained in section 5.4.3.2 later, which subsequently will impact the candidates' evaluation results and thus the final decision.

4) Operational Profile

The user is prompted to specify the values only for the operating modes of the mission profile, as classified in Chapter 4; transit, loitering /or stand by and assist. Each operating mode is defined by a number of representative mission characteristics, as shown in Table 5-1. The duration of the mode operation is inserted by the user in operating hours per year and is converted automatically by the tool into percentage utilisation.

Table 5-1: Operating modes mission characteristics

Task	Description of the mode task
Service	The operational service for the mode: transit, idle, assist
Speed/ Tow pull percentage	Vessel speed for transit operation (knots) / Tow pull requirement for tow pull service (%)
Time	The duration of the mode (hours/year)

Upon completion of the operating modes the time at "Port" is automatically calculated in an annual basis, by subtracting the sum of operating hours from the total hours in a year; a year is supposed to consist of 365 days.

5) External costs

The user should specify if the environmental impacts of air pollution will be internalized. If chosen to be accounted the external costs will be included in the economic calculations and will be reflected in the financial outcome.

6) Other user-defined parameters

There are certain input parameters that will vary with the prevailing circumstances and the market conditions depending on the year of delivery and the intended area of operation. To avoid incorporating additional uncertainty in the design process, it was chosen to provide the user with the flexibility to define a series of uncertain parameters. It goes without saying that altering those parameters will also affect the final comparison outcome. This is shown in the sensitivity analysis later. The user may specify directly or choose between predetermined values for the following parameters:

a) ECA designation

The user is called to define if the intended area of operation during the chosen "year of delivery" has been designated an "ECA" already or not. As explained in Chapter 1 there is a list of areas that are considered likely to become ECAs in the next 15 years to come. For all areas that are already announced to become ECAs in the upcoming years, in particular the Baltic Sea, North Sea and English Channel with effective date beginning of 2021, the option has been embedded in the underlying algorithm.

b) Cold ironing necessity

Cold ironing has been considered one of the most probable strategies that could be implemented to strengthen mitigation measures and that would affect tug operations. For this reason, it has been incorporated in the tool as an option. The user is called to specify for the "area of intended operation" during the intended "year of delivery" if tugboats need to use shore power or not.

c) Bunkering availability

As discussed in Chapter 3, the bunkering availability for the fuels under consideration varies with the "area of operation". Since there is no way of predicting for each area of operation during the next fifteen years if the infrastructure for bunkering will be in place it is left for the user to estimate. Of course, if the user declares unavailability of bunkering for a fuel, it means that all candidate propulsion configurations on that fuel will be automatically excluded from selection.

d) Price scenarios (Low/Central/High)

i) Fuel Price scenarios
ii) Urea price
iii) Shore power cost
iv) CO_2 external cost

For all price scenarios the user is urged to choose between low, central and high price scenarios, instead of a direct input of the anticipated costs. This way a user is not expected to be familiar with the development of prices, rather is provided with predetermined price variation scenarios, extracted from the database. More on the specification of the various scenarios is provided in section 5.3.2.

e) Economic analysis parameters

i) Period of economic analysis
ii) Discount rate
iii) Inflation

By default, the tool operates with the following input values; Period of economic analysis: 25 years, which is considered a typical tug life expectancy; Discount rate: 8%, Inflation rate: 2%. However, these parameters are adjustable by the user. More information on the discount and inflation rate, in the context of the applied financial analysis, are provided in section 5.4.3.1.

5.3 Database

The tool contains a database consisting of five (5) separate sections. Within each section there might be various sections. The normal user is not presented with the ability to edit any of the information contained in the database, as to avoid complexity in the tool and facilitate the decision-making process. The database has been constructed after careful research among different sources. Below the data contained in the database will be presented under the section that are controlled, along with the assumptions made for each case.

5.3.1 World sea ports

The world sea ports database section contains information on the areas, regions, countries and ports of operation, as compiled for the purpose of this thesis. The areas to be covered has been decided to be categorized according to a slightly modified "continents classification scheme"; Africa, America, Asia, Europe and Oceania. The list of regions, countries and ports is compiled in a tabular format, based on WPS and are taken from the [77]. The complete list, including the regions with their associated countries can be found in Appendix D.2.

It must be highlighted that the intended area of operation affects directly the emission regulations in place, and thus the emission limits which the installed engines must attain in order to comply. With that in mind and based on the regulations to be followed, in an international and regional level, as set out in Chapter 2, the following apply. Firstly, for the purpose of this thesis IMO regulations is assumed to apply worldwide, even though normally they would apply only to those countries that have ratified MARPOL Annex VI Convention. Secondly, EPA regulations is assumed to apply only to the countries belonging in North America and Caribbean, which are considered US territory. In South and Central America, the IMO MARPOL Annex VI Convention applies. Thirdly, EU regulations apply only to EU member states. Furthermore, it is noted that the continent of Antarctica is omitted from consideration because Kotug International is not intending to operate in this zone in the timespan of this thesis.

5.3.2 Specifications

The Specifications database section contains information on the fuel specifications, the emission reduction factors of alternative fuels compared to 4-stroke compression ignition engines running on MGO, fuel and consumable prices, cold ironing prices and emission factors and external cost factors. All costs in his thesis are in United States Dollars (USD - $)

i. **Fuel specifications**

The fuel specifications that are taken into consideration are the density, the energy content, the volumetric energy density, the carbon content and the sulphur content for the candidate fuels. These values are summarized in Table 3-3, as compiled through the research presented in Appendix B.2.2.

ii. **Emission reduction factors of prime movers running on alternative fuels for combustion-related air pollutants**

Regarding the emission reduction potential, as explained in section 3.3, the analysis will be conducted by comparing the emission performance of the selected prime movers when combusting their associated fuels against the reference 4-stroke compression engine running on MGO. The emission reduction percentages are summarized in Table 3-4.

Particularly for gas engines HC/VOC emissions consist of CH4 and NMHC emissions. For estimating the relevant proportion, a fixed NMHC to THC ratio, depending on the engine type is assumed, as deliberated in section 3.4.1. Specifically, for gas engines running on LNG, this ratio will be 6.8% for LBSI engines and 5.5% for LPDF engines, while for LPDF engines running on Methanol the ratio is 100%, signifying that no methane slip is expected.

iii. Fuel prices

Fuel costs directly affect the operating costs of the propulsion configuration investigated, thus it is also very important to try and have good estimate values, as much as possible. However, there is big uncertainty on how prices for alternative fuels will be developed. [78] contains a list of all bunkering fuel projection studies, including LNG until 2105. By comparing the projected results with current prices, it was concluded that they are not accurate and cannot be considered reliable to use in this thesis. Moreover, no recent marine bunker fuel projections including the total of the investigated fuels could be obtained.

Developing a predictive fuel price projection algorithm for the next 55 years (15 years as the study's horizon plus 40 years as the maximum economic life of a tugboat) for the investigated alternative fuels for the different areas of intended operation is not in the scope of this thesis. Since the important factor for comparing alternative options against a baseline case are the price differentials rather than the exact fuel prices and given the fact that no concrete fuel price outlook was found in the literature, containing all the investigated fuels, it was decided to base the estimation of the pricing on the historical fuel price differentials from 2014 until 2019. The fuel prices have been based on various resources, where among other parameters the pricing of the investigated alternative fuels has been evaluated from different research bodies or market prices were able to be gathered form legit sources. Three fuel price scenarios are assumed; a low, a central and a high "MGO price differentials" scenarios, which the user should specify in the Input interface. The established prices for each fuel, for all three scenarios are increased annually by 1%, in order to account for the expected increase in feedstock production costs. The rationale behind the choice of the three "MGO price differentials" scenarios, is explained in Appendix 0.

It goes without saying that prices vary considerably across different regions, a parameter which is not taken into consideration in this thesis. Not only that but, it is highlighted that the spread between the examined alternative fuels in each scenario is kept constant during the economic lifetime of the tugboat, an assumption which on the one hand cannot be considered accurate, given the fact that historically the spread between the various alternative fuels against diesel fuels varies, as illustrated in Figure D-2, but on the other hand, in absence of a fuel price projection algorithm, it can be considered sufficient enough for reaching to conclusions, with regard to the economic evaluation. After all, even if a fuel price development scenario was implemented it would still be considered highly uncertain. To conclude, for these reasons the results of this study are subject to the uncertainty imposed by the fuel prices and the end-user should approach them with caution. A power user can modify the scenarios with updated data. The fuel price values for each "MGO price differentials" scenario are summarized in Table 5-2.

Table 5-2: Fuel price differentials scenarios used in this study (in $/ton)

Fuel	**MGO Price differentials scenarios ($/ton)**		
	Low	**Central**	**High**
MGO	565	551	940
LNG	493	471	536
Methanol	450	240	354
DME	537	411	558
Biodiesel	824	878	963

iv. Consumable price (urea)

Aqueous urea solution (AUS) at 40% concentration is assumed to be used as a reducing agent when selective catalytic reduction after-treatment technology is employed. Regarding the anticipated urea price; a low, an average and a high price was established. Even though, the price of urea will be varying across different ports it is assumed to be between 187.2 to 234 $/ton, according to [11]. In the same report, it is estimated that there will be no problem in supplying urea in almost each port worldwide, since urea consumption for marine use is just a tiny fraction of the total urea consumption.

v. Cold ironing price and emission factors

It should be highlighted that cold ironing emission factors and costs vary from port to port also in the same region of operation, mainly due to how advanced the port's and the landside electricity infrastructure are. In this thesis, it is assumed for the sake of simplicity that the same emission factors and costs apply irrespectively of the area of operation. Anyhow it is not within the objectives of this study to assess the exact impact of cold ironing on the selection of a propulsion concept layout, rather provide an indication on the emission reduction potential and the cost savings. Two important points should be highlighted. Firstly, cold ironing is considered as complementing the emission savings achieved through choosing a different power plant for the purpose of this thesis. Secondly, depending on the fuel price there is a probability to be preferable strictly on economic terms to avoid connecting to the grid, rather keep the auxiliary engines running. The emission factors and shore power costs assumed in this thesis are summarised in Table 5-3 and Table 5-4 below.

Specifically, the emission factors for the cold ironing are taken from [79, 80] where the emission output of the air pollutants has been determined based on the electricity generation mix used for a number of countries.

Table 5-3: Cold ironing emission factors in g/kWh

HC	PM	CO	NOx	CO_2	SOx
0.028	0.03-0.203	0.0125-0.088	0.35	330-514	0.46-1.13

Table 5-4: Cold ironing cost in $/kWh

Shore Power cost ($/kWh)		
low	central	high
0.04	0.085	0.13

The same two studies have been used to derive the range of the expected costs for shore-side electricity. In order to account for variations on grid prices, which might be imposed by the fluctuations on electricity demand to ports but also to the level of investment required to be made at a certain location, in terms of electricity equipment it is assumed that the cost will vary from 0.04 $/kWh to around 0.13 $/kWh, with the average price set at 0.085 $/ton. Depending on the preference scenario selected by the user, the relevant price will be determined for use in the calculations.

vi. Air pollution external cost factors and climate change avoidance cost factors

With respect to air pollution external cost factors and climate change avoidance cost factors the [81] study was used. The air pollution external cost factors are estimated according to the damage cost approach and are expected to differ depending the intended sea region of operation. The factors are summarized in Table 5-5. The price values were initially given in Euro price levels of 2016 per kilo emission output, and are converted to $ per kilo emission output, using a conversion rate of 1.17.

Table 5-5: Air pollution external cost factors in \$/kg emission (\$2016) relevant to the sea region

Sea region	Air pollution external cost factors in \$/kg emission (\$2016)				
	HC	PM	CO	NO_x	SO_x
Baltic Sea	1.2	21.4	0	9.2	8.1
Black Sea	0.2	35.1	0	9.1	13.0
Mediterranean Sea	0.6	28.8	0	3.5	10.8
North Sea	2.7	40.2	0	12.5	12.3
Atlantic & Remaining	0.5	8.4	0	4.4	4.1

With respect to greenhouse gases external costs on climate change, they are estimated according to the climate avoidance cost approach. Specifically the CO_2eq climate change avoidance cost factor based on the target set in the Paris Agreement (temperature not to rise above 1.5-2 degrees Celsius) is used, in order to account for the emissions originating from all gases contributing to global warming (CO_2, CH_4, N_2O). These factors differentiate depending on the time period and are estimated for three scenarios; a low, a central and a high price scenario, as summarized in Table 5-6. These factors remain the same irrespectively of the sea region.

Table 5-6: Climate change avoidance cost factors in \$/ton CO2eq (\$2016)

Time period	Climate change avoidance cost factors in \$/t CO_2eq (\$2016)		
	Low	Central	High
Short-and-medium-run (up to 2030)	70.2	117	221.13
Long run (from 2040 to 2060)	182.52	314.73	582.66

5.3.3 Equipment database section

In this section information concerning the technical, operational and cost parameters for the various equipment are contained. Specifically, the database contains performance data for the engine types under consideration, maintenance intervals, costs, equipment efficiency losses, after-treatment technical and operational parameters, dual-fuel engines' operational parameters, battery technical parameters and ship-specific endurance parameters.

a) Engine database

All engines contained in the database are high speed (1800 rpm) 4-stroke diesel engines from a common manufacturer (Caterpillar) and are minimum IMO Tier II, EPA Tier III and EU Stage IIIA compliant. It is not the scope of this thesis to build a comprehensive equipment database. As explained in Chapter 4, the engines have been preselected for the candidate propulsion configurations running on diesel fuel. For the variants under consideration running on alternative fuels, commercial engines were decided not to be considered, due to the denial of manufacturers to provide performance data. It is assumed that for these engines, the same output is maintained and the performance characteristics (specific fuel consumption and emission factors are adjusted based on their associated fuel's lower heating value and emission reduction potential compared to MGO as specified in Table 3-3 and Table 3-4. Further explanation on the exact calculation of variant's performance is provided in section 5.4.2.5.

i. Fuel and emission specific factors

Data for each of the diesel engines under consideration were provided by Caterpillar. Specifically, data for engine power, fuel oil consumption factors, emission specific factors for all four (4) combustion-related air emission pollutants under consideration (CO, HC, PM, NO_x) and efficiency for a number of operational points were collected. These data are accessible in tabular format in the relevant section of the "Database" spreadsheet. It has to be mentioned that the revolutions of the engines at those operating points are not listed, since for the auxiliary engines the performance data gathered are representative of fixed-speed operation while for engines acting as prime movers, even though the performance data are representative of variable-speed operation, it was deemed sufficient to keep only the power band with respect to the operating point for modelling the performance data extraction formula, as will be explained later in section 5.4.2.4. In the future if variable-speed engines used as generators based on a DC topology are examined the need to include revolutions as a parameter will arise.

ii. Equipment recommended maintenance schedule and cost

As the focus of this thesis has been set on prime mover combinations, emphasis was put on determining an indicative maintenance schedule for main and auxiliary engines. The planned maintenance required for the rest of the machinery equipment, fitted in the candidate propulsion configurations is not taken into consideration in this thesis. The maintenance plan for the considered diesel engine models has been defined in cooperation with the stakeholders (Kotug international) and after taking into account the manufacturer's proposed maintenance scheme and spare parts acquisition cost. The maintenance plan for both the main and auxiliary engines is supposed to consist of the same four (4) basic stages with differing intervals and costs. The four stages consist of filter replacement, lubricating oil change, top end overhauling and major (complete) overhauling. Moreover, the acquisition cost for these engines has also been estimated based on the manufacturer's received data and is expressed in $ per kW installed power capacity. Due to confidentiality reasons the values cannot be disclosed.

The aforementioned data for the examined 4-stroke diesel engines running on MGO are presented in Table 5-7.

Table 5-7: 4-stroke diesel engine's recommended maintenance schedule and costs for use as a prime mover and as a generator

Model	Equipment Use	Type	Combustion Fuel	Purchase Cost [$/kW]	Maintenance	Interval (hrs)	Cost/ event ($)
C3512	Main Engine	4xCI	MGO	[redacted]	Filter	[redacted]	[redacted]
					Top End O/H	[redacted]	[redacted]
					major O/H	[redacted]	[redacted]
					Lube oil change	[redacted]	[redacted]
C18	Auxiliary Engine	4xCI	MGO	[redacted]	Filter	[redacted]	[redacted]
					Top End O/H	[redacted]	[redacted]
					major O/H	[redacted]	[redacted]
					Lube oil change	[redacted]	[redacted]
C9	Auxiliary	4xCI	MGO	[redacted]	Filter	[redacted]	[redacted]
					Top End O/H	[redacted]	[redacted]
					major O/H	[redacted]	[redacted]
					Lube oil change	[redacted]	[redacted]
3512C	Auxiliary	4xCI	MGO	[redacted]	Filter	[redacted]	[redacted]
					Top End O/H	[redacted]	[redacted]
					major O/H	[redacted]	[redacted]
					Lube oil change	[redacted]	[redacted]
C4.4	Harbour Genset	4xCI	MGO	[redacted]	Filter	[redacted]	[redacted]
					Top End O/H	[redacted]	[redacted]
					major O/H	[redacted]	[redacted]
					Lube oil change	[redacted]	[redacted]

In order to account the implications of the fuel choice in the prospective variation of purchase and maintenance cost certain assumptions were made. For the sake of simplicity, it is assumed that the maintenance plan of different prime movers will consist of the same four stages, as for a compression ignition engine. In addition, even though it is obvious that the fuel/engine choice will directly impact the maintenance intervals either by delaying or by speeding up the maintenance, it was decided to keep the same interval for all stages irrespectively of the engine type and the fuel burnt. That was decided because it was unfeasible to obtain information, enabling the prediction of the effect on maintenance for the considered engine types; especially due to limited published information and the unwillingness of manufacturers to share this kind of information. Thus, the decisive factor on maintenance cost variations between the candidate propulsion configurations will be the differing total running hours of their respective main and auxiliary engines.

In terms of capital expenses, it was decided to consider only the acquisition costs of the engines, the storage tanks, the after-treatment systems and the drivetrain's associated machinery equipment. The cost of machinery adaptation needed for allowing an engine running on an alternative fuel to operate, such as additional investment on modifying the fuel supply piping and the fuel treatment system, or additional safety measures such as fitting gas detection units and alarms for firefighting are not taken into consideration. Emphasis is given at the extra costs for installing an appropriate storage tank to accommodate a fuel different than diesel as well as the consideration of an extra tank for storing urea, if a SCR treatment system is fitted. Special consideration is given to dual fuel engines, necessitating the installation of two separate storage tanks, one for MGO used as pilot fuel and one for the primary fuel used.

In terms of acquisition costs, the effect of fuel choice, is the decisive factor for estimating storage tank cost, while it is partly taken into consideration for estimating an engine's acquisition cost; the defining factor is instead the type of engine. In particular, for compression ignition engines running on Biodiesel and DME a slight increase in acquisition cost is assumed in order to take into account the absence of optimised commercial marine engines to date, which would probably lead to a price premium. The prices used in this study are 370$/kW for Biodiesel and 380 $/kW for DME. Furthermore, the capital expenditure required for gas engines is assumed to be 20% to 30% higher than a similar output 4-stroke compression ignition engine, ranging from 432 to 468 $/kW. Dual-fuel engines are assumed to cost 10% more than mono-fuel gas engines. The aforementioned costs are based on verbal discussions with various industry experts. Thus, the cost of a lean-burn spark ignited engine running on LNG is assumed to be 432$/kW while the cost of a low-pressure dual fuel engine would be 468 $/kW, both for LNG and Methanol fuels. Investment cost for buying a gas engine, either spark ignited or dual-fuel, is expected to fall during the next 15 years, as more engine manufacturers will offer a plethora of commercial solutions targeting all power ranges. However, these prices are kept constant in the analysis, irrespectively of the year of investment. The purchase cost for the candidate prime movers are summarised in Table 5-8.

Table 5-8: Purchase cost for candidate prime movers

Type	Combustion fuel	Purchase Cost [$/kW]
4xCI	MGO	360
4xCI	Biodiesel	370
4xCI	DME	380
LBSI	LNG	432
LPDF	LNG	468
LPDF	Methanol	468

Storage tank acquisition prices are based on the opinion of experts and are expressed in $ per volumetric capacity of the fuel in cubic meters (m^3). The capacity of the installed tanks is calculated depending on the propulsion configuration and the ship-specific endurance estimation parameters, as explained in section 5.4.2.5 later. The acquisition cost for a Biodiesel storage tank is considered to be the same as for a diesel tank, since its physical properties are relatively similar to diesel oil and normal acid proof tanks is understood to suffice for storing. Hence, the tank cost for both MGO and Biodiesel are assumed to be 250 $/m^3$. On the other hand, the tank cost for the rest of the fuels under consideration will be higher. In particular, DME, due to its low boiling point (-25 ºC) should be stored in liquid form under elevated pressure (around 5 bar) in ambient conditions, thus it is expected to come at a higher price in relation to a diesel tank. It is assumed to be 50% more expensive, at 375 $/m^3$. A storage tank for Methanol needs a more complex configuration compared to a diesel tank, because of its physical properties. For instance, it is cited that it would require additional precautions in terms of monitoring and control, by fitting overfill alarms, proper ventilation, both liquid and gas leakage detection and shutdown. [82]. Tank cost for Methanol is assumed to be 5 times the cost of a diesel tank, which is to say 1250 $/m^3$. Finally, the cost for an LNG tank is considered considerably higher than the rest of the fuels under examination due to the extra precautions needed in order to allow storing under cryogenic conditions. Two reasons which justify the high price are firstly the extra equipment needed to be installed inside the tank to ensure that the tank's internal pressure will remain within the set limits even in bad weather conditions and secondly the consideration of covering the tank with suitable insulation, so as to delay the boil-off gas building up inside the tank, for 10 to 20 days as cited in [39, 65]. It is estimated to vary from 1000 $/m^3$ to 5000 $/m^3$, according to [26]. A price of 2000 $/m^3$ is used in this study, 1.5 times higher than a Methanol tank. Regarding the consumable (urea) storage tank cost, a price of 85 $/m^3$ is used, as estimated in [53], assuming that the material used for construction of the tank will be 304 stainless steel 1mm thick, due to the corrosive nature of urea. The tank costs are summarized in the Table 5-9.

Table 5-9: Storage tank acquisition cost for candidate fuels

Equipment	Equipment Use	Purchase Cost [$/m^3]
MGO Tank	Fuel Storage	250
Biodiesel Tank	Fuel Storage	250
DME Tank	Fuel Storage	375
Methanol Tank	Fuel Storage	1250
LNG Tank	Fuel Storage	2000
Urea Tank	Consumable storage	85

Apart from that, as mentioned before the cost of the propulsion's configurations associated equipment is taken into consideration. A summary for all possible additional drivetrain participating equipment purchase costs can be found in Table 5-10. The prices have been estimated based on available purchase prices for such equipment already installed on similar tugboats, and were also validated based on a published paper [75] and discussions with industry experts.

Table 5-10: Cost of additional drivetrain participating equipment

Additional Components	Cost	unit
Electric machine	40	[$/kW]
frequency converter (with AFE)	135	[$/kW]
frequency converter (both PWM and LCI)	120	[$/kW]
LD3000 Clutch	50000	$
Twindisc MCD Clutch	150000	$
Shaftline	100	[$/kW]
Systems integration (AKA)	510000	$
Batteries	500	[$/kW]

DC Switchboard	500000	$
Transformer	40	[$/kVA]

Additional driveline-specific components such as the integration of a suitable power and energy management system, inverter cooling systems, control panels, cabling, etc are not taken into consideration in this thesis. To conclude, it goes without saying that actual prices for all equipment should be obtained from the suppliers, for improving the accuracy of the analysis results.

b) After-treatment technical, operational and cost parameters

In this section information on technical and operational characteristics and costs for each of the three selected after-treatment emission control technologies are presented. Information were gathered by available publications and consultation from industry experts. It is understood, based on industry experts' opinion that each of the considered after-treatment technologies, either employed alone or in conjunction with another, are paired with an engine exclusively; hence it is assumed that an after-treatment system serves its corresponding engine. The emission reduction potential for each after-treatment system when used stand-alone, is summarized in Table 3-5, as presented in section 3.4. It has to be highlighted that the emission reduction percentage, when more than one system are coupled together is assumed to be the maximum attainable percentage reduction achieved between the participating systems. The rest of the information for the considered after-treatment technologies are presented below.

i. SCR

The various assumptions, based on the technical and operational considerations, as outlined in Chapter 3 are summarized in Table 5-11 below. A 40 percent urea in water solution is selected as a reducing agent with a density of 1141 kg/m^3. The urea consumption is assumed to be 15 liters/hour/MW at full load, for achieving a 90% reduction in NO_x emissions, as reported in [36]. In order to account for the reported inefficient operation of SCR systems at engine start-up and at operating points with a low exhaust temperature, it is assumed that a SCR will be in-use only for operating conditions over 10 percent load. In addition, an extra electrical consumption premium has been established, to account for the electrical needs of the urea dosing unit and the control system. Finally, a fuel efficiency gain of 2 percent is assumed, attributed to the fine tuning, as explained in section 3.5.1.

Table 5-11: SCR technical and operational parameters

SCR operation minimum load	10	%
Electrical consumption premium	3	kW
Fuel Efficiency penalty/gain	-2	%
Urea content	40	%[m/m]
Urea Rate	15	l/MWh
Urea Density	1141	kg/m^3

The acquisition cost of a SCR system is assumed to be the same irrespectively of the engine type on which it is fitted, the fuel used or the equipment use (main or auxiliary engine), as it is widely considered an "add-on" solution. This cost is set at 53 $/kW, based on [11]. Moreover, maintenance costs are assumed to be equivalent similarly to the acquisition cost, based on feedback received by Caterpillar. The maintenance schedule of a SCR is supposed to consist of four (4) basic stages with differing intervals and costs. The four stages consist of catalyst block replacement, reactor inspection, cleaning of urea injection nozzles and overhauling of urea pump unit. The aforementioned maintenance plan, along with the associated intervals in hours and cost per event in $, for a typical SCR sized for use in a tugboat's IMO Tier II certified engines. Values have been estimated after consultation with Caterpillar experts and also by recommended maintenance practise and prices available in published reports [11, 36]. These data are presented in Table 5-12.

Table 5-12: SCR recommended maintenance schedule and costs

Equipment	Equipment Use	Purchase Cost [$/kW]	Maintenance	Interval (hrs)	Cost/ event ($)
SCR	After-treatment	53	Catalyst block replacement	20000	26475
			Reactor inspection	10000	500
			Cleaning urea injection nozzles	167	150
			O/H urea pump unit	8760	500

The maintenance cost is understood to change relevant to the levels of sulphur contained in the fuel; for instance a phenomenon called catalyst poisoning leads to catalyst replacement on a more frequent basis. [36]. Typical catalyst block replacements intervals of 16000 to 20000 hours of operation have been reported, depending on the use of a residual or a distillate fuel respectively. Since fuels used have all low levels of sulphur content (lower than 0.1 % [m/m] an estimated lifespan of 20000 hours of operation is adopted. Finally, it worth repeating that the rest of maintenance activities are assumed to be the same for all engines.

ii. DPF/OxiCat

Regarding the application of DPF and OxiCat on marine engines, no technical limitations are considered in this thesis. No fuel efficiency penalty or gain is assumed for these technologies, as discussed in section 3.5. Regarding DPFs of wall-flow filters, it has been reported that after a period of times lubricating oil ash accumulates on the catalyst layer surface, which cannot be burnt during filter regeneration. The accumulation of ash material leads to the creation of backpressure on the engine, resulting in inferior performance. For this reason, manufacturers propose use of low-ash lubricating oils and periodical cleaning of filters. Typical filter cleaning operation intervals of 2000 to 5000 hours of operation are suggested from vendors. Concerning OxiCat solutions, after direct expert consultations it was understood that are widely considered as maintenance-free. Information on purchase cost and maintenance are summarized in Table 5-13.

Table 5-13: DPF & OxiCat recommended maintenance and costs

Equipment	Equipment Use	Purchase Cost [$/kW]	Maintenance	Interval (hrs)	Cost/ event ($)
DPF	After-treatment	63	Cleaning ash filters	5000	150
OxiCat	After-treatment	40	NA		

c) Dual-fuel engines operational parameters

Regarding the dual-fuel engines and specifically the low pressure dual-fuel engines, as explained in section 3.4.1, it is assumed that they run on two modes; the diesel mode and the gas mode. The engine is assumed to run necessarily on diesel mode, under the transition limit, set at 20% operating load. In addition, when the engine runs on gas mode the pilot fuel consumption level is set at 1%. The aforementioned operational parameters are summarized in Table 5-14.

Table 5-14: Dual Fuel Engine Technical and Operational parameters

DF mode	Operation Range Load %	Alternative Fuel	Pilot Fuel (MGO)
Diesel mode	0-20%	0.00%	100.00%
Gas mode	20-100%	99.00%	1.00%

d) Battery technical parameters

For the limited scope of this thesis, the lithium ion batteries are considered to be lithium polymer batteries using a Nickel Manganese Cobalt (NMC) cathode material. The battery system consists of a number of battery banks with certain power capacity, including one or more battery strings connected in parallel, to make up the desired system capacity. The battery bank's capacity is set to be 220 kWh, but this can be further reduced or increased by the user. The effects of altering the power capacity on economics and environmental performance can be investigated in a sensitivity analysis. In terms of battery charging and discharging certain assumptions are made, which have been established after consultation with industry experts. Table 5-15 lists these parameters. A power user can alter them. However, he/she is prompted to ask advice from battery manufacturers/vendors. The reader is perceived to be acquainted with battery terminology. A short guide on battery specifications, providing clarifications on the terms used, are provided in Appendix D.4. Comprehensive explanations on batteries intended for marine use can be found in [83]. A dedicated Battery Management System (BMS) is fitted on the vessel, so as to monitor the proper operation of the installed battery packs and ensure that they will not be overcharged or over-discharged. Moreover, a thermal management system, complemented by a liquid cooling system, is also supposed to be integrated inside the battery modules, ensuring the battery will not suffer a thermal runaway or fire. The vessel's PMS is assumed to interface with the BMS.

The variables used in this study to simulate a battery's operating condition, are the power capacity for a specific C-rate, the State of Charge (SOC)(%) and the discharge/charge efficiency. It goes without saying that the faster a battery is charging the more time it can be used, leading to more discharge/charge cycles. Specific limitations however apply to maximum charging and discharging, depending on the battery technology, captured through the respective C-rate. For an NMC lithium ion battery both maximum charging and discharging C-rate of 2 are assumed, based on industry-experts opinion. Charge/discharge efficiency is understood to range between 96%-99%. For the scope of this thesis it is supposed to be 96%.

Table 5-15: Battery for Hybrid Configuration [Technical parameters]

Number of batteries fitted	2	banks
Power capacity	220	kWh
Maximum SOC	85	%
Minimum SOC	30	%
maximum charging C-rate	2	
maximum discharging C-rate	2	
Discharge/charge efficiency	96	%

The effect of transient operation on the behavior of a battery is not taken into consideration into this thesis, nor do more complex parameters, like temperature, aging of battery, internal resistance, self-discharge, etc. It's not in the scope of this study to capture the full effect of a battery in the energy efficiency gain achieved, rather provide an indication on the benefits related to financial and environmental aspects. After all, only through a time domain simulation would it be possible to capture the full effect of integration of batteries in a power train. Moreover, two important assumptions need to be highlighted. Firstly, until the minimum SOC the battery is assumed to provide stable voltage, thus for the whole discharge cycle, the complete usable power capacity will be exploited. This assumption can be considered accurate, since lithium ion batteries demonstrate a flat discharge curve, when the SOC is in the range of 85% to 15%, as illustrated in Figure 5-2. Secondly, it is assumed that the usable power capacity will be fully exploited until the end of battery's life duration; no degradation due to aging is taken into consideration.

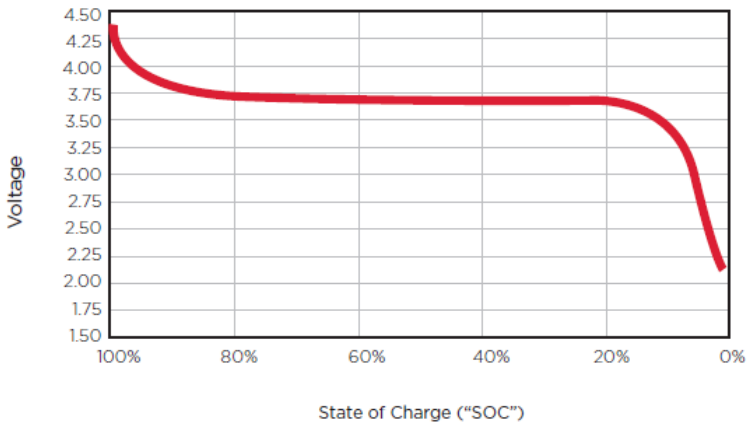


Figure 5-2: Discharge voltage curve for a lithium ion battery[51]

NMC Lithium-ion batteries intended for marine use are commonly considered maintenance-free. In case a battery cell is faulty or malfunctions during the lifetime of the battery pack, the replacement cost might be high, since the whole battery pack will most probably be impacted. However, it is assumed that the installed battery packs will operate as designed; thus, only the replacement cost after the end of a battery's lifespan is taken into consideration. The life duration of a lithium-ion battery depends mainly on the utilization of the battery, specifically on the charge/discharge way and is usually evaluated by counting the number of discharge/charge cycles. The lifespan of lithium-ion batteries will vary relevant to the Depth of Discharge (DoD), having a longer lifespan when the DoD is lower. It is understood, after consultation with industry experts that by reducing the DoD from 80 per cent to 60 per cent, the number of cycles the battery can endure is increased a factor of three. Modern NMC lithium-ion batteries offered by vendors are thought to have a cycle life of over 2000 cycles at 100 per cent DoD. For the sake of simplicity, the lifespan of a battery is not modelled to differ with a varying DoD. For a DoD equal to 55% (maximum SoC – minimum SoC) the lifespan of the batteries fitted are assumed to be 10 calendar years, rather than being based on cycle count, based on expert-opinion. As technology progresses it is anticipated that batteries' lifespan will increase, estimated to reach 17 calendar years, assuming similar DoD. For the purpose of this thesis, the rate of decline in battery's lifespan is assumed to be a linear function. Concerning battery acquisition costs, a price of 600 $/kWh is assumed, reflecting 2018 prices, which is expected to drop considerably over the next 15 years. For the purpose of this thesis, as explained in section 3.6.3, it is assumed that a threshold price of 300 $/kWh will be reached in 2033, ant the rate of annual decline would be a linear function. The same price used for the initial purchase of a battery is also used as replacement cost. Information on purchase cost and maintenance are summarized in Table 5-16.

Table 5-16: Battery system recommended maintenance and costs

Equipment	**Equipment Use**	**Purchase Cost [$/kW]**	**Maintenance**	**Interval (years)**	**Cost/ event ($/kW)**
Battery	Energy Storage	300-600	Replacement of battery system	10-17	300-600

e) Endurance estimation parameters

For determining the tank capacity of the alternative fuels and the urea, as well as the endurance of the tugboat, for each candidate drivetrain configuration, certain assumptions are introduced, as summarized in Table 5-17. Firstly, it must be highlighted that the endurance estimation is based on the baseline's case ART 80-32 tank capacity of 185 m^3. Then, the endurance and the bunkering-interval are estimated as explained in section 5.4.2.5. Kotug's International policy is to allow for 3 days reserve fuel and consumable capacity, as a safety factor for hull roughness and sea state, which is translated to 10% of the baseline ART 80-32 capacity. In addition, it is assumed that a quantity of fuel and urea inside their respective storage tanks will be un-pumpable. For this reason, it is set at 5 per cent of the total storage tank's capacity. Finally, the operational scenario, under which the endurance is estimated, is based on an economical speed of 8 knots and a minimum bunkering interval of 30 days. A power user can alter all ship-specific endurance estimation parameters.

Table 5-17: Endurance estimation parameters

Total tank capacity provided	185	m^3
Intended bunkering interval	30	days
Percentage of un-pumpable fuel/urea	5	%
Reserve fuel/urea required	10	%
Operational Scenario	Economic Transit	
Vessel Speed (knots)	8.0	Knots

f) Equipment efficiency losses

Table 5-18 lists the on-board equipment efficiency parameters, which are used for the calculation of the both for the mechanical and the electrical transmission losses, in the candidate propulsion configurations, but also for the cold ironing distribution losses. More on the estimation methodology for the drivetrain transmission and electrical distribution efficiency will be provided in Appendix D.7.

Table 5-18: Equipment efficiency in percentages

Propulsion shaft line	99	%
Clutch	99	%
Z-drive gearing	98	%
Generator	98	%
Frequency Converter (VFD)	98	%
Transformer	98	%
Motor Efficiency (EM)	98	%
AC Switchboard	99.9	%
DC Switchboard	99.9	%
Active Front End Converter (Island AFE)	98	%
DC/DC Converter	99	%
Battery	96	%
Connecting cable socket (Shore supply JB)	99	%

The established efficiency percentages of the different components are typical textbook steady-state losses, which are also used in various publications. [75, 76, 84]. It must be noted that the efficiency data are nominal values at their rated power. It is assumed that they do not vary depending on the loading factor or the rating of the equipment. For the scope of this thesis, it is considered adequate, in order to derive useful conclusions, since no optimization is attempted and there would be no apparent usefulness by establishing complex functions (linear, logarithmic) for the relevant components' efficiency values. Finally, the main engine's thermal efficiency is considered in the fuel consumption calculation, as explained in section 5.4.2.5.

5.3.4 Regulations

The regulations database section contains information on emission regulations concerning new engine installations from 2018 onwards for IMO, EPA and EU Inland waterways vessels regulations, as presented in Chapter 3. It also contains the test cycles and weighting factors to be applied for verification of compliance of marine engines with the combustion-related emission limits (NO_x, HC, CO, PM), according to the ISO 8178 specifications. More information can be found in appendices D.5 and D.6.

5.3.5 ART 80-32 power requirements

In this section information concerning the power requirements of the baseline tugboat (ART 80-32) are contained. Specifically, the database contains shaft output measurements and electrical load demand on different operating conditions measured during reference vessel's initial sea trials.

a. Power measurement results

The shaft torque measurements have been performed during the first sea trials of the baseline Rotortug, after delivery from Damen Shipyard. Measurements during bollard pull and free-running operating conditions were performed. The transmitted shaft torque had been measured with strain gauges, attached on the intermediate shafts, while the rpm was measured with an infrared pick-up system. The shaft output in kW, was calculated from the shaft torque and rpm. The results of the trial measurement report, produced by Damen Shipyard are used in this thesis, as input in the Duty Cycle block, with the purpose of predicting the required propulsion power depending on the operating mode, as explained in section 5.4.2.1. The measured shaft outputs for the various conditions are not presented within this report, due to confidentiality reasons. It has to be highlighted that the bollard pull is set equal to 80 metric tons, which is the average value measured during the bollard pull test performed at sea trials and certified by Lloyds Register.

b. Electrical load analysis

The electrical load demand during various operating conditions is based on the Electrical Load analysis, prepared by the design department of the Shipyard. The electrical power demand is assessed for various operational conditions, including transit (night), towing, maneuvering, harbour and rest at pier. For each service the connected load is calculated from the rated load (output power) multiplied by a power factor and a utilization factor, as estimated by the shipyard. Among the operational conditions assessed, for the scope of this thesis only the transit, towing and stop (rest at pier) operating modes are used. The results of the electrical load analysis are also not presented herewith, due to confidentiality reasons.

5.4 Design Methodology (Techno-Economic evaluation)

In this section, the design methodology, as depicted in Figure 5-1 is explained. The explanation follows the steps in the diagram's process flow. Firstly, the "computation input" blocks are explained. Then each one of the eight model blocks, which constitute the calculation process are described. Depending on the nature of calculations performed, calculation blocks are classified into technical and techno-economic blocks. The former pertains on the technical part, the latter on the techno-economic part. The design philosophy of each model block is discussed in the next sections, along with its associated input parameters, assumptions and interconnections with the data contained in the tool's database.

5.4.1 Computation modules

The "computation" modules interact with the database in order to extract the necessary data, according to the user input. The output from these blocks is used as an input for a number of blocks, participating in the calculation process. Two are the main "computation" modules, the "equipment selection" and the "scenario generation". The operation of these two blocks is explained below.

5.4.1.1 Equipment selection clock

The function of this block is to choose the suitable type for all components of candidate propulsion configurations under investigation and extract their associated technical and economic parameters, contained in the "Equipment technical, operational and cost parameters" section of the database. As discussed in Chapter 4, the candidate propulsion configurations have been predefined. With the drivetrain machinery equipment known, the relevant type/model for the participating main engines, auxiliary engines and batteries if applicable, is extracted for each configuration into its underlying spreadsheet. The corresponding machinery equipment specifications, like rated power for engines and number of batteries together with their total capacity are also extracted. It has to be highlighted that for each candidate propulsion configuration a separate spreadsheet has been created, in which the majority of calculations are performed. The operation principle of this block is schematically presented in Figure 5-3.

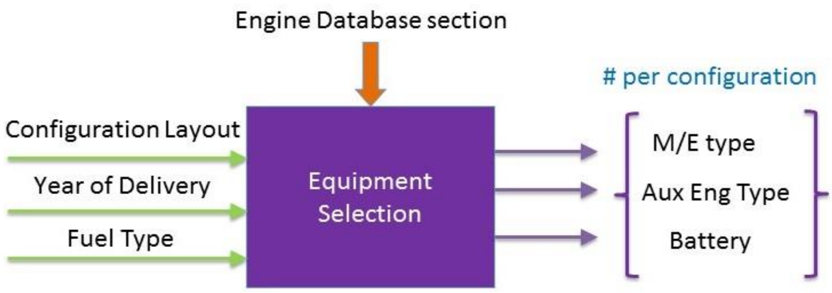


Figure 5-3: Equipment selection block operation schematic

5.4.1.2 Scenario generation block

The function of this block is to generate the scenario, upon which the analysis will be performed. In particular, the applicable regulation regime, the fuel, urea and shore-power costs, the availability of the bunkering infrastructure, the technology-related specifications, as well as the external cost and shore power emission factors at the at the intended port of operation in the expected newbuilding year of delivery are defined. Specifically, the user by selecting the year of delivery and the intended area of operation, automatically defines the applicable regulations regime, contained in the "Regulations" section of the database. Moreover, it must be highlighted that the applicable regulations might overlap. For example, if the chosen port of operation is in Den Helder, in the Netherlands and the desired year of delivery is set at 2023, then that tugboat will have to comply with both the IMO Tier III and the EU Stage V regulations. Furthermore, the user by selecting if tugboats are mandated to use shore-power and if external costs are going to be accounted in the economic analysis, together with the anticipated price scenarios (low/central/high) results in the determination of the actual cost values and the external cost and cold ironing emission factors contained in the "Specifications" section of the database. Finally, the year will also define the engine, after-treatment and battery performance, as already discussed in section 5.2. The operational principle of this block is schematically presented in Figure 5-4

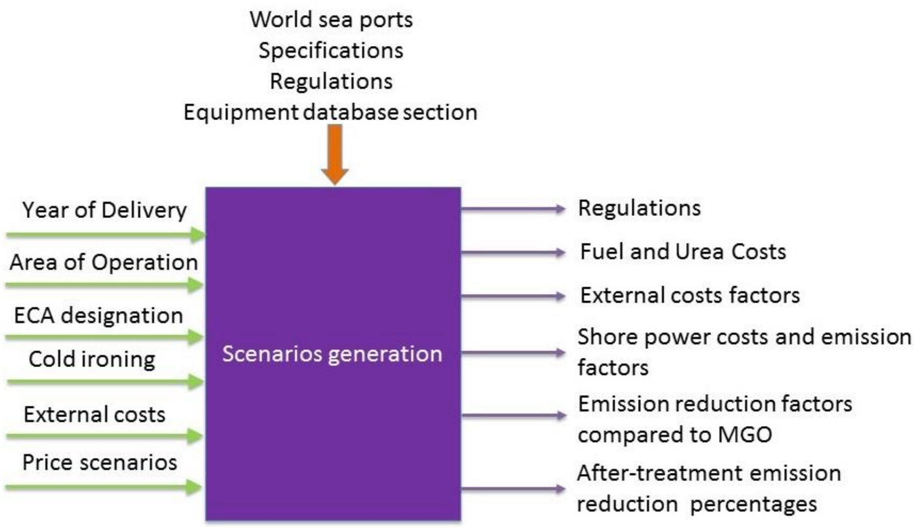


Figure 5-4: Scenarios generation block operation schematic

5.4.2 Technical Part

In this section the blocks, which constitute the technical part of the analysis process are explained. The operational principle of these blocks are discussed, according to the order of execution followed.

5.4.2.1 Duty Cycle block

The function of this block is to establish the propulsion and electrical power demand, in relation to the anticipated mission profile. The user-defined operational profile is used as an input. For each operating mode selected, the required propulsion and electrical power is estimated. The most important assumption made is that since the hull geometry and the propulsors remain the same, in conjunction with the decision to ignore the effect of candidates' additional machinery weight in ship's resistance, the propulsion power required remains the same for all candidates. Moreover, it is assumed that the same apparatus/equipment are installed on all candidates' drivetrain machinery. For instance, winches are kept hydraulically-operated and the effect of replacing them with electrically-driven is not considered in this thesis. This means that in terms of the electrical load demand, the baseline's load analysis is considered representative for all candidates.

Inside this module, two different functions are running, one for estimating propulsion power demand and the other for estimating electrical demand. Both functions classify the operating modes, into transit or assist (bollard) conditions. According to the condition under investigation, the following applies. The "propulsion power estimation" function extracts the propulsion power demand from the relevant table, either the one containing the power measurements during bollard pull conditions or the one with the free-running operating conditions. For estimating the propulsion power demand value, a linear interpolation is conducted according to the input value (transit speed or BP percentage). Limits on the maximum attainable values are set, in order to take into account the maximum design speed and the BP condition. The "electrical load demand estimation" function, calculates the total intermittent and continues load, based on the condition under investigation, according to the shipyard's electrical load analysis. It is assumed that irrespectively, of the transit speed or the BP percentage, the utilisation and power factors for the connected loads remain the same, as the ones estimated by the Shipyard. All data are extracted from tables contained in the "ART 80-32 power requirements" section of the database. For the stop and stand-by conditions the propulsion and electrical power demand is estimated differently. For the stop mode, the propulsion power demand is zero, while the electrical power demand is calculated from the "rest at pier" operating condition, of the electrical load analysis. For the stand-by mode, indicative values, as measured by the crew and witnessed by the company's fleet manager, on-board the baseline Rotortug are used. Even though the manufacturer states the idle speed setting of the engine, for accurately determining the actual power output at idle condition, the power is measured. The operational principle of this block is schematically presented in Figure 5-5.

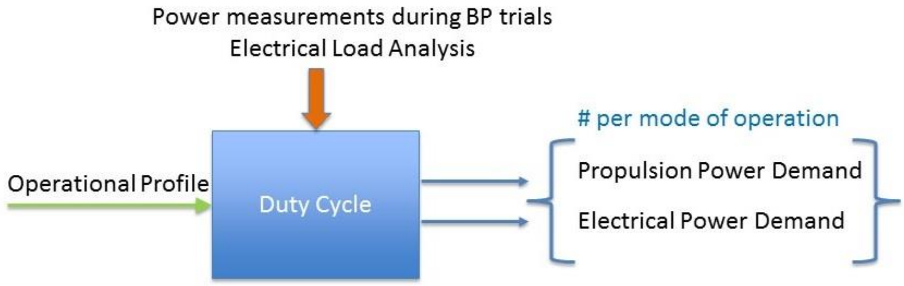


Figure 5-5: Duty Cycle block operation principle

5.4.2.2 Power management block

The function of this block is to estimate the loading condition of the installed machinery equipment, used either as main engines or for auxiliary purposes, in relation to the user-defined mission profile, for each candidate propulsion configuration. Specifically, for each operating mode, based on the propulsion and electrical demand, as established from the "Duty Cycle" block in the previous step, the corresponding operating point for the engines used as prime movers is determined. For each candidate configuration, an energy management strategy has been developed. To begin with, the utilization of main engines, auxiliary engines and batteries has been predetermined, based on a rule-based algorithm developed for this purpose, which is unique for each candidate. The rule-based algorithm was developed after consultation with Kotug's fleet manager, taking into consideration the operating philosophy of similar tugboats and factors such as guaranteeing redundancy of available power sources for the completion of a task. Again, the reader is reminded, as stated in Chapter 4, that the code developed does not seek to optimize the performance of the candidate drivetrain in terms of fuel consumption, emission output or any other factor. It rather provides the loading point for the participating equipment, based on experience-based preset rules. One of the key EMS design philosophies is to ensure that the energy sources available can support the power and propulsion system, according to the operating mode under investigation. The operating modes determine which resources the candidate propulsion configuration will use to support vessel services and propulsion. Certain conditions in terms of ensuring that the loading level of the participating equipment will be within the efficient margins of their respective fuel and emission envelopes have been also established.

This algorithm is developed in VBA programming language and is running automatically in the background. The philosophy, behind the powering resources usage for each candidate configuration, based on the relevant operating mode is presented in Appendix C.3. The power management system developed is not configured to allow operation with faulted resources. All sources of power for each mode are supposed to be able to come on-line if deemed necessary. Moreover, the program has not integrated the effect of slipping clutches. Clutches are assumed to be fully-engaged or fully-open. Furthermore, a preference for certain resources in the sequence of connection to the distribution switchboard, for each candidate has been preselected.

For estimating the apparatus loading, the total required propulsion and electrical power demand in the propellers is translated into required delivered brake power by the drivetrain's prime movers, taking into consideration the mechanical and electrical transmission losses. The distribution losses are calculated for each candidate configuration separately and remain the same for all fuel-variants. However, it is very important to highlight that the transmission losses are dependent of the power flow, which might be different according to the operating mode under investigation. This is evident, especially in the case of the "hybrid configuration" versions, since power is supplied by main engines, auxiliary engines, shaft generators, batteries or combinations of the aforementioned apparatus. Appendix D.7 supplies more information on the mathematical derivation of transmission losses for the drivetrain alternatives.

Especially for the case of the "Hybrid based on DC topology" candidate, the usable power capacity of the battery is also determined and its effect on the loading distribution over time, for the running prime movers is calculated. The battery arrays are connected to the DC bus using DC/DC converters capable of operating bi-directionally. The batteries will be charged from the DC bus, or alternatively discharge to the DC bus to support propulsion and hotel loads. The batteries are configured to provide power only in the stop and idle conditions. This is due to the limitations imposed by the decision of conducting a steady-state analysis, which negates to account the effect of transient load behavior and exploiting the full potential of using batteries on the rest of the operating modes. An algorithm has been developed in VBA code, whose function is to determine the total charge and discharge time of the batteries, thus their total time utilization as well as the loading condition of the gensets, both at the batteries charge and discharge stages. The principle behind battery utilization for the two modes is presented in Appendix C.3.3. The operational principle of this block is schematically presented in Figure 5-6.

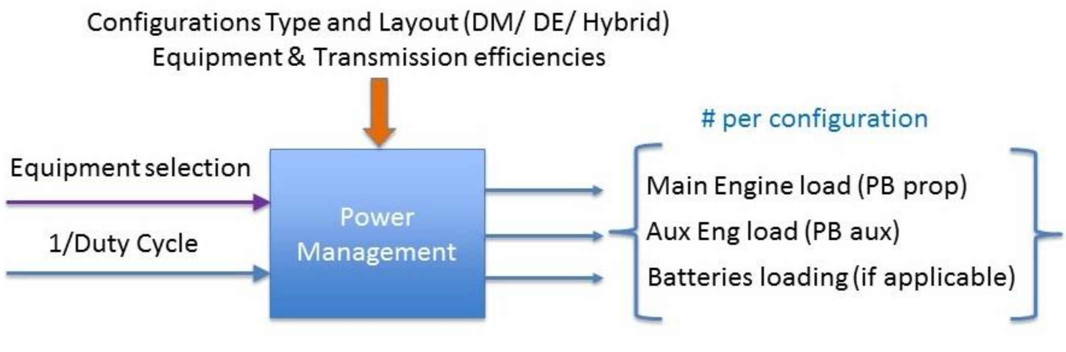


Figure 5-6: Power Management block operation principle

5.4.2.3 Compliance testing block

The function of this block is testing compliance of the investigated candidate propulsion configuration machinery equipment (main and auxiliary engines), based on the applicable emission standards and determining the after-treatment technologies needed for emission compliance.

It must be reminded that emission compliance testing is engine-based. A tugboat's machinery configuration for being compliant with the applicable regulation regime, needs to have all installed engines, emission compliant. A five-step procedure is followed.

- The first step is determining the applicable emission limits for each engine used as a prime mover, for each propulsion configuration. The applicable regulation regime, as established from the "scenario generation" block is used as an input. With reference to the applicable regulations, each prime mover's category type is defined, as explained in Chapter 3. In summary, the engine category is determined based on its displacement volume per cylinder, its rated power and the intended use (auxiliary or main engine) for EPA and EU regulations, while prime movers' classification is not part of IMO regulation regime. Next, based on the category type and the intended year of tugboat's delivery, the applicable emission limits are extracted from the relevant tables, contained in the "Regulations" section of the database. It is assumed that the intended year of delivery is also the manufacture and commissioning year of the engine to be installed in the tugboat. Thus, this date is compared against the regulation's Tier standard phase-in date.

- The second step is determining the applicable emission test cycle, according to ISO 8178. According to the envisaged application (variable/constant-speed for use as auxiliary or main engine) the appropriate test cycle is chosen, from the relevant test cycles contained in the "Regulations" section of the database.

- The third step is the determination of the emission factors of the machinery equipment under investigation. It is stressed that specifically for compliance with EPA regulations ULSD is used as baseline fuel, instead of MGO and also that all investigated alternative fuels have a sulfur content less than 15ppm, therefore all suffice as candidates; in the rest of the text, whenever the word MGO is used, when it comes to compliance with EPA standards, the reader should keep in mind that ULSD applies. For the diesel counterparts, the emission specific factors contained in the "Equipment database" section are used. However, for the main engines running on alternative fuels the specific emission factors are adjusted, so as to be representative of the anticipated emission performance. This happens, because commercial engines with real performance data could not be obtained. The SEF data are adjusted based on the emission reduction potential compared to 4-stroke CI engines running on MGO, as specified in the "Scenario generation" block. However, particularly for the dual-fuel engines specific emission factors, the transition limit as set in the "dual-fuel engines operational parameters" section of the database is taken into account. Under the transition limit the emission output is considered similar to a 4*CI diesel engine of the same rated power, while over the transition limit the SEF is calculated as for the other engines running on alternative fuels, but corrected for the small contribution of MGO, used as pilot fuel.

- The fourth step is verifying compliance of each engine's combustion-related emission average weighted factor with the emission limits for the relevant applicable regulation regimes, according to the relevant test procedure (appropriate test cycle ISO 8178). For IMO regulations only NO_x compliance is judged. For EPA and EU regulations all combustion-related average weighted emission output is compared against the related emission limits.

- The fifth step is the determination of the appropriate after-treatment solution for each engine which emits more than allowed. It is reminded that with regard to the selection of the suitable after-treatment technologies
  - a SCR is selected if the applicable NOx limit is surpassed
  - a DPF is selected if the applicable PM limit is surpassed or if compliance based on PN limit is required (see below clarification on the PN limit)
  - an OxiCat is selected if either the CO or the NMHC limit is surpassed.

Special attention should be paid in the 4th step of the process regarding compliance verification with HC and PN limits, which will subsequently affect in the 5th step the determination of the need for an oxicat or a DPF solution respectively. Because of the two critical differences between the EPA and EU imposed standards with regard to HC and PM emissions compliance, as discussed in section 2.1.1.2, the following applies with regards to the

- hydrocarbon compliance, EPA standards are imposing a limit only to the NMHC emissions, while EU standards to the THC. This means, that particularly for determining compliance of gas engines running on LNG, which suffer mostly from methane slip, with respect to EU standards the estimated total hydrocarbon average-weighted should be compared against the set limit, depending on the applicable stage, while with respect to EPA standards, one should subtract the methane-hydrocarbon proportion from the estimated average-weighted factor and compare that number against the set NMHC limit, depending on the applicable tier. Finally, it is reminded that an oxidation catalyst is considered ineffective on limiting the methane-hydrocarbon proportion.
- particles compliance, EU Stage V regulations, in contrast to EPA regulations, introduce an additional limit on the number of particles of $1x10^{12}$ #/kWh for all engines above 300kW, irrespectively of the combustion fuel or their type (constant/variable-speed or propulsion/auxiliary use), which phase in beginning of 2020, apart from the set limit on particle mass. It has been cited that such PN limit would mandate the installation of DPF for all engines. [34]. In view of absence of performance data concerning PN emissions, which could allow the direct verification against the set limit, this assumption is adopted for the scope of this thesis.

After selecting the after-treatment system to be fitted, for each initially non-compliant engine, the engines are retested for emission compliance. Their respective combustion-related specific emission factors are adjusted accordingly with the after-treatment emission reduction potential percentages, as specified in the “scenarios generation” block. It has to be highlighted that when more than one systems are coupled together, the emission reduction percentage is assumed to be the maximum attainable percentage reduction achieved between the participating systems, for each air pollutant. The final step is the judgment for emission compliance for the tugboat. This is done by verifying that each of the participating machinery equipment, after fitted with the necessary after-treatment solution is compliant with the applicable regulation regime. Even if only one of the engines is non-compliant automatically deems the candidate propulsion configuration non-compliant. The choice of altering the non-compliant engine model does not constitute an option for this thesis. The candidate will be marked as non-compliant for the relevant regulation regime and the same will be displayed in the “Output” results. The operation principle of this block is schematically presented in Figure 5-7.

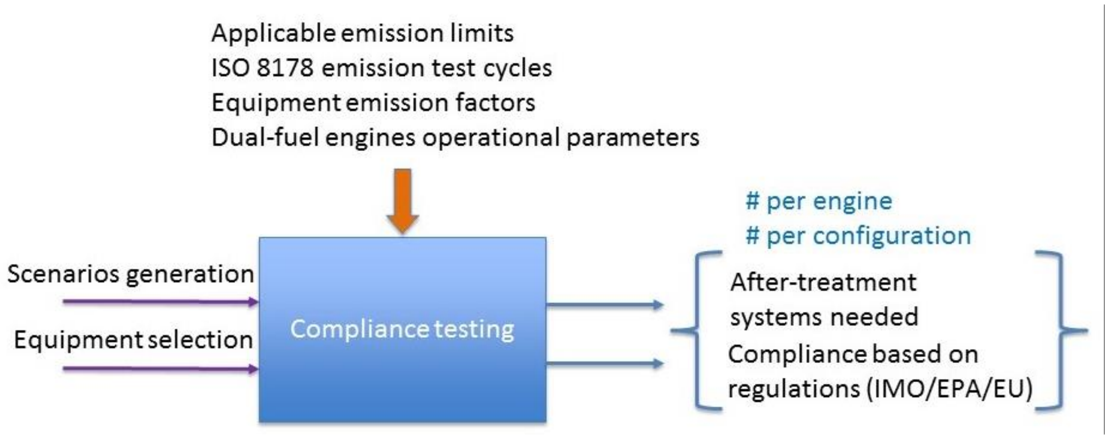


Figure 5-7: Compliance testing block operation principle

5.4.2.4 Components data extraction block

The function of this block is to mine from the database all parameters related to fuel consumption, emissions, maintenance intervals and costs for the participating machinery equipment of the candidate drivetrain variants. The mining process is done in two steps. In the first step the specific fuel and emission factors of the installed machinery equipment, used either as main engines or for auxiliary purposes, in relation to the user-defined mission profile, only for each of the candidate propulsion configuration, running exclusively in MGO are extracted. In the second step, the equipment acquisition cost and the recommended maintenance schedule with its associated costs are extracted for each candidate propulsion configuration.

In relation to the first step of the mining process, it has to be noted that the module takes as an input from the “Equipment selection” block, the specific type and model of the diesel engines selected for each one of the four candidate configurations running exclusively on MGO; namely the Conventional, the Diesel-Electric and the two variants of Hybrid configurations. For each one of these four configurations, a separate spreadsheet is developed. Each spreadsheet takes as input the equipment loading condition, determined from the “Power Management” block and estimates for each operating mode of the mission profile the specific fuel and emission factors for all participating diesel engine models. A function for estimating these factors is running in the background, which based on the operating point (load factor) of the engine under investigation interpolates from the relevant tables with the fuel and emission data contained in the “Fuel and emission specific factors” section of the database. It is reminded that the interpolation process is needful because the data contained in the database, as provided by Caterpillar are covering only a certain number of operational points. Where the data are below or over the given operating points of the aforesaid tables, the estimated values are extrapolated. The specification of the specific factors for the rest of the candidate configurations based on alternative fuels is part of the next block “Performance calculation”.

Regarding the second step of the mining process, attention should be given that all mentioned parameters are extracted from the relevant tables contained in the database, for each participating candidate variant, contrary to what happened in step 1. The module takes as input the predefined machinery configuration and the installed after-treatment systems, as determined in the “Compliance testing” block, for each candidate variant and extracts the aforementioned parameters. The extracted parameters are going to be used as input in the “TCO Analysis” block later. It is worth noting that the candidate drivetrains have differences regarding the machinery components (engines, shaft lines, distribution networks, frequency converters, electric motors, etc.), the fuel and consumable tanks and the after-treatment systems fitted. However, for the same candidate propulsion configuration the differences in the CAPEX will be because of the dissimilar after-treatment systems installed and the differing tank costs. The operation principle of this block is schematically presented in Figure 5-8.

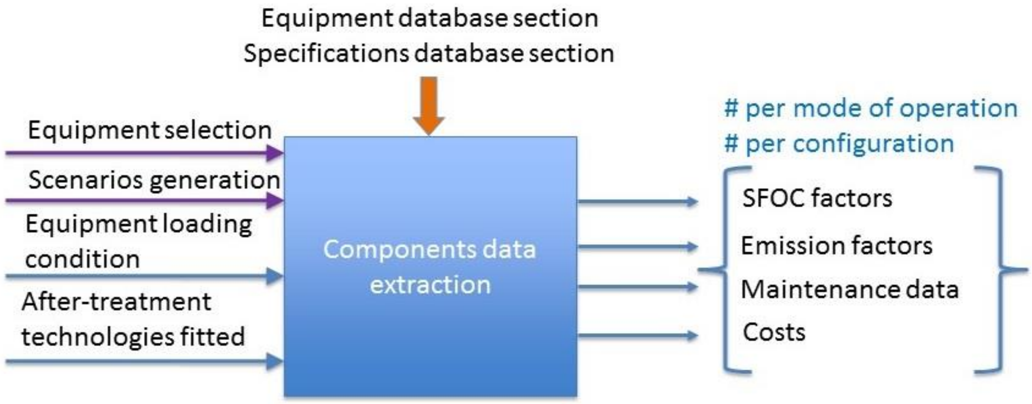


Figure 5-8: Components data extraction block operation principle

5.4.2.5 Performance calculation block

The function of this block is to estimate the performance metrics of the candidate propulsion configurations. These metrics consist of the fuel and urea consumption, the emission output for all exhaust air pollutants, the energy consumption and the running hours of prime movers per operating mode as well as the endurance, the range and the bunkering interval per candidate. For each candidate, as mentioned before, a separate spreadsheet has been created where these values are calculated. The methodology followed as described below, applies to all candidates. All data have been computed by building relevant functions in Microsoft Excel®. The loading condition (load factor) of the installed prime movers, used either as main engines or for auxiliary purposes, in relation to the user-defined mission profile, for each candidate propulsion configuration has been established in the "Power management" block and is used as input in the relevant spreadsheets.

5.4.2.5.1 Engine running hours

The running hours for the participating prime movers, both intended for use as main engines and as auxiliary engines are calculated for each operating mode. Depending on whether the prime mover is running or not per investigated operating mode, defined in the relevant machinery/equipment power usage matrix and provided that the load factor is not zero, the running hours are equal to the duration of the operating mode, as inserted by the user initially, converted to hours per day, based on 365 days per year; 24h per day. The function for calculating an engine's running hours can be defined as

$$RH_{Eng} = \sum_{i=0}^{n} duration_i/365 \ \ for\ Eng(LF)_i > 0 \qquad (1)$$

Where

- RH_{Eng} is the operating time of the engine in hours/day
- duration is the modes duration in hours/year, as inserted by the user
- Eng(LF) is the loading condition of the engine in percentage (%) at the investigated operating mode
- i the operating mode including also the stop mode.
- n is the total number of operating and non-operating modes of the defined operational profile

5.4.2.5.2 Fuel consumption calculation

The fuel consumption is calculated for each operating mode and for each participating engine.

Firstly, the fuel consumption for the diesel variants candidates is calculated, according to the following equation

$$FC_{x,y,z} = SFC_{\ x,y,z} * Eng_{output_{x,y,z}} * RH_{Eng_{x,y,z}} \quad (2)$$

Where

- FC is the daily fuel consumption in tons for candidate x, engine y and operating mode z. (tons/day)
- SFC is the specific fuel consumption for candidate x, engine y and operating mode z in gr/kWh.
- $Eng_{output,z}$ is the output of the engine y (kW) for investigated candidate x, which is the multiplication of its rated power and the load factor (%) at the investigated operating mode z.
- RH_{Eng} is the operating time candidate's (x) prime mover (y) in hours, in operating mode (z), as calculated before.

For the estimation of SFC, it is assumed that fuel efficiency gain of the SCR, of the order of 2%, contained in the "Equipment database" section is added to the relevant SFC values extracted from the "Components data extraction" block for the engines fitted with a SCR system.

Next, the thermal efficiency for each prime mover, per operating mode, is calculated, according to the following formula.

$$\eta_e = \frac{3600000}{SFC \cdot LHV \cdot 1000} \quad (3)$$

Where η_e is thermal efficiency, (SFC) is the specific fuel consumption and (LHV) is lower heating value of MGO.

Because of not including commercial engines with real performance data in this thesis, the direct calculation of the thermal efficiency or the use of known SFC maps for all prime movers running on alternative fuels is not possible. There is also little available in publications concerning the efficiency of such prime movers in comparison to the 4-stroke high speed diesel engines. Regarding gas-engines, as discussed in section 3.4.1, they are considered to have similar performance as the diesel engines. Also the combustion of DME or Biodiesel instead of MGO in the same type of prime mover; a 4-stroke high-speed compression ignition engine is considered to exhibit similar performance as well. Thus, it is considered reasonable to assume that the thermal efficiency values per engine for each operating mode are the same for the rest fuel variants of the same drivetrain. With that in mind, the fuel consumption for the candidate fuel variants will be calculated according to the same equation, as before, but the SFC will change. Specifically, the SFC is given by inverting the η_e and the LHV in equation (3). Then, the equation becomes

$$SFC = \frac{3600000}{\eta_e \cdot LHV \cdot 1000} \quad (4)$$

In this way, the differing energy content (LHV) of the alternative fuels is accounted. Given the fact that the same power output should be achieved fuels with lower LHV will lead to a bigger amount of fuel being injected, while fuels with higher LHV will lead to smaller amount of fuel being injected. Apart from the alternative fuel consumption calculated, for dual fuel engines, used as main engines the pilot fuel consumption is also calculated separately and the main combustion fuel consumption is corrected so as to take into account the pilot fuel consumption level and the transition limit. As before, the SCR gain is also considered.

The sum of the $FC_{x,y,z}$ values for all engines per operating mode will yield the total daily fuel consumption of the candidate propulsion configuration under investigation in tons/day. The annual fuel consumption is estimated by multiplying the resulting daily total fuel consumption with 365.

5.4.2.5.3 Urea consumption calculation

The urea consumption (UC) is calculated for each engine fitted with a SCR, for each operating mode. For those engines, the start-up threshold of 10% load, as defined in the "SCR technical and operational parameters" section of the database is accounted for. The urea consumption (UC) is calculated according to equation (5)

$$UC = Urea\,rate\ * Eng(LF) * RH_{SCR} \tag{5}$$

$$RH_{SCR} = \sum_{i=0}^{n} duration_i/365\ \ for\, Eng(LF)_i > 10\% \tag{6}$$

Where

- i expresses the investigated operating or non-operating mode of the mission profile
- the urea rate is assumed to be 15 litres/MWh at 100% load
- Eng(LF) is the loading condition of the engine in percentage
- $RH_{SCR}$is the operating time of the SCR system in hours/day

5.4.2.5.4 Emissions output calculation

The emission output is calculated for each operating mode for each participating engine. A distinction applies in the calculation methodology between the combustion related and the fuel related air pollutants. It is reminded, that as discussed in section 3.3.2, even though the renewability potential of the fuels affects the final GHG intensity if examined under an LCA perspective, in this thesis the TTP emission output of all fuels will be calculated. To this end, the zero-CO_2 emission assumption adopted at LCA studies for biofuels is neglected.

For the calculation of the combustion related emission output per engine and operating mode, the following the following equation is used

$$(E_{x,y})_{cand,airpoll} = SEF_{x,y}\ * Eng_{output_{x,y}} * RH_{Eng_{x,y}} \tag{7}$$

Where

- $(E_{x,y})_{cand,airpoll}$ is the daily emission output in kilos for engine x in operating mode y, for the investigated candidate and air pollutant, expressed in kg/day
- $SEF_{x,y}$ is the specific emission factor for engine x in operating mode y of the investigated air pollutant, expressed in gr/kWh.
- $Eng_{output_{x,y}}$ is the output of the engine (kW) x, which is the multiplication of its rated power and the load factor (%) at the investigated operating mode y
- $RH_{Eng_{x,y}}$is the operating time of the prime mover x in hours, in operating mode y, as calculated before

The sum of the $E_{x,y}$ values for all engines per operating mode will yield the total daily emission output of the candidate propulsion configuration under investigation in kg/day. The annual emission output is estimated by multiplying the resulting daily emission output value with 365.

Specifically, for the diesel variants of the investigated concept layouts the relevant SEF values extracted from the "Components data extraction" block are used. For the rest of the alternative fuel variants the SEF data are adjusted based on two factors. The first factor is the emission reduction potential of the alternative fuels compared to MGO, as specified in the “Engine database” section and the second factor is the after-treatment emission reduction potential percentages, as resulted from the “Compliance testing” block for each engine fitted with after-treatment systems.

However, two additional corrections in the aforementioned SEF adjustment procedure are taking place in the following cases. The first case concerns the variants based on dual-fuel engines. Their respective specific emission factors are further adjusted so as to take into account the transition limit as set in the “dual-fuel engines operational parameters” section of the database. Specifically, under the transition limit the SEF is the same as the SEF of its diesel engine counterpart, while over the transition limit the SEF is corrected for the small contribution of MGO, used as pilot fuel. The second case applies only to the SEF calculation for NO_x emissions. For each engine fitted with a SCR the start-up threshold of 10% load, as defined in the “SCR technical and operational parameters” section of the database is accounted. Below the threshold level the SEF is the same as the SEF of its diesel engine counterpart, while above the threshold level the after-treatment emission reduction potential percentage is considered. To summarize, the basic assumption is that DPF & OxiCat after-treatment systems have been modeled to have an effect when installed on their respective engines, while SCR system’s effect is dependent on whether it is operational depending on the loading condition of its associated engine.

For the calculation of the fuel related emission the following equations are used.

For CO_2 the total emission quantity for each engine per operating mode consists of three (3) terms, the emission output derived by the combustion of the alternative fuel, the combustion of the pilot fuel in case of dual fuel engines and the emission output from urea conversion to CO_2 related to the SCR operation. Hence, the formula is

$$Emission_{CO2} = Emission_{CO2\ of\ alt.fuel} + Emission_{CO2\ of\ pilot\ fuel} + Emission_{CO2\ of\ urea} \quad (8)$$

$$Emission_{CO2\ of\ alt.fuel} = FC_{alt\ fuel} * EF_{CO2(alt\ fuel)} \quad (9)$$

$$Emission_{CO2\ of\ pilot\ fuel} = FC_{pilot\ fuel} * EF_{CO2(pilot\ fuel)} \quad (10)$$

$$Emission_{CO2\ of\ urea} = Urea\ consumption * \frac{12}{60} * Urea\ content * \frac{44}{12} \quad (11)$$

Where

- the $FC_{alt\ fuel}$ is the daily fuel consumption in tons/day, as calculated before
- the $FC_{pilot\ fuel}$ is the daily pilot fuel consumption in tons/day, as calculated before
- the EF $CO_{2\ (alt\ fuel)}$ is the CO_2 emission factor of the considered alternative fuel and is given by the following equation, according to [31]

$$EF_{CO_2} = \frac{M_{CO_2}}{M_C} \cdot x_C \quad (12)$$

where M stands for the molecular weight and x_c for the carbon content of the fuel. The molecular weight of carbon is 12 and the molecular weight of carbon dioxide is calculated as follows:

$$M_{CO_2} = M_C + 2 * M_O = 12 + 2 * 16 = 44\ kg/kmol \quad (13)$$

- the EF $CO_{2\ (pilot\ fuel)}$ is the carbon content of MGO multiplied by 44/12

- Urea consumption is the daily urea consumption in tons per day, as calculated before
- Urea content is the percent urea in water solution, assumed to be 40%.
- The factors 12/60 and 44/12 represent the stoichiometric conversion from urea ($CO(NH_2)_2$) to carbon and from carbon to CO_2 respectively.

For SO_x the total emission quantity for each engine per operating mode consists of two (2) terms, the emission output derived by the combustion of the alternative fuel and the combustion of the pilot fuel in case of dual fuel engines. Hence, the formula can be defined as

$$Emission_{SOx} = Emission_{SOx\ of\ alt.fuel} + Emission_{SOx\ of\ pilot\ fuel} \quad (14)$$

$$Emission_{SOx\ of\ alt.fuel} = FC_{alt\ fuel} * EF_{SOx(alt\ fuel)} \quad (15)$$

$$Emission_{SOx\ of\ pilot\ fuel} = FC_{pilot\ fuel} * EF_{SOx(pilot\ fuel)} \quad (16)$$

Where

- the $FC_{alt\ fuel}$ is the daily combustion fuel consumption in tons (tons/day), as calculated before
- the $FC_{pilot\ fuel}$ is the daily pilot fuel consumption in tons (tons/day), as calculated before
- the $EF_{SOx(alt\ fuel)}$is the sulphur content of the alternative fuel under investigation multiplied by 64/32
- the $EF_{SOx(pilot\ fuel)}$ is the sulphur content of the pilot fuel (MGO) multiplied by 64/32.

It is assumed that for calculating the emission factor of sulphur oxides, all emissions will be in the form of sulphur dioxide (SO_2), which is considered a good approximation since the sulphur oxides emissions indeed mostly comprise of sulphur dioxide. In this way the EF according to [31] is given by the following equation

$$EF_{SO_2} = \frac{M_{SO_2}}{M_S} \cdot x_S \quad (17)$$

Where M stands for the molecular weight and x_s for the sulphur content of the fuel. The molecular weight of sulphur is 32 and the molecular weight of sulphur dioxide is calculated as follows:

$$M_{SO_2} = M_S + 2 * M_O = 32 + 2 * 16 = 64 \text{ kg/kmol} \quad (18)$$

It is evident from the equations that the fuel consumption of fuel related emissions is solely dependent on the carbon or sulphur content of the fuel and is proportional with the fuel consumption, while the engine combustion factors are not playing a part, as explained in Chapter 2. Both fuel related emissions are limited by the amount of carbon or sulphur content in the fuel respectively. The DPF & OxiCat after-treatment technologies employed do not contribute in the reduction of the non-combustion related emissions, while the SCR is indirectly contributing to their reduction, through the reduction of total fuel consumption, because of its considered efficiency gain of 2%, attributed to the better tuning of the engine by the manufacturers.

At this point it must be stressed that specifically for port mode, when cold ironing is chosen at the “Input” as a requirement, the calculation of emissions follows a different procedure. The total emission output would be estimated, based on the daily energy consumption in kW for satisfying the mode’s auxiliary needs, after accounting for the transmission losses from the point of origin. Finally, the emission factors for cold ironing, taken from Table 5-3, are multiplied with the estimated energy consumption yielding the emission output.

The transmission losses for port mode are the same for all drivetrain concepts, because the electrical distribution losses will not differ, since the power flow to hotel loads does not change. The transmission losses would be the product of electrical losses incurred between the power generation and the load. Specifically, the required power transformer η_{TF}, the AC switchboard efficiency $\eta_{AC\,SB}$ and the connecting cable socket (Shore supply JB) η_{JB} have to be taken into account. Thus, the propulsion transmission efficiency η_{TRM} would be given by:

$$\eta_{(TRM)cold-iron} = \eta_{TF} \cdot \eta_{AC\,SB} \cdot \eta_{JB} \quad (19)$$

which takes into account the individual participating components' distribution losses, as summarized in Table 5-18 inside the "Equipment efficiency losses" section of the database.

Then, for the calculation of the cold ironing emission output, the following the following equation is used

$$(E_{x,y})_{cold-iron} = (SEF_y)_{cold-iron} * EC_{cold-iron} * \eta_{(TRM)cold-iron}/1000 \quad (20)$$

Where

- $(E_{x,y})_{cold-iron}$ is the daily emission output in kilos for the investigated candidate x and air pollutant y, expressed in kg/day
- $(SEF_y)_{cold-iron}$ is the specific emission factor for cold ironing of the investigated air pollutant, expressed in gr/kWh, summarized in Table 5-3.
- $EC_{cold-iron}$ is the energy consumption for port mode in kWh. It is estimated by multiplying the electrical power demand at port mode by the duration of the same mode, as inserted by the user initially, converted to hours per day, based on 365 days per year; 24h per day.
- $\eta_{(TRM)cold-iron}$is the transmission losses, as calculated in Eq. (19).

5.4.2.5.5 Energy consumption calculation

The energy consumption is calculated for all participating prime movers, both intended for use as main engines and as auxiliary engines for each operating mode, according to the following formula

$$EC = Eng_{output} * RH_{Eng} \quad (21)$$

Where

- EC is the daily energy consumption in kW. (kWh/day)
- Eng_{output} is the output of the engine (kW), which is the multiplication of its rated power and the load factor (%) at the investigated operating mode.
- RH_{Eng} is the operating time of the prime mover in hours per day, as calculated before.

For all aforementioned parameters, the totals are calculated as well, so as to facilitate the later comparisons against the baseline configuration. Specifically, the totals are summarized in tables per operating mode and per configuration. Moreover, the values are also annualized. Moreover, the fuel and urea consumption are also converted to cubic meters per day and litres per day as well as cubic meters per year and litres per year to facilitate the developing of relevant figures.

5.4.2.5.6 Endurance, range and bunkering interval calculation

For estimating the endurance, the range and the bunkering interval the following methodology is followed. All data have been computed by building relevant functions in Microsoft Excel®. The endurance estimation parameters as contained in the relevant database section are used as input for the calculations. The methodology consists of two steps.

In the first step the fuels' and urea tank capacities are estimated based on the pre-set operational scenario (economic transit), without taking into consideration the user-defined mission profile. For the pre-set economic speed, the loading condition of the installed machinery equipment is derived, based on the applicable energy management strategy, defined in the power management block, as presented before. Next, the total equipment fuel and urea consumption are calculated for this operating condition, using the relevant equations, as described before. Next, the tank capacities are estimated by solving the following system of first-degree equations with two unknowns, based on the assumption that the endurance is the same for both tanks:

$$V = V_A + V_B \tag{22}$$

$$\frac{\dot{m}A}{V_A} + \frac{\dot{m}B}{V_B} \tag{23}$$

Where V is the total tank capacity (known) equal to 185 m^3, V_A and V_B are the alternative fuel's and the MGO tank capacities respectively (unknown) and $\dot{m}A$ and $\dot{m}B$ are the calculated fuel consumptions (known). It is reminded that all non-diesel propulsion configuration variants will have two separate tanks, one for the alternative fuel and one for MGO, used as fuel for gensets and as a pilot fuel in dual-fuel engine variants. With the tank capacities known, the pumpable quantities of both fuels are estimated, after being adjusted with the percentage of unpumpable fuel factor and the reserve fuel factor, introduced in the "endurance estimation parameters" database section. The endurance is then calculated, according to the equation.

$$endurance = \frac{\dot{m}A}{V_{A(pumped)}} + \frac{\dot{m}B}{V_{B(pumped)}} \tag{24}$$

With the endurance known the urea tank capacity can be calculated as the product of the urea consumption and the endurance and adjusted with the same two factors for the remaining unpumpable urea quantity, discussed before.

In the second step the fuels' and urea tank capacities are estimated based on the pre-set operational requirement (fixed bunkering interval) and the user-defined mission profile. The aim is to estimate the required minimum fuels' and urea tank capacities, by comparing them against the capacities calculated in the first step. After establishing the aforementioned tank capacities, the remaining parameters are estimated. The procedure is not explained in detail, however it is noted that the MGO capacity is always rounded up marginally, so as to establish that MGO bunkering interval will be 30 days and for optimizing the vessel's endurance (maximizing alternative fuel's usable capacity), based on the initial tank capacity of the baseline ART. This is because it is assumed that the endurance is equal with the usable fuel tank capacity, which will be depleted first. Finally, the range is equal with the product of calculated endurance and pre-set transit speed, given in nautical miles. The operation principle of this block is schematically presented in Figure 5-9.

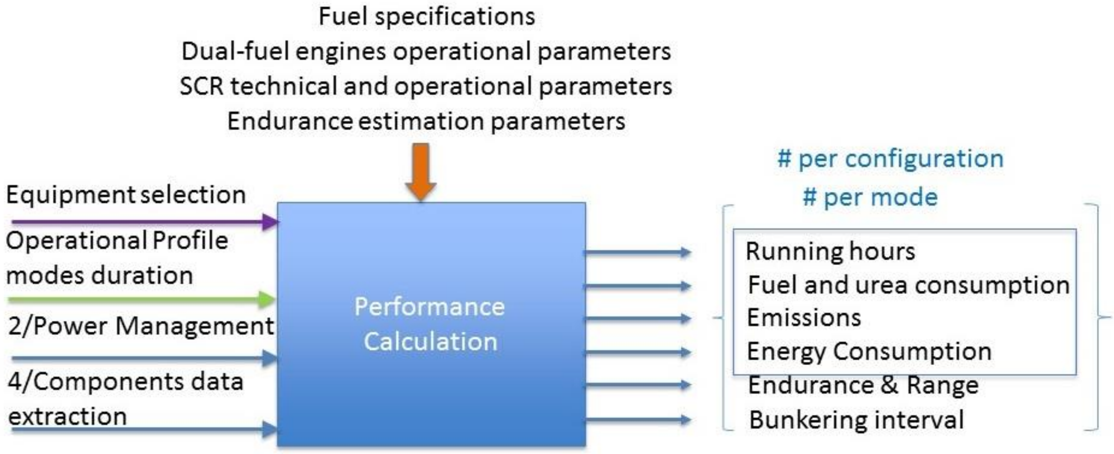


Figure 5-9: Performance calculation block operation principle

5.4.3 Techno-Economic Part

In this section the blocks, which constitute the techno-economic part of the analysis process are explained. The operational principle of these blocks is discussed, according to the order of execution followed. The economic analysis chosen as the basis of decision-making pertains in the comparative life cycle analysis and is conducted from both a ship-owner perspective and a societal perspective. Specifically, from a ship-owner perspective the Total Cost of Ownership (TCO) is calculated for the baseline propulsion configuration and for each candidate configuration, expressed in Net Present Value (NPV). Then the cost differences are calculated between the alternatives and the baseline case and presented as incremental free (non-discounted) and discounted cash flow statements. The same analysis, by adding the external costs, reflecting the environmental impact caused by exhaust air pollution originating from the considered alternative tugboats to society shifts the perspective to a society-related. The methodology will become clear to the reader after reading this section.

5.4.3.1 TCO analysis block

A typical cost of ownership for a tug owner would consist of capital expenses (CAPEX) and operational expenses (OPEX). The capital expenses consist of the depreciation costs, which refer to the decline in value of the asset over its expected lifetime and the investment costs, which generally have to be made upfront, such as the deck and machinery equipment purchase and installation costs and the shipyard’s construction costs. The operational expenses consist mainly of fuel costs, repair and maintenance costs, crewing costs, management costs, insurance costs, stores, lubricants and other consumables costs and port dues/charges. A typical TCO structure, with the individual participating cost contribution for a harbour tugboat is shown in Figure 5-10.

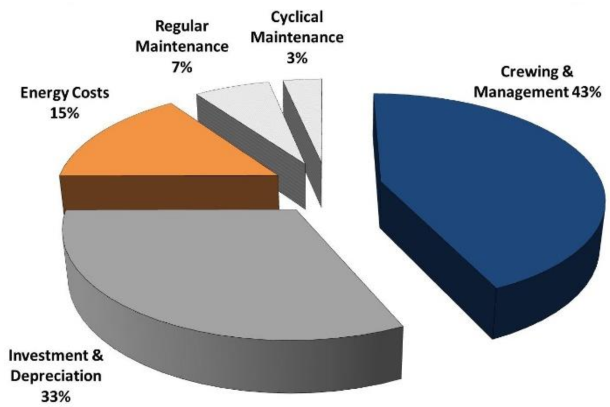


Figure 5-10: Typical harbour tug TCO components share contribution [ITS 2014}

For this thesis, a partial TCO analysis is performed comprising of the costs that differentiate between the alternatives and the baseline case. It has been decided, that even though the decline in asset value (expected salvage value), the crewing costs, the management costs, the port dues, the stores and other consumables costs and the insurance costs will differ between the candidate propulsion configurations, to be considered equal. Moreover, the installation cost for the drivetrain engines and associated machinery equipment, even though they will differ between the alternatives, are not accounted. Furthermore, regarding the repair and maintenance costs, the mechanical breakdowns, the spare parts replacement costs and the periodic maintenance (afloat repairs and dry-docking costs) are not taken into consideration. Only routine maintenance is considered. Also, regarding the lubricants cost it was decided to be omitted from estimation, in view of the absence of data from commercial engines. The contribution of lubricants oil cost in the total operational expenses is considered rather small, as indicated in Figure 5-11, since lube oil costs account for around 0.5% of a single engine's annual operating expenses; thus the results will not be affected greatly when comparing the TCO between the candidates. In terms of consumables only the cost of urea for use with SCRs is considered. Therefore, the capital expenses will include the associated with the investigated propulsion configuration machinery equipment including the installed after-treatment systems and the storage tanks acquisition costs, with their related assumptions as outlined in "Equipment" database section and the operational expenses will include only the fuel, consumable (urea) and routine maintenance, with their related assumptions as outlined in "Specifications" and "Equipment" database section. Of course, such life-cycle analysis results will be subject to the key uncertainties and the assumptions made.

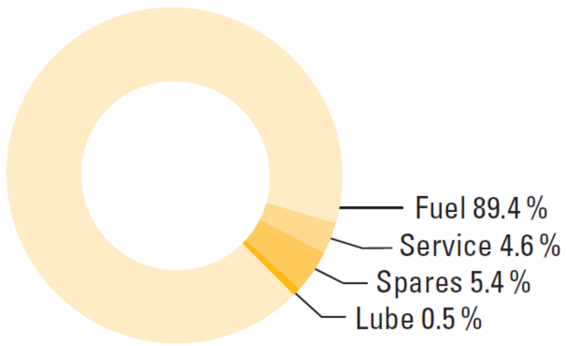


Figure 5-11: Typical operating cost chart for a high-speed 4-stroke marine diesel engine fitted in harbour tugs with 2200 operating hours per year [Caterpillar]

The function of "TCO analysis" block is to calculate the expected TCO for each propulsion configuration expressed in net present value, based on the user-defined operational profile, the expected lifetime of the tugboat and its dedicated engine machinery equipment. The life-cycle approach is used, with an economic life length equal to the expected lifetime of the tugboat. The discounted cash flow is calculated for all operating expenses at given inflation and discount rates, defined by the user. Then the total discounted OPEX is added to the total CAPEX, which is considered an upfront cost. The sum of this costs equals the TCO expressed in NPV. It must be highlighted that only the costs (cash outflows) are included in the created cash flows. The financing as well as the expected annual income (cash inflows) generated by the operation of the tugboat are not included in the cash flow. This is because it is assumed that all candidates will have the same operational performance when delivered and hence, they will yield the same economic benefits, irrespectively of their drivetrain. Moreover, it is assumed that the lifetime of all machinery equipment will be the same as the expected lifetime of the vessel. Furthermore, the keel laying date of the newly built Rotortug is assumed to be also the shipyard's delivery date, thus all capital expenses are assumed to be made within that year. In the applied cash flow technique, the nominal operating cost values are utilized, thus they are adjusted with the inflation and discount rates, for deriving the present value of the future cash outflow stream. The inflation rate used reflects the loss of purchasing power over the years. Because the economic-life of a tugboat is over a long term period, typically varying from 20 to 40 years, the inflation is expected to be approximately 1% to 4%, according to the IMF World Economic Outlook [85]. However, in such an analysis it is highly uncertain how the inflation will vary in the years to come, since it depends on the prevailing conditions. It is assumed that the inflation rate is constant throughout the expected economic-life time. The discount rate is the rate of return a ship-owner is expecting and depends on the risk that an investor is willing to take and the investor's preferences. The discount rate is also kept constant, and can typically vary from 4% to 14%, reflecting the investor's risk tolerance. It must be highlighted that assuming a constant discount rate does not allow accurately prizing the risk neither reflects the flexibility offered to an investor, such as postponing the investment on a specific solution for a future time. Furthermore, the chosen economic analysis does not permit financial considerations, such as investing in fuel or emission-saving equipment or even removing part of the machinery equipment, to be made at a later stage within the lifetime. All financial considerations are limited to the initial investment made and remain unaltered until the end of tug's economic lifetime. Furthermore, all outflow events in the cash flow series are considered to occur at the last date of the year for each time period. Finally, the TCO estimation is based on a single tugboat being delivered; the effect of multiple orders of the same drivetrain candidate on the reduction of the total cost has not been accounted for.

The formula for calculating TCO, expressed in NPV, is the following

$$TCO_{NPV} = CAPEX_{NPV} + OPEX_{NPV} \tag{25}$$

while the estimation procedure for CAPEX and OPEX discounted cash outflows can be mathematically expressed as follows

CAPEX

The capital expenses consist of the summation of the acquisition cost of main engines (A_{ME}), auxiliary engines (A_{GEN}), associated drivetrain machinery equipment (A_{EQ}), fuel (A_{FT}) and urea tanks (A_{UT}) and the installed after-treatment systems (A_{AFT}), given by the following equation

$$CAPEX_{NPV} = \sum_{i=1}^{u} A_{ME_i} + \sum_{j=1}^{v} A_{GEN_j} + \sum_{k=1}^{w} A_{AFT\,k} + \sum_{l=1}^{x} A_{FT_l} + \sum_{m=1}^{y} A_{EQ_m} + A_{UT} \tag{26}$$

Where i denotes the number of installed main engines, j denotes the number of installed auxiliary engines, k denotes the number of after-treatment systems installed, k denotes the number of fuel tanks and m denotes the number of additional equipment associated with the investigated propulsion configuration layout. It is stressed that the acquisition cost of a urea tank will be accounted in the cases where at least one SCR system is fitted in a candidate's engine.

Based on the purchase prices of the aforementioned equipment, as extracted from the "Components extraction" block and their related parametric expression the acquisition cost is estimated for each plant component. The parametric expressions used for estimating the acquisition cost for the plant components are the following linear equations

The acquisition cost for both the main and auxiliary engines is given by:

$$A_{eng} = Eng_{rated\,power} * C_{eng} \tag{27}$$

The acquisition cost for the installed after-treatment systems is given by:

$$A_{aftertr} = Eng_{rated\,power} * C_{aftertr} \tag{28}$$

The acquisition cost for the installed fuel and urea tanks is given by:

$$A_{tank} = Tank_{capacity} * C_{tank} \tag{29}$$

The acquisition cost for the rest of the machinery equipment associated with the propulsion configuration under investigation is given by:

$$A_{eq} = N * Equip_{rated\,power} * C_{equip} \tag{30}$$

Where

- A reflects the acquisition cost of the subscript plant component, expressed in USD dollars ($)
- C reflects the purchase cost of the subscript plant component, expressed in the relevant unit ($/kW or $/m^3 or $)
- N is the number of installed equipment in the drivetrain topology.
- Engine rated power is the rated power of the engine (kW)
- Tank capacity is the calculated capacity expressed in m^3
- Equipment rated power is the rated power for operation of the equipment, applicable for transformers, electric motors, frequency converters and batteries.

OPEX

The total OPEX discounted cash outflow is the summation of the following four (3) discounted cash outflows; the fuel cash outflow, the consumables cash outflow and the maintenance cash outflow. Functions in Microsoft Excel® are developed for calculating the aforesaid discounted cash outflows, based on the following procedure:

$$OPEX_{NPV} = \sum_{i=1}^{x} DCF_{\iota} \tag{31}$$

$$DCF_{\iota} = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} \tag{32}$$

$$CF_i = C_a * (1+q)^i \tag{33}$$

Where for each of the discounted cash outflow, all terms are defined as follows:

- DCF is the discounted cash flow, expressed in net present value ($)
- CF is the nominal (free) cash outflow in $
- r is the discount rate
- n is the analysis economic life in years
- q is the inflation rate
- C_α is the calculated cost function

For calculating the participating cost function C_a in each of the three cash outflows the following equations have been developed.

Fuel cash outflow

The fuel consumption cost is a function given by the following equation (34)

$$C_a = \sum_{i=1}^{n} C_{M/E} + \sum_{i=1}^{n} FC_{Aux.E} * FP_{MGO} \tag{34}$$

$$C_{M/E} = FC_{M/E(alt\,fuel)} * FP_{M/E(alt\,fuel)} + FC_{M/E(pilot\,fuel)} * FP_{pilot\,fuel} \tag{35}$$

$$FP_{k,t} = FP_{k,t-1} * (1 + i) \tag{36}$$

Where

- $C_{M/E}$ is a function given by equation (35) for estimating the main engines total annual fuel consumption
- FC is the total annual fuel consumption in tons/year
- FP is the fuel price in $/ton in the user-defined year of newbuilding's delivery date (t) and is a function given by Eq. (36), where k is the MGO price differential scenario chosen and i is the fuel price annual increase of 1%.
- n is the number of operating modes defined from the user

It has to be highlighted that depending on whether the user has defined the necessity for cold ironing in the investigated port the shore power consumption cost is taken into consideration for the stop mode instead of the fuel consumption cost, based on the equivalent energy consumption, as calculated in the "Performance calculation" block and the cold ironing cost, as extracted from the "components data extraction" block instead of the fuel price.

Consumable cash outflow

The urea consumption cost is a function given by the following equation

$$C_a = \sum_{i=1}^{n} UC * UP \tag{37}$$

Where

- UC is the total annual urea consumption in tons/year
- UP is the urea price in $/ton
- n is the number of operating modes defined from the user

Maintenance cash outflow

The maintenance cost is a function that reflects the maintenance cost of the investigated machinery plant equipment, as defined in "Equipment recommended maintenance schedule and cost" database section. It is reminded that for the purpose of this thesis, the machinery equipment which are assumed to be subject to routine maintenance are all prime movers, whether used as main or auxiliary engines, the after-treatment systems and the batteries. To this end, the maintenance cost can be broken down to the summation of its respective participating cost components, given by the following equation

$$C_a = C_{M/E} + C_{Aux.E} + C_{aft-treat} + C_{bat} \tag{38}$$

The maintenance cost for each one of the participating cost components is given by the following set of equations. It is stressed that the maintenance plan differs between those components. Detailed explanations of the maintenance plan structure for each component is provided in the "Equipment recommended maintenance schedule and cost" database section.

Main or Auxiliary engine maintenance cost can be expressed by the same equation

$$C_{M/E\,or Aux.E} = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{q} E_k * P_{e_k} \tag{39}$$

Special attention should be given on the fact that top end overhauling is linked to major overhauling. Specifically, it is assumed that top end overhauling scope of work is integrated at major overhauling, hence cost of top end overhauling is not double counted.

After-treatment system maintenance cost consists of the summation of the maintenance cost for the total number of installed SCRs, DPFs and OxiCat systems. Since the OxiCat solution is considered maintenance-free and the DPF has a single-stage maintenance plan, the function is given by the following equation

$$C_{aft-treat} = \left(\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{q} E_k * P_{e_k}\right)_{SCR} + \left(\sum_{i=1}^{n}\sum_{j=1}^{m} E_j * P_{e_j}\right)_{DPF} \tag{40}$$

Battery maintenance cost can be expressed by the following equation. It has to be highlighted that since the batteries are also considered maintenance-free, however have to be replaced after the end of their expected lifespan, a different methodology taking into account the calendar years rather than the running hours is followed, which is expressed as follows

$$C_{bat} = \sum_{j=1}^{m} E_j * P_{e_j} \tag{41}$$

For equations (39) and (40) the following terms are defined as

$$E_j = \frac{(Cum\ Run\ hours_i)_{j+1} - (Cum\ Run\ hours_i)_j}{Interval_k} \tag{42}$$

$$(Cum\ Run\ hours_i)_j = j * (Run\ hours_i) \tag{43}$$

While for equation (42) the same terms are defined as

$$E_j = Cum\ ev_{j+1} - Cum\ ev_j \tag{44}$$

$$Cum\,ev_j = \begin{cases} \left\lfloor \frac{j}{bat.life} \right\rfloor, if \ \frac{j}{bat.life} > 1 \ and \left\lceil \frac{j}{bat.life} \right\rceil < \frac{j+1}{bat.life} > \frac{n}{bat.life} \\ \lfloor Cum\ events_{j-1} \rfloor + 1, \quad elsewhere \end{cases} \tag{45}$$

Where

- n is the number of installed equipment (i) per investigated drivetrain
- m is the user-defined economic-analysis horizon in number of years (j)
- q is the number of the equipment's maintenance schedule stages (k), as defined in "Equipment recommended maintenance schedule and cost" database section.
- C are separate linear functions for estimating the relevant plant components' annual maintenance cost in $/year
- E is the number of events per year for the examined equipment's maintenance schedule stage, which is a separate linear function of cumulative running hours and maintenance schedules stage interval in hours per event.
- Run hours is the running hours of the relevant plant equipment in hours/year. It is stressed that for the prime movers and the DPF systems, the running hours are given by equation (1) multiplied with 365, in order to convert it to hours per year, while for SCR systems it is given by equation (6) multiplied with 365, for the same reason.
- Cum ev is the cumulative number of events happening until the investigated calendar year
- Pe is the relevant maintenance schedule stage cost per event in $/event, as defined in "Equipment recommended maintenance schedule and cost" database section.
- bat.life is the expected battery lifespan in calendar years

It is noted that the cash flow table is generated within each candidate propulsion configuration variant's spreadsheet.

Finally, by adding the external costs to the calculated TCO would give the Total Cost for Society (TCS), expressed in NPV. The estimation procedure follows the same principles of calculating the discounted cash outflows, as presented in the mathematical derivation of OPEX before. In short, it is given by the following equation.

$$TCS_{NPV} = TCO_{NPV} + Ext_{NPV} \tag{46}$$

$$Ext_{NPV} = \sum_{i=1}^{x} \sum_{i=1}^{n} \frac{C_a * (1+q)^i}{(1+r)^i} \tag{47}$$

Where all terms are defined as follows:

- Ext_{NPV} is the discounted external costs cash outflow, expressed in net present value ($)
- r is the discount rate
- i is the number of years
- n is the analysis economic life in years
- q is the inflation rate
- C_α is the calculated cost function, given by Eq. (48)

External costs cash outflow

The external cost is a function that reflects the environmental impact imposed to society by exhaust air pollution, originating from the tugboat, as a system. Other external costs like the noise costs originating from tugs, depending on the propulsion layout are not considered in this thesis. For this reason, the total external costs will consist of the summation of the total external air pollution costs imposed by the combustion-related exhaust air pollutants, SO_x (fuel-related) and the total external climate change costs of CO_{2eq} for the envisaged economic horizon. The air pollution external cost factors are referenced in Table 5-5 and the climate change avoidance cost factors in Table 5-6, as specified in the "Specifications" database section. For estimating the CO_{2eq} emission, the GWP values for CO_2 and CH_4 for a 100-year time horizon are accounted. The contribution of N_2O in the intensification of global warming is not taken into consideration. External costs are estimated according by the following equations

$$C_a = \sum_{i=1}^{n} EO_{CO_{2eq}} * P_{CO_2} + \sum_{i=1}^{n} EO_{SO_x} * P_{SO_x} + \sum_{i=1}^{n} EO_{comb} * P_{comb} \tag{48}$$

$$EO_{CO_{2eq}} = EO_{CO_2} * GWP_{CO_2} + EO_{CH_4} * GWP_{CH_4} \tag{49}$$

$$EO_{CH_4} = \begin{cases} EO_{HC} * \left[1 - ratio\left(\frac{NMHC}{THC}\right)_x\right], \text{for gas engines} \\ 0, otherwise \end{cases} \tag{50}$$

Where

- EO is the total annual emission output in kilos/year for CO_2-equivalent (CO_{2eq}), for SO_x and for all combustion-related (comb) exhaust air pollutants (NO_x/HC/PM/CO)
- P is the external cost factor in $/kilos all exhaust air pollutants
- ratio is the proportion of NMHC to THC, as specified in "specifications" database section
- n is the number of operating modes
- x is the type of gas-engine, either LBSI or LPDF

The operation principle of this block is schematically presented in Figure 5-12.

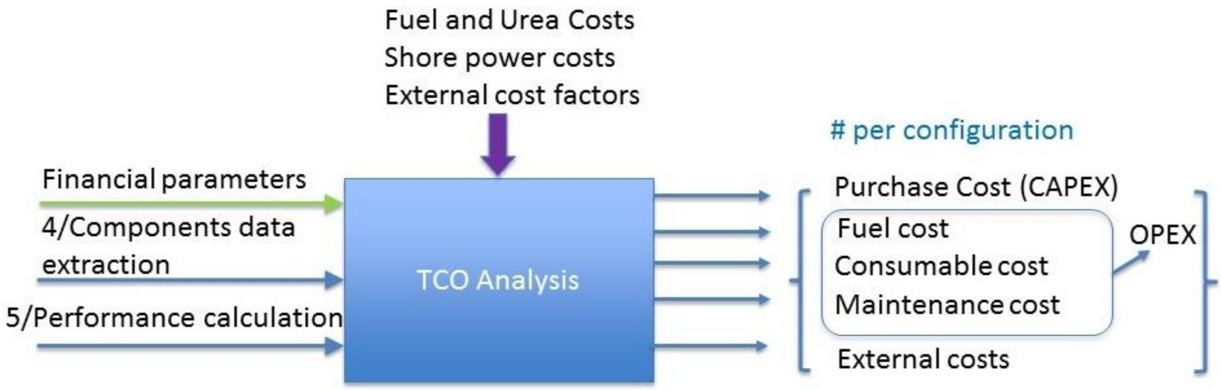


Figure 5-12: TCO analysis block operation principle

5.4.3.2 Techno-Economic analysis block

The function of the "techno-economic analysis" block is to evaluate in techno-economic terms the candidate propulsion configurations against the baseline Rotortug. The decision will ultimately be supported by the results of the comparison of the available options against the baseline Rotortug, conducted in this block. The established valuation metrics are used in the next block for ranking the candidate propulsion configurations and subsequently leading to the selection of the preferred solution, based on the decision criterion considered as input. Each decision criterion can be considered a different objective; the first is based on cost-related (financial) terms, the second on environmental performance terms (emission reduction potential) and the third is based on cost-effectiveness, which is a combination of the two previous objectives. The block can be broken down in three (3) separate sub-blocks, producing the valuation metrics relevant to each decision objective. The architecture of this block is schematically presented in Figure 5-13. The rationale behind the use of each objective on enabling the ship owner to make decisions about the preferable propulsion concept-layout is explained in each of the three sub-blocks described below.

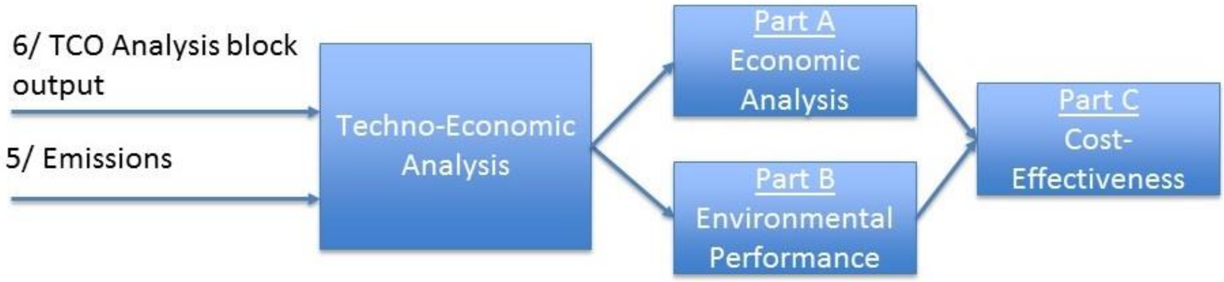


Figure 5-13: Techno-Economic analysis block architecture

Economic analysis sub-block

In the first sub-block the candidates are compared purely on financial terms against the baseline Rotortug. The economic analysis is conducted on the principles of a comparative lifecycle analysis. The varied TCO expressed in NPV is calculated, based on the free and the discounted cash flow analysis results of the TCO analysis block. Owners would be eager to comprehend the cost-related differences of alternative options, before making an investment decision between those options. Therefore, instead of estimating the TCO, including all participating cost components, it was decided to include only the differing ones, as explained in the "TCO analysis" block. By estimating the variations in CAPEX and OPEX between the candidates, against a reference tug already in service (business as usual), the owner gains valuable insight into the economic evaluation of the alternative options. Key areas where operational savings are expected can be identified and the monetary magnitude of these savings can be appraised, thus revealing if there is ground for justifying the additional capital investment required. For an owner to be persuaded to choose to invest for a specific option between various alternatives, appropriate cash flow valuation metrics must be in place, which are easily interpreted. Then the decision will be based on whether certain financial criteria are met. For the purpose of assessing competing choices a multi-metric comparison approach is established. The cash flow valuation metrics implemented consist of:

- Net Investments
- Payback period
- Net Present Value (NPV)
- Internal Rate of Return (IRR)

In this way, an owner will be presented with a plethora of valuation metrics to review the incremental cash flow streams of the competing candidate options, enhancing the analyst's confidence level to proceed forward with a specific option. The candidates are anticipated to yield differing outcome scores between the established valuation metrics. The investor should weigh the importance of the different valuation metrics before reaching to a conclusion, based on factors such as the current financial situation, the risk tolerance, the company's business objectives or other investment considerations. Nonetheless, these valuation metrics will certainly help on deeper comprehension of the investment considerations.

For comparing the results of the alternatives against the results of the baseline case, one can subtract the relevant free or discounted cash flows between the investigated candidate and the baseline case, at each time increment. Hence the free and discounted incremental cash flow statements are generated, representing only cash flows due to the investment. The incremental values ($\Delta_{i,j}$) are given by the following formula

$$\Delta(CF\ or\ DCF)_{i,j} = Candidate\,(CF_{i,j}\ or\ DCF_{i,j}) \ - Baseline\,(CF_{i,j}\ or\ DCF_{i,j}) \qquad (51)$$

Where $\Delta_{i,j}$ denotes the investigated *free* Cash Flow or Discounted Cash Flow i in year j.

By doing so, savings or losses will result for candidates with less or more operating expenses than the baseline case respectively. Savings can be illustrated in the generated free and discounted cash flow statements as free or discounted cash inflows respectively, while expenses as free or discounted cash outflows respectively. It is noted that in the generated cash flow statements, inflows appear as positive numbers, while outflows appear as positive numbers inside parentheses. Moreover, the difference in capital investment needed to be paid up-front for investing in the candidate propulsion configuration will still be a cash outflow, since in all cases additional capital is required for investing to a candidate propulsion configuration.

A financial model is implemented in MS Excel for estimating the valuation metrics for all participating candidates. In this assessment the cost differentials between the investigated candidate and the baseline case are used. The estimation of these metrics is based for some on the nominal (free) cash flow results, while for the rest on the discounted cash flow results, generated from the varied TCO analysis. Specifically, the Net Investment and Payback period metric are based on the free cash flow results, while the NPV and the IRR on the discounted ones. It must be highlighted that candidates are considered "mutually exclusive projects", meaning that the investor would choose to invest only in one project out of the total number of candidate projects. Below, the estimation procedure for each metric is explained.

Net Investments

Net Investments represent the total amount of money that the investor should pay over the economic-life frame, for a specific option. It consists of the initial capital expenses plus all the anticipated future cash outflows. It can be expressed mathematically by the following equation

$$\begin{aligned} Net\ Investments &= total\ free\ cash\ outflows\ to\ end\ of\ economic\ lifetime\ year \\ &= -\left[\Delta(CAPEX_{NPV}) + \sum_{j=1}^{m}\sum_{i=1}^{n}\Delta Cash\ outflow_{i,j}\right] \end{aligned} \qquad (52)$$

$$\Delta(CAPEX_{NPV}) = -(CAPEX_{NPV_{candidate}} - CAPEX_{NPV_{baseline}}) \qquad (53)$$

Where n denotes the number of the following four (4) incremental nominal cash outflows; the fuel losses, the consumable losses and the maintenance losses, if applicable, and m denotes the investment horizon in number of years. The minus (-) in Eq. (52) denotes that the result is a positive number, while in Eq. (53) is used to signify that the specific differential is an outflow, thus a negative number.

As decision rule, the Net Investments should be the least among the candidates. A ship-owner is expected to prefer to pay the least, as a premium for investing in a different drivetrain topology, instead of buying a Rotortug with the reference drivetrain.

Payback period

Payback period shows the time period in number of years needed for an investment to break-even, meaning projected earnings to equal the costs for the investment. It is a metric that reveals the feasibility of a project. It can be expressed mathematically by the following equation

$$Payback\ period = Y + {}^{A}/_{B} \tag{54}$$

Where

- Y is the time period in number of years before the cumulative comparative net free cash flow becomes positive
- A is the absolute resulting value of the cumulative comparative net free cash flow at the end of period Y
- B is the comparative total net free cash flow resulting value during period A until the start of next year

Payback period is a metric that accounts for the timing and size of the cash flows, both inflows and outflows. Since, in this thesis the data are projected in an annual basis, it is assumed that the incremental cash flow events are happening at the end of each year. Two points must be highlighted for cash flow streams which have a variation profile between net gains and net losses across the economic analysis lifespan. Firstly that multiple break-even points could occur and secondly that the payback period metric reveals nothing with respect to the final economic outcome of the candidate option's assessment, following the point of the recovery of the initial investment costs, meaning that payback period must be evaluated in conjunction with a profitability metric. Finally, it is noted that there might not be a payback period within the economic lifespan.

As decision rule, for a candidate to be eligible for investment, a payback period should exist within the economic lifespan and usually before a predefined by the investor limit. Also, the candidate option with the smallest payback period will be the preferred choice.

NPV

NPV reveals the anticipated net profit of the investment expressed at present value. It is the subtraction of the total projected incremental net cash outflows (Cost of Investments) from the total projected incremental net cash inflows. It can be expressed mathematically by the following equation

$$NPV = total\ discounted\ cash\ inflows\ from\ investments - Cost\ of\ Investments$$

$$= \sum_{j=1}^{m}\sum_{i=1}^{n} \Delta DC\ inflow_{i,j} + \sum_{j=1}^{m}\sum_{i=1}^{n} \Delta DC\ outflow_{i,j} = \tag{55}$$

$$\Delta(OPEX_{NPV}) + \Delta(CAPEX_{NPV}) + \Delta(Ext_{NPV})$$

$$\Delta(OPEX_{NPV}) = OPEX_{NPV_{candidate}} - OPEX_{NPV_{baseline}} \tag{56}$$

Where Δ denotes the cost differential between the candidate propulsion configuration and the baseline case, $\Delta(CAPEX_{NPV})$ is given by Eq.(53), $\Delta(Ext_{NPV})$ is the incremental discounted external costs and $OPEX_{NPV}$ is calculated according to Eq. (31).

It is a metric that accounts for the timing and size of the cash flow streams, taking into account the discounting effect, thus integrates the terms of opportunity, risk and inflation. NPV is generally considered as the most accurate approach for investment evaluation, with such cash flow streams.

A positive value of NPV suggests that the candidate would have a return in excess of the additional capital invested initially. The NPV metric is a form of valuating expected profits but shows nothing with respect to profitability. This happens because it does not provide an insight into the financing of the cash outflows generated within the investigated economic lifetime, but just provides an indication of the expected profits, assuming that the necessary budget for paying all cash outflows across the investment horizon will be available. However, an investor might be unwilling to allocate money at certain time periods. To this end the inclusion of another complementary profitability index is deemed imperative for aiding the decision-making process. IRR is a suitable index, which serves this function.

As a decision rule, the NPV should be positive and the higher the value, the preferable the respective solution.

IRR

The IRR is the percentage rate of return that the NPV equals to zero. It takes into consideration the discounting effect. It identifies the annual growth rate (or annualized ROI) for an investment. It can be expressed mathematically by the following equation

$$IRR = r \; when \; NPV = \sum_{j=1}^{n} \sum_{i=1}^{x} \frac{\Delta(CF_{i,j})}{(1+r)^{j}} = 0 \tag{57}$$

The above equation is not solved directly, rather through an iterative process of successive approximation trials. Excel has a dedicated function for IRR, which is used for this purpose. Depending on the profile of the cash flow streams the IRR might not exist, be negative or have multiple solutions. A non-existing IRR, in this thesis, indicates a cash flow stream profile in which cash inflows never outweigh outflows for each period throughout the investment horizon, whereas a negative IRR indicates a “net loss” result. In addition, alike NPV metric, it is sensitive to the timing of the cash inflows, resulting in a higher price for cash inflows coming earlier than cash inflows coming later throughout the economic lifespan, for two cash flow streams with the same total Net Cash Flow value (sum of all net cash flows through the end of investment horizon). It must be highlighted, that for varying discount rates, solutions might result in contradictory prices for IRR and NPV, yielding the questioning on which criterion the decision should be based. Then the decision-maker is prompted to base the decision on the NPV result, which is the total profits over the lifetime of the investment. When comparing competing options, with a cash flow profile consisting of net cash outflows at the start and mostly net cash inflows throughout the economic lifespan, like in this thesis, the IRR is considered a useful metric.

As decision rule, the IRR should exist, be a positive number and bigger than the discount rate. In addition, the option with the highest IRR is the preferable one.

The operation principle of this block is schematically presented in Figure 5-14.

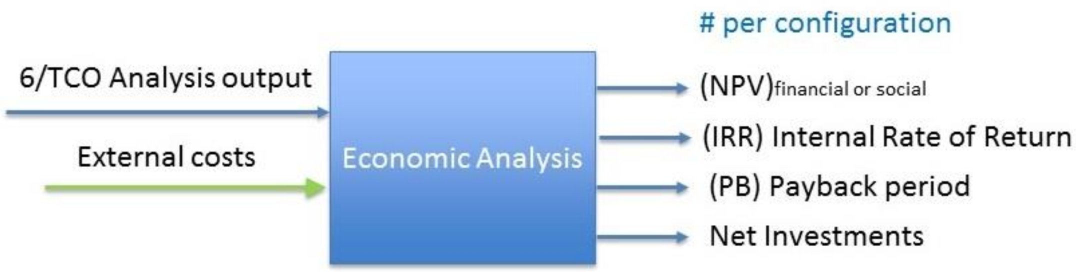


Figure 5-14: Economic analysis sub-block operation principle

Such a decision-support analysis will be subject to the variable values. Only through a sensitivity analysis an investor can identify how uncertain the results of decision metrics really are. However, even when performing a sensitivity analysis usually one parameter is altered while the rest remain constant. In reality, variables would change simultaneously.

Environmental performance sub-block

In the second sub-block the candidates are compared solely on the basis of their environmental performance (emission output). The objective of complying with certain emission regulations in the desired area of operation would yield a plethora of different solutions, especially with regard to the number of after-treatment systems fitted in the candidate drivetrain variants participating engines. Alone the preference on a specific prime mover used as a main engine, running on an alternative fuel comes in many instances with a certain trade-off between the different air pollutants emission potential, as indicated in Table 3-4. The addition of after-treatment systems complicate even further the final emission potential of a combined solution, as indicated in Table 3-5, particularly when examined from a system-integration perspective, like for the scope of this thesis. It is interesting for the decision-maker to know the expected emission reduction achieved for each air pollutant, expressed in percentage, for each candidate propulsion configuration when compared against the baseline vessel. These emission reduction percentages are estimated inside this block. The calculation is made by using the following formula

$$ER_{cand,air\ pol} = \frac{E_{cand,air\ pol} - E_{base,air\ pol}}{E_{base,air\ pol}} \quad (58)$$

$$E_{cand,air\ pol} = \sum_{y=1}^{m} \sum_{x=1}^{q} (E_{x,y})_{cand,air\ pol} \quad (59)$$

$$E_{base,air\ pol} = \sum_{y=1}^{m} \sum_{x=1}^{q} (E_{x,y})_{base,air\ pol} \quad (60)$$

where

- $ER_{cand,air\ poll}$ is the total Emission Reduction per investigated candidate (cand) per year for the air pollutant (air. poll) expressed in percentage (%)
- $E_{Bas,air\ poll}$ is the total Emission Reduction per year for the baseline configuration (base) for the investigated air pollutant (air pol) expressed in percentage (%)
- $(E_{x,y})_{cand,air\ poll}$ is the annual emission output of the examined air pollutant for the investigated candidate in kilos (kilos/year) and is given by Eq. (7) multiplied by 365
- $(E_{x,y})_{base,air\ poll}$ is the annual emission output of the examined air pollutant for the baseline configuration in kilos (kilos/year) and is given by Eq. (7) multiplied by 365
- q denotes the number of installed prime movers for the investigated candidate configuration and
- m denotes the number of mission profile's modes

It must be highlighted that the result might be negative or positive, depending on the sign of the numerator. In the cases that the ER is positive, indicates that the candidate is considered will emit more than the baseline configuration for the respective air pollutant examined. A negative value on the other hand, would indicate emission savings.

As a decision rule, the ER should be negative. Additionally, the candidate option with the lowest ER percentage (%) per air pollutant will be the preferred choice. The operation principle of this block is schematically presented in Figure 5-15.

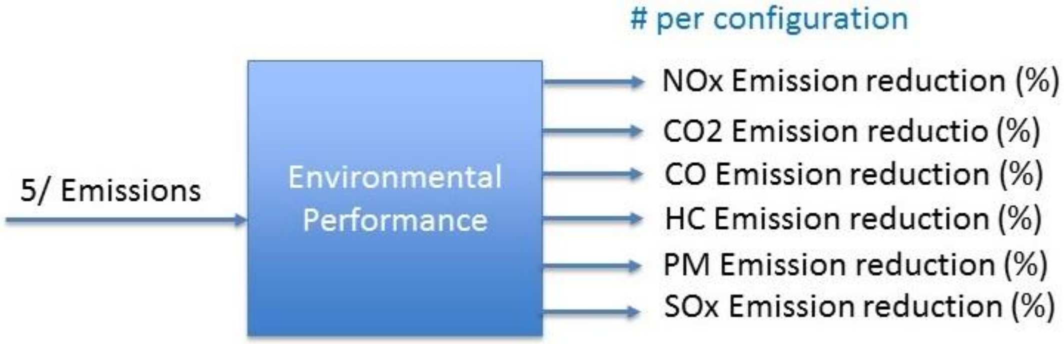


Figure 5-15: Environmental Performance sub-block operation principle

Cost-effectiveness sub-block

In the third sub-block the candidates are compared based on their Cost-Effectiveness (CE), as perceived form a ship-owner perspective and a societal perspective. CE is a combination of the emission reduction potential of an investigated propulsion configuration and its anticipated economic performance. When the analysis is conducted from an owner's perspective, the environmental burden (climate change, biodiversity losses, soil and water pollution, peoples' health impact) expressed in terms of external cost imposed to the society is not considered, while when the analysis is conducted from a society perspective they are accounted. Such an approach, which utilizes a traditional cost-benefit analysis, is meaningful when conducted from a port authority or government perspective, with the purpose of evaluating the most meaningful policy action. It is also particularly useful for a ship-owner, because it provides a methodology, based on which can contest for funding. The CE results would be single-ship based but can easily be transformed to fleet-based.

The desired solution would be of course one that would yield the lowest emission output while simultaneously having the lowest cost. Due to the conflicting nature of the two objectives, a trade-off criterion is introduced; the cost-effectiveness. Cost-effectiveness is measured in kilos emission avoided per USD $ invested (kg/$), both for the combustion-related and fuel-related air pollutants. Through this analysis the cost-effectiveness of the candidate propulsion configurations is evaluated against the baseline propulsion configuration with respect to each air pollutant emission reduction potential, as a system. It is not possible to break down the percentage of cost-effectiveness achieved due to the influence of each individual emission-abatement technology introduced. After all, it is not an objective of this thesis to compare individual emission-abatement technologies or other emission control strategies. In addition, it is stressed that the benefits of two different solutions with the same cost-effectiveness value, would yield different benefits, due to the varying nature of the individual air pollutants emission reduction percentages and thus their related benefits, as discussed in Appendix A.3. The operation principle of this block is schematically presented in Figure 5-16.

Functions in Microsoft Excel® are developed for calculating the cost-effectiveness per air pollutant for each candidate, $CE_{cand,airpol}$, based on the following procedure

$$CE_{cand,airpol} = \begin{cases} \dfrac{\Delta(E)_{cand,airpol} * Econ\ life}{-NPV_{financial,cand} * {}^{1}/_{6}}, for\ NPV_{financial,cand} \\ \dfrac{\Delta(E)_{cand,air\ pol} * Econ\ life}{NPV_{social,cand} * {}^{1}/_{6}}, for\ NPV_{social,cand} \end{cases} \tag{61}$$

$$\Delta(E)_{cand,airpol} = -(E_{cand,air\ pol} - E_{base,air\ pol}) \tag{62}$$

Where Econ life is the investment horizon in number of years, NPV(financial or social) $NPV_{financial,cand}$ is given by Eq. (55) and are multiplied by 1/6 in order to estimate the amount of money allocated towards the reduction of each exhaust air pollutant, $E_{cand,air\ pol}$ is given by Eq. (59) and $E_{base,air\ pol}$ is given by Eq. (60). The minus (-) in Eq. (62) denotes that emission savings are a positive number, whereas in Eq.(61) for the $NPV_{financial,cand}$ case, it denotes that money spent are a positive number whilst money saved will be indicated as a negative number, resulting in a negative ratio, which denotes a "win-win" situation. It is stressed that it is assumed that money invested from a ship-owner are equally allocated amongst the six (6) primary exhaust air pollutants under consideration in this thesis.

It must be highlighted that the result might be negative or positive, relevant to the sign of the numerator or the denominator. A negative value in the nominator would reflect that there are no emission savings for the particular air pollutant under investigation. Such negative value means that the environment would suffer an additional emission output burden in kilos per USD ($) spent or saved in that particular candidate propulsion configuration under examination. To this end, since it contradicts with the sense of effectiveness, those prices are completely disregarded inside this block, resulting in an error value. For the $NPV_{financial,cand}$ case keeping the nominator positive (emission savings), for negative NPV values, meaning that the investment is not profitable, the Cost-effectiveness will be positive, revealing the amount of air pollutant being saved in kilos per each dollar spent. On the other hand, positive NPV values will result in negative CE values, reflecting benefits both in monetary and environmental terms, indicating the amount (kilos) of exhaust air pollutants saved per dollar (USD $) saved. The opposite applies to the $NPV_{social,cand}$ case.

The decision rule will differentiate whether the CE value per exhaust air pollutant is negative or positive, depending on which case, $NPV_{financial,cand}$ or $NPV_{social,cand}$ is investigated.

For the $NPV_{financial,cand}$ case, if the CE is negative, it means that benefits arise both in monetary and emission terms; thus, it will always be the preferred choice. Otherwise, the candidate option with the higher CE per air pollutant will be the preferred choice according to the formula given by Eq.(63).

$$CE_{cand,air pol} = \begin{cases} preffered\ , if\ \ NPV_{financial,cand} > 0 \\ \dfrac{\Delta(E)_{cand,air\ pol} * Econ\ life}{-NPV_{financial,cand} * {}^{1}/_{6}}, if\ NPV_{financial,cand} \leq 0 \end{cases} \tag{63}$$

For the $NPV_{social,cand}$ case, if the CE is positive, it means that benefits arise both in monetary and emission terms; otherwise, it means that money ($) have to be spent for avoiding emissions in kilos. The candidate option with the higher CE per air pollutant will be the preferred choice.

Figure 5-16: Cost-effectiveness sub-block operation principle

5.4.3.3 Decision-making block

The function of the "decision-making" block is establishing the decision framework for selecting the most suitable propulsion configuration variant, based on the selected analysis decision criterion. Given the fact that for none of the selected decision criteria a single valuation metric exists for reaching a conclusion, a way for producing a meaningful score, based on which the candidates will be ranked, was considered imperative to be developed. The purpose was to find a method which would assist the decision-maker to decide quickly and reasonably, without having to struggle for interpreting each different established metric or deciding the decisive metric, on which to base the decision. It is evident that the preference of the decision-maker on certain valuation metrics will play an important role in the final selection of the preferable candidate to invest in. To this end, the decision framework established pertains in the Multiple Attribute Decision Making (MADM) methods. These methods are particularly useful, with many applications, in problems with a finite number of competing (mutually exclusive) options from which only one should be favored. [86] The decision-maker is required to prioritize the valuation metrics, on which the number of alternatives would be ranked. Since the objective of this thesis was set to select one solution among many options that comply with the anticipated emission regulations in the envisaged area of operation, it meets the purpose of the MADM methods. Specifically, the Grey Relational Analysis (GRA) method was chosen to be implemented.

The GRA method belongs to the classical MADM methods, with numerous publications in the literature, while it is also applied in practice on several occasions. [87-89] Moreover, it provides to the user the ability to properly manage the input data and is appropriate for handling both quantitative and qualitative performance attributes. Finally, this method can easily be implemented in the Microsoft Excel® program.

The performance attributes in this study, which are relevant to candidate evaluation and selection are only of quantitative nature, for all three (3) analysis decision criteria. Qualitative criteria like the quality of the installed equipment, the reputation of the vendors, warranty on equipment, supply lead time, etc. are not considered. Generally, the model formulation process plays a major role in the result of the decision-making process. The purpose of the GRA method is to transform the performance attribute data (valuation metrics) into information that would lead to a uniform quantification, represented by the so called grey relational grade. The mathematical formulation of the methodology is included in Appendix D.8.

The relative importance of the performance attributes is already preselected, as summarized in Table 5-19. However, the ability to alter the preselected values within the block is given to a power user. It must be highlighted that a power user is also allowed to disregard certain criteria, by assigning a value of zero (0) or give the same importance on more than one (1) criteria, by assigning the same number.

Table 5-19: Performance attributes ranking order

Rank order	**Economic Performance**	**Rank order**	**Environmental Performance**	**Rank order**	**Cost-Effectiveness**
4	Net Investments	1	ER_{NOx}	1	CE_{NOx}
1	NPV	2	ER_{CO2}	2	CE_{CO2}
3	Payback period	6	ER_{CO}	6	CE_{CO}
2	IRR	5	ER_{HC}	5	CE_{HC}
	-	4	ER_{SOx}	4	CE_{SOx}
	-	3	ER_{PM}	3	CE_{PM}

The GRA method also offers the ability to a user to quantify the desired targets, as threshold values; for instance the desired emission-reduction percentage for each air pollutant, the desired IRR, the desired Payback period, the desired cost-effectiveness value per targeted air pollutant, etc. and aim for the solution that would be closer to the set target instead. However, this ability has not been integrated in this tool. It must be stressed that the uncertainty of the various factors, used as input throughout the calculations, cannot be addressed by using the GRA technique. There are other multi-criteria decision methods, such as stochastic models, or probability ranking techniques, such as Monte Carlo simulation, proposed in literature, which allow for evaluation under uncertainty. [90-92] It is deemed though adequate for the scope of this thesis not to include uncertainty in the evaluation. The impact of certain input factors will be explored in the sensitivity analysis. Finally, it was chosen not to use compliance with enforced regulations for available candidates as a cut-off criterion, because it was deemed more appropriate to display this info at the output spreadsheet. The operation principle of this block is schematically presented in Figure 5-17.

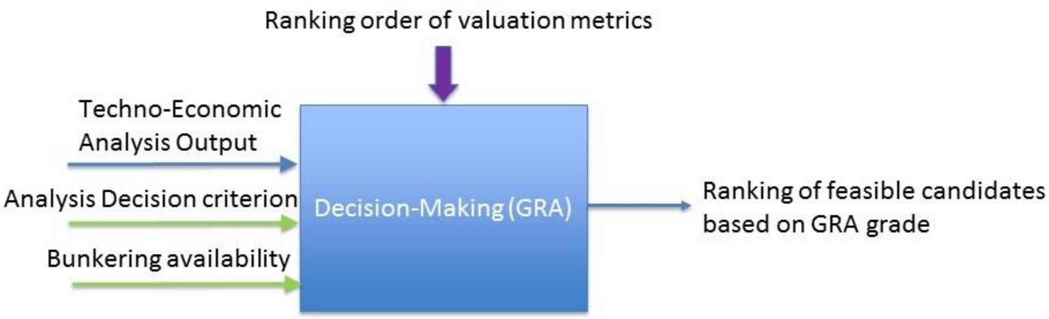


Figure 5-17: Decision-making block operation principle

5.5 Output

The output spreadsheet is the interface where the results of the decision-support tool are displayed. The results consist of a list of the different available propulsion configuration variants and the economic and environmental results of their comparison with the baseline Rotortug. They are accompanied by a series of interactive diagrams, so that it can facilitate the end-user comprehension of the comparison results.

The list contains always in the first row the details of the baseline case Rotortug and then the candidates are ranked in descending order, relevant to their achieved Grey relational grade. The following information are provided for each candidate:

- Nomenclature
- Combustion fuel
- GRA grade
- Endurance
- Range
- Bunkering interval for MGO, alternative fuel and urea
- Compliance with applicable emission regulations

It must be stressed that both the compliant and non-compliant with emission regulations candidates are listed. However, for the user to easily recognize the non-compliant candidates, they are highlighted in red. Moreover, candidate related results from the technical part of the analysis, like the fuel consumption, energy consumption, urea consumption, prime movers running hours and emissions output as well as the power (MCR) utilization of the participating engines per mode of operation and for the techno-economic part, like the contribution of fuel, maintenance, external cost and consumable savings in the total operational savings for each option considered and the TCO cash flow tables generated, can be found in the individual spreadsheets developed.

5.6 Conclusion

In this chapter the design methodology of the decision-support tool was presented in depth, through the elaboration of the principal function for each individual block, its underlying assumptions and its interactions with the input, the database and the other modules. Two input factors determine the applicable regulations regime; the year of delivery and the intended area of operation. It is worth noting that the applicable regulations might overlap. In turn, the attained emission limits will determine the after-treatment solutions fitted both for the baseline configuration and the other candidate drivetrains. The comparison of the candidate propulsion configurations is done against the established baseline case tug. Hence, it is evident that the baseline case would not be the same for each scenario; it would rather change with the applicable regulation regime.

The main objective of the tool is to establish the framework for selecting one drivetrain variant among many competing options that comply with the anticipated emission regulation in the envisaged area of operation. It is stressed that the bunkering availability would serve as a cut-off criterion for shortlisting the competing options. The decision framework is based on a techno-economic evaluation. After establishing a list of available candidates that indeed comply, the question would be on which criterion should a ship-owner base its decision. Owners would be eager to comprehend the cost-related differences of alternative options, before making an investment decision between those options. This is possible through a comparative TCO analysis. The incremental cash flow technique is used for performing the financial analysis, based on the generation of both the free and discounted cash flow streams. It is stressed that instead of estimating the TCO, including all participating cost components, it was decided to include only the differing ones. The evaluation would then be conducted on the basis of a multi-metric comparison approach, consisting of different financial valuation metrics.

However, choosing the most economically preferable option, would not indispensably designate the candidate which emits less than the baseline configuration, rather it might indicate a candidate which just suffices regarding the emission limits at place. Owners would be eager to find out the emission reduction potential of each alternative for each individual exhaust air pollutant, before making a final selection. Due to the trade-off between the different combustion-related emissions in prime movers together with the impact of different after-treatment solutions installed, might yield contradicting results for the constituent exhaust air pollutants. After all, the ship-owner might be willing to invest on the greenest option, with other rewards in mind, such as the promotion of the company's image and reputation. It is important to note that the specific economic analysis does not take into consideration other business-related benefits apart from financial ones. Only cost savings or losses are really differing between the competing options.

Furthermore, the attained cost-effectiveness of each air pollutant for the candidates, would add valuable insight on how good money are allocated towards emission reduction targets or might reveal combined savings in both the vessel's efficiency and emission abatement. Not only that but depending on the existence of market-based incentives in the anticipated port of operation, or the availability to gain access to funding, such cost-effectiveness results might be used from the regulating body for deciding in favour of allocating subsidies. This will be based on the internalization of the external costs of air pollution.

Finally, it must be highlighted that the risk is not properly addressed with this analysis. There is no guarantee that the envisioned cost savings, in terms of cash inflows, would actually be the predicted, since pricing development is highly uncertain, while price variations throughout the investment horizon have not been accounted. Moreover, the aging or breakdown of machinery equipment is not accounted, which would significantly impact the vessel's performance (fuel consumption, emission output) and the maintenance costs respectively, while financial factors, such as inflation and discount-rate are assumed constant. Of course, there is no investment without uncertainty, hence with the decision framework in place, the vital factors that influence imperatively the results, remain to be investigated. This would be part of the next chapter, where two indicative case studies are presented. The decisive input data would be revealed, while the significance of uncertain parameters will be discovered in the sensitivity analysis.

6 Validation

The use of the decision-support tool will be validated with two case studies, one for terminal and one for harbour duty. With the purpose of verifying the decision-support tool, the parameters which are sensitive, are attempted to be discovered and their impact to be assessed. Apart from the sensitivity analysis, great effort has been given in the evaluation of the validity of results, by detecting errors and checking if the results for each block correspond to the expected outcome. In addition, the insertion of extreme values has been tested in the model to determine its response, with success (degeneracy testing). The outcome of parts of the program has been verified against published studies by simulating the respective scenario or by comparing results with on-board measurements (i.e. daily fuel consumption for the conventional propulsion configuration). Particularly, for the results of alternatives set up on different propulsion configuration than the conventional drivetrain, with prime movers running on alternative fuels, validation needs to be performed by conducting measurements on-board such Rotortugs (fuel consumption, emission output). Given the fact that such Rotortugs have not been constructed yet and in the absence of objective performance data from commercial engines, the decision-maker should approach the results with caution.

6.1 Case Studies

Two case studies are presented in this chapter, one on terminal duty and one on harbour duty in different areas of operation and time. In the first case study; terminal tug, the reasoning behind the ranking order of candidates for all three decision criteria is explained in detail. It becomes clear that the decision criterion, on which a ship-owner would base the final selection, is a decisive factor for the ranking of different alternative propulsion configuration variants. In the second case study; harbour tug, the impact of regional regulations on compliance of alternatives is illustrated. The need for installation of after-treatment systems on alternatives for complying with the expected emission standards is clarified. The results of the case studies, as extracted from the "techno-economic analysis" and the "decision-making" blocks are summarized in Appendix E in tabulated format. It is highlighted that the relative importance of the performance attributes is the default for all decision criteria, as summarized in Table 5-19.

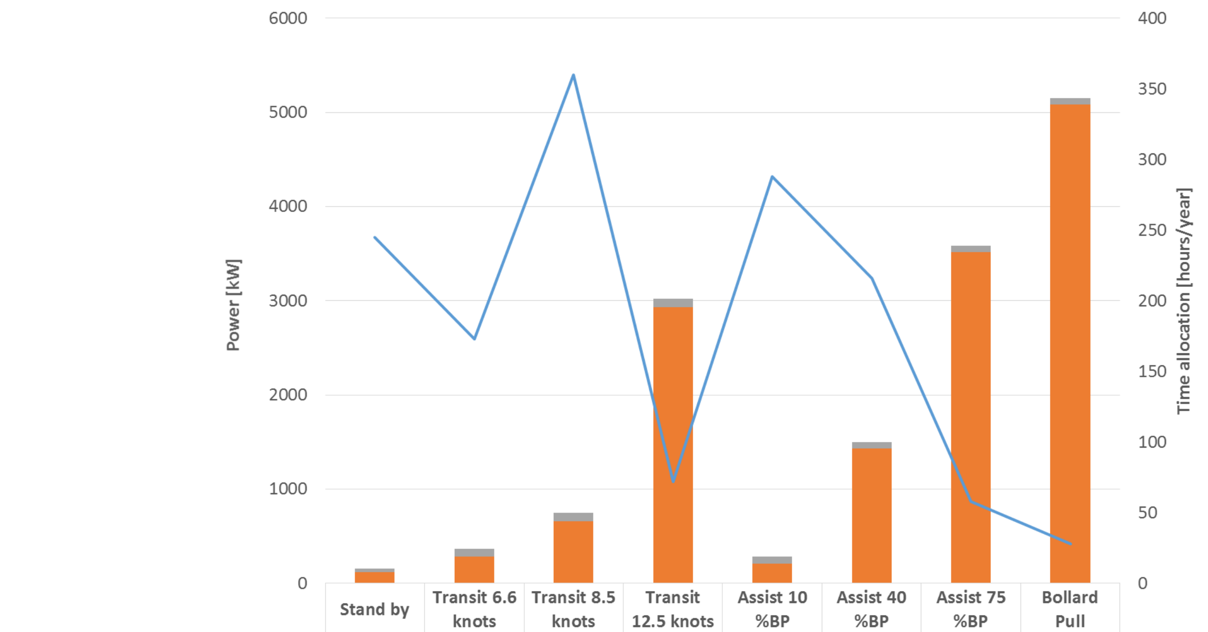
6.1.1 Case Study 1 – Terminal tug

In the first case study, the focus is set in presenting the output of the comparison analysis for each one of the three decision criteria and providing the reasoning behind the ranking order of candidates.

6.1.1.1 Description of the case study

The terminal tug is envisioned to serve the Rovuma LNG [RLNG] project, envisioned to start-up in 2025. The origin of the gas will originate from three (3) reservoirs of the Mamba fields in the Area 4 block offshore Rovuma basin, located approximately 250 km north east of Pemba and 50 km from the coastline of Cabo Delgado coast, in Mozambique, Southern Africa and is estimated to have an initial production life of 30 years. Two (2) LNG liquefaction trains, in the first phase of the project, will transfer the LNG extracted through a 45km-long subsea pipeline to the onshore facilities on the Afungi Peninsula, in Palma Bay, located towards the northern end of the Quirimbas Archipelago. One (1) LNG export jetty with two (2) loading berths is planned to be constructed, able to accommodate LNG carriers with storage capacities ranging from 35,000 to 266,000 m^3. Kotug is interested to tender for undertaking the towage assistance services during onloading from the LNG jetty to the LNG carriers. A long-time commitment is envisioned to be established between Kotug and the

Mozambique Rovuma Venture (MRV), comprising of a joint venture between a consortium of energy companies, for a period of 30 years with the option of extending the contract of towage services. Kotug believes that an ART-8032 is the most suitable tug to be deployed for this kind of operation and wants to examine which driveline variant could constitute a viable solution in 2025 for building up the fleet of ART-8032, which will operate in rotation. The annual operating hours of such a Rotortug is estimated to be 1440 hours/year in total, based on 4 hours per day for 360 days per year. The utilization rate is summarized in Table E-1 and the resulting operational profile, including the power demand, as established by the "Duty cycle" block is illustrated in Figure 6-1 below.



	Stand by	Transit 6.6 knots	Transit 8.5 knots	Transit 12.5 knots	Assist 10 %BP	Assist 40 %BP	Assist 75 %BP	Bollard Pull
Paux (Auxiliary load (power)) kW	40	87	87	87	69	69	69	69
PD (average deliverd power) kW	115	279	658	2933	210	1431	3516	5083
duration [hours/year]	245	173	360	72	288	216	58	28

Figure 6-1: Anticipated operational profile of terminal Rotortug envisioned for operation in Rovuma Basin, Mozambique (1440 annual operating hours)

At 2025 Mozambique coastlines are not anticipated to have been designated ECA. Cold ironing is not expected to be a requirement at Pemba port and bunkering infrastructure for all candidate fuels is assumed to be in place. External costs are not taken into consideration. Furthermore, a central "MGO differentials" price scenario is assumed. Lastly, with respect to the financial parameters, the economic period is assumed to be 30 years, equal to the initial production horizon, the discount rate 8% and the inflation rate 2%. The model input variables are summarized in Table 6-1.

Table 6-1: Input variables for 1st case study (terminal tug)

Region of Operation	Southern Africa
Country of Operation	Mozambique
Port of Operation	Pemba
Year of Delivery	2025
Has Southern Africa at 2025 been designated ECA?	No
Cold ironing	No
External costs	No
Bunkering availability (LNG/Methanol/Biodiesel/DME)	Yes for all
Fuel price scenario	Central
Price scenarios (Urea/Shore power/CO_2 external costs)	Central/NA/NA
Period of economic analysis	30 years

Discount rate	8%
Inflation rate	2%

6.1.1.2 Analysis of results

This scenario is representative for a terminal tug which has to comply only with MARPOL Annex VI Convention emission standards. The baseline ART-8032, complying with these standards, would be one based on a diesel-direct drivetrain with 4-stroke high-speed compression ignition engines running on MGO, without any after-treatment systems installed. The interpretation of the results according to the decision criterion are presented below.

6.1.1.2.1 Economic performance

In this section the results based on economic performance are presented and then analysed. The results, summarized in Table E-2, indicate as the preferable solution CONV-S2, a conventional propulsion configuration based on LBSI gas-engines running on LNG. The GRA grade of this solution is the highest amongst the three candidates, deemed suitable. It is highlighted that 15 out of the total 18 alternatives are deemed unsuitable and are not shown in the table of results. The reason behind the elimination of candidates is because their results are negative for all financial evaluation metrics. When it comes to the evaluation of the results for the viable alternatives and for understanding the reasoning behind the ranking order, a careful look at the cash flow metrics results found in Table 6-2 is compulsory.

Table 6-2: Financial valuation metrics results for case study 1(terminal tug)

Cash flow metrics results	CONV-S2	CONV-S1	HYBRID-S2
Net Investments	$677,148	$865,860	$2,661,285
NPV	$-148,675	$-516,345	$-854,125
IRR	5.92%	1.38%	0.41%
Payback period	15.6	25.5	26.7

The results reveal that no alternative can be considered better than the baseline Rotortug, based solely on the $NPV_{financial}$ metric. All options yield negative $NPV_{financial}$ values and thus no profits are anticipated, under the assumed financial parameters. However, it was considered important for the decision-maker to be presented with the options, if any, which exhibit positive IRR and a payback period within the investment horizon. This way, a decision-maker understands that by altering certain sensitive parameters might constitute a candidate profitable. This ability will be further clarified in section 6.2. Lastly, the Net Investments are the representative expenses throughout the investment horizon, which the ship-owner will have to pay. The amount of those expenses is also important to know beforehand, since it might indicate a shortage of financing.

Exploring the reason that all alternatives result in negative NPV values can be done by studying the comparison results of the alternatives against the baseline case, in terms of anticipated losses and savings. As can be seen in Figure 6-2 in terms of operational expenses, only fuel and maintenance cost savings can be anticipated. Since no SCR after-treatment system is needed for any option to comply with the emission regulations, no benefit could arise from urea consumable expenses. In addition, since external costs are not considered, monetary benefits from lower emissions cannot contribute to savings.

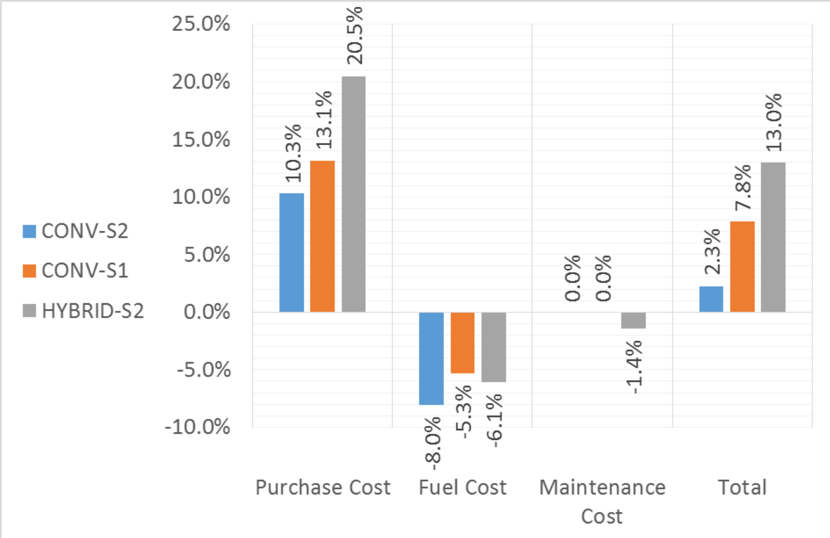
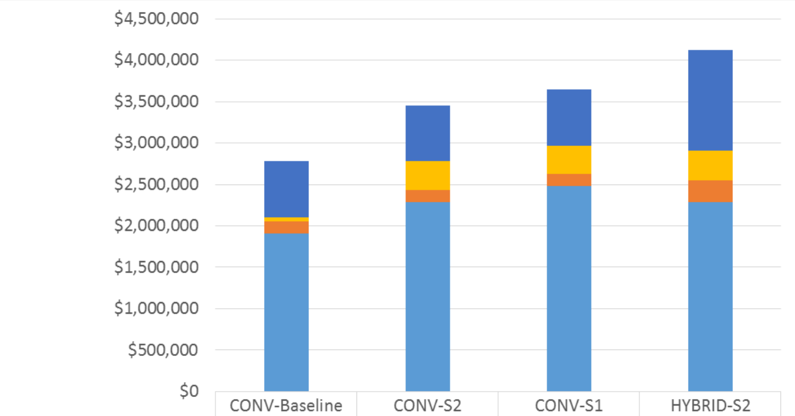


Figure 6-2: Cost comparison of alternative options using baseline vessel's propulsion system as reference

It is evident that fuel and maintenance cost savings are not enough for counteracting the initial up-front investment, resulting in total losses for all candidates. It is stressed that fuel-variants on the same propulsion configurations will not exhibit any maintenance savings, due to the same energy management strategy implemented, resulting in the accumulation of the same number of engine running hours and subsequently to the same amount on maintenance costs. This is depicted with 0% for CONV-S1 and CONV-S2 in the above graph. In terms of the initial up-front investment costs for the candidates' machinery equipment relevant to the baseline configuration, it is revealed as anticipated, that conventional drivetrain topologies running on alternative fuels have lower purchase cost than their hybrid counterparts. This can be explained if we look at Figure 6-3. It is evident that the difference between fuel-variant on conventional propulsion configuration against the baseline case lies purely on the lower tank and engine acquisition costs, while for hybrid-versions the additional machinery equipment is the decisive cost.



	CONV-Baseline	CONV-S2	CONV-S1	HYBRID-S2
Additional Equipment	$679,500	$679,500	$679,500	$1,219,500
Tank	$46,250	$342,158	$340,250	$354,250
After-treatment	$0	$0	$0	$0
Genset	$147,534	$147,534	$147,534	$266,000
Main Engine	$1,906,200	$2,287,440	$2,478,060	$2,287,440

Main Engine Genset After-treatment Tank Additional Equipment

Figure 6-3: CAPEX for the evaluated alternatives for case study 1 (terminal tug)

With respect to the operational savings potential, the power utilisation charts can offer valuable insight. To begin with, the mission profile is directly linked with the efficiency gains anticipated in each mode, depending on the propulsion configuration. Since, the results for the terminal tug case study have revealed the conventional and the hybrid based on AC topology as viable solutions, it is significant to explore their differences in efficiency gains. This is possible by investigating the two concept layouts' power utilization charts for the given mission profile, assuming the same fuel. The power utilization charts for the diesel-direct drivetrain is illustrated in Figure 6-4, while for the hybrid based on AC topology drivetrain is illustrated in Figure 6-5. By understanding the expected gains, both in fuel efficiency and in engine running hours' reduction, the decision-maker can envision the conditions which will favor an alternative propulsion configuration.

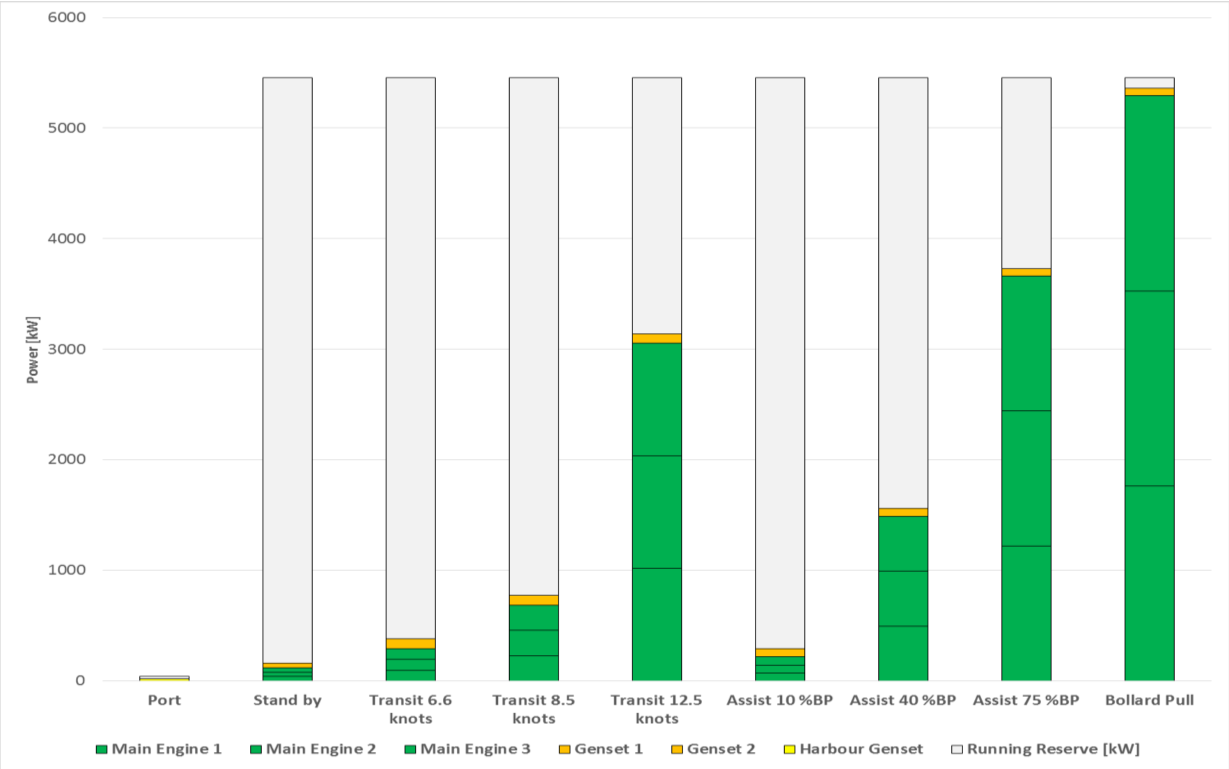


Figure 6-4: Baseline Rotortug (diesel-direct) power chart for case study 1 terminal tug

Looking at the conventional propulsion configuration power chart it is evident that high utilization rates are exploited on a limited number of operating modes; particularly transit high (12.5 knots), assist 75% and 100%, in which the propulsors demand high propulsion power from the installed main engines. In addition, the utilization rate is also high when the vessel is docked (non-operating mode), because only the dedicated harbour generator is on, covering the total of hotel loads. The low utilization rate for the rest of the operating modes is due to all three main engines required to be switched on and running, each driving its respective thruster. In addition, in these modes one of the two C9 auxiliary generators is always online for providing the power for hotel and auxiliaries.

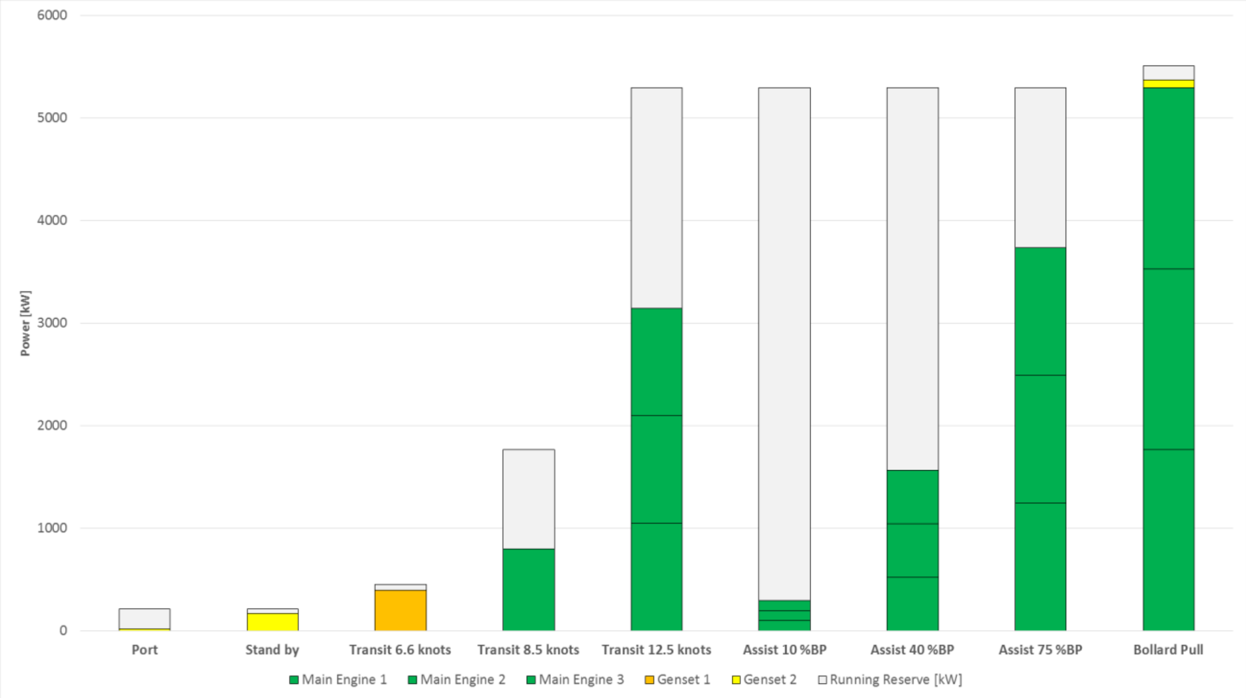


Figure 6-5: Hybrid based on AC topology (without batteries) drivetrain power chart for case study 1 terminal tug

In Hybrid versions the EMS dictates the exact power management, differentiating the energy flow strategy depending on the propulsion demand on the respective operating mode. As can be observed from Figure 6-5 it is evident that high utilization rates are exploited on the standby, the low to medium load transit conditions and on the high assist BP conditions. In the port mode the Hybrid version exhibits a lower utilization rate in comparison to the conventional version, because of the bigger installed genset; signifying a higher fuel consumption for this mode. As can be observed, in transit medium and high conditions as well as in the assist conditions apart from the BP, there is no auxiliary generator on. Power is provided by the M/Gs operating in PTO mode. It is interesting that for transit 8.5 knots there is only one ME running and its dedicated M/G is supporting both propulsion and hotel loads, signifying a high efficiency loading for the running ME and probable fuel savings. Particularly for the high transit (12.5 knots) condition and the assist conditions, all three main engines are running similarly to the conventional propulsion configuration; hence, it is anticipated to result in extremely small savings if not net losses. The biggest proportion on savings will most probably not be attributed to fuel consumption savings, but are expected to come from lower total engine running hours, which will prolong their maintenance and thus lead to high maintenance cost savings.

Two are the parameters that characterize a mission profile, the utilization rate and the annual operating hours. It is clear that by keeping the same utilization rate and increasing the duration, then the tug will operate more hours in each operating mode annually. This implies that for alternatives running on the same fuel, in case a net efficiency gain is expected, this will be translated to less fuel consumption compared to the baseline case. Then with higher duration, the annual fuel consumption savings will also be higher. Specifically, for alternative propulsion configurations for which less cumulative annual running hours for their prime movers are estimated would signify additional maintenance savings. Therefore, the combined fuel consumption and maintenance benefits throughout the lifetime expectancy of the tug can exceed the investment costs and lead to profits. It is highlighted that even if an alternative propulsion configuration for a given mission profile leads to savings or losses for fuel consumption or maintenance compared to the baseline case, the combined total savings is what matters.

Of course, the power chart and the investigation on efficiency gains is only one side of the story. Things get complicated when alternative fuels with differing energy efficiency (LHV) are combusted in different prime movers. Then the fuel's energy efficiency and the combustion-related properties of the prime mover will dictate the resulting fuel consumption. It is stressed that even if an alternative shows an efficiency loss, for the total mission profile, depending on the fuel price difference between MGO and the respective alternative fuel, might still lead to less fuel cost for the alternative. The opposite is also possible; less annual fuel consumption together with a higher price for the alternative fuel might lead to net fuel cost loss, compared to the baseline case. For this reason, it is imperative to investigate the impact on total combined cost savings, by altering the fuel price scenario and the annual operating hours. That would be covered in section 6.2, by conducting a sensitivity analysis.

6.1.1.2.2 Environmental performance

In this section the results based on environmental performance are presented and analyzed. It is evident from the environmental performance results, summarized in Table E-7, that the preferred solution would be CONV-S2, the same as for the economic decision criterion. The GRA grade of this solution is marginally higher than the 2nd option and somehow higher than the 3rd option. The scoring for the rest of the alternatives is of lower range, constituting the first three options the most appealing candidates. It is highlighted that all 18 alternatives are displayed as candidates. Exploring the reasoning behind the ranking order of the alternatives can be done by studying the comparison results of the alternatives against the baseline case, in terms of emission output per exhaust air pollutant. The results for the first three options, deemed as the most appealing candidates are illustrated in Figure 6-6.

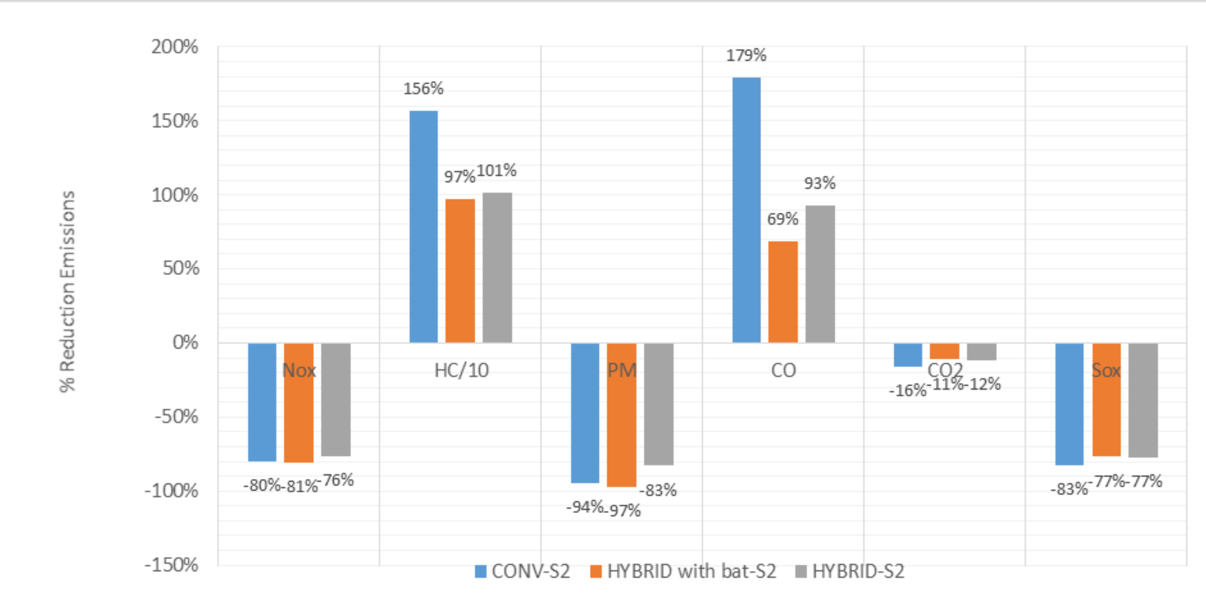


Figure 6-6: Comparison of candidates' overall emissions (%) using Baseline vessel's propulsion configuration - [Diesel-direct] as reference

As can be observed all three options emit less in terms of NO_x, PM, CO_2 and SO_x, while they emit more in terms of HC and CO. There is a substantial reduction of the same magnitude more or less (between 77%-85%) for NO_x and SO_x emissions, bigger for PM (83%-97%) while for CO_2 is smaller, around 13%. Looking at Figure 6-6 it is clear that CONV-S2 emits less SO_x and CO_2 than the rest of the options, but more NO_x and PM compared to Hybrid-with bat-S2. Not only that, but it is observed that it emits more than the competitive options in terms of CO and HC. These observations raise the question, how is it possible for CONV-S2 to be ranked as the top candidate, given the fact that it exhibits inferior environmental performance in comparison with the other competing alternatives, in certain exhaust air pollutants, especially given the fact that the superiority on environmental performance for the rest of the exhaust air pollutants is not considerably higher. Two are the reasons explaining this phenomenon. Firstly, the different ranking preference of exhaust air pollutants, attributing a bigger weighting on NO_x, PM and SO_x reduction over the rest of the exhaust air pollutants. Secondly, the model formulation process of GRA at step 1 is taking into consideration the decision rule for generating the reference data series x_0. In particular candidates that do not achieve emission reduction for a respective exhaust air pollutant are assigned a value equal to 0 for that particular exhaust air pollutant. This means that the magnitude of exhaust increase compared to the baseline case is not accounted for. Then in step 2 of the GRA process those cases will attain the minimum score (zero).

Examining the exhaust emission output for each exhaust air pollutant per mode of operation is enhancing the understanding of the decision-maker about the actual environmental performance of the considered alternatives, enabling also to understand the implications of varying the operational conditions. This is possible by looking the relevant figures (Figure 6-7 through Figure 6-12), provided below. It is highlighted that in the graphs, the minus sign for the emission reduction percentages, signifies emission reductions while the plus sign emission increase compared to the baseline case.

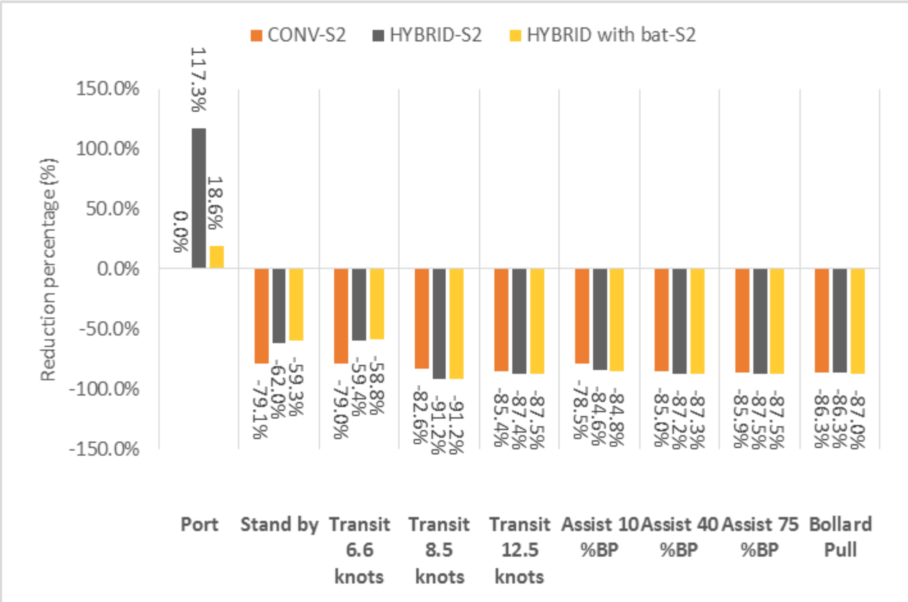


Figure 6-7: NOx reduction (%) results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile compared against the baseline case

In terms of NO_x emission output, it can be observed that in all operating modes substantial emission reduction is achieved in comparison to the baseline case. Only in the port mode (non-operating mode) the emission output of hybrid versions is bigger, specifically for the non-battery version the highest, while for the conventional-LNG-variant is the same. That can be explained. To begin with in port mode, the conventional drivetrain uses only the harbour diesel generator for hoteling purposes, thus no gains can be anticipated based on the alternative fuel. It is assumed that only prime movers intended for use as main engines combust alternative fuels. On the other hand, hybrid versions have a bigger auxiliary engine for hoteling purposes, hence it runs on an inefficient point within its emission envelope, resulting in more NO_x emissions. The integration of batteries allows for emission-free operation for a specific duration which explains the less emissions in comparison to the hybrid-without batteries version in harbour mode. Noticeably, the emission output for transit and assist conditions for hybrid versions are almost the same, as expected. Batteries addition is assumed to contribute only in the standby and the port mode. Small differences are attributed to the different total transmission losses between the two topologies. Specifically, for standby mode though, it is observed that in terms of NO_x emission there is a minor increase (3%) in NO_x emissions, compared to the hybrid without batteries, attributed to the high loading of auxiliary engine, resulting in an operating point outside the efficient specific emission contour curve. This should prompt for reconsideration on the installation of a bigger size auxiliary engine, in conjunction with the effect on the other operating modes.

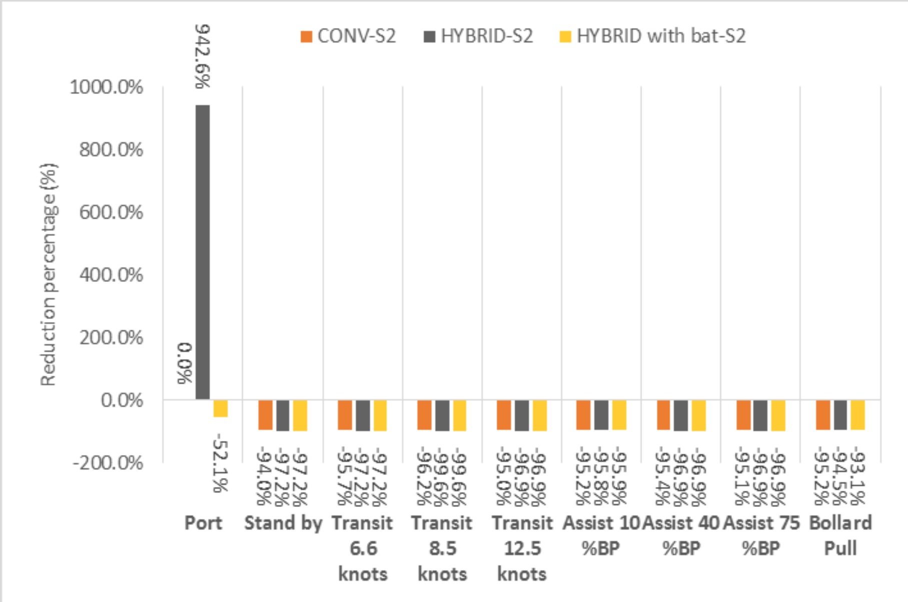


Figure 6-8: PM reduction (%) results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile compared against the baseline case

As can be observed PM are almost non-existent for all alternative in all operating modes, attributed to the high emission reduction potential of LBSI engines running on LNG compared to 4*CI compression ignition engines running on MGO. The situation is different only in harbour mode. It is observed that there is a net increase in PM emissions for HYBRID-S2 alternative, attributed to the low loading of the bigger auxiliary engine, resulting in higher specific emission factor for NO_x in comparison to the conventional case. Moreover, there is no gain for the conventional alternative, due to the same loading condition as the baseline case. Lastly, a significant reduction is accomplished for the hybrid with batteries version. This reduction originates from the better loading condition of the auxiliary generator, which is operating only when it is charging the battery, thus the power demand to satisfy is the combined hoteling needs and battery charge power demand. It is stressed, that in harbour mode, the alternatives cannot exploit the advantages of an alternative fuel's emission reduction potential, since it has been assumed that they still operate on auxiliary engines running on MGO.

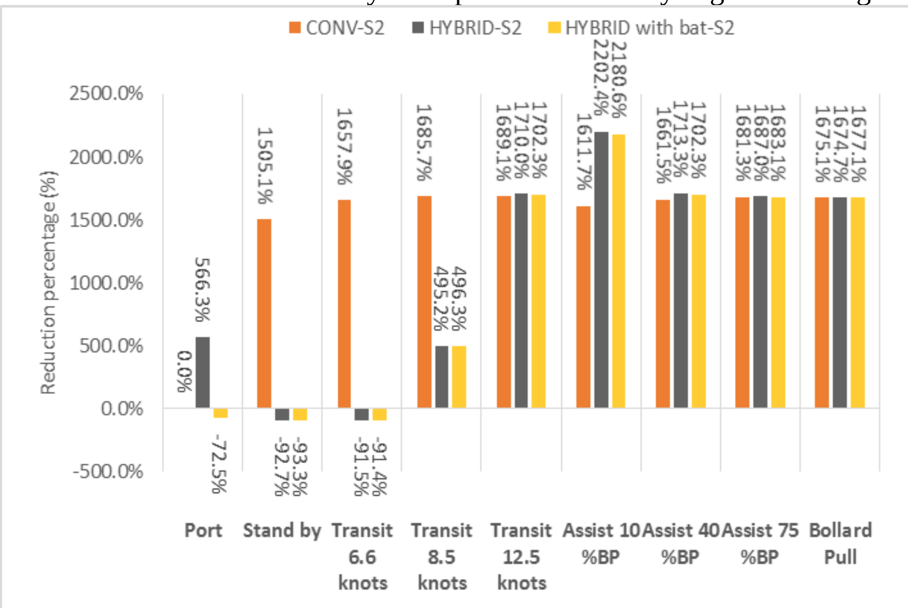


Figure 6-9: HC reduction (%) results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile compared against the baseline case

Based on the emission comparison results indicated in Figure 6-9 it is evident that HC emissions exhibit an increase for all alternatives running on LNG, as anticipated for the majority of operating modes. This is attributed to the negative emission reduction potential of LBSI engines running on LNG compared to 4*CI engines running on MGO. The situation is somehow different for harbour, standby and transit 6.6 knots. Particularly, for harbour mode CONV-S2 shows no difference (0%), Hybrid-S2 results in an increase of 566%, and Hybrid who bat-S2 shows a decrease of 72.5%, which is explained similarly to the PM trend. Particularly for standby and transit 6.6 knots results indicate a decrease in HC emissions for the Hybrid options, which is attributed to the main engines remaining off in comparison to the baseline case. There is a minor difference in reduction potential between the hybrid versions which is attributed to the different distribution efficiency.

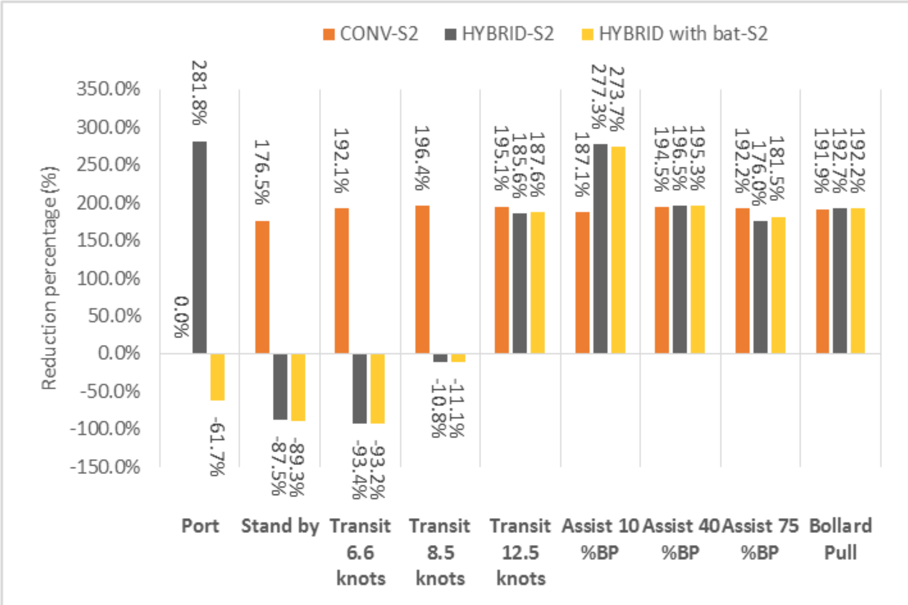


Figure 6-10: CO reduction (%) results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile compared against the baseline case

As can be observed CO emissions are illustrating the same trend as HC emissions. CO emissions similarly to HC emissions exhibit an increase for all alternatives running on LNG, as anticipated for the same operating modes, apart from transit 8.5 knots. The reason is again the negative emission reduction potential of LBSI engines running on LNG compared to 4*CI engines running on MGO. The trend is explained as in the HC case. Particularly, for the transit 8.5 knots, in which hybrid versions exhibit a small decrease in CO emissions, it is attributed in the fact that only one engine is running, instead of three main engines and one auxiliary engine, as in the baseline case. The minor difference in reduction potential between the hybrid versions is attributed to the different distribution efficiency.

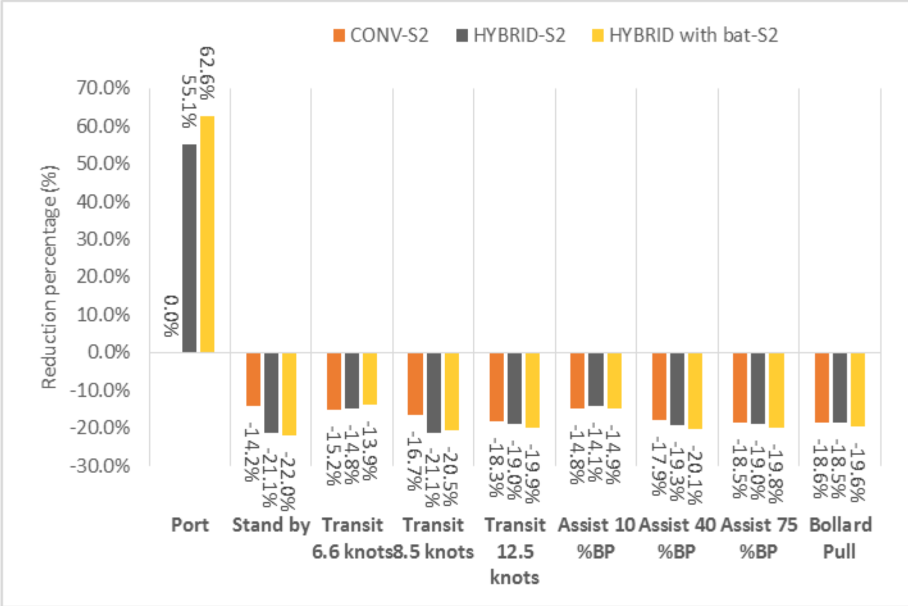


Figure 6-11: CO_2 reduction (%) results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile compared against the baseline case

Carbon emissions are associated with the carbon content of the fuel and the fuel consumption per mode of operation. For the same fuel-variants based on different propulsion configuration architectures the decisive parameter is the fuel efficiency, given the fact that the energy content of the fuel remains the same. Therefore, the power utilization charts are indicative of the expected fuel efficiency gains per mode of operation. It is noted that for port mode there is an increase in CO_2 emissions for hybrid alternatives, attributed to the size of the auxiliary engine and the higher fuel consumption, due to operation in an inefficient point of the specific fuel consumption curve. The duration that the tugboat is operating in harbour mode is under this scenario substantially higher than the rest of the modes, which justifies the small total net CO_2 emission reduction result. This, prompts for the consideration of shutting down the auxiliary engines, by using shore-power, which will have as an impact the negation of the negative result for alternatives in the harbour mode, and thus the emission reduction benefits on the rest of the operating modes could be exploited, leading to considerably higher total net CO_2 emission reduction. It is stressed that if the differences are investigated for different fuels under the same propulsion topology, then the energy content of the fuel would also be a decisive parameter.

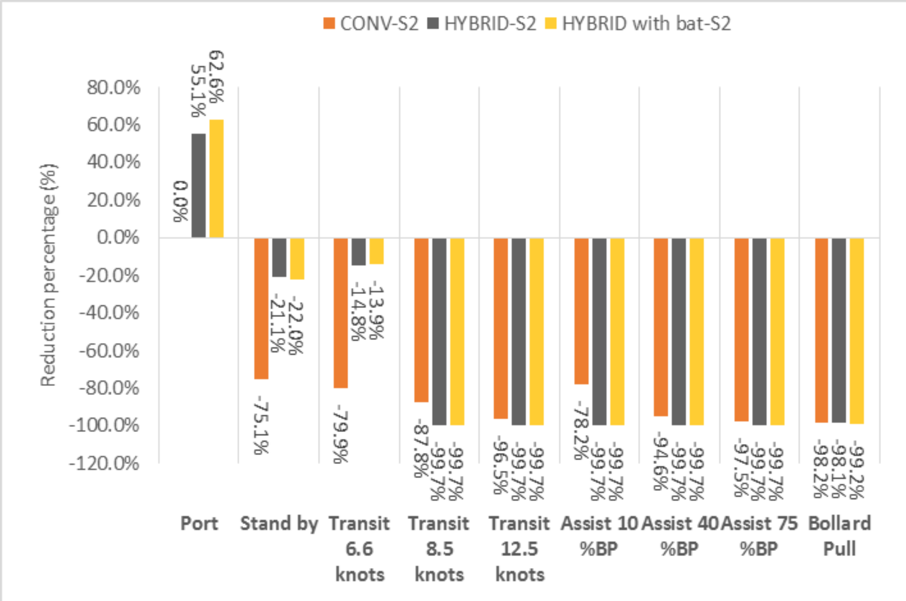


Figure 6-12: SOx reduction (%) results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile compared against the baseline case

As can be observed SO_x emissions are almost eliminated in transit and assist modes for hybrid versions, because auxiliary engines running on MGO are off and only LBSI engines used as main engines are on, combusting solely LNG fuel, which contains only minimal sulphur content. Moreover, for the CONV-S2 case, in standby mode the reductions are attributed in the fact that main engines are combusting LNG instead of MGO whereas for the hybrid cases in the fact that main engines are kept off and only the auxiliary engine is providing power. Lastly, in harbour mode the differences are explained as before, similar to the CO_2 case.

6.1.1.2.3 Cost-effectiveness

In this section the results based on cost-effectiveness are presented and analyzed both from a ship-owner and a societal perspective. Again, also for the cost-effectiveness decision criterion, the results, summarized in Table E-17, indicate CONV-S2 as the preferred solution. Its GRA grade is considerably higher than the rest of the candidates. Similarly, to the environmental performance decision criterion none of the candidates is eliminated; thus all 18 candidates will appear on the table of results. Exploring the reasoning behind the ranking order of the alternatives can be done by studying the comparison results of the alternatives against the baseline case, in terms of cost-effectiveness per exhaust air pollutant. The results for all 18 options from a ship-owner perspective are summarized in Table E-18. Below in Table 6-3, part of the results, for the top three ranked alternatives are illustrated.

Table 6-3: Part of the cost-effectiveness comparison results per exhaust air pollutant for case study 1 (terminal duty) without the inclusion of external costs, using the baseline case as reference

Configurations	CE-NO_x	CE-HC	CE-PM	CE-CO	CE-CO_2	CE-SO_x
CONV-S2	13.1	#N/A	0.9	#N/A	207.6	0.7
Diesel Electric-Base Case	1.7	0.0	0.3	0.6	#N/A	#N/A
HYBRID with bat-Base Case	0.2	0.1	0.1	0.2	6.0	0.0

The selection of the most preferable alternative in terms of cost-effectiveness from a ship-owner perspective is based on the maximum attained cost-effectiveness. A positive index shows the kg emissions reduction per $ spent, while a negative index shows the kilos emissions reduction per $ saved, which signifies a “win-win” situation. Lastly a #NA value means that the environment would suffer an additional emission output burden in kilos per USD ($) invested in that particular candidate propulsion configuration under examination. This means that a ship-owner would opt for a solution, which exhibits a “win-win” situation for the majority of exhaust air pollutants. In order to account for the “win-win” situations, the model formulation process of GRA at step 1 is taking into consideration that decision rule for generating the reference data series x0. It is evident from Table E-18 that CONV-S2 scores better in almost all exhaust air pollutants, apart from HC and CO, where there is an increase on emission output. In addition, there is no case which yields a negative cost-effectiveness value. This means that from a ship-owner perspective if there are no other benefits considered, but a decision is made purely on cost-related terms, there is no business case for investing on any option; thus, the results are interpreted similar to the economic performance results.

Usually it is not the case to achieve benefits both in environmental and economic performance. This case study is representative on this sense; no option exhibits a positive $NPV_{financial}$ under the assumed financial parameters. Moreover, as already understood from the environmental analysis, alternatives are normally effective in reducing some of the exhaust air pollutants, not all. A port-authority on the other hand might be interested in the decrease of certain exhaust air pollutants, if not all major pollutants. For motivating the adoption of emission abatement strategies targeting air pollutants of interest, a port-authority might decide to allocate subsidies towards the most cost-effective ones. To this end, it gets interesting to explore the cost-effectiveness of the alternative options on the reduction of each individual exhaust air pollutant from a port-authority perspective. The results can then be used from the ship-owner by presenting them to the relevant port-authority, with the purpose of contesting for funding.

For doing such an analysis from a port-authority perspective, the external costs of air pollution have to be included in the financial calculations in the comparative TCO analysis. It is understood that the societal benefits of air pollution reduction are not accounted in a financial return on investment, hence cannot alter the financial feasibility of an option on the basis of a ship-owner perspective. However, with a system that internalizes the external costs, a ship-owner might find motive to invest on cleaner (less-polluting) tugboats, because an economic reward (subsidy) is obtained. The port-authority will conduct an analysis on other effective emission reduction strategies, that when applied to the existing tug fleet, targeted exhaust air pollutants will be reduced. Such an analysis would consider a fleet of tugs, comprising of a reference tugboat, based on which the benefits of strategies are compared. The reference tugboat could be one based on a conventional drivetrain fitted with 4-stroke high-speed compression ignition engines running on MGO, without any after-treatment systems. It is clear therefore that the derived cost-effectiveness values from the decision-support tool could be valuable and can be compared against the marginal abatement cost (MAC) estimated by the port-authorities. In case the CE values of the respective exhaust air pollutants of interest for an alternative tugboat are below the MAC values, then that alternative will be eligible for funding.

Including the external costs, the results based on economic performance are modified, as presented in Table E-19. The results, under the assumed financial parameters, indicate 10 options as viable candidates. However, only the first two result in positive NPV_{social} value. CONV-S2 is again the preferable one, as expected. The reasoning behind the elimination of the rest of the alternatives as well as the ranking order is the same as presented in economic performance section. It is stressed that the $NPV_{financial}$ remains the same for all candidates, as estimated in the economic performance section, since the same financial parameters have been assumed. Part of the societal cash flow evaluation metrics results for the first two options are summarized in Table 6-4.

Table 6-4: Part of the societal cash flow valuation metrics results for case study 1(terminal tug)

Societal cash flow metrics results	CONV-S2	CONV-S6
Net Investments	$677,148	$1,174,686
NPV_{social}	$303,073	$67,379
$NPV_{financial}$	$-148,675	$-460,962
$NPV_{external\ costs}$	$451,748	$528,341
Benefit/cost ratio	2.04	0.45
Benefit/investment ratio	0.15	0.06

It is stressed that the environmental performance is not changing with the inclusion of external costs. The results of cost-effectiveness are different though, based on the NPV_{social} instead of the $NPV_{financial}$, as presented in Table E-20. The results indicate as undisputable favorite CONV-S6, based on 4-stroke compression ignition engines running on DME, with a GRA grade equal to 1 (maximum possible attained grade). The reasoning behind this is revealed by studying the comparison results of the alternatives against the baseline case, in terms of cost-effectiveness per exhaust air pollutant. The results for all 18 options are summarized in Table E-21. Below in Table 6-5, part of the results, for the top three ranked alternatives are illustrated.

Table 6-5: Part of the cost-effectiveness comparison results per exhaust air pollutant for case study 1 (terminal duty) with the inclusion of external costs, using the baseline case as reference

Configurations	CE-NO_x	CE-HC	CE-PM	CE-CO	CE-CO_2	CE-SO_x
CONV-S6	11.56	0.00	2.10	0.00	221.82	1.52
CONV-S2	6.41	#N/A	0.45	#N/A	101.85	0.34
HYBRID-S6	-1.26	-0.01	-0.18	-0.15	-10.75	-0.14

It is important to note that there is a difference on the sign between the society and the ship-owner CE values; thus, also in their interpretation. The selection of the most preferable alternative in terms of societal cost-effectiveness is based again on the maximum attained cost-effectiveness. In this case though a positive index shows the kg emissions reduction per $ saved for society, signifying a “win-win” situation, while a negative index shows the kilos emissions reduction per $ spent from society (social costs). An #NA value means that the environment would either suffer an additional emission output burden in kilos per USD($) invested in that particular candidate propulsion configuration under examination or that the $NPV_{external\ costs}$ results in negative value, meaning that there are monetary losses for the particular alternative under consideration compared to the baseline case. Again, a “win-win” situation for the majority of exhaust air pollutants is the preferable solution for both ends. It is evident from Table E-21 that CONV-S2 scores better in almost all exhaust air pollutants, apart from HC and CO, where there is an increase on emission output. The rest of the alternatives result in negative cost-effectiveness values or #NA. Particularly, for CONV-S4, which results in #NA value for all exhaust air pollutants, can be explained because of its negative $NPV_{external\ cost}$ value.

This means that from a societal perspective if there are no other benefits considered, such as innovation promotion, noise reduction, etc., but a decision is made purely on the cost benefits of air pollution reduction, then it seems reasonable for a port-authority to promote the construction of a new tugboat, based on 4*CI main engines running on DME. However, the available amount for funding is expected to be limited. Not only that but also for a ship-owner to come forward asking for funding, the subsidy should be such that it turns the $NPV_{financial}$ positive (at least break-even). Usually, the attained IRR will have to reach a set target. It is understood that a benefit/cost ratio must be introduced which indicates the efficiency of funding from a port-authority perspective. The following two indicators are used for this reason,

$$Benefit/_{Costs} = \frac{NPV_{society}}{-NPV_{financial}} \quad (64)$$

Which indicates the monetary benefits attained per $ invested including the total lifecycle financial effects of the investment (TCO).

$$Benefit/_{Investment} = \frac{NPV_{society}}{Net\ Investments} \quad (65)$$

Which indicates the monetary benefits attained per $ invested including only the expected investment costs (cash outflows) paid by the ship-owner.

The port-authority can then judge, by comparing the results of the alternatives based on these two indicators, which option is the most preferable to fund. The option with the higher ratios will be the preferable choice. The results of those two indicators for the viable options are summarized in Table 6-4. It is evident that CONV-S2 scores better on both indicators. The last thing would be for the ship-owner to include the subsidy amount on the comparative TCO analysis and review the economic performance results. If the $NPV_{financial}$ is positive and the IRR is above the set target, then it means that there is a business case for building such a Rotortug.

It is noted that the dispatch of such subsidies are not taken into consideration in this thesis. There is a variety of subsidy options, which can be allocated; either as up-front investment subsidy, or discount in harbour dues for a specific time span, or exemption from paying taxes, if a passive taxation system on specific exhaust air pollutants is implemented, etc. Not only, that but the funding can be spread over a time span as cash inflows or allocated in total in year 0. Additionally, it has to be considered under the complete financing scheme (own equity and debt capital) which is also not considered in this thesis. It is obvious that the financing scheme will further implicate the results on economic performance.

6.1.2 Case Study 2 – Harbour tug

The focus of this case study is set in the effect of the intended area of operation and the expected year of operation on the need for installation of after-treatment systems on alternatives for complying with the expected emission standards. The impact of these two parameters will be attempted to be explored by analyzing the effect on a most-preferable option with respect to $NPV_{financial}$ and the attained emission performance. Moreover, it will be illustrated that there are occasions that certain alternatives are predicted not to comply with the expected regulations. Lastly, the results on cost-effectiveness will not be deliberated for this case study. Cost-effectiveness has been shown to be particularly useful for a ship-owner, when competing for funding. This would be in conjunction with internalizing external costs of air pollution in the comparative TCO analysis. However, when the baseline Rotortug is one with the addition of after-treatment systems, like in this case study, the basis on which the cost-effectiveness is compared against the MAC will not be proper. A port-authority would compare strategies or solutions against a Business-As-Usual (BAU) scenario, for which the tugboats already in operation would be diesel-direct drivetrain without after-treatment systems. For this reason, cost-effectiveness from a ship-owner perspective is considered to have been covered on the previous section.

6.1.2.1 Description of the case study

Kotug is interested to investigate which ART-8032 driveline variant could constitute a viable solution in 2020 for building up the fleet of ART-8032, which will operate in rotation undertaking the towage assistance services in the port of Rotterdam and in the port of New York and New Jersey. Newbuildings are supposed to have a lifetime of 25 years. The annual operating hours of such a Rotortug is estimated to be 4320 hours/year in total, based on 12 hours per day for 360 days per year.

The utilization rate is summarized in Table E-22 and the resulting operational profile, including the power demand, as established by the “Duty cycle” block is illustrated in Figure 6-13.

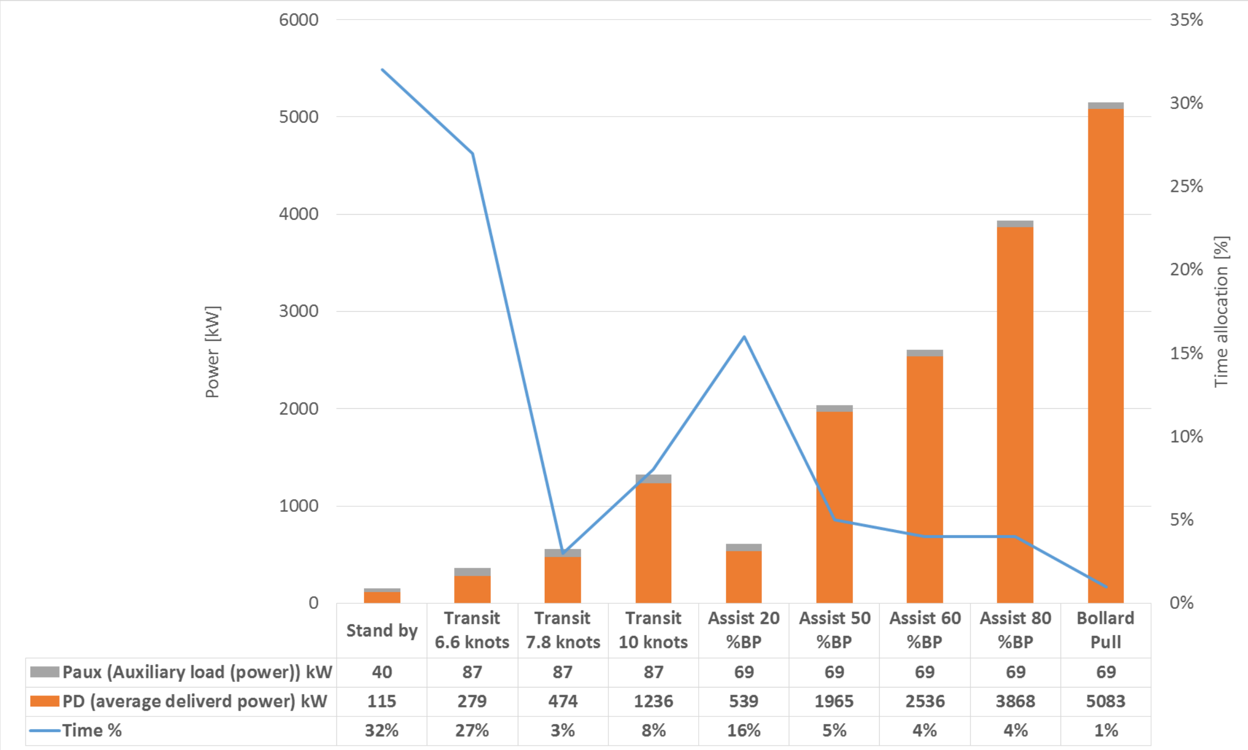


Figure 6-13: Anticipated operational profile of harbour Rotortug envisioned for operation in Rotterdam, the Netherlands (4320 annual operating hours)

At 2020 North Sea will still not have been designated ECA, however US coastlines have already been designated ECA since 2014. Cold ironing is not expected to be a requirement at none of these two ports, even though the infrastructure is already in place. Bunkering infrastructure for all candidate fuels is assumed to be in place. External costs are not taken into consideration. Furthermore, a central “MGO differentials” price scenario is assumed. Lastly, with respect to the financial parameters, the economic period is assumed to be 25 years, the discount rate 8% and the inflation rate 2%. The model input variables are summarized in Table 6-6.

Table 6-6: Input variables for 2nd case study (harbour tug)

Region of Operation	Western Europe	North America
Country of Operation	The Netherlands	United States
Port of Operation	Rotterdam	New York &New Jersey
Year of Delivery	2020	2020
ECA designation	No (North Sea)	Yes (North America)
Cold ironing	No	No
External costs	No	No
Bunkering availability (LNG/Methanol/Biodiesel/DME)	Yes for all	Yes for all
Fuel price scenario	Central	Central
Price scenarios (Urea/Shore power/CO_2 external costs)	Central/NA/NA	Central/NA/NA
Period of economic analysis	25 years	25 years
Discount rate	8%	8%
Inflation rate	2%	2%

6.1.2.2 Analysis of results

It is interesting to explore the effect of more stringent regional requirements on the selection of suitable solutions. This will be investigated for a newly-built Rotortug, with a fixed year of delivery, constructed to comply with EU and EPA emission standards. If all parameters are kept the same, apart from the intended area of operation, then the results for the same alternatives will differentiate for all the decision-criteria.

6.1.2.2.1 Harbour duty in Rotterdam port

Regarding operation in the harbour of Rotterdam, a Rotortug will have to comply with MARPOL Annex VI Convention emission standards and the EU Stage V regulations. The baseline ART-8032, complying with these standards, would be one based on a diesel-direct drivetrain with 4-stroke high-speed compression ignition engines running on MGO, with a combination of after-treatment systems (SCRs/DPFs/OxiCat) installed, as summarized in Table 6-7.

Table 6-7: Summary of after-treatment system fitted per engine for the baseline case (harbour duty in Rotterdam port)

Equipment	SCR	DPF	OxiCat
Main Engine 1	yes	yes	yes
Main Engine 2	yes	yes	yes
Main Engine 3	yes	yes	yes
Genset 1	yes	no	no
Genset 2	yes	no	no
Harbour Genset	no	no	no

The economic performance results based solely on $NPV_{financial}$, summarized in Table E-23, indicate as the preferable solution HYBRID-S2, a hybrid based on an AC topology propulsion configuration with LBSI main engines running on LNG. The GRA grade of this solution is the highest amongst the viable candidates. The 2nd alternative, namely CONV-S2 has a moderate difference in comparison to the 1st. The scoring for the rest of the candidates is well below the first two options. It is highlighted that 9 out of the total 18 alternatives are deemed unsuitable and are not illustrated in the table of results. Attention though should be paid in the fact that the exhibited alternatives based on LPDF engines running on LNG are not compliant with the EU legislation regime, thus cannot be considered as viable candidates. Therefore, the results reveal that only 6 out of 14 candidates (excluding LPDF-variants) can be considered compliant with the emission regulations and better than the baseline Rotortug, based solely on the $NPV_{financial}$ metric. All other options yield negative $NPV_{financial}$ values and thus no profits are anticipated, under the assumed financial parameters.

It is evident from the environmental performance results, summarized in Table E-35, that the preferred solution would be the HYBRID with bat-S6, different than the alternative based on economic performance decision criterion. The GRA grade of this solution is the highest amongst the viable candidates, constituting this option as the most appealing.

From a technical perspective, with regard to after-treatment systems, it is noted that all alternatives are fitted with DPFs. This is mandated because of the introduction of an additional limit of $1x10^{12}$ #/kWh on the number of particles for all engines above 300kW, irrespectively of the combustion fuel or their type (constant/variable-speed or propulsion/auxiliary use) on EU Stage V emission standards. As explained in section 3.5.2, the only effective way to attain the set PN limit would be by installing a DPF. Moreover, a SCR is installed on all alternatives that surpass the NO_x limit while an OxiCat is selected if either the CO or the HC limit is surpassed. It is stressed that SCRs are installed on auxiliary engines running on MGO in order to attain the stricter EU NO_x limit. Particularly for LPDF main engines running on LNG, the HC limit cannot be attained even with the installation of oxidation catalysts. This is due to the ineffectiveness of the oxidation catalysts to capture the methane slip, originating from those engines, as explained in section 3.5.3.

Since engines running on alternative fuels has been assumed to become more effective on reducing emissions throughout the timespan of this thesis, LPDF engines are expected to become more effective on limiting the methane slip. It is interesting to explore on which year they would be considered capable of meeting the EU Stage V requirements. It is envisaged that a Rotortug employed with such engines would be compliant after 2024.

6.1.2.2.2 Harbour duty in New York and New Jersey port

With regard to operation in the harbour of New York and New Jersey a Rotortug will have to comply with MARPOL Annex VI Convention emission standards and the EPA regulations. The baseline ART-8032, complying with these standards, would be one based on a diesel-direct drivetrain with 4-stroke high-speed compression ignition engines running on ULSD, with a combination of after-treatment systems (SCRs/DPFs/OxiCat) installed, as summarized in Table 6-8. Hence, it would be the same as the one complying with the EU regulations. It has to be highlighted that the combusting fuel differs, because of the imposed EPA requirement on bunkering only with 15 ppm marine diesel fuel oils in the US territory.

Table 6-8: Summary of after-treatment system fitted per engine for the baseline case (harbour duty in New York port)

Equipment	SCR	DPF	OxiCat
Main Engine 1	yes	yes	yes
Main Engine 2	yes	yes	yes
Main Engine 3	yes	yes	yes
Genset 1	yes	no	no
Genset 2	yes	no	no
Harbour Genset	no	no	no

To start with, it is evident from the economic performance results based solely on $NPV_{financial}$, summarized in Table E-29, that now all 16 viable alternatives are compliant both with the IMO and EPA emission regulations. With relation to the EU regulations, HYBRID-S2 is not anymore, the preferable solution. In contrast, CONV-S2 is now ranked first. Its GRA grade is the highest amongst the viable candidates. It is highlighted that in this case only 2 out of the total 18 alternatives are deemed unsuitable and are not illustrated in the table of results.

As can be observed from the environmental performance results, summarized in Table E-40, the same option (HYBRID with bat-S6), as for the EU regulations case, is also considered preferable in terms of environmental performance for the EPA regulations case. Its GRA grade is again the highest amongst the viable candidates, constituting this option as the most appealing.

From a technical perspective, with respect to the after-treatment systems, it is observed that SCRs are needed for all alternatives. Nonetheless, this is not attributed to EPA emission standards, rather to the IMO Tier III standard, which imposes to all prime movers with a power output bigger than 130kW to be fitted with a SCR in order to attain the strict NO_x limit. If the tugboat had to comply only with EPA regulations, then the prime movers with a power output below 600 kW would need to comply with EPA Tier 3 requirements instead of EPA Tier 4, imposing a combined emission limit on both NO_x and HC, instead of regulating both independently, as in the EPA Tier 4 standards. This would allow the auxiliary engines to attain the imposed emission standard and avoid the installation of costly SCRs. Another observation made from Table E-40 is that all alternatives are fitted with an oxidation catalyst apart from the Biodiesel variants. EPA standards are imposing a limit only to the NMHC emissions, while EU standards to the THC. Prime movers running on alternative fuels, used as main engines are not capable to attain the strict NMHC limit without the addition of an oxidation catalyst.

For this particular case study, although the baseline case is the same and assuming all things equal apart from the intended area of operation, it is evident that with differing regulations in place the single-best option does not remain the same in terms of economic performance, while it remains the same in terms of environmental performance. It is reasonable to assume that in other cases, when comparing alternatives with different after-treatment systems fitted against a different baseline case, the comparison results are expected to differ for both decision criteria.

The economic and environmental results for the EU case top ranked alternatives, compared against the respective results for the EPA case is also interesting to be discussed. On the one hand, regarding economic performance, even though the HYBRID-S2 results in higher GRA grade for the EU case, the cash flow metric results, summarized in Table 6-9, indicate that it is more financially attractive when envisaged for use within US territory, in contrast to operation within European Union territory. The difference on the economic results for the EPA case, is attributed primarily in the lower capital expenses and secondary in the higher maintenance cash inflows, because of the different combination of installed after-treatment systems.

Table 6-9: Comparison between financial valuation metrics' results for case study 2 (harbour tug) for compliance with EU and EPA regulations

Cash flow metrics results	HYBRID-S2 (EU)	HYBRID-S2 (EPA)	Comparison
Net Investments	$1,685,289	$1,534,017	-8.98%
NPV	$1,452,145	$1,604,156	+10.47%
IRR	21.99%	26.08%	+18.60%
Payback period	4.1	3.7	-9.76%

On the other hand, regarding environmental performance, the emission output comparison results, summarized in Table 6-10, indicate that the equally-scored single-best option (Hybrid with bat-S6) pollutes less for three (3) of the exhaust air pollutants (PM,HC,CO) when designed to comply with the EU emission standards instead of EPA. Moreover, for two of the exhaust air pollutants the environmental performance remains the same (CO_2 and NO_x), while only SO_x emission output is inferior in comparison to a tug designed according to EPA requirements. The higher emission output for HC, CO and PM for the EPA case is attributed solely in the absence of DPFs, in contrast to the EU case, where DPFs are added for all prime movers above 300 kW. It is reminded that a DPF achieves emission reduction for these three exhaust air pollutants. Lastly, with respect to SO_x difference, this is attributed purely on the lower sulphur content of ULSD, in comparison to MGO.

Table 6-10: Comparison between emission output results per exhaust air pollutant for case study 2 (harbour tug) for compliance with EU and EPA regulations

Overall emissions per year in kilos	HYBRID with bat-S6 (EU)	HYBRID with bat-S6 (EPA)	Comparison
NO_x	1727	1727	0%
HC	204	240	+17.65%
PM	19	36	+89.47%
CO	765	883	+15.42%
CO_2	2371993	2371993	0%
SO_x	401	6	-98.50%

To sum up, it is revealed that an option obtaining a higher score (GRA grade) for a certain area of operation in contrast to another does not necessarily reflect also superior performance, either economic or environmental. It is therefore concluded that a preference for a certain alternative, based on the attained GRA scoring, should be judged only for the envisioned operation. It is not within the objectives of the decision-support tool to indicate the suitability of a particular drivetrain solution under different circumstances, rather indicate the preferable solution for specific conditions. However, it is imperative for a decision-maker to comprehend which are the decisive factors which shape the results. Not only that but the decision-maker should also understand which are the sensitive parameters that when modified can constitute a specific solution more attractive, depending on the investigated decision criterion. This is realized by conducting a sensitivity analysis; the results are presented in section 6.2.

6.2 Sensitivity analysis

In this section the impact of decisive and sensitive parameters in the variation of the results for all three decision criteria is explored. It is not the point of a sensitivity analysis to explore the effects of altering each and every parameter, rather examine the most important taking into consideration the limitations imposed by the assumptions made. With that in mind, the effect of changing technical parameters is not part of the sensitivity analysis. For instance, it is obvious that if the emission reduction potential of alternative fuels or the machinery equipment acquisition cost is changed this will lead to different environmental and economic performance results respectively. The effect of varying technical parameters was part of the verification of results and the robustness of the software tool.

For a specific area and year of operation, a baseline case Rotortug is established for complying with the expected emission standards. The baseline Rotortug would either need to use shore power when docked or not, provided the necessity for cold ironing, imposed as a port requirement. Moreover, the decision-maker chooses whether will account for the external costs in the incremental TCO analysis. Keeping those parameters unaltered, three are the decisive factors which directly affect the outcome of the analysis; firstly the mission profile, secondly the price scenarios and thirdly the financial parameters (tug lifetime expectancy, discount rate and inflation rate). The impact of these parameters in the variation of results is explored by conducting a sensitivity analysis using the first case study; a tug envisioned for terminal duty. Specifically, the sensitivity analysis is performed by varying the aforementioned factors and investigating the effect on either the $NPV_{financial}$, the IRR or the GRA grade. The complete sensitivity analysis can be found in Appendix F. The results are summarized below.

Mission profile - High Sensitivity

It was found that the mission profile is a decisive parameter for all three decision criteria. The results suggest that there is a linear relationship between the $NPV_{financial}$ and the annual operating hours.

Fuel price scenario - Moderate Sensitivity

The sensitivity to fuel price scenario was explored by changing the price spread between LNG and MGO based on the initial mission profile of 1440 hours of operation annually. It was found that the fuel price scenario influences both the economic and cost-effectiveness results but does not have any effect on environmental performance results. Another finding emerged from the analysis was that there seems to be a linear relationship between $NPV_{financial}$ and price spread.

Financial parameters – High Sensitivity

The investigation has shown that the financial parameters (investment horizon, discount rate, inflation rate) do not influence the environmental performance results but are highly affecting the results for the rest of the decision-criteria. Regarding the discount rate, the sensitivity analysis revealed that a decrease in the discount rate has a positive effect on the results, while an increase a worsening result. Also, the results suggest that the relationship between $NPV_{financial}$ and discount rate is non-linear, indicating that the discount rate has a greater effect on results than the fuel price difference. Regarding the inflation rate, the sensitivity analysis revealed that a decrease in inflation leads to both lower $NPV_{financial}$ and IRR, while an increase on higher $NPV_{financial}$ and IRR. The same was found to apply for investment horizon. Lastly, $NPV_{financial}$ seems to be a non-linear function of inflation rate, indicating that the inflation rate also has a great effect on the results, while there seems to be a linear relationship between $NPV_{financial}$ and investment horizon.

Finally, it is very important to highlight two points. First, that the preference order on the valuation metrics will determine the ranking order of the options and second, that in case the external costs are accounted in the incremental TCO analysis, then the results will also be sensitive to the external cost factors prices.

6.3 Conclusion

In this chapter it was attempted to establish the decisive factors which influence the output of the decision-support tool. Two case studies were presented with the purpose of validating the model. The results were analyzed for each one of the three decision-criteria, explaining the reasoning behind the ranking order of candidates. It became clear that the operational profile and the intended area of operation together with the envisioned year of delivery of the newbuilding Rotortug are decisive factors, dictating the ranking order of the alternative options for all three decision criteria. Particularly, for the latter, which determines the applicable emission regulation regime, it was clarified that it directly correlates with the determination of both the baseline propulsion configuration and the rest of the alternatives, with respect to the needed after-treatment systems in order to comply with the imposed emission standards. The effect of complying with dissimilar regulations on a most-preferable option with respect to economic and environmental performance was explored, illustrating that the legislation regime has a catalytic impact on the performance results.

Regarding economic performance, it was shown that it is linked with the up-front investment costs and the anticipated comparative lifecycle savings. The up-front investment costs differentiate between alternatives depending on the propulsion configuration (machinery equipment) and the combustion fuel (tank acquisition cost and after-treatment systems fitted). For an alternative to become financially attractive the combined savings should outweigh the net investments over the investment horizon. Regarding environmental performance it was illustrated that the net emission benefits for an alternative have to be examined under the entire mission profile spectrum. The benefits are linked with the mission profile and the power management strategy employed, affecting the emission reduction potential per exhaust air pollutant, depending on the individual operating modes. The maximum benefits can be expected only at those operating modes, for which prime movers running on alternative fuels are switched on, in order to exploit the emission reduction potential of alternative fuels. Lastly, regarding cost-effectiveness, the analysis was conducted for an illustrative case study both from a ship-owner and a society perspective. The difference between the two perspectives lies in the internalization of external costs in the comparative TCO analysis. It was illustrated that by including the external costs, the decision-support tool provides to a ship-owner a methodology framework for competing for funding.

Knowing the impact of sensitive parameters in the variation of the results, a decision-maker can realize the circumstances which would allow pursuing of a specific solution. For this reason, a sensitivity analysis was conducted. It was derived that the price scenarios and the financial parameters (tug lifetime expectancy, discount rate and inflation rate) are crucial sensitive parameters affecting the economic performance and the cost-effectiveness. However, have no effect on the environmental performance. The impact of varying the aforementioned factors was explored by investigating the effect on $NPV_{financial}$. It was concluded that there is a linear relationship between $NPV_{financial}$ and price spread, as well as between $NPV_{financial}$ and investment horizon, while the relationship between NPV and discount rate, as well as between NPV and inflation rate are non-linear, indicating that the discount and inflation rates have a greater effect on results. The importance of IRR, as an indicator of the required discount rate to turn an investment option profitable was clarified. A decision-maker can bracket the fiscal risk by conducting the analysis with varying certain financial parameters and establishing the range of critical financial valuation metrics, like the NPV, IRR and Payback period. It is stressed, that the sensitive parameters are expected to vary simultaneously throughout the investment horizon in reality, and thus the joint influence should be taken into consideration. In this way the worst and the best-case results can provide context to the decision maker. Of course, certain constraints, like the technical parameters are assumed constant, therefore the outcome of the decision-support tool is subject to the limitations imposed by the assumptions made. In the next chapter general conclusions are drawn and recommendations for future improvements are provided.

7 Conclusions

This chapter will examine

a) General conclusions that can be drawn from the conducted research
b) Whether the main objective of this thesis was accomplished
c) Possibilities for expansion of the decision-support tool

7.1 General conclusions

The main objective of this study was the development of a decision-support tool which would facilitate the selection process between alternative prime mover combinations, when installed on different propulsion configurations, with the goal to comply with anticipated emission regulations at ports, in which future Rotortugs are expected to operate, whilst considering technical challenges, environmental performance and economic returns.

To develop such a decision-support tool, a number of sub-objectives were established. Those are listed below:

1) Specify the marine related exhaust air pollutants originating from tugboats
2) Investigate the current and future emission regulations at the envisaged sea areas of operation
3) Determine the most promising prime mover combinations that would allow future Rotortugs to comply with the anticipated emission regulations
4) Determine the applied methodology of the decision-support tool
5) Develop and validate the decision-support tool

The goal of setting sub-objectives is to set the number of necessary steps to reach the final objective; the development of the decision-support tool.

The first step was to determine the marine related exhaust air emissions. Six exhaust air pollutants were identified as primary pollutants originating from the combustion of fuels in reciprocating engines. These exhaust air pollutants are categorized into two groups, fuel related, consisting of CO_2 and SO_x, and combustion process related emissions, consisting of NO_x, PM, HC and CO. Each group has a different emission output calculation method and because of that is of great importance.

The second step was the investigation of the current and future emission regulations at the envisaged areas of operation worldwide, according to Kotug's interest. Rotortugs, as harbour vessels, must comply with both international and local regulations. At an international level IMO MARPOL Annex VI Convention regulations apply. At a regional level the legislative regimes that were found to be worth investigating were the United States and the European Union regimes. It was concluded that there are no emission regulations for CO_2 in place that target tugboats. At an international level, with respect to harbour vessels the regulations are targeting only NO_x and SO_x emissions, while at a regional level all the exhaust air pollutants are targeted.

As Kotug's primary aim is to build future Rotortugs, which will comply with the imposed emission regulations in the near future, the third step was the investigation of emission reduction measures that would allow that. The focus had been set from the beginning, out of a variety of methods, at the contribution of prime movers running on alternative fuels in the reduction of exhaust gas emissions. The research revealed LNG, Methanol, DME and Biodiesel as the most promising alternative fuels. LNG and Methanol, were associated with gas-burning engines. Specifically, two types of gas-burning engines were identified as suitable for use in harbour tugboats; Lean-Burn Spark-Ignited engines

(LBSI) and Low Pressure Dual-Fuel engines (LPDF). LNG was matched to both engine concepts while Methanol only to LPDF. On the other hand, Biodiesel and DME were matched with a conventional 4-stroke medium speed compression engine. Depending on the engine technology and the associated fuel, different emission performance is expected. However, the net environmental benefit of the candidate prime mover combinations, can be assessed only in the context of the propulsion configuration line-up. Thus, it was imperative to investigate the potential efficiency improvements in terms of fuel consumption and emission reduction of alternative propulsion configurations. It was concluded that the final outcome of a comparison between power plant configurations on fuel consumption and emission savings will be dictated both by the transmission losses for each operating mode, when examined throughout the complete mission profile but also by the power management strategy employed. Three drivetrains were decided to be investigated with the intention of reducing the ecological footprint of the future Rotortug; a diesel-electric and two hybrid topologies, one with batteries and one without. The environmental performance is assessed by accounting only the tank-to-propeller emission output. In addition, it was concluded that after-treatment systems are necessary to be installed for attaining the imposed emission standards. In particular, three technologies were identified as suitable; SCR, DPF and OxiCat.

Since Kotug already operates a fleet of diesel-direct Rotortugs, employing 4-stroke high speed compression ignition engines running on MGO it was decided that such a solution complemented by proper after-treatment systems, should be considered the baseline case in order to satisfy the emission regulations. It was decided that it would be meaningful for all other options to be compared against that baseline case. In total 18 options are considered in the decision-support tool, which are compared against the baseline case. The fourth step was to establish an appropriate methodology that would allow the ship-owner to select the most preferable option amongst the competing alternatives, which comply with the anticipated emission regulation in the envisaged area of operation. To this end, three decision criteria were considered; economic performance, environmental performance and cost-effectiveness. The decision framework was based on a techno-economic evaluation. With respect to the economic performance, a partial TCO analysis comprising of the costs that differentiate between the alternatives and the baseline case was deemed as the most suitable technique to be modeled. The evaluation is based on a multi-metric comparison approach, consisting of free and discounted cash flow valuation metrics. With respect to environmental performance, the decision is based on the comparison results of emission output per exhaust air pollutant between the alternatives and the baseline case. Lastly, with respect to cost-effectiveness, the evaluation is based on the attained cost-effectiveness of each air pollutant. It is stressed that the analysis can be conducted either from a ship-owner perspective or a societal perspective.

The last step was the validation of the developed decision-support tool. This process was conducted by implementing two case studies, one for terminal and one for harbour duty. The analysis of the results was complemented by a sensitivity analysis. The main aim behind the choice of those specific case studies was capturing the effect of the mission profile and the impact of anticipated emission regulations on compliance for the considered alternatives. It was clarified that both factors are decisive for the selection of the most-preferable alternative, depending on the examined decision-criterion. The results were found to be sensitive to the price scenarios and financial parameters (tug lifetime expectancy, discount rate and inflation rate.

It is concluded that the decision-support tool can assist ship-owners to make fact-based decisions, both in environmental and economic terms. With respect to environmental performance, the proposed tool offers valuable insight to the emission reduction potential of each alternative for each individual exhaust air pollutant. Regarding the economic performance, it allows the ship-owner to gain insight into the cost-related differences of alternative options and the importance of the financial parameters, before making an investment decision between those options. Lastly, an extra benefit for the ship-owner that arose from the decision-support tool is the possibility to use the results of the attained cost-effectiveness per exhaust air pollutant, in order to contest for funding from a port-authority. However, this benefit can be capitalized only when the baseline case would be one without after-treatment systems.

7.2 Discussion

The proposed decision-support tool was designed based on certain limitations, as exposed in section 1.3. As with each problem, by narrowing down the complexity through making certain assumptions, there is always the inherent risk of reaching a suboptimal decision. However, if the assumptions are logical and the limitations well framed the risk can be tolerable. To provide context to the selection process between alternative options, it is imperative to see the larger picture. A ship-owner willing to finance a newbuilding project will need to consider all associated costs. In this sense, both the CAPEX and OPEX are vital to be put into perspective in combination with the projected earnings from operation, as well as the financial plan. In the proposed model a partial TCO analysis is performed comprising of the costs that differentiate between the alternatives and the baseline case, while the financing and the expected annual income (cash inflows) generated by the operation of the tugboat are not considered at all. At first, a question concerning the validity of such an approach could arise.

If it is assumed that a ship-owner has already decided to invest money for the construction of a new tugboat, this will normally include taking a loan from a bank and a proportion sponsored by owner’s equity. Moreover, under this assumption it is obvious that funds that should be allocated towards the non-differing constituents cannot be avoided. The drive-train equipment capital expenses will be only a portion of the total capital expenses, approximately 20-30% of the total CAPEX. Therefore, the financing is not expected to differentiate substantially depending on the drivetrain variant. With respect to the expected income from a tugboat’s operation, after consultation with the management representatives it was understood that customers are not expected to be willing to pay a premium, depending on the drivetrain; except in extraordinary circumstances. Hence, it makes sense to omit the expected income. Therefore, the approach of investigating the effectiveness of allocating money on the items that indeed differentiate gains ground.

When examined under the economic lifetime of the tugboat it is easy to comprehend that annual operating costs have a larger effect than capital expenses. Over 20 years, which is a typical tug’s lifetime expectancy, it is understood that by choosing an alternative which has annually fewer operating expenses than a baseline case, will lead to significant total monetary savings, which could outweigh the additional required initial capital expenses. Of course, such life-cycle analysis results will be subject to the key uncertainties and the assumptions made. Capital expenses may be rather simple to accurately estimate but operational expenses are not. The prevailing circumstances have an impact on these costs, which is not easy to capture with any analysis. There is a great degree of speculation concerning fuel price development as well as the financial parameters variation. However, the risk is unavoidable when deciding to invest. Therefore, by providing a way to bracket the fiscal risk a decision-maker can move forward confidently. By conducting the sensitivity analysis, the effect of these parameters on the results was illustrated and the decision-maker can better understand the risk involved. For this reason, the decision-support tool is considered useful as a first step to help an owner get a certain direction on which option could be purposeful to be examined.

The next step would be conducting a feasibility study to determine if the project should be effectuated. Part of the feasibility study would be the technical feasibility of the modifications that the engine room has to undergo in order to accommodate the candidate prime movers, the changes in the design (hull shape) of the Rotortug and the compliance with safety standards, rules and class regulations. Part of the limitations of the study can therefore be addressed in a subsequent step. Other considerations not directly reflected in the economic analysis will also need to be addressed. Indicative considerations are the crew familiarization needed with respect to new technologies or different drivetrain layout and the simplicity of control for ensuring smooth tug operation.

Regarding the environmental performance, the decision-support tool can offer information regarding the emission impact of engine types and fuel options, which especially when deciding many years ahead in the future could be particularly valuable. For instance, the results can indicate certain variants which are less polluting. Nowadays the focus has started shifting more and more towards environmentally friendly solutions. If environmental performance becomes the decisive factor, then owning a tugboat which could prove less emitting than the competition could prove a significant advantage, especially if it is combined with a port’s strategy to lower its overall emission activity profile. In addition, by revealing the after-treatment systems needed to be installed for a particular alternative, in order to comply with the expected emission standards can timely prepare the technical department of the shipping-company to discuss with the shipyard the equipment arrangement, so as to facilitate minimum disruption to normal crew operations.

Lastly, another limitation worth discussing is the decision to conduct the analysis under a steady-state domain. Unfortunately, with such an approach the implications of transient behaviour are not possible to be calculated. This would have been possible only under a time-domain simulation; this is not possible with Microsoft Excel® which was the software used for developing the decision-support tool. A time-domain simulation, apart from the effects of short-term load variations on target vessel’s performance, would also enable to develop a robust energy management strategy, with the purpose of optimising each candidate’s performance. The contribution of batteries could then be fully exploited, allowing their use at other operating modes as well. In addition, the effect of substituting fixed speed with variable speed generator sets on energy efficiency and emission output would ideally be examined if a time-domain simulation had been selected. Even a variety of energy management algorithms could be developed for each candidate configuration and evaluate them against each other. Despite the aforementioned limitations, a simple analysis of average load cases depending on the anticipated operating modes throughout the year, is considered adequate for an initial direction concerning the preferred candidate to invest in. However, after reaching a conclusion, a simulation would be purposeful to be included in the feasibility analysis, considering also the optimum energy management strategy.

7.3 Recommendations

Recommendations can be made for further study and expansion of the decision-support tool.

- Simulation in time-domain in order to capture the transient performance of engines and exploit the benefits of energy storage methods.
- Further development of the energy management strategies.
- Alternative function of MG/s to be explored (like operating in boost mode), allowing to downsize main engines and thus lead to less acquisition costs, fuel consumption and maintenance costs.
- Fuel price development should be incorporated to capture the anticipated trend on fuel price projections.
- Actual costs and environmental performance factors should be obtained from manufacturers and incorporated inside the database.
- Account for the use of different propeller types and diameters.
- Develop a more comprehensive drivetrain-specific maintenance plan for calculating the total maintenance cost
- Account for the implications of fitting the additional drive-train machinery equipment inside the engine room
- Impact of weight in added resistance; Algorithm to be developed for estimating the required propulsion demand based on the resistance curves.
- Include the financing scheme in the cash flow analysis and explore the effect of subsidies in the economic analysis.
- Examine the reduction potential of CO_2 emissions from alternative fuels under a well-to-propeller analysis, in order to apprehend the renewability potential of the alternative fuels.

Appendix A Background information on air pollution

A.1 Air pollution

Air pollution is not a recent problem. Even before human beings started inhabiting the planet there was pollution primarily coming from ash emitted by volcanoes or from smoke produced by forest fires. However, the human activities through time have led to the increase of air pollution. Before the industrialisation, the main source of air pollution was the combustion of wood or coal mainly for heating needs. Since the industrial era began, around the year 1750, fossil fuels were introduced, and the problem of air pollution was intensified. The main human-related sources of air pollution are electricity, heat production, transportation and agriculture. Nowadays, air pollution is recognised as a problem on a global scale and there is scientific consensus that human activities lead to climate change. [93] High concentrations of air pollutants can have catastrophic effects on the health of organisms but also on the environment. Air pollutants can impair the ecosystem functions and degrade cultural buildings' materials, which constitute global heritage. Extreme weather conditions, distribution of species and ecosystems and sea level rise are considered the main results of climate change. [5] In the report of World Health Organisation, it is stated that, in 2012, one in eight of the total deaths worldwide was the result of exposure to air pollution. The same report estimates that three million deaths per year are associated to air pollution exposure. [94]

Anthropogenic air pollutants are categorised into two groups, primary and secondary pollutants. The difference between primary and secondary pollutants lies in the fact that primary pollutants are considered to be the direct emissions of identifiable sources, whereas secondary pollutants are polluting substances, with different chemical composition, created by the reaction of primary pollutants in the atmosphere. The most common primary air pollutants are Nitrogen Oxides (NO_x), particulates (PM), Sulphur Oxides (SO_x), Hydrocarbons and Volatile Organic Compounds (HC/VOCs), Carbon Dioxide (CO_2) and Carbon monoxide (CO). Secondary pollutants include the sulphuric acid and substances which are formed after being exposed to sunlight. The formation of photochemical smog, caused by the reaction of NOx with UV light or the creation of tropospheric ozone are two indicative examples of such substances. [5]

Primary pollutants are further categorised into two groups, the greenhouse gases (GHG) and the non-greenhouse gases (non-GHG). The greenhouse gases are capable of trapping the radiated heat inside the atmosphere, a phenomenon called the "greenhouse effect". This effect is widely argued that leads to global warming and associated climate change. The main greenhouse gases are Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O) and Fluorinated gases (F-gases). Among them, CO_2 and CH_4 are the most prevalent ones. Non-Greenhouse gases include the rest of the primary pollutants. [22]

A.2 The role of shipping

In this section, the focus is placed on the contribution of shipping to the problem of air pollution. Special consideration is put on the impact of air pollution in ports, which is the intended area of operations for future Rotortugs.

A.2.1 Contribution of shipping in air pollution

Shipping is a mode of transportation, which is a major source of air pollution. The main air pollutants related with transportation are all the primary ones. As can be illustrated at Table A-1 according to the Second IMO Greenhouse Gas Study (2009), among the shipping related greenhouse gases emitted worldwide, the CO_2 is the main contributor, while the contribution of the rest is negligible. Because CO_2 is the most important GHG emitted by shipping, the following sections focus only on CO_2.

Table A-1: Summary of GHG emissions from international shipping during 2007 [IMO GHG Study 2009]

Pollutant	Total shipping (million tonnes)	CO_2 equivalent
CO_2	1050	1050
CH_4	0.24	6
N_2O	0.03	9
F-gases	0.0004	<6

Total shipping can be divided in international shipping and domestic shipping. As can be seen in Figure A-1 shipping has a relatively small contribution to the total volume of CO_2 emissions. According to estimates presented in the Second IMO Greenhouse Gas Study (2009), international shipping is estimated to emit 1050 million tons of CO_2 annually, which accounts for about 2.7 percent of the total emission volume. The three biggest contributors were Electricity and Heat Production (35%), Road Transport (21,3%) and Manufacturing Industries and Production (18,2%). Comparing the data presented in Figure A-1, it is clear that the contribution of the transport sector in comparison to the non-transport is less, concerning the GHG emissions. Moreover, road transport is clearly much more polluting than freight rail, aviation or shipping.

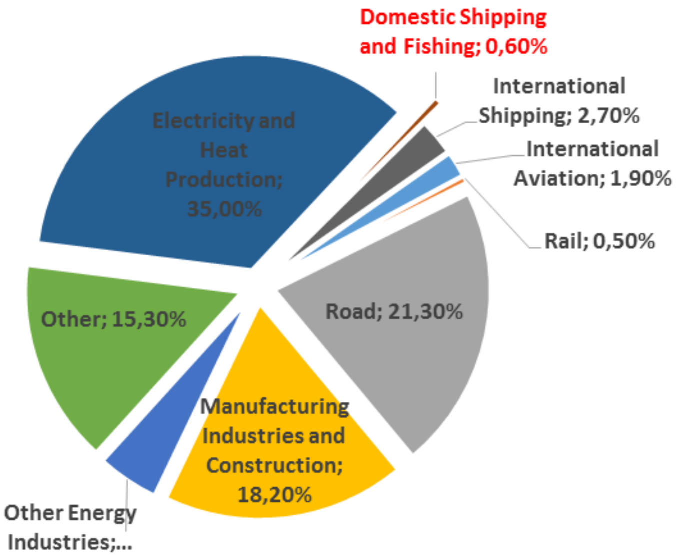


Figure A-1: Global total emissions of CO2 by Source and transportation mode [IMO GHG Study 2009]

Concerning the Non-GHG pollutants, shipping has a significant contribution to the total volume of anthropogenic air pollution. NO_x, SO_x and PM are considered the most important in the ship emissions[23]. It is estimated that, annually, approximately 18.6 million of NO_x (as NO_2) are produced, which represents 13 percent of global NOx totals. Moreover, the mass of SO_x (as SO_2)

emitted annually is approximately 10.6 million tonnes, around 12 percent of global SO_x totals. Contribution to global PM2.5 emissions from international shipping is approximately 15-25% The contribution of shipping to PM levels also varies per region. Approximately 60,000 people die yearly from heart lung diseases and lung cancer related to PM emissions of ships near coastlines in Europe, South Asia and East Asia [8]. HC/VOCs emissions represent 0.07% and 0.8% respectively of all VOCs emitted in the EU[10] . Shipping is only a minor source of VOCs, compared to other sectors. Shipping Non-GHG emissions compared with the other transport modes are substantially higher. Whereas road transport CO_2 emissions are calculated to be approximately six times those of shipping, NOx and PM emissions are almost equal, while SO_x emissions of shipping are 1.6 to 2.7 times higher than those of road transport. According to ITF report, international shipping compared with aviation produces about 9.2 more NO_x emissions, 80 times more SO_x emissions and around 1200 times more PM.[20]

A.2.2 Impact of shipping emissions in ports

The Marine industry can be divided in terms of function, between transport and non-transport vessels. Vessels are usually separated in three broad categories. The first category is the Ocean Going Vessels (OGVs), which are commercial vessels travelling between ports internationally or domestically and their main function is to transport cargo or people. Typical OGVs are bulk carriers, oil, gas and chemical tankers, passenger ships, container ships and other general cargo or specialised cargo ships. The second is the Port or Harbour Vessels, which have diverse functions. Mostly they comprise of vessels that provide assistance services to OGVs when they approach a harbour or support services like supplying fuel or cargo to other vessels and offshore sites near the port. Other port vessels just transport passengers in or out of the port or are dedicated for shipping or military use. Typical types of harbour vessels include tugs, fishing boats, military vessels and dredges. The third category is the Inland Vessels, which are floating crafts mainly for the transport of cargo or people through inland waterways (rivers, canals, lakes). The Rotortug, which is the vessel under consideration in this thesis, is a tugboat, therefore pertains in the “Harbour Vessel” category. More information about the design characteristics of Rotortugs can be found in section 4.1. The composition of world fleet in 2015, by percentage of vessel type is presented in Table A-2.

Table A-2: World fleet: total number of ships in 2015, by type and size [Equasis]

Ship Type	**Small(1)**		**Medium(2)**		**Large(3)**		**Very Large(4)**		**Total**	
General Cargo Ships	4367	13.6%	11729	30.6%	222	2.0%			16318	18.7%
Specialized Cargo Ships	8	0.0%	211	0.6%	65	0.6%	3	0.1%	287	0.3%
Container Ships	16	0.0%	2269	5.9%	1605	14.2%	1284	23.6%	5174	5.9%
Ro-Ro Cargo Ships	30	0.1%	645	1.7%	613	5.4%	201	3.7%	1489	1.7%
Bulk Carriers	310	1.0%	3770	9.8%	5596	49.5%	1613	29.7%	11289	12.9%
Oil and Chemical Tankers	1854	5.8%	6749	17.6%	2517	22.3%	1601	29.4%	12721	14.6%
Gas Tankers	39	0.1%	1096	2.9%	275	2.4%	397	7.3%	1807	2.1%
Other Tankers	318	1.0%	538	1.4%	7	0.1%			863	1.0%
Passenger Ships	3729	11.6%	2577	6.7%	272	2.4%	163	3.0%	6741	7.7%
Offshore Vessels	2612	8.1%	5339	13.9%	112	1.0%	169	3.1%	8232	9.4%
Service Ships	2466	7.7%	2441	6.4%	25	0.2%	6	0.1%	4938	5.7%
Tugs	16387	51.0%	987	2.6%					17374	19.9%
Total	**32136**	**100%**	**38351**	**100%**	**11309**	**100%**	**5437**	**100%**	**87233**	**100%**
(1) GT < 500 – (2) 500 ≤ GT < 25000 – (3) 25000 ≤ GT < 60000 – (4) GT ≥ 60000										

All vessel types are emitting exhaust air pollutants while underway but also while docked. Within the shipping industry, tugs account for only 20 per cent of overall shipping [95].Therefore, when tugs are placed in the broader context of emissions, as part of domestic shipping, which accounts for only 0.6% of total GHG emissions, they are an even smaller contributor. So, one could argue that focusing on tugs is not really that important.

However, it is not the total volume of greenhouse gas emissions which matters most, but the geographical location of the emissions in combination with the harmful effects of the non-greenhouse gases, especially particles and nitrogen oxides, on the health of people living in or near ports. As can be illustrated in Figure A-2, which shows the ship traffic distribution worldwide, while large proportions of gases are emitted at sea, the highest exposure levels are found in ports and near ports, since 80% of the world fleet is either navigating in coastal areas or positioned in ports. [96]

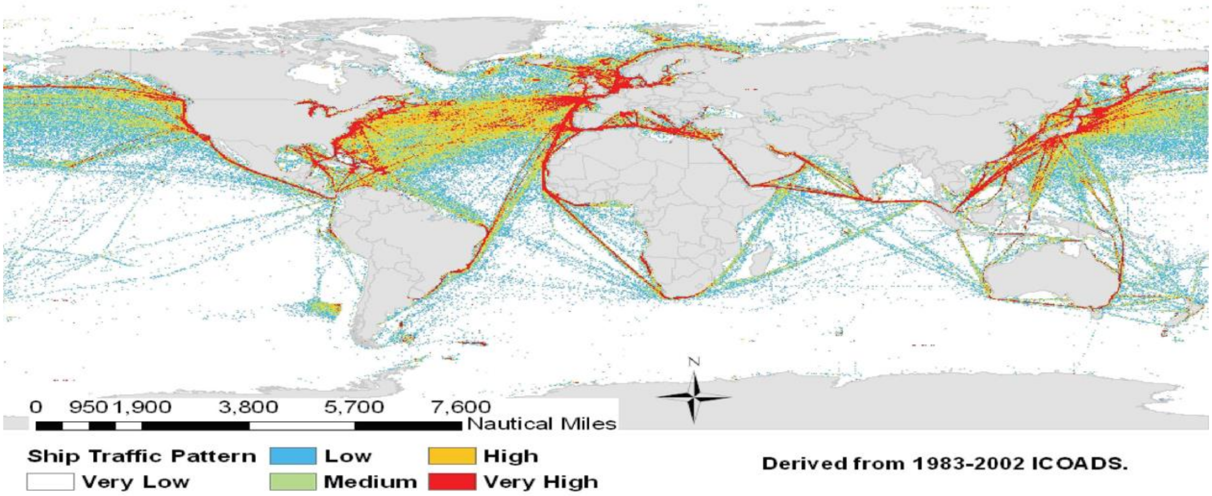


Figure A-2: Sihp traffic distribution until 2002 [GHG Study 2009]

Approximately 70 % of the emissions from water-borne navigation, as highlighted in the book of Andersson, are emitted within 400 km of land. The emitted exhaust air gases can be transported in the atmosphere, due to the weather conditions, from sea to land, over long distances, intensifying the air pollution problem in the ports. [5] According to ITF calculations presented in the report of [20], vessel emissions in ports account for a substantial mass of exhaust-gas air pollutants, summarised in Table A-3.

Table A-3: Estimated shipping emissions in ports in 2011 [Merk]

Pollutant	**Shipping emissions in ports (million tonnes)**
CO_2	18.3
NO_x	0.4
SO_x	0.2
PM_{10}	0.03
$PM_{2,5}$	0.03
CO	0.03
CH_4	0.002

If we examine how emissions are allocated between various source categories in the port of Los Angeles in 2012, we could extract some useful conclusions. The port of Los Angeles could be considered indicative of the air pollution situation in other ports worldwide, even though the category sources and their respective emissions are dependent on parameters like the number of port calls and the time of stay of each ship type. It is evident, however, from Figure A-3 that OGV's is the major source of air pollution for all pollutants. Harbour crafts accounted though for 19% for CO, 15% for PM and HC/VOCs emissions and 12% for NOx emissions.

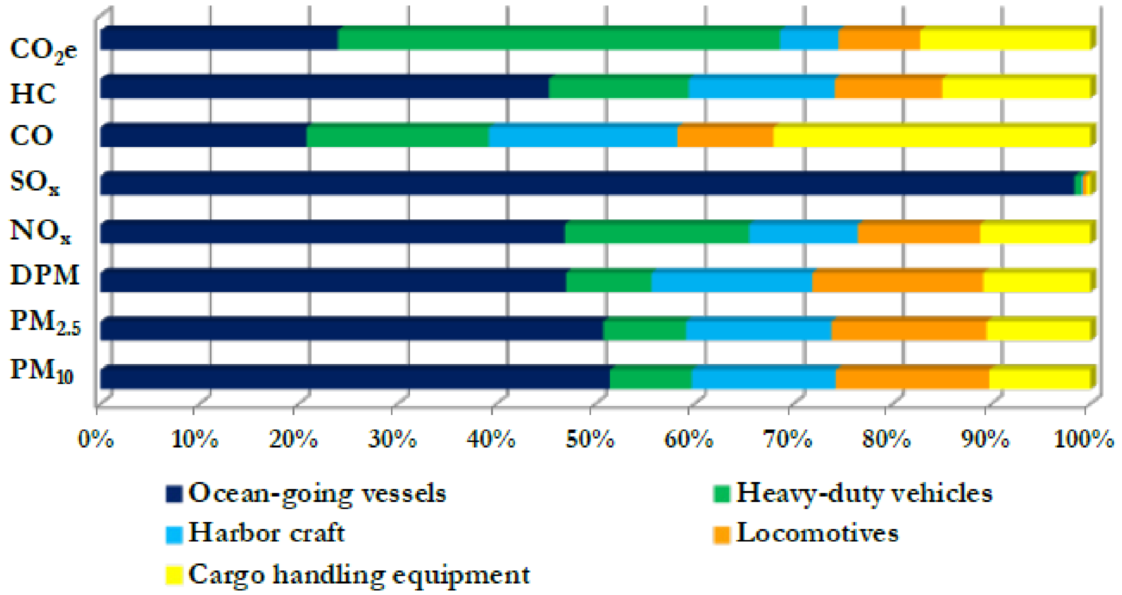


Figure A-3: Distribution of the 2012 total port-related emissions of each pollutant from different source categories. DPM : Diesel Particulate Matter [Air Inventory 2012]

As presented in Merk [2014], approximately 230 million people are exposed to shipping related emissions in the top 100 world ports. Moreover, the volume of CH_4, CO, CO_2 and NOx is projected to increase fourfold until 2050. Asia and Africa are anticipated to be the two continents affected the most from the increasing exhaust air emissions, firstly due to the projected port traffic growth but also due to the lack of adequate mitigation measures. [97] Figure A-4 zooms in how emissions are allocated between different types of harbor vessels in the port of Los Angeles in 2012. It is understood that tugboats collectively account for almost 50% of all exhaust emissions produced from harbour vessels.

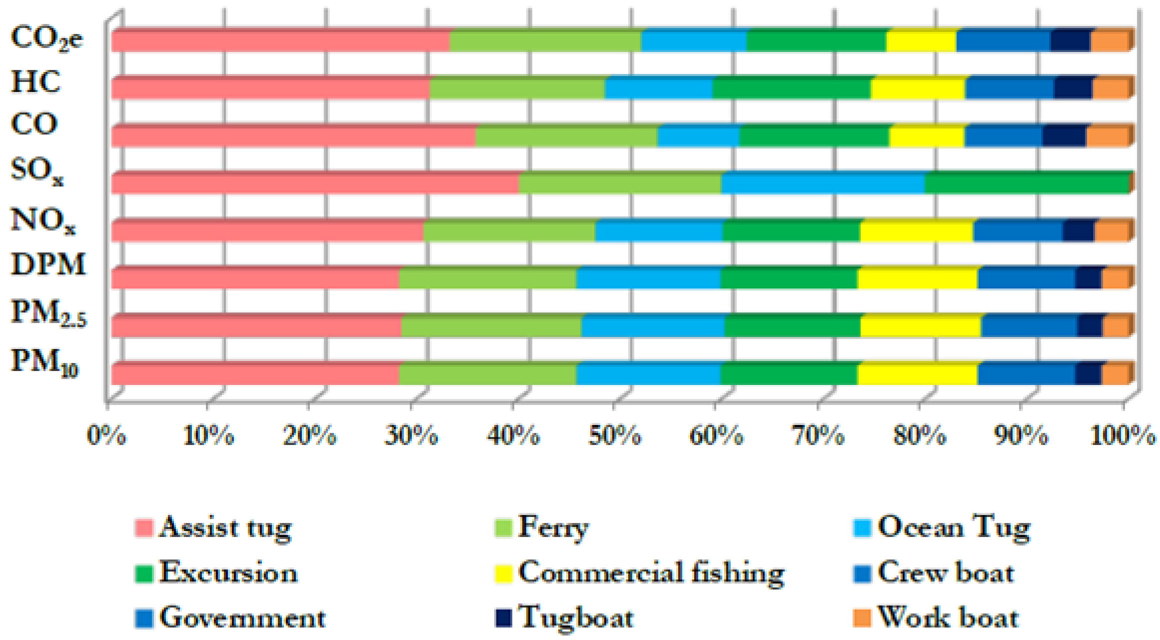


Figure A-4: Harbour craft emissions distribution in the port of Los Angeles in 2012 [Air Inventory 2012]

Harbour tugs therefore, since they operate in ports, located in or near big cities, are playing a crucial role in the increase of air pollutants, thus having large impacts on the health of local populations. That is the reason why minimising the direct exhaust air emissions of tugs is worth investigating.

A.3 Marine Emissions and Impacts

The emissions from ships, according to the second IMO Greenhouse Gas Study 2009 report, can be categorised as:

- Emissions of exhaust gases
- Cargo emissions
- Emissions of refrigerants; and
- Other emissions

According to the same report, emissions of exhaust gases is the dominating source of emissions from shipping. Emissions of exhaust gases are produced by Main Engines (ME), Auxiliary Engines (AE), emergency engines, boilers and incinerators. The emission magnitude of the aforementioned sources though is different. In particular, according to ENTEC and the Second Greenhouse Gas Study (2009), emissions from emergency engines, boilers and incinerators are considered negligible, in comparison with emissions from main and auxiliary engines[27, 98]. This can be illustrated in Figure A-5, where the percentages of emissions from OGVs, by machinery equipment for each pollutant, as measured in the port of Los Angeles in 2012, are shown.

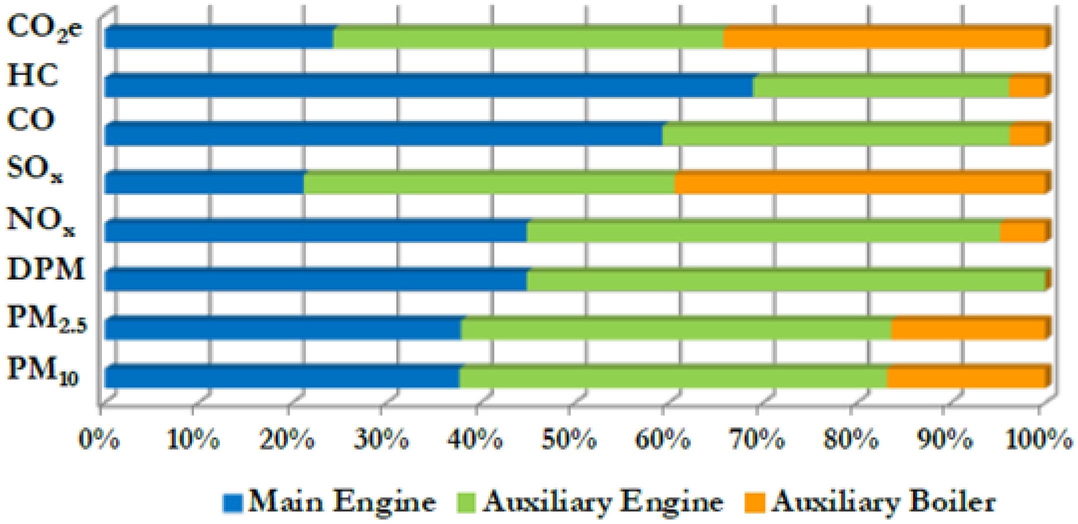


Figure A-5: Ocean-Going Vessel Emissions by engine type [Air Inventory 2012]

Cargo emissions are emissions from cargo spaces and cargo-handling equipment. Emissions of refrigerants are typically considered the cooling system emissions from refrigerant and air conditioning units, occurring during the maintenance or operation of the units, but also during the scrapping. Other emissions include emissions originating during the operation, testing or maintenance of fire-fighting equipment or scrapping. In this study only the exhaust-gas emissions originating from prime movers, used either for propulsion or auxiliary power within vessels respectively, are going to be covered.

Exhaust emissions from marine engines comprise mostly of non-polluting products, comprising of Carbon Dioxide (CO_2), nitrogen (N_2), oxygen (O_2) and water vapor (H_2O) and small quantities of polluting products, comprising of SO_x, CO, NO_x, HC and PM, as shown in Figure A-6. It is important to highlight that, even though CO_2 is non-polluting, it still is (considered) harmful, since it is a "greenhouse gas". [31]

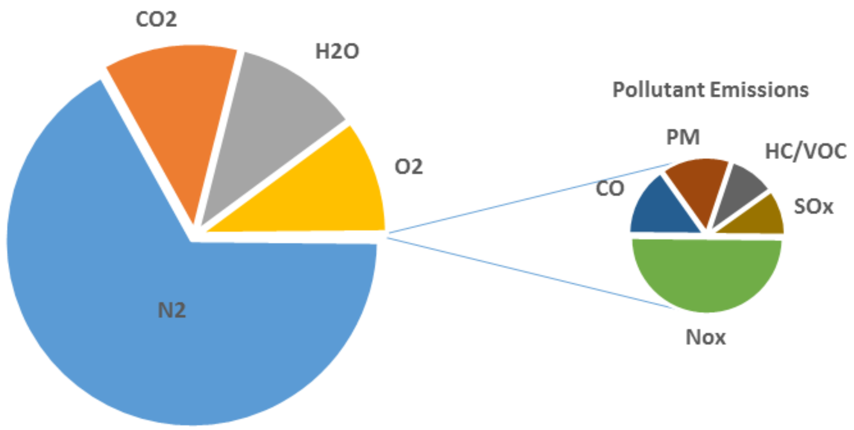


Figure A-6: Marine diesel engine exhaust emission compositions [[99]]

Regarding the formation of exhaust air emissions, a distinction between cylinder process related (or combustion related) and fuel related emissions is possible, according to [31]. Fuel related emissions are emissions caused by the complete combustion, while cylinder process related emissions are emissions from incomplete combustion. Therefore, fuel related emissions are dependent only on the fuel composition, while cylinder process related emissions depend on the combustion conditions inside the engine [27]. CO_2 and SO_x are considered fuel related emissions. CO, NO_x, PM and HC/VOC are considered cylinder process related [9].

Scientists have come to a consensus that GHG emissions should be compared in the same basis, and thus, as a result, a carbon dioxide equivalent (CO_2eq) value was established. Consequently, each GHG pollutant was assigned a value, which determines its ability to absorb heat in the atmosphere relative to CO_2, for a specific time horizon. This term was called global warming potential (GWP). Then, in order for its CO_2eq value to be derived, the GHG pollutant's emission estimates are multiplied by its GWP, [23, 100]. The GWP for CO_2, CH_4 and N_2O for a 100-year time horizon are:

- CO_2 – 1
- CH_4 – 25
- N_2O – 298

Below, a description of the formation and the effects of shipping exhaust-gas emissions from all the primary air pollutants will be briefly discussed. An extensive description on the formation, the chemical reactions taking place and the hazards of exhaust air emissions from marine engines can be found in the book of [31].

Carbon Dioxide (CO_2)

CO_2 is a colourless, odourless gas. It is a non-polluting gas that composes 0.04% of the atmosphere and is both an essential element of the photosynthesis and the natural greenhouse effect, responsible for keeping the average world temperature around + 14,5^{o}C, instead of -18 ^{o}C. It is considered the most prevalent greenhouse gas, and the mainstream scientific opinion is that the increase due to human-based CO_2 emissions have a large influence in the increase of global average temperature, and consequently in climate change [31, 101]. The emission of CO_2 during the combustion of fuels in marine engines is a certainty. The production of carbon is a function of the quantity and the type of fuel burnt, specifically its carbon content. The concentration of CO_2 in the atmosphere is low, posing no threat to a human's health. However, high concentrations, i.e. around 5000 ppm, can cause breathing disorders or lead to unconsciousness, even death. [101]

Carbon Monoxide (CO)

Carbon monoxide is colorless and odorless, as well. However, in contrast to CO_2, it is a poisonous gas and extremely toxic to people. Low concentrations of CO, around 3 ppm, can cause poisoning symptoms, that could prove fatal for people with weak immune system. If inhaled in higher concentrations it can result to asphyxiation as it is combined with hemoglobin to form carboxyhemoglobin, preventing absorption of oxygen[31]. In the same book it is stated that: "0.1% of CO in air may prove fatal in less than half an hour by transforming over 50% of the hemoglobin in carboxyhemoglobin." It also effects certain animals, those that have haemoglobin, but also the respiration of plants by inhibiting photosynthesis. CO is the result of the incomplete combustion of hydrocarbons and is cylinder process related. Finally, CO contributes to the formation of greenhouse gases indirectly, acting as a catalyst [101].

Nitrogen Oxides (NOx)

Nitrogen oxides (NO_x) is a brown, odorless gas. NOx, consisting of Nitric Oxide (NO), Nitrous Oxide (N_2O) and nitrogen dioxide (NO_2) are considered by-products of the reaction of nitrogen and oxygen in the air, formed under high temperature. Even though a substantial part of the fuel-based nitrogen is converted to NO, this only accounts for a very small percentage of the total NO_x produced from the fuel combustion, as the amount of nitrogen in the fuel is quite low. The biggest percentage of NO_x originates from the nitrogen which is contained in the air and which is converted to NO_x during the combustion process. In fact, NO_x emissions are considered cylinder related emissions. Specifically, the formation of NO_x is a function of fuel type, engine technology, temperature, air excess ratio and engine load [27, 31]. Nitrogen oxides are not considered to pose an immediate danger to human health, because they are not found in high concentrations. However, it still remains toxic, and, in high concentrations, it can cause respiratory system infection and eye irritation. It is also reported that it may degrade the ability of the body to resist bacterial infection. The environmental impacts of NO_x emissions are also well documented. One of the main problems associated with NO_x is acidification. It is affecting the ecosystems and the agricultural sector, by damaging the soil, but also corrodes the surface of buildings. Moreover, it is associated with the depletion of ozone layer, acting as a catalyst. In addition, NO_2 may further be converted to nitric acid, a constituent of acid rain, and contributes to the formation of smog [101].

Hydrocarbons and Volatile Organic Compounds - (HC/VOC)

Hydrocarbons (HC) are a number of substances, whose chemical structure composes of carbon and hydrogen in different quantities. The most known are methane (CH_4), gasoline (C_8H1_8) and various diesel vapors like benzene (C_6H_6), formaldehyde (CH_2O), butadiene (C_4H_6) and acetaldehyde (CH_3CHO). A distinction is recognized between methane (CH_4) and the rest of the hydrocarbon substances. CH_4, which refers exclusively to methane hydrocarbon emissions, is typically known as "methane slip". The rest of the hydrocarbon substances are known as Non-Methane Hydrocarbon (NMHC) emissions. NMHC are sometimes also referred as Volatile Organic Compounds (VOC). In fact, VOC is the term used for the gaseous form of HC at 190ºC. It must be noted that Total Hydrocarbon (THC) emissions entails both CH_4 and NMHC emissions. The proportion of CH_4 in THC will vary with respect to the engine type. In particular, the proportion would be negligible for compression ignition engines, while it would vary in gas-burning engines, depending on the type and fuel. More will be discussed on section 3.5, assessing the emission performance of various engine types running on alternative fuels. In general, hydrocarbons are the products of incomplete combustion of fuel and un-bunt lubricating oils. The quantity and the nature of the final products are related to the combustion characteristics, thus HC/VOC are classified as cylinder process related emissions [31, 99]. All HC/VOC are carcinogenic to some extent, but the intensity depends on the chemical structure of the substance examined. In general, light HC, like methane, are less carcinogenic than heavy ones, like benzene. At high concentrations they can be fatal. All HC/VOC have an impact on environment. They contribute to the formation of tropospheric ozone and photochemical smog [101]. It would be worth to mention that CH_4 is an important contributor to the greenhouse effect due to its high GWP [5].

Particulate matter (PM)

Particulates or Particulate matter (PM), according to the book Diesel Engines B, Volume 4, [31] are considered the solid-based emissions of marine engines, usually found in suspension in the atmosphere. They are composed of three main fractions; insoluble fraction, sulphates and soluble organic fraction. All PM may contain ash, carbon, sulphates, soluble hydrocarbons (traces of HC/VOC) and lube oil remnants. The formation of PM is complicated, because it consists of three different fractions, hence it depends on the formation mechanism of each fraction. A clear correlation between the sulphur content of marine fuels and the sulphate fraction of particulates emissions exists. Particularly, the lower the sulphur content of the fuel, the lower the sulphate portion of the PM and consequently the lower the PM emissions. So, PM emissions are significantly reduced when distillate fuels are used instead of residual fuels[13]. However, for equal sulphur content fuels, it is the engine type and specifically the combustion process characteristics that determine the final outcome[27]. Overall, it can be concluded that the formation of PM is combustion related[8]. PM emissions come in different sizes and quantities of particles ranging up to many 1000s of nm. PM are usually measured as coarse particulate matter (PM10), having a diameter lower than 10 μm, or as fine particulate matter (PM2.5), having a diameter lower than 2.5 μm. PM are considered carcinogenic. The impact on human health is dependent on the size of particles. Specifically, the smaller the particle the bigger the impact. They cause respiratory diseases, heart and lung diseases, asthma and are associated with premature mortality. The environmental effects of PM consists of accumulation of dirt on the buildings and the plant growth retardation, due to the deposition of particles on leafs, which reduces the photosynthesis process [101].

Sulfur Oxides (SO_x)

The abbreviation SO_x refer to sulphur dioxide (SO_2) and sulphur trioxide (SO_3). However, sulphur trioxide is a minor proportion of the total SO_x products. Sulphur dioxide is a heavy, colourless gas with a strong odor. The production of SO_x is a function of the quantity and the type of fuel burnt. Specifically, SO_x emissions will be proportional to the fuel's sulphur content. A small part of SO_x emissions will be produced because of the sulphur content of the burned lubricant oil [31]. Sulphur dioxide is an irritating gas for humans and animals and may cause respiratory and cardiovascular diseases. In enough concentration, it may damage plant life and vegetation. The main environmental problems connected with SO_x are acidification but, in contrast with CO_2, CH_4 and N_2O, it blocks radiation, counteracting the greenhouse effect [99].

To summarize, the formation mechanism and the effects of primary air pollutants are presented in Table A-4 below:

Table A-4: Summary of impact of primary air pollutants [composed by sources used in text]]

Pollutant	Formation	Health Effects	Environmental effects
CO_2	Fuel related	-	Major constituent of greenhouse effect
CO	Combustion related	Heart and cardiovascular problems, toxic gas	Indirect ozone formation, Dirt
HC/VOC	Combustion related	Carcinogenic	Ozone formation, photochemical smog, CH_4 intensifies the greenhouse effect
NO_x	Combustion related	Respiratory damage and other damage, toxic gas	acidification of soil and water, weathering erosion, smog, contributes to ground-level ozone, Dirt
PM	Combustion related	Lung and respiratory damage, bronchitis toxic gas	Dirt
SO_x	Fuel related	Respiratory problems	Acidification

The direct and indirect impact of air pollution, listed in Table A-4, originating from ships are translated to monetary terms from policy makers, with the purpose of imposing suitable prevention measures. This concept is called the internalization of external costs to society; in this case the costs from air pollution. The air pollution prevention measures consist of regulations (control measures), incentives of various forms, or a combination of the two aforementioned measures, as presented in section 2.4. [81] explains the concept of external costs and the main valuation methodologies.

To recap, from the primary air pollutants, CO_2 and SO_x are fuel related, while the rest (CO, NO_x, PM, HC/VOC) are cylinder process related. Fuel related emissions are emissions caused by the complete combustion, while cylinder process related emissions are emissions from incomplete combustion. Therefore, fuel related emissions are dependent only on the fuel composition, while cylinder process related emissions depend on the combustion conditions inside the engine. It is important to highlight that the final quantity of fuel related emissions emitted is also related to the engine type, through the engine's efficiency.

At this point, it is critical to mention the widely known “diesel dilemma”, as introduced in the book Diesel Engines B, Volume 4, [31]. “Diesel dilemma” is the terminology used for showing the existence of a certain trade-off between NO_x emissions and the rest of the cylinder process related pollutants. NO_x emissions show a reverse trend to CO, PM, HC/VOC. Specifically, when the peak temperature inside a diesel engine is increasing NO_x emissions increase, while the rest of the aforementioned pollutant's emissions decrease. On the other hand, when the peak temperature is decreasing, it leads to less NO_x emission but to higher emissions for the rest.

Appendix B Assessment of alternative fuels for use in tugboats

The alternative fuels, most commonly considered today, are Natural Gas (LNG, CNG), Liquefied Petroleum Gas (LPG), Biodiesel, Alcohols (Methanol, Ethanol), Dimethyl Ether (DME), Hydrogen, Nuclear fuel and Wind/Solar Energy. From this list the alternative fuels which showed to be infeasible have not been further considered but are presented here with emphasis on the reasoning behind their rejection. Even though different fuels are predicted to show a good environmental performance potential the analysis in this thesis is limited to only the ones that are most commonly considered today and satisfy the time span of 15 years set as research time length and show a high potential with respect to the application on tugboats.

B.1 Categorisation of alternative fuels

Before going into details concerning the alternative fuels suitable for the tug industry, it is necessary to highlight the ability to distinct alternative fuels based on different classification schemes. The way that fuels can be categorised, designates certain attributes to them, which are important for determining the suitability of those fuels.

To begin with, [5] in his book categorises fuels based on the energy carrier that they carry. A distinction is made between the primary energy sources and the energy carriers. Primary energy sources are considered to be unprocessed sources of energy, originating from nature. The result of different processing method, depending on the energy source, are fuels with different types of energy carriers. The type of energy carrier in the fuel will determine which prime mover is suitable for use. Figure B-1 illustrates the primary energy sources and the originating fuels/energy carriers, as presented in the book [5]. Of course, there are even more comprehensive ways to regroup the energy carriers.

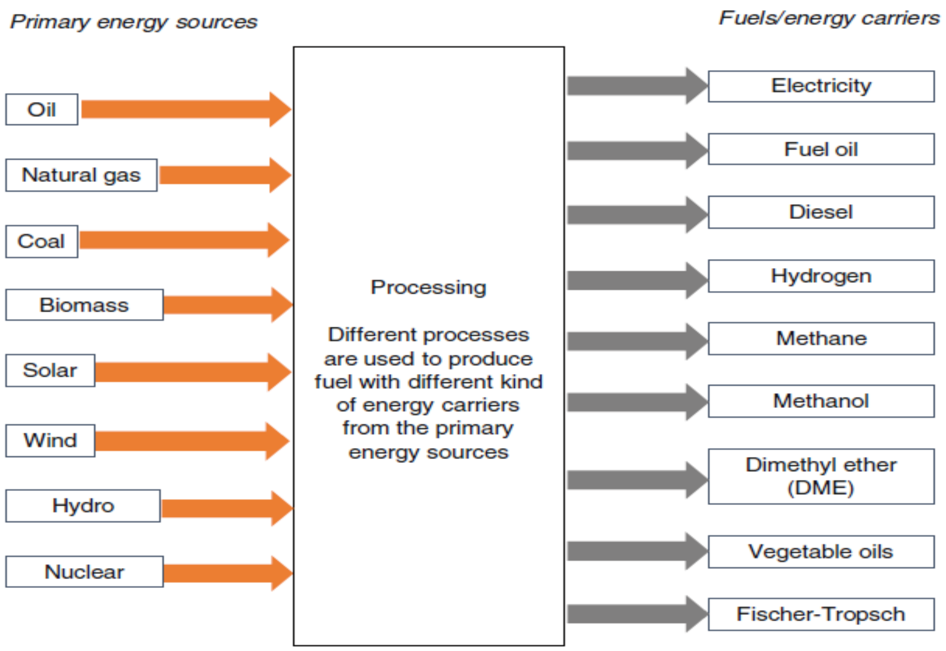


Figure B-1: A schematic representation of the link between energy sources and fuels/energy carriers [Andersson]

Based on the form, fuels can be further regrouped into three categories: solid, liquid and gaseous fuels. The form of the fuel is directly related to the engine type used to burn the associated fuel.

The main liquid marine alternative fuels include:
- Bio-liquid fuel (Bio-diesel)
- Alcohols (Methanol, Ethanol)

The main alternative gaseous fuels include
- Hydrogen
- Natural Gas (LNG and CNG)
- LPG
- DME

The solid fuel form is
- Nuclear propulsion.

An important distinction could be made from an infrastructure and handling point of view. Then fuels are divided between “drop-in fuels” and “non-drop-in fuels”. Drop-in fuels can be used in engines that already operate with a conventional fuel, without adaptations to the existing fuel distribution system while non-drop-in fuels require a completely new infrastructure or even adaptations in one or more of the engine components or fuel handling/storage systems. [41] Hence, the decision on selecting a drop-in or a non-drop-in fuel will have significant technical and economic impact for the ship-owner. From the fuels under investigation only Biodiesel is considered a drop-in fuel.

The main marine engine types for the combustion of alternative fuels in tugboats are 4-stroke compression ignition engines and 4-stroke gas-burning engines. Details on the gas-burning engines suitable for use on Rotortugs are provided in section 3.4.1.

The fuels that are used in Diesel engines are:
- Biodiesel
- DME

The fuels that are used in Gas engines are:

- Alcohols (Methanol, Ethanol)
- Natural gas (LNG/CNG)
- LPG
- Hydrogen

Finally, fuels can be split up in renewable and non-renewable, based on the feedstock origination. The nature of feedstock could be of fossil or biomass resources. Some of the alternative fuels can be produced from various feedstocks, either from bio feedstock or from fossil feedstock using a different process. Those fuels are almost identical products. The difference lies in the environmental impact, based on the pathway of production of the final product. The same final product produced from a bio feedstock is considered to be a biofuel, instead when produced from a fossil resource is not considered a biofuel. The way to denote the origin of the feedstock the term "Bio" is added in front of the name of the fuel. For instance, Bio-LNG, Bio-DME, Bio-Methanol have the same end-point specifications with their non-bio counterparts but differ in environmental performance. Further elaboration will be provided in section B.2.1.

B.2 Overview of candidate marine fuels

From the different classification schemes presented we understand that the fuel options can be mainly discussed on the basis of their renewability potential and engine adaptation. Firstly, the renewability potential will be addressed in the "Biofuels" section, where it will become clear that the pathway of production determines the greenhouse gas reduction potential of the candidate alternative fuels. Then, the alternative fuels will be discussed based on the form they have; solid, liquid or gaseous, which constitutes the major parameter for determining their engine adaptation. Throughout this section elaboration on the reasoning behind the selection of the most suitable fuels will be provided.

B.2.1 Biofuels

Biofuels can be classified according to generations. Generally, a distinction is made between first, second and third generation biofuels. First generation biofuels are also called classic or traditional biofuels, and they are made from vegetable oil, sugar, starch or animal fats. Second generation are also called advanced biofuels, and they are made from non-food crops, such as waste organic material or by cellulosic materials (e.g. trees, wood), while third generation biofuels are derived from algae. Today biofuels are being used mainly as blending components in conventional fuels, to reduce the greenhouse gas intensity of the fuel. [102] However, [103] in his report explains that there are reasons which constitute blending biofuels in marine fuels an unattractive future option. The main reason is that this practice cancels the benefit of the low sulphur content of biofuels. Other practicality reasons are the difficulty in handling and sampling procedures imposed to crew. Thus, blending is not considered as an option in this thesis.

For a biofuel to suffice as a viable solution for marine use it is expected to fulfil certain criteria, as listed in the previous section. Biofuels should be technically compatible with existing engines, refueling infrastructure, handling and storage facilities while at the same time provide at least the same quality and a better environmental performance compared to conventional fossil fuels. However, in the case of biofuels the focus should be put on criteria that are relevant to the feedstock and production process. As highlighted in [102] the following factors are the most decisive : the availability of biomass, the cost of biomass, the assurance that the feedstock production will be harmless to the environment (will not cause deforestation or ground pollution) and of course the anticipated cost of the final product, which will impact the investment decisions for certain biofuels.

The suitability of biofuels for marine use has been evaluated in various studies [39, 41, 43, 47, 103-105]. Several issues associated with first generation's biofuels have been raised. The most important are relating to the sustainability of the feedstock, the competition with land use for food supply and negative environmental impacts as a result of biofuel production. [43, 102-104] In contrast, a number of second generation biofuels are considered to be realistic alternatives for use in the shipping industry, because they address most of the aforementioned issues. The most common second-generation fuels suitable for marine use are considered to be Biodiesel, Bio-Methanol, Bio-LNG, DME, Hydrogen and GTL. Third generation biofuels are considered the most promising option concerning sustainability potential but their production route is still at a conceptual phase [104].

There is a wide variety of raw biomass from which different types of biofuels can be produced. Moreover, the conversion technologies along the supply chain are numerous and diverse. In Figure B-2 an overview of the most common conversion routes to biofuels are illustrated.

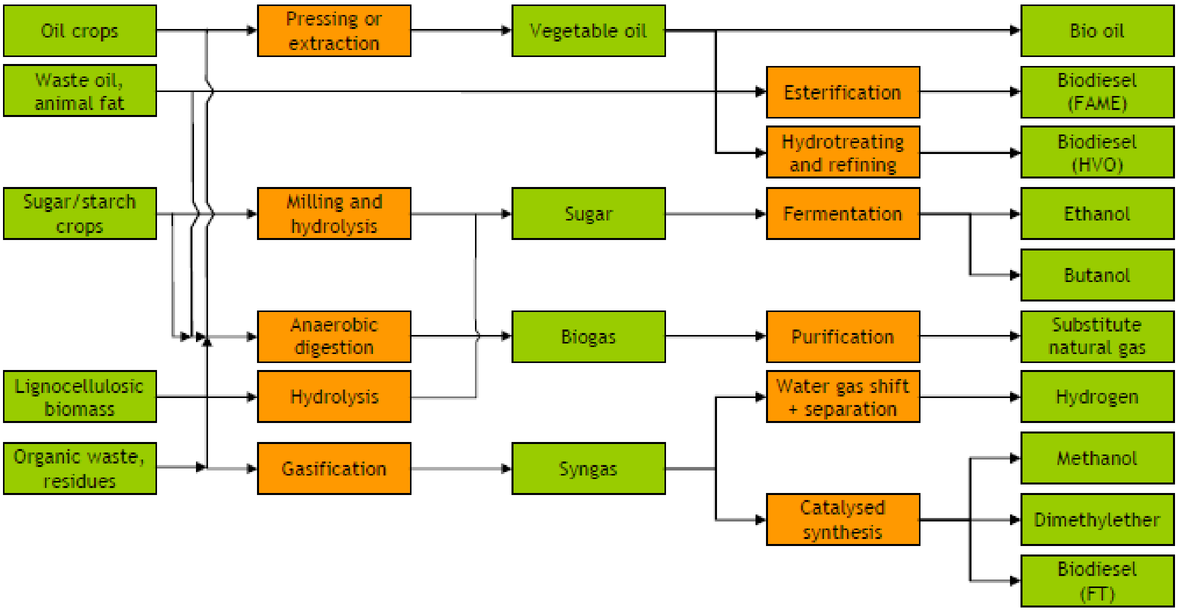


Figure B-2: Overview of conversion to biofuels [Potential of Biofuels Ecofys]

Biofuels can realise a reduction of GHG emissions, and the effectiveness is usually assessed on a well-to-propeller basis, through a quantitative Life Cycle Assessment (LCA), expressed in gCO_{2eq}/MJf (grams CO_2 equivalent emissions per Mega Joule of fuel – MJf). In an LCA, the life cycle of a marine fuel can be thought of consisting of two distinct phases. The first one, called well-to-tank phase, consisting of extraction, processing, transport and storage of the fuel. The fuel is now ready for use and the second phase called tank-to-propeller phase begins, as illustrated in Figure B-3

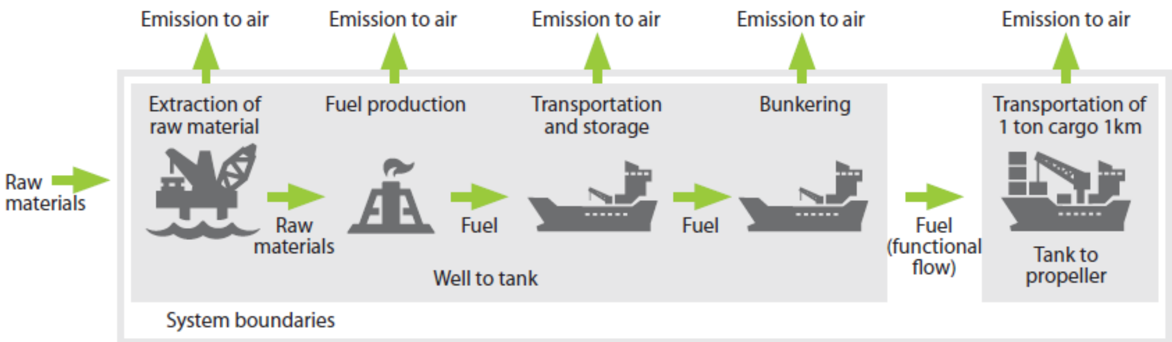


Figure B-3: Life cycle of a marine fuel from well-to-propeller [fcbi-Methanol]

Most LCA studies assessing the greenhouse intensity of biofuels have been targeting the automotive business, using the well-to-wheel concept, similar to shipping's well-to-propeller, expressed in a standardised format of gCO_{2eq}/km. Those studies differ significantly in several aspects and methodological choices in comparison to LCA studies on biofuels for shipping. Until now, few LCA studies on biofuels for shipping have been published and all indicate a substantial variation on the GHG intensity of the biofuels assessed, based on the route of production followed. [106] summarizes the reasons of such variations, including the agricultural practice and region, the fuels and by-product use and the process efficiencies. There are concerns though raised on the validity and accuracy of those LCA assessments, due to incomplete boundaries and uncertainty in a lot of factors in the formulation of the LCA. The main weaknesses are regarding factors relevant to the production chain, the engine characteristics and the emission factors used.[106] However they can provide an indication on the greenhouse gas intensity of certain fuels and as such it could be useful, because emissions originating in upstream processing is likely to become a target of future carbon reduction legislation. The results of an indicative LCA assessment, from the report [38], are presented in Figure B-4.

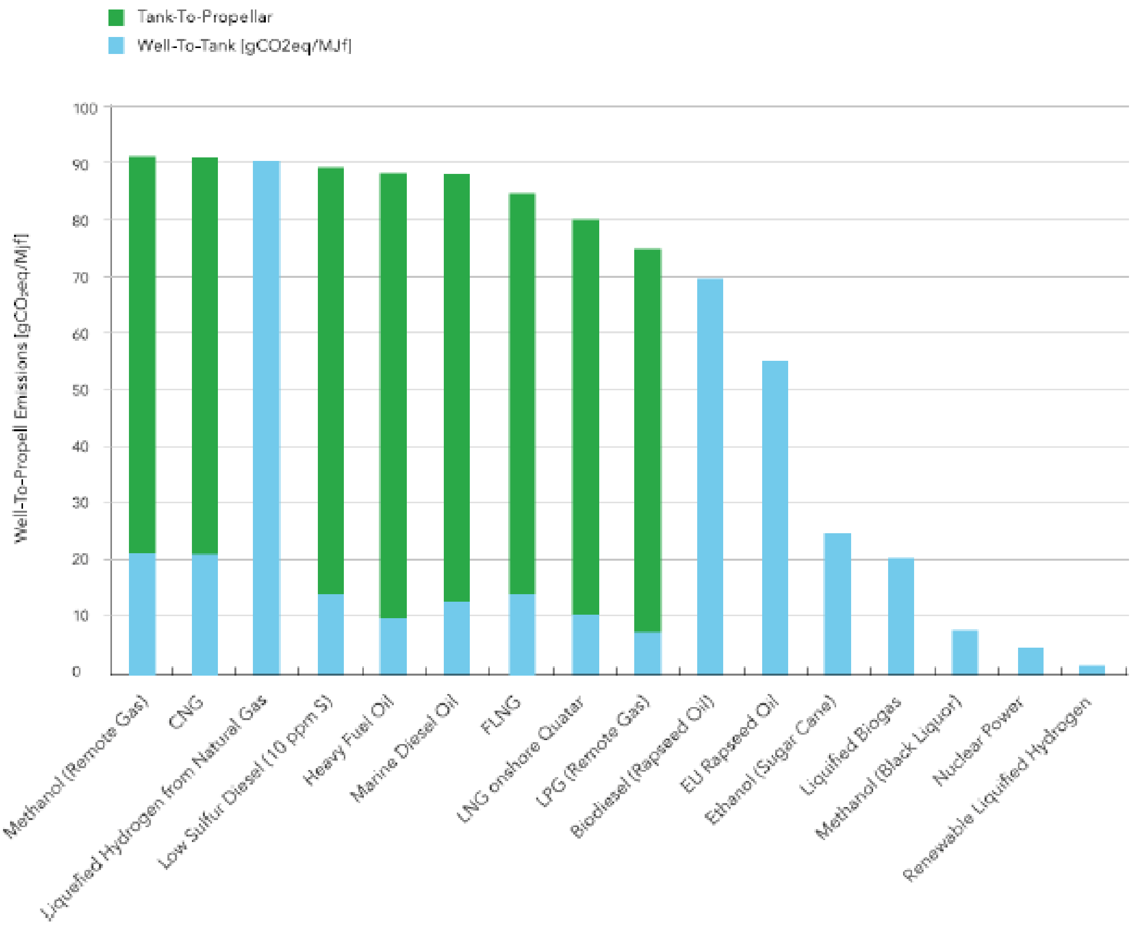


Figure B-4: Comparison of WTP emissions for alternative fuels [[33]]

A fuel's greenhouse gas emission (CO_{2eq}) reduction potential expressed in percentage is the sum of the reduction percentage achieved in the upstream and downstream process. The first one, is identified from the well-to-tank calculations, shown in blue, while the second one from the tank-to-propeller measurements, shown in green. As can be seen from Figure B-4 some fuels, under the perspective of the LCA assessment do not produce any TTP CO_2 emissions. These fuels are always produced from organic materials. The rationale behind this, is that all the carbon dioxide emitted after combustion of those fuels has first been taken out of the atmosphere by the plant it was produced from, resulting in a net emission of zero. [93] By this it becomes evident that significant GHG emission reductions can be achieved only by using fuels of bio-origin.

If the GHG emission intensity of methanol from various production methods is examined, as shown in Figure B-5 it becomes evident that there are variations on greenhouse gas intensity not only between different feedstocks, as anticipated, but also for the same origin of biomass when produced in different countries. The difference on performance lies on the different route of production followed. It becomes evident from this figure that variations in the results of a life-cycle analysis are expected, based on the initial assumptions.

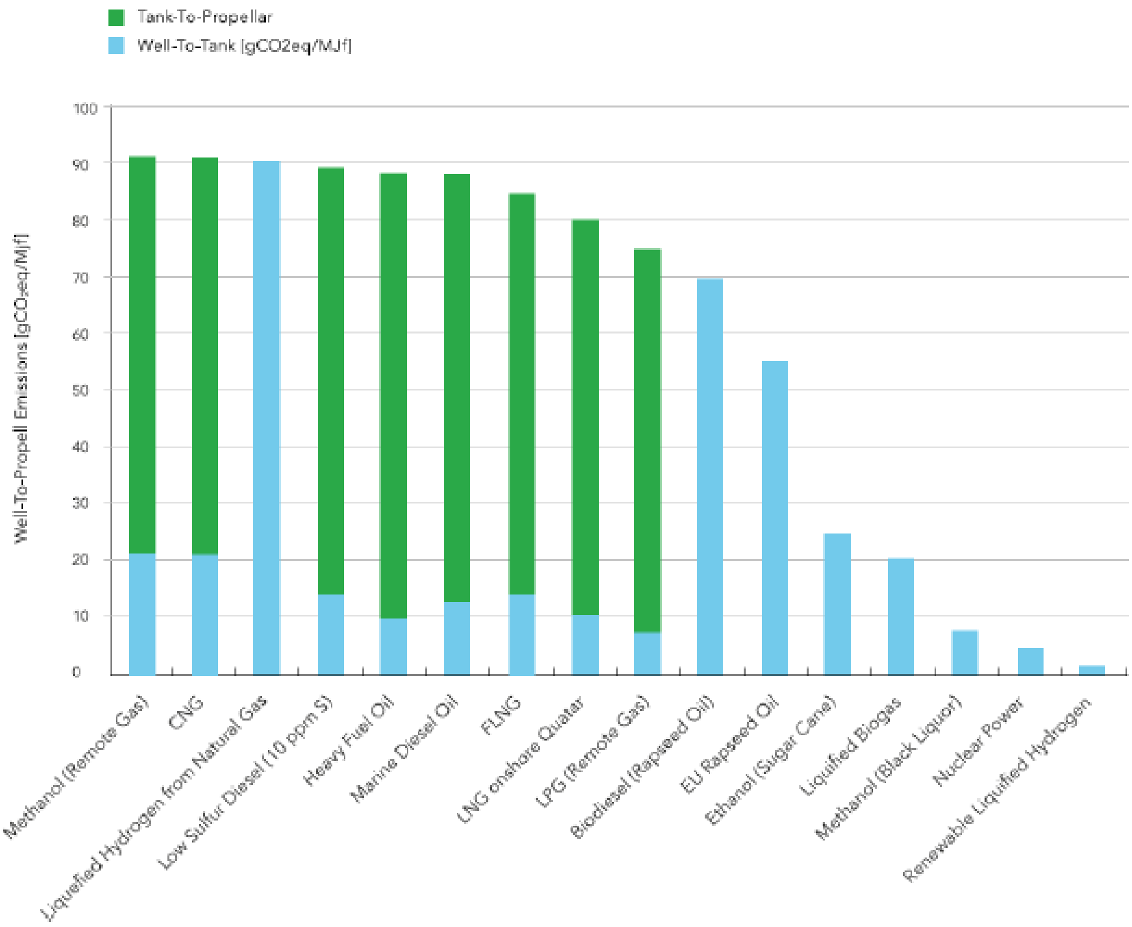


Figure B-5: Overview of GHG emissions of Methanol originating from different production pathways[[45]]

The purpose behind the presentation of alternative fuels under the classification scheme of biofuels was to illustrate that the renewability potential of the fuels affects the final GHG intensity. In this thesis the overall environmental performance of alternative fuels will be assessed by taking into account only the tank-to-propeller emissions. This means that the life-cycle emissions of the biofuels under examination will not be considered. It must be highlighted that the CO_2 emission output of all fuels (TTP) will be calculated, neglecting the zero-CO_2 emission assumption adopted at LCA studies. The deployment of different engine technology combusting the associated energy sources will lead in different tank-to-propeller emissions. For the fuel-related emissions, two are the decisive parameters which will judge the final emission percentage, firstly the carbon or sulphur content of the fuel and secondly the efficiency of the engine. The emission reduction potential of the non-GHG exhaust pollutants is discussed in the next section, where the alternative fuels under evaluation for marine use are briefly described.

B.2.2 Presentation of alternative fuels classified based on their form

In this section, the candidate options under investigation are briefly presented. From the candidate options CNG, LPG, Ethanol, Hydrogen and Nuclear fuel have been rejected. A brief discussion with the reasoning behind the rejection of those fuels is presented. LNG, Biodiesel, Methanol and DME are the fuels selected. Those fuels are either in liquid or gaseous form. The fuel properties, the availability, the engine compatibility and the emission reduction potential in comparison with MGO, both for the fuel-related (CO_2 and SO_x) and the cylinder process related (CO, NOx, PM, HC/VOC) emissions is going to be discussed.

Emission data from various sources has been collected by literature reviews, with emphasis in studies containing data from on-board and manufacturer test-bed measurements. It must be highlighted that there were limited data regarding the cylinder process related emission performance in the literature reviews. Especially concerning HC/VOC and CO emissions, which are not directly regulated from MARPOL Annex VI hardly any data have been published for most of the alternative fuels under consideration. The lack of comprehensive data adds uncertainty in the emission reduction potential of the alternative fuels under examination.

Generally, emission factors are found in two formats, specific values in [g/kWh] and in [g/kg fuel]. When the emissions are given as [g/kWh], then the efficiency of the engine is incorporated, therefore comparisons between engines can be made.

Gas Fuels

Gases include all fuels that are gaseous at standard temperature and pressure, e.g., Natural Gas (LNG and CNG), dimethyl ether (DME), Liquefied Petroleum Gas (LPG) and Hydrogen. There is a code adopted by IMO, called International Code of Safety for Ships using Gases or other low-flashpoint Fuels (IGF code), which ensures the safe use of gaseous fuels on-board ships.

Natural Gas (LNG and CNG)

Natural gas is a fossil fuel extracted from sub terrain reservoirs. [107] Natural gas can be transported in two different states. The first state is the liquid state (LNG, Liquefied Natural Gas), while the second state is the compressed (CNG, Compressed Natural Gas). LNG is natural gas in its liquid form. It contains mostly methane, usually 85 - 95 %, but also some nitrogen and other hydrocarbons like ethane, propane and butane. Properties of LNG depend on its exact composition. Typically, natural gas liquefies approximately at -162°C and the volume decreases to about 1/600th. Density of LNG depends on its consistence and temperature but is typically 0.44 - 0.47 t/m^3. LNG is transformed back to its gas form by simply heating the liquid. CNG is compressed natural gas to less than 1% of the volume it occupies at standard atmospheric pressure. It is stored in suitable tanks under high pressure, usually between 200- 248 bar (2900–3600 psi) and is also distributed under the same pressure. Density of CNG likewise depends on the pressure it is stored, varying between 0.18 (at 200 bar) – 0.215 (at 248 bar) t/m^3. As a result, the volumetric reduction potential achieved by LNG is higher than CNG. In addition, it is understood that the energy density of Natural Gas depends on the lower heating value. It can be safely assumed that LNG and CNG have the same mass energy content. [47] In this case, through an example it can be shown that CNG's volumetric energy density is 40 percent of LNG

Variables

- a mass energy content of 46.2 MJ/kg for both LNG and CNG
- LNG density = 0.45 t/m^3
- CNG density = 0.18 t/m^3

Calculation

$$LNG\ volumetric\ density = 46200 \frac{MJ}{ton} \times 0{,}45 \frac{t}{m^3} = 20790\ MJ/m^3$$

$$CNG\ volumetric\ density = 46200 \frac{MJ}{ton} \times 0{,}18 \frac{t}{m^3} = 8316\ MJ/m^3$$

$$ratio \frac{CNG}{LNG} volumetric\ density = \frac{8316}{20790} = 40\%$$

At the moment, both CNG and LNG-powered harbour tugboats have been built. After consultation with Kotug's representatives it was suggested that LNG seems more prominent for use in their newbuilt Rotortugs, due to storage limitations, thus only LNG will be under further review.

LNG is considered to be abundant and there is no fear about future scarcity. There are proven gas reserves worldwide, which are larger than the current oil reserves. Russia, Iran and Qatar are considered the biggest producers. [107] Moreover, a new extracting technique used called "fracking" has convinced scientists that the supply could be guaranteed in the long term. [47] Concerning LNG's bunkering availability, it must be noted that currently exists in some ports in Europe, Incheon (Korea) and Buenos Aires (Argentina). However, there is a constant development of bunkering infrastructure worldwide. [33] DNV GL's 2016 report finds that the total LNG-fuelled fleet numbered 77 in service and 85 on order, as at the end of March 2016. From this list, as illustrated in Figure B-6 tugs account for around 6 % (5 vessels) of the LNG-fuelled orderbook. Thus, it can also be concluded that the powering technology, using LNG, is well established.

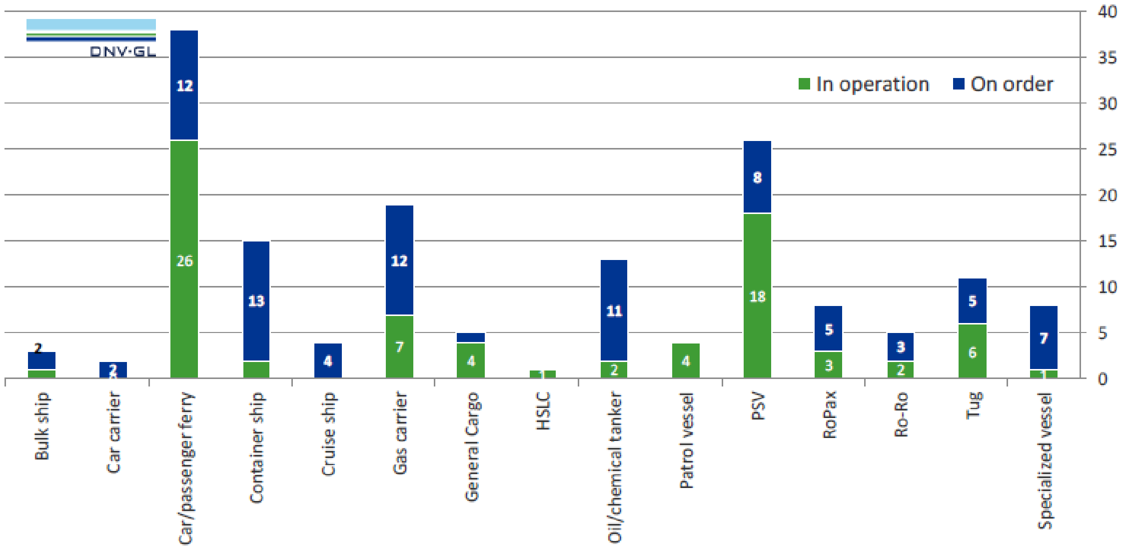


Figure B-6:LNG-fuelled fleet statistics as of March 2016 other than LNG-carriers and inland vessels [retrieved from www.dnvgl.com/LNGi]

LNG is combusted in gas engines. LNG's sulphur content is insignificant, only about 0.003%. Thus, SO_2 emissions will be equal to zero. The CO_{2eq} reduction potential of LNG depends on its origin. That is because the composition of LNG will affect its carbon content. The carbon intensity of the fuel is proportionally related to the carbon ratio of the fuel. It must be highlighted though, that combustion of LNG in gas-burning engines has led to methane slip (CH_4), which has 28 times higher GWP than CO_2. Thus, possible methane slippage may lead to increase of total greenhouse gases' intensity. Data collected in Sintef report compose of on-board measurements and verification of the collected data against the claimed manufacturer data (test-bed measurements documented in technical files of the ships in concern). Emission performance data from Sintef report has indicated that both engine concepts running on LNG suffer from unburned methane emissions, alleviating the total CO_{2eq} reduction potential. In addition, it is shown that when LNG is combusted in mono-fuel gas engines the total hydrocarbon emissions are almost pure methane. In the same report the two main reasons for methane slip are revealed, which are related to the existence of "dead volume in form of crevices between cylinder unit components" and "incomplete combustion in form of quenching at the coldest part of the combustion chamber". Methane slip for both engine concepts has been reported to be in the same range at high load, but differs at low load. The range of methane slip for LPDF is higher than the LBSI at low load conditions. [46, 48] Moreover, according to data presented in the same report, dual-fuel engines have in general higher emissions than single-fuel engines when running on LNG. Average-weighted emission factors for both LNG fueled engine concepts are presented in Table B-1.

Furthermore, in the same report, it is anticipated that both LPDF and LBSI commercial engines will achieve an upper bound in methane slip of 4 g/kWh. Specifically, it is assessed that methane emissions will be at a level of 3 - 4 g/kWh for LPDF engines and 2.5 – 3 g/kWh for LBSI. With these values in mind the emission reduction potential of gas-burning engines running on LNG is estimated against a reference 4-stroke high-speed compression-ignition marine diesel engine running on MGO. It is reminded, that such engine is expected to emit around 0.2 g/kWh HC, consisting almost entirely of NMHC, and 0.5 gr/Kwh CO. Thus, the CO emission reduction factors are estimated to increase by 160% - 240%, for LBSI engines and by 260% - 280% for LPDF engines. However, for estimating the THC emission reduction factor range, the respective NMHC values of Table B-1 are taken into account. Then, the relevant gas-engine's respective CH_4 emission factor limit of 3 g/kWh for LPDF engines and 2.5 g/kWh for LBSI, as mentioned before, is added to the calculated value, serving as the lower limit of the range. For determining the upper limit of the range, the gas-engines' respective proposed emission factor of 4.1 g/kWh for LBSI engine and 6.9 for LPDF engine are added instead. Finally, these values are compared against the reference value of 0.2 g/kWh. Hence, the HC emission reduction factors are estimated to increase by 1300% - 2100%, for LBSI engines and by 1600% - 3550% for LPDF engines.

Table B-1: Emission factors for gas-burning engines combusting LNG [46]

Engine type	NOx		CO		THC		CH_4		NMHC	
	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh
LBSI	5.1	08 - 0.9	9.8	1.3 - 1.7	25.4	4.4	23.2	2.5 - 4.1	2.2	0.3
LPDF	10.4	1.8 - 1.9	11	1.8 - 1.9	43.2	7.3	40.9	3 - 6.9	3.3	0.4
Gas fuel : Hn ~ 49.3 KJ/kg density 0.78 ~ kg/Nm^3										

It is stressed that the proportion of NMHC to THC is assumed to be the same with the progression of technology. Therefore, it is estimated to be 6.8% for LBSI engines and 5.5% for LPDF engines, based on the respective values, listed in Table B-1.

Lastly, concerning the rest of the non-GHG emissions, data collected from various sources, show that the use of LNG in gas-burning engines results in NO_x reduction by 75%- 90% and PM reduction by 95%-99%. However, higher concentrations of nanoparticles in contrast to compression-ignition engines are observed. The formation of formaldehyde, a toxic compound, is also a byproduct of the combustion of LNG in gas engines, attributed to incomplete combustion inside the engine's cylinders.[26, 33, 35, 38, 46, 59]

<u>Liquefied Petroleum Gas (LPG) or Propane</u>

LPG is either the product of process of natural gas, or a by-product of the crude oil refining process. It contains mostly propane and butane, mixed in any proportion. The properties of LPG depend on its exact composition. LPG is a fuel considered as a candidate fuel for water borne transport. This is because, it has already been successfully applied in different sectors. In the transportation sector, LPG has an extensive record of over 26 million vehicles running on LPG in 2015. [108] Moreover, the LPG is also considered to be abundant and there is no fear about future scarcity. There are proven gas reserves worldwide, which are larger than the current oil reserves. LPG like LNG and CNG is combusted in gas engines.

However, there are certain characteristics which deem it unfeasible in the short-term for marine use. Firstly, there is limited information available on LPG for marine applications. There are currently no marine engines suitable for LPG combustion in the market. Secondly, in comparison to other alternative fuels, even though the supply network is developed worldwide, LPG costs more than MGO, constituting it a premium product, unaffordable for extensive use on-board vessels. Moreover, it is reported that LPG could constitute a safety risk, due to its density characteristic. It is heavier than air and a possible leakage in the fuel system would lead to accumulation in the bilge tanks, situated in an engine room, posing an explosive hazard. Finally, the sulphur content of LPG is at similar levels with LNG. But, since LPG originates from fossil fuel, the greenhouse gas reduction potential is not better than MGO. So, for the abovementioned reasons LPG is not considered to constitute a better alternative than MGO. There is consensus that it is rather difficult to penetrate the marine sector in the short-term. LPG's share in the automotive transportation and domestic heating markets though is going to be expanded. [47, 108] Thus, LPG will not constitute a viable option for this thesis.

DME

Dimethyl ether (DME), also known as methyl ether, is a colourless nontoxic gas. Dimethyl ether's energy density is quite similar with LNG's, around 19 GJ/m^3. DME in terms of safety, in the case of an accidental spill it will not cause environmental damage. In terms of handling and storage precautions DME behaviour is similar to propane's, so it is subject to the same requirements and precautions as LPG. Consequently, no trouble is expected for a vessel's crew to adapt. In ambient conditions it is gaseous and requires a pressure of about 5 bar to stay liquid. However, in contrast to LNG it does not require cryogenic storage [82]. Concerning infrastructure availability, [103] argues that unlike LNG, there is already an extensive global propane infrastructure in place, which is considered inexpensive. Hence, the existing propane network can be used to facilitate distributors in moving and storing dimethyl ether.

The biggest advantages of DME is that its carbon content is lower than MGO and LNG, which means lower CO_2 emissions and that DME's sulphur content is zero, meaning no sulphur emissions. Moreover, the price of dimethyl ether is lower than MGO on an energy equivalent basis in most markets. Particularly, in the developing countries without oil reserves DME can be produced at or below the cost of importing diesel oil. [109] Finally, concerning engine compatibility the biggest advantage of DME is that unlike LNG and LPG it can be used in internal combustion engines, because of its high Cetane number. Some modifications to the existing fuel network and storage system, addressed at [109] would be needed. Moreover, even though researchers have raised concerns concerning DME's high viscosity, which may cause substantial leakage in pumps and fuel injectors, it is considered a manageable risk. In addition, as reported in [38] it can also be used with spark ignition engines and fuel cells.

Still there are not yet commercially available dimethyl-ether optimized marine engines. However, there are under development. Specifically, it is reported that MAN Diesel & Turbine has developed an engine combusting DME, which attains the Tier III limits. Moreover, dimethyl-ether use in a converted marine auxiliary engine, was evaluated in the SPIRETH project from 2011 until 2014. For this project Methanol was converted to DME, on-board a vessel. It is important to highlight the complete absence of PM formation in the exhaust gases. [109] Since, third-party data from real operation are absent, the emission performance remains uncertain. In particular in medium or high-speed four-stroke engines, commonly employed in harbour tugs, it appears to be a 35% reduction in NOx emissions [26] ,but data concerning the emission performance of CO and HC for marine engines are not available. It has been reported from various studies, investigating the potential of di-methyl ether as an alternative fuel for compression-ignition engines used in the automotive sector, that HC and CO emissions are lower or equal to those from diesel engines. The reasons have been documented in [110-112]. The "diesel dilemma" exists also for DME combustion in internal combustion engines. For, this reason it is assumed that the same effect will also stand for optimised marine engines running on DME.

Liquid Hydrogen (LH_2)

Hydrogen is thought to be a very promising alternative for marine application. The selected pathway of Hydrogen production affects its environmental performance. Scientists agree that when it originates from renewable sources, then there is no CO_2 emitted. There are still problems that remain to be resolved. Production, Storage and transport are the main barriers for the market adoption. [5, 33]

Moreover, the cost of liquid Hydrogen (LH_2) is considered high in comparison with other alternative fuels, in the range of 2200 to 3300 Euro/ton, based on the production method used. [105] Hydrogen is suitable for use in internal combustions engines and fuel cells. However, there are certain reasons that deem the combustion of LH_2 in the aforementioned engines unfavourable for application on a tug.

To begin with, LH_2 even though it has a very high mass energy density, 120 MJ/kg due to its extremely low density, typically 0.053 t/m^3 results in a very low volumetric energy density, approximately 6 GJ/m^3. [113] As a result, it would require increased storage capacity, a luxury for harbour tugboats. In this case, through an example it can be shown that the hydrogen needs six to seven times larger storage tanks than MGO, and 3.5 times larger than LNG, depending on the pressure. [33, 45]

<u>Variables</u>

- a mass energy content of 43 MJ/kg for MGO
- MGO density = 0.89 t/m^3
- a volumetric energy density of 6000 MJ/kg for Hydrogen
- a volumetric energy density of 20790 MJ/kg for LNG (see LNG section above)

<u>Calculation</u>

$$MGO\ volumetric\ density = 43000\frac{MJ}{ton} \times 0{,}89\frac{t}{m^3} = 38270\ MJ/m^3$$

$$ratio\frac{MGO}{Hydrogen}volumetric\ density = \frac{38270}{6000} = 6{,}4$$

$$ratio\frac{LNG}{Hydrogen}volumetric\ density = \frac{20790}{6000} = 3{,}5$$

Secondly, liquid hydrogen should be stored at low temperatures (-253ºC) in cryogenic tanks, adding to the complexity of the installation and safety. Furthermore, currently, hydrogen bunkering infrastructure in ports is limited. [33].

Use of liquid Hydrogen in internal combustion engines is also limited; commercial engines are unavailable. It has been reported that combustion of Hydrogen in internal combustion engines leads to lower emissions, compared to MGO, in all pollutants except NO_x, due to high peak-combustion temperatures inside the combustion chamber. [35] The only way to comply with the upcoming Tier III NO_x limits would only be in combination with an additional emission-reduction technology. For this reason, use of LH_2 in internal combustion engines is ruled out of consideration. The focus is primarily directed towards the use of hydrogen in fuel cells. The reasons why fuel cells are not going to be examined in this thesis are discussed in section 3.4.2

Liquid Fuels

The main liquid marine alternative fuels include Bio-liquid fuel (Bio-diesel) and alcohols (Methanol, Ethanol).

<u>Bio-liquid fuel (Bio-diesel)</u>

Biodiesel is a renewable fuel that can be manufactured from new and used vegetable oils and animal fats. Today biodiesel is often being used as blending component in conventional diesel fuels, to reduce the greenhouse gas intensity of the fuel, as stated in Biofuels section. When Biodiesel is used in pure (“neat”) form it is typically known as B100. In that section the technical challenges of biodiesel production have been addressed. The quality of biodiesel varies with the feedstock, as well as the greenhouse intensity. The biggest advantage of biodiesel is that it can be used in existing internal combustion engines as a “drop-in fuel”. Data from several sources have identified a plethora of manufacturers, who are offering certified engines for combustion of Biodiesel.

The density of Biodiesel, typically 0.86 - 0.90 t/m^3 is close to MGO’s density, while the mass energy content is 8%-11% less than MGO, leading to similar volumetric energy content. [25] Moreover, even though researchers have raised concerns concerning cold weather starting and storage instability issues, which may affect the fuel system and engine compatibility, B100 is considered safe and biodegradable. [114] These factors are not expected to cause trouble in the wider adoption and use of B100 in internal combustion engines installed on ships. [102]. Not only that, but the combustion performance of B100 has been found to be superior compared to conventional diesel fuels, due to its higher Cetane number. [114] Moreover, logistical challenges concerning bunkering of biodiesel for harbour tugboats can be solved, as tugs generally bunker in the port, they are operating in.

A number of studies have examined the emission performance of biodiesel in internal combustion engines. [43, 102, 104, 114] The findings indicate that it leads to the emission reduction of PM by 47% to 70%, CO by 16% to 47% and HC from 65% as high as 74%. However, emissions of NO_x generally increase by 5% to 10%. Biodiesel has essentially no SO_x emissions, due to zero sulphur content, and may also provide CO_2 reductions concerning the TTP emissions, depending on the production process used. This is because the carbon content of Biodiesel is reported to be typically 77 % mass base; lower than MGO, 87% mass base.

Finally, B100 prices depend on the feedstock. In General, at the moment prices are higher than MGO in most markets but remain competitive. Since Biodiesel offers emission benefits in all pollutants except NOx, and the prices are anticipated to become even more competitive, probably at the same level as commercial MGO in the next 15 years, as production volume is increased it has been decided that B100 will be part of the options accessed in this study.

Ethanol

Ethanol is mainly produced from agricultural feedstock, such as sugarcane grown. Ethanol is currently used in the automotive industry, as a replacement of petrol. [5] No projects using ethyl alcohol as marine fuel were identified in the course of this study. There is some reference to ethanol blended with gasoline for small pleasure boat gasoline engines, but nothing was found in relation to use in marine diesel engines suitable for tugboats. The lack of ethanol projects could be due to the consistently high price of ethanol as compared to methanol, making it unattractive as a primary candidate for a ship fuel [115] For these reasons it is excluded from further consideration.

Methanol

Methanol also referred to as Methyl alcohol has the chemical formula CH_3OH. It is the simplest of the alcohols, and is a colourless, flammable liquid at ambient temperatures. Methanol can be produced from many different feedstocks such as fossil natural gas, coal, farmed wood, wood waste, and even carbon dioxide. Methanol could be totally renewable, but today the main raw material is natural gas. The chemical composition remains the same regardless of the source. [5, 47, 115] The density of Methanol, typically 0.79-0.80 t/m^3 is close to MGO’s density, while the mass energy content is the lowest between the alternatives, at 20 MJ/kg. However, the high density leads to similar volumetric energy content with LNG’s, around 16 GJ/m^3.

Methanol is considered abundant and the bunkering infrastructure network mature enough to serve the marine sector. The reason is that methanol is already available at the majority of shipping hubs worldwide, since it is exported to cover the chemical’s industry demand. [82] Methanol for marine use is currently distributed through tank trucks. Specifically, Methanol is delivered from the trucks to a bunkering facility with pumps built in containers on the quay. (Stefenson, 2014).

Projects investigating the use of methanol as a marine fuel are relatively recent. The METHAPU project was the first project, starting in 2006. Since then there have been a number of projects (Effship, Spireth, Germanica, Methanship, Leanships, Summeth) initiated to further investigate the potential of methanol for ship fuel, but most of them are pilot studies. In all those projects Methanol is tested in modified internal combustions engines or in fuel cells. It is reported in both field and laboratory tests, that converted methanol engines have performed at equivalent or higher levels than diesel engines. (Haraldsson, 2015a; Stojcevski, 2015) Still there are not yet commercially available methanol-optimized marine engines. However, there are under development [82] For these reasons, Methanol is considered a feasible alternative.

Concerning the emission performance of Methanol, the carbon content is the lowest between the alternatives under review, which translates to low CO_2 emissions. Additionally, like DME the sulphur content is zero, meaning no sulphur emissions. Concerning Non-GHG emissions in the [115] report it is stated, that various laboratory testing in the use of Methanol in 4-stroke dual-fuel engines, with diesel as a pilot fuel resulted in NO_x reduction by 30% - 50% and PM reduction by 95%-99%. However, THC and CO emissions in these engines were reported to be < 1 g/kWh, nonetheless still higher than 4-stroke compression engines running on MGO. [82, 115]. It must be highlighted that PM emissions are attributed purely to the combustion of the pilot fuel, when the gas-engine runs on the diesel mode (refer to section 3.4.1) and that methane slip (CH_4) are considered negligible. Moreover, on-board measurements on retrofitted engines have been reported, which verify the aforementioned emission levels. Specifically, NO_x emission reduction is in the range of 30%. This percentage is expected to be even higher in future commercial Dual Fuel engines. If it is assumed that the upper limit of 1 g/kWh is adopted for the scope of this thesis regarding NMHC and CO emissions, then this is translated in an increase by 400% for HC and by 100% for CO, compared to a 4-stroke high-speed marine CI engine running on MGO (0.2 g/kWh for HC and 0.5 g/kWh for CO).

Solid Fuel : Nuclear energy

One option proposed for reducing emissions is using nuclear energy for powering vessels. Two are the main advantages. First, is that CO_2 emissions are eliminated. Secondly, if nuclear power is used then the vessel has a high endurance capability. However, it is deemed highly unlikely for nuclear power to be adopted as option at least for harbour tugs, since there is no need for long endurance. Furthermore, due to public concerns, related to possible accidents, like the ones occurred in the past in nuclear factories, limits the possibility to see a nuclear-powered harbour tugboat in the next 15 years.

A summary of the characteristics of the candidate fuels is provided in Table B-2

Table B-2: Comparison of candidate fuel's fuel properties

Fuel	**Density** [t/m^3]	**Energy Content (LHV)** [MJ/kg]	**Volumetric energy density** [GJ/m^3]	**Carbon content** [% m/m]	**Sulphur content** [ppm]
MGO/ULSD	0.89	43	38.3	87	1000/15
LNG	0.45	46.2	20.8	75.8	3.5
Methanol	0.792	20	15.8	37.5	0
DME	0.668	28.4	19	52.2	0
Biodiesel	0.86-0.90	37.3	32.078	77	10

Appendix C Candidate Propulsion configurations

C.1 ART 80-32 General Arrangement

Not disclosed due to confidentiality reasons.

C.2 Background information on alternative propulsion configurations

At this point, the differences between the two main distribution network topologies, AC and DC, must be pointed out.

AC topology

The AC distribution network topology is the one conventionally used in numerous types of ships. An AC distribution system is considered reliable in terms of equipment protection. The interruption of fault current by circuit breakers is a well-established practice. On a fixed frequency AC distribution network, the diesel engines used as prime movers for power generation are fixed speed engines. Those engines are running at the rated speed, depending on the output frequency; typical values for tugboats are 1500 rpm for 50Hz and 1800 rpm for 60Hz. The prime movers are controlled by the fuel governor, which tries to maintain the output frequency constant over the load range. When 4-stroke medium/or high speed diesel engines are used as prime movers on AC distribution networks, the speed has been set usually at the right-end limit of a diesel engine's layout diagram, giving a distinct specific fuel consumption curve, as depicted in Figure 4-7 above. Modern approaches are also investigating the use of variable frequency main switchboards (40 to 60 Hz), which allow variable speed operation of a generator's prime mover, usually between the speed range of 60-100% rpm. The advantages of the use of such electric network architectures has been demonstrated primarily in larger vessels utilising a high voltage AC distribution network, as highlighted in [116]. The effect of such a network topology on efficiency and emissions lies outside the scope of this thesis.

DC topology

DC power distribution systems offer several key advantages over AC, as highlighted in [116, 117]. The key advantages are that in a DC distribution system, the need for generator and network frequency synchronisation is detached, allowing variable-speed engine operations and faster start-up of generator sets, including fast system recovery in the unlikely event of a power failure. Of course, fixed speed engines can also be used. In any case, a rectifier either integrated or stand-alone is needed for feeding the generated power from AC generator sets into a DC bus. Moreover, fixed or variable frequency inverters will also be needed for feeding the various AC consumers or motors, contributing to the energy transformation losses.

Variable-speed engine operation has been demonstrated to improve efficiency, resulting in significantly reduced fuel consumption and emissions.[117, 118] In particular, in contrast to the fixed speed engine operation, it permits for adjustment of speed in order to match the optimum SFC as designed from the engine manufacturer. Not only that, but the potential for noise and vibration levels reduction is present. Figure C-1 illustrates the specific fuel consumption curves of a fixed and a variable speed 4-stroke medium speed diesel engine. It is evident from that graph that the greatest efficiency benefits arise mainly on the low-load power zones, between 0-40%. Finally, another key advantage is that the use of DC networks also enables seamless integration with renewable energy sources and energy storage devices.

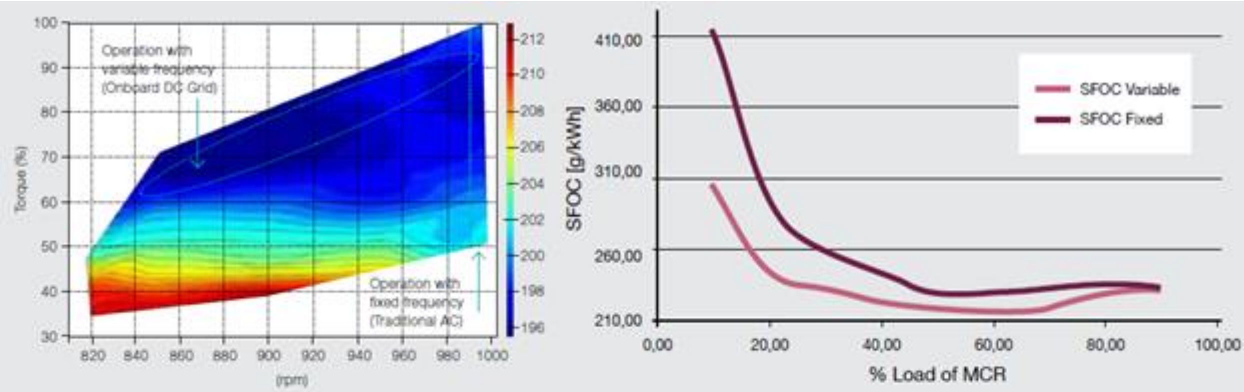


Figure C-1: Comparison of a 4-stroke diesel engines sfc performance between fixed and variable speed operation [ABB DC Grid]

Power Take Out (PTO) / Power Take In (PTI) functions

In addition to the terms "generating" and "motoring" to distinguish a motor/generator's function another classification is also broadly used in the marine industry. When electric power is generated from e-motors and delivered back to the distribution network that function is also known as Power Take Out (PTO), while when the e-motor is used to drive the propulsor is known as Power Take In (PTI). The following figures illustrate for a hybrid parallel configuration the flow of energy that distinguishes the two functions.

PTO function

In this function parallel running of the motor/generator with the auxiliary engines is possible, by introducing frequency converters between the e-motor and the bus bar. This way, the benefits of variable-speed operation of main engines for powering the e-motor is maintained. By enabling electric power to be delivered by the e-motors to the distribution network, implies that a number of auxiliary engines can remain either switched off or come offline, depending on the operating mode. In combination with the subsequent better loading of the main engines fuel and emission saving potential is reinforced. Additional benefits are also the lower running hours of the auxiliary generator sets, leading to lower maintenance cost. It must be highlighted than when the electrical power generated by the motor/generators can satisfy the whole electrical network demand, then the motor/generator is considered to work at "island" mode.

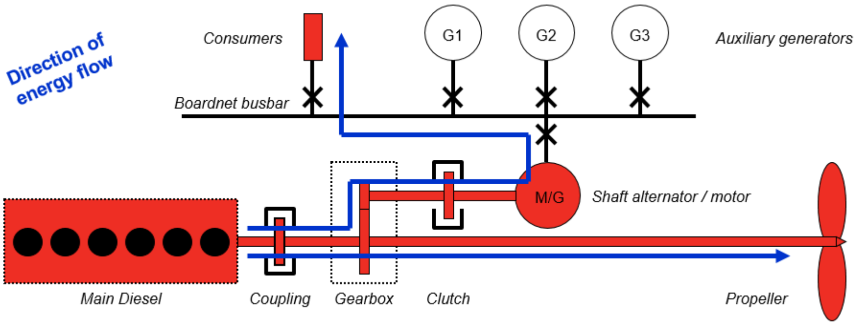


Figure C-2: PTO function [google]

PTI function

PTI can be further distinguished in “boost” mode, when the e-motor supplements the engine torque curve at higher speeds and “normal” mode, when the e-motor is the only source driving the propulsor. In “normal” mode a frequency converter is usually introduced between the bus bar and the electric motor for enabling variable speed operation of the propulsor. Particularly for OGV’s the term “take me home” is also identified, related to emergency cases, where the main engine is kept switched off due to a fault, enabling a vessel to find shelter or return safely at a nearby harbour. In Figure C-3 the “boost mode” is illustrated. A combination of diesel and electric power thus can be used for transit, assist and maneuvering, with the purpose of optimizing the operating mode’s efficiency, for wielding the maximum advantages in terms of fuel efficiency and emission reduction.

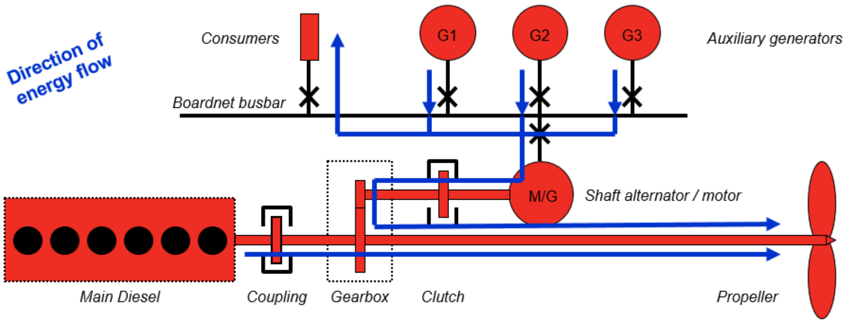


Figure C-3: PTI function in boost mode [google]

C.3 Power Management

Depending on the anticipated operational profile, as discussed in section 4.2, certain distinct operating modes can be distinguished. Breaking down the operational profile on its basic modes; transit, standby and assist, the powering resources usage for providing propulsion power to the vessels' thrusters and supporting vessel services is presented. Apart from the basic operating modes, the powering resources usage for the standby and harbour (vessel docked) modes is also presented.

C.3.1 Conventional propulsion configuration

The machinery/equipment power usage of the Conventional propulsion configuration is summarized in Table C-1.

Table C-1: Equipment power usage per operating mode for Conventional propulsion configuration

Device	Service				
	Standby	**Transit**	**Stop**	**Tow pull**	**Cold ironing**
Main Engine 1	On	On	Off	On	Off
Main Engine 2	On	On	Off	On	Off
Main Engine 3	On	On	Off	On	Off
Genset 1	On	On	Off	On	Off
Genset 2	Off	Off	Off	Off	Off
Harbour Genset	Off	Off	On	Off	Off

Transit

In this mode the main engines of a tugboat will be running in a typically steady load pattern for producing the amount of thrust needed to obtain the predefined transit speed. Irrespectively, of the transit speed all three (3) engines are always running, each driving its respective thruster. One C9 auxiliary generator is always online for providing the power for hotel and auxiliaries.

Standby

In this mode the tug is loitering at sea. Standby mode could be considered a "propulsion" mode. The wheelhouse throttle controls are enabled and limited propulsion and steering is available. Standby mode is intended to be used for minor station keeping in a reasonably safe position where sudden high-power operation of the thrusters will not be necessary. The thrusters are driven again by their respective main engine, which is kept running at idle speed (approximately 600rpm). One C9 auxiliary generator is always online for providing the power for hotel and auxiliaries.

Assist

In this mode the tugboat is normally experiencing extended periods of lightly-loaded fluctuation pattern, while there are short peaks of high-power demand. All three (3) main engines are running, driving their respective thrusters. An auxiliary C9 generator is always online for providing the power for hotel and auxiliaries. The tugboat can respond sufficiently fast to load fluctuations.

Harbour

All main engines are off. Electric energy demand for hoteling purposes is provided either by the C4 harbor generator, or by shore power.

C.3.2 Diesel-Electric propulsion configuration

In summary, the basic principle of the energy management is based on sequential loading of the generator sets. This means that the generators will automatically start and come online in parallel operation with each other, responding to the load demand. When the load is low, one or more engines can be shut down to maximize the load on the engines which are left running. Based on the operating mode under consideration, a pre-determined strategy has been developed which determines the order in which the chosen generators will come on-line and parallelized.

The machinery/equipment power usage of the Diesel-Electric propulsion configuration is summarized in Table C-2.

Table C-2: Equipment power usage per operating mode for Diesel-Electric propulsion configuration

Service	**Device**								
	Gen 1	**Gen 2**	**Gen 3**	**Gen 4**	**Gen 5**	**Gen 6**	**M/G 1**	**M/G 2**	**M/G 3**
Cold Ironing	Off	Off	Off	Off	Off	Off	Off	Off	Off
Stop	Off	Off	Off	Off	Off	On	Off	Off	Off
Standby	Off	Off	Off	Off	Off	On	On	On	On
Transit	Off/On	Off/On	Off/On	Off/On	On/Off	On/Off	On	On	On
Tow pull	On	On	On	On/Off	On/Off	Off	On	On	On

<u>Transit</u>

In this mode the necessary number of generators will come online and run in parallel, so as to satisfy the total load demand, depending on the transit speed and the electrical load balance. The goal is to have the minimum number of gensets, able to satisfy the load demand while simultaneously operating in-between an efficient power zone, which is pre-defined by the user. The priority of the gensets to come online is dictated by the developed energy management strategy. Synoptically, in lower transit speeds, where the propulsion load is low the bigger 3512C are off. The load demand in this case will be met by running the smaller C18 and C9 gensets, with the priority set for the C18 genset to come on-line first. In higher transit speeds, where the propulsion load is higher than the combined rated capacity of the C18 and C9 gensets, the 3512C gensets are configured to allow staging. The generators are assumed to be able to come on-line immediately, if the power demand necessitates so and run in parallel with each other sharing unsymmetrically the load. A minimum operating power band for starting a diesel generator is established for every genset.

<u>Standby</u>

In this mode, since limited propulsion power is anticipated, again the minimum number of generator sets are on-line. The priority is for the C9 genset to come online for providing the power for hotel and auxiliaries.

<u>Assist</u>

In this mode, similarly to the assist mode, the energy management system will dictate the number and sequence of diesel generators to come on-line. The priority is set for 3512C gensets to come on-line over the two smaller engines, in order to meet the highly varying load demand while simultaneously operating in-between a pre-set power zone.

<u>Harbour</u>

Electric energy demand for hoteling purposes, when the tugboat is moored, is provided either by the C9 generator set, or by shore power.

C.3.3 Hybrid propulsion configuration

The machinery/equipment power usage of the Hybrid propulsion configuration for both distribution network topologies is summarized in Table C-3. It must be highlighted that the batteries are also utilized by the EMS in the case of the "Hybrid based on a DC topology" candidate in the cold ironing, stop and standby operating modes.

Table C-3: Equipment power usage per operating mode for Hybrid propulsion configuration

Task	Service	Device							
		ME 1	**ME 2**	**ME 3**	**Gen 1**	**Gen 2**	**M/G 1**	**M/G 2**	**M/G 3**
Shore Power	Cold Ironing	Off	Off	Off	Off	Off	Off	Off	Off
Dock	Stop	Off	Off	Off	Off	On	Off	Off	Off
Standby	Idle	Off	Off	Off	Off	On	On	On	On
Low Transit	Transit	Off	Off	Off	On	On/Off	On	On	On
High Transit	Transit	On	Off/On	Off/On	Off/On	Off/On	On/PTO Off	On/PTI On/PTO	On/PTI On/PTO
Assist	Tow pull	On	On	On	On/Off	On/Off	On/PTO	On/PTO	On/PTO

Transit

In this mode for both the AC and DC candidates, depending on the transit speed and the electrical load balance a combination of main engines, e-motors and auxiliary engines will be running to satisfy the total load demand. The exact control will be dictated by the EMS.

Standby

For the AC hybrid layout, in this mode, since limited propulsion power is anticipated, again the minimum number of generator sets are on-line. The priority is for the C9 genet to come online for providing the power for hotel and auxiliaries.

For the DC hybrid layout, the preferred energy source in Standby Mode is the battery arrays, but if their state of charge was to fall below a certain level, the PLC will automatically start and connect a designated auxiliary generator. Priority is set to the smaller C9 engine to come online over the bigger C18.

Assist

In this mode, all three main engines are started and their respective motor/generator can support the bus bar, depending on the total load demand, for both AC and DC candidates. The plant is operating in almost the same configuration as a conventional Rotortug, with the difference lying that the motor/generators operate in PTO mode, supporting the hotel loads. In addition, auxiliary generators may come online and run in parallel to satisfy the electric demand. The EMS again will dictate the exact control of the electrical components.

Harbour

For the AC hybrid layout, electric energy demand for hoteling purposes, when the tugboat is moored, is provided either by the C9 generator set, or by shore power.

For the DC hybrid layout in contrast, the batteries will be depleted until a predetermined state of discharge. Then, the C9 auxiliary generator is started and connected. The generator will support the charging of the batteries and hotel loads, until the batteries are charged to a predetermined level. From that point on, batteries will resume the role of supporting the vessel, and the generator will be disconnected and stopped. This cycle will be repeated for the time the tug remains docked.

Appendix D Decision-support tool supporting material

D.1 Functional requirements

In this section the main functional requirements that the decision support tool is envisaged to fulfill are attempted to be listed. The functional requirements should not be confused with technical specifications. It sets out the features that are present in the tool from a user's perspective. The non-goals of the program have been listed in Chapter 1 and are not contained in the list below.

- The tool consists of multiple spreadsheets at the same workbook, which are protected by default. The user can access the tool with normal or advanced editing rights. In the first case the user can be considered to be a normal user, while in the second case a power user. The normal user can access all spreadsheets with the purpose of navigating throughout the calculations or the database parameters, but will have no editing rights, apart from specifying the input data inside the "Input" spreadsheet. On the other hand, the power user will have advanced editing rights additionally for the "Database" spreadsheets, by unprotecting the relevant spreadsheets, but not for the rest.
- The user while being at the Input or Output spreadsheet will be able to redirect to any of the calculation spreadsheets with the intention to get an overview of the detailed calculations for each candidate configuration.
- The user while accessing any of the spreadsheets will be able to be redirected to the Input or Output tab by clicking a link at the left upper corner of the spreadsheet
- The output should provide a synoptic table listing the candidate propulsion configurations compared against the baseline configuration accompanied by interactive diagrams, which are automatically updated based on the input data, so that it can facilitate the end-user comprehension of the comparison results.
- The user when entering the input data will be informed if a non-valid entry is made in order to correct it. Moreover, in case certain entry fields are not specified by the user the program will prompt the user to insert the missing values, by highlighting the respective cell yellow, before the computation process can be initiated.
- The tool is going to be accompanied by the thesis report where the user can comprehend the reasoning behind the candidate propulsion configurations choice, the design methodology and the assumptions made.

D.2 World sea ports

For the readers convenience the list of regions pertaining in their associated area of operation is presented in Table D-1 below.

Table D-1: List of regions pertaining in their associated area of operation

Area of operation	Region
Europe	Eastern, Western, Northern, Southern
America	South, North, Central, Caribbean
Asia	Eastern, Southeast, Southern, Middle East
Oceania	Micronesia, Oceania
Africa	Eastern, Western, Northern, Southern

The list of countries pertaining in their associated region are presented in the next tables below. The list of ports is not included in this report, due to the size of the database. It is reminded that it is based on WPS and can be found at [77] site.

Table D-2: List of countries pertaining in their associated region for Europe

Northern Europe	Southern Europe	Western Europe	Eastern Europe
Denmark	Albania	Belgium	Bulgaria
Estonia	Croatia	France	Czech Republic
Faroe Islands	Gibraltar	Germany	Hungary
Finland	Greece	Monaco	Poland
Iceland	Italy	Netherlands	Romania
Ireland	Malta	Switzerland	Russia
Latvia	Montenegro		Slovakia
Lithuania	Portugal		Ukraine
Norway	Serbia		
Svalbard and Jan Mayen	Slovenia		
Sweden	Spain		
United Kingdom	Canary Islands		
Isle Of Man			

Table D-3: List of countries pertaining in their associated region for America

Central America	North America	South America	Caribbean
Belize	Canada	Argentina	Anguilla
Costa Rica	Greenland	Bolivia	Antigua and Barbuda
El Salvador	St. Pierre and Miquelon	Brazil	Aruba
Guatemala	United States	Chile	Bahamas
Honduras		Colombia	Barbados
Mexico		Ecuador	Bermuda
Nicaragua		Falkland Islands (Malvinas)	Cayman Islands
Panama		French Guiana	Cuba
		Guyana	Dominica
		Paraguay	Dominican Republic
		Peru	Grenada

		South Georgia and the South Sandwich Islands	Guadeloupe
		Suriname	Haiti
		Uruguay	Jamaica
		Venezuela	Martinique
			Montserrat
			Netherlands Antilles
			Puerto Rico
			Saint Kitts and Nevis
			Saint Lucia
			Saint Vincent and The Grenadines
			Trinidad and Tobago
			Turks and Caicos Islands
			Virgin Islands (British)
			Virgin Islands (U.S.)

Table D-4: List of countries pertaining in their associated region for Asia

Eastern Asia	**Southeast Asia**	**Southern Asia**	**Middle East**
China	Brunei Darussalam	Bangladesh	Azerbaijan
Hong Kong	Cambodia	India	Bahrain
Japan	Christmas Island	Maldives	Cyprus
Korea (North)	Indonesia	Myanmar	Georgia
Korea (South)	Malaysia	Pakistan	Iran, Islamic Republic of
Macau	Philippines	Sri Lanka	Iraq
Taiwan	Singapore		Israel
	Thailand		Jordan
	Timor-Leste		Kazakhstan
	Vietnam		Kuwait
			Lebanon
			Oman
			Qatar
			Saudi Arabia
			Syria
			Turkey
			Turkmenistan
			United Arab Emirates
			Yemen

Table D-5: List of countries pertaining in their associated region for Oceania

Micronesia	**Oceania**
Guam	American Samoa
Kiribati	Australia
Marshall Islands	Cook Islands
Micronesia, Federated States of	Fiji
Nauru	French Polynesia
Northern Mariana Islands	New Caledonia
United States Minor Outlying Islands	New Zealand
	Papua New Guinea
	Samoa
	Solomon Islands
	Tonga
	Tuvalu
	Vanuatu

Table D-6: List of countries pertaining in their associated region for Africa

Northern Africa	**Eastern Africa**	**Southern Africa**	**Western Africa**
Algeria	Comoros	Angola	Benin
Egypt	Djibouti	Congo, Democratic Republic of	Cameroon Republic
Libya	Eritrea	Madagascar	Cape Verde Islands
Morocco	Kenya	Mauritius	Congo, Republic of
Tunisia	Uganda	Mozambique	Cote D'Ivoire
	Seychelles	Namibia	Equatorial Guinea
	Somalia	Reunion	Gabon
	Sudan	South Africa	Gambia
	Tanzania	Saint Helena	Ghana
			Guinea
			Guinea-Bissau
			Liberia
			Mauritania
			Nigeria
			Sao Tome and Principe
			Senegal
			Sierra Leone
			Togo

D.3 Fuel price scenarios

For MGO the global average monthly bunker price for all port prices published on the [119] site was used. Specifically, historical prices in $/ton for the years 2014 to 2019 where reviewed and the following reference prices were established; 465 $/ton as minimum price, 659 $/ton as average price and 940 $/ton as maximum price.

Regarding the fuel pricing of LNG it was based on the Henry Hub price development as presented in the [120] site. Prices are presented in $/mmBTU. The Henry Hub price is considered representative for the cost of the feedstock gas, without accounting for processing, transportation, storage and bunkering costs. These additional costs have to be added in the Henry Hub price in order to get the bunkering price. Of course, all the aforementioned costs will vary depending on how mature the respective supply chain in the intended port of operation will be, enhancing the uncertainty of the price estimate. However, it is assumed for the purpose of this thesis, based on the reasoning provided in [121] that a total surplus cost of 7 mmBTU would be indicative of the anticipated supply chain costs for harbour vessels. Multiplying the sum of the Henry Hub price with the total supply chain cost with the assumed LHV value of 46.3 GJ/ton yields the LNG bunker price in $/ton. With that in mind, the minimum price is 414 $/ton, the average price is 471 $/ton and the maximum price is 544 $/ton.

Regarding the methanol price, it was based on natural gas as a feedstock. The European selling price data as gathered from [122] monthly average regional posted contract price history database from 2014 until 2019 were used. It indicated a minimum of $225, an average of $341 and a maximum of $450. Those prices are considered indicative of the bunkering price, because as reasoned in [115] sellers are expected to offer a discount on ship-owners interested to bunker Methanol, which would be approximately at the same range as the additional supply chain costs.

Regarding DME, estimation of the prices has been based on the monthly average market price development of DME 99% or above sold in China from 2014 to 2019 as published in [123] site. From reviewing the price development during this period and using a conversion rate of 0.15 USD/CNY (2019 rate) it is clear that there is a low price of 383$/ton in February 2016 and a top price of 731$/ton in December 2017. The average price is 524$/ton. As most of the world's DME is currently produced in China and finding DME price development for other regions was not possible, it was decided to keep the aforementioned market prices. It is quoted in various studies that the DME cost is 75% to 90% of LPG cost; being approximately at the same levels as LNG prices in the USA, so the assumed costs are within the proposed limits.

Regarding the Biodiesel price the historical development of prices was based on the FAME biodiesel spot prices, as appeared on the [124] yearly average regional posted contract price database from 2014 to 2019. It was established that the minimum price was $772, the average 906 and the maximum $1460.

The historical price development for the period 2014-2019 for all fuels under consideration in this thesis is presented in Figure D-1 on a tonne basis.

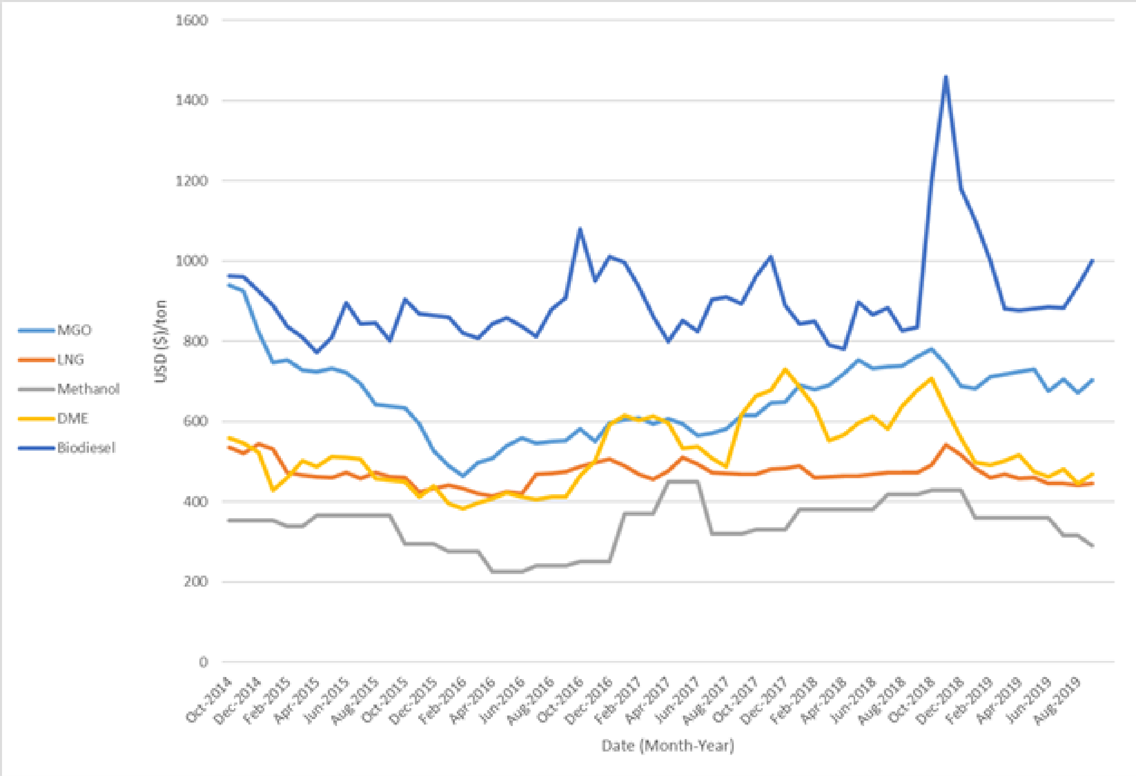


Figure D-1: Historical price development for candidate fuels from 2014 until 2019

Certain observations can be made based on that graph. It is evident that both LNG and Methanol prices are consistently lower than MGO, while Biodiesel price is constantly higher. DME price was from October 2014 until October 2016 lower than MGO, but afterwards surpassed MGO on certain time intervals which did not in general last long. Overall DME exhibited a lower price than MGO. Finally, it is assumed that in the next 15 years LNG and Methanol bunkering costs will remain lower than distillate oil prices, due to the increased adoption of both aforementioned fuels as marine bunkering fuels. For Biodiesel price, it is expected to remain higher than MGO bunker price. Concerning the MGO price it is expected to be highly impacted from the sulphur cap phasing in 2020. [125] Taking the above assumptions into consideration and with the purpose of establishing the fuel price projection scenarios, the fuel differentials are explored for the same period (2014-2019), illustrated in Figure D-2.

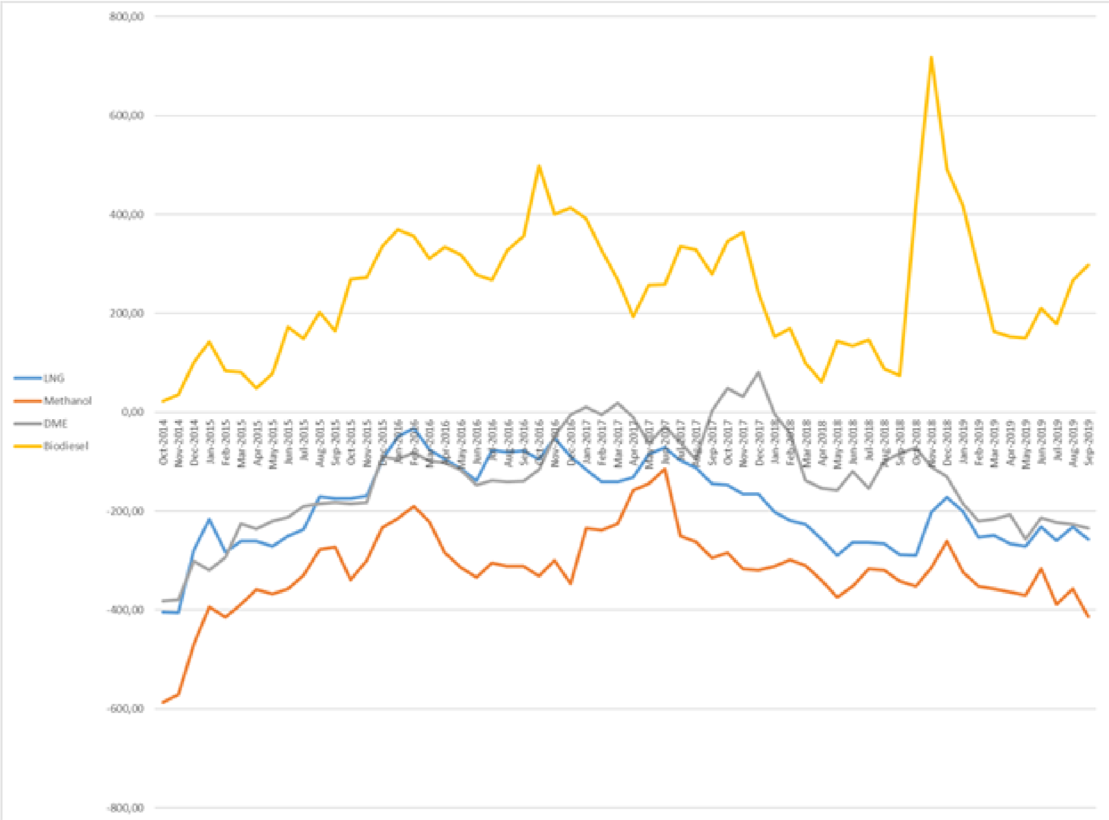


Figure D-2: Spread between the alternative fuels under examination against MGO historical prices for 2014 until 2019

For the high price scenario, the March 2018 gas price sold in Japan market was selected; 12.06 \$/mmBTU. It is evident from the above graph that between July to October 2016 LNG, Methanol and DME exhibited a relatively constant price differential against MGO. For this reason, August 2016 was picked as a representative month for the central scenario. With the purpose of defining a "favourite" and a "least-liked" scenario for the adoption of alternative fuels as marine fuels, the historical prices for October 2014 and June 2017 were selected, because the price differentials showed the maximum and the minimum spread compared to MGO price respectively.

In addition, low, average and upper limits for each of the investigated fuels have been established, from the comparison of the historical price data obtained, for the user to get an overview of the anticipated fuel price fluctuation. It is important to highlight however that these values should not be perceived as absolute and exact future estimates, rather than as reference values. The estimated alternative fuels' price ranges are summarized in Table D-7 below.

Table D-7: Fuel price ranges (in \$/ton)

Fuel	**Price ranges (\$/ton)**		
	minimum	average	maximum
MGO	465	659	940
LNG	414	471	544
Methanol	225	341	450
DME	383	524	731
Biodiesel	772	906	1460

D.4 Battery terminology

The terminology listed below cannot be considered complete; it merely addresses the terms used in the main report. The definitions are taken from [126].

C-rate – C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour.

State of Charge (SOC)(%) – An expression of the present battery capacity as a percentage of maximum capacity.

Depth of Discharge (DOD) (%) – The percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity.

Nominal Voltage (V) – The reported or reference voltage of the battery, also sometimes thought of as the "normal" voltage of the battery.

Cut-off Voltage – The minimum allowable voltage. It is this voltage that generally defines the "empty" state of the battery.

Capacity or Nominal Capacity (Ah for a specific C-rate) – The coulometric capacity, the total Amp-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage.

Energy or Nominal Energy (Wh (for a specific C-rate)) – The "energy capacity" of the battery, the total Watt-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage.

Cycle Life (number for a specific DOD) – The number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions.

Maximum Continuous Discharge Current – The maximum current at which the battery can be discharged continuously. This limit is usually defined by the battery manufacturer in order to prevent excessive discharge rates that would damage the battery or reduce its capacity.

Charge Voltage – The voltage that the battery is charged to when charged to full capacity.

D.5 Emission regulations

IMO regulations

- CO_2, CO, HC and PM are not regulated for tugboats.
- SO_x emissions are indirectly regulated through limiting the sulphur content on fuel oils.
- NO_x emissions: a vessel with a keel-laying date after 2016, should comply with either IMO Tier II or Tier III regulations depending on the area of operation (ECA or not). The applicable NO_x limits are summarized in Table D-8. Attention should be given to the fact that engines with a power capacity below 130 bkW are not subject to IMO regulations.

Table D-8: IMO Regulation 13 of Annex VI to the MARPOL 73/78 Convention NOx limits

IMO Tier	Date	NOx Limit, g/kWh		
		n < 130	*130 ≤ n < 2000*	n ≥ 2000
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96
† In NOx Emission Control Areas (Tier II standards apply outside ECAs)				

EPA regulations

- Similarly to IMO regulations, EPA does not regulate CO_2 emissions for tugboats.
- With respect to SO_x emissions they are indirectly regulated through limiting the sulphur content (15 ppm) on marine fuel oils, sold on US territory.
- In contrast to IMO regulations, EPA regulates all combustion-related emission pollutants.

The standards and implementation schedules applied to commercial Category 1 and 2 marine engines, for use as main and auxiliary power applications in newly-built Rotortugs are shown in Table D-9 through Table D-11. It must be highlighted that Tier 4 standards are in force since 2017. Tier 4 standards are applied to newly-manufactured commercial marine engines at or above 600 kW. For power levels below 600 kW the previous Tier 3 standards continue to apply, based on the Category type.

Table D-9: Tier 3 Standards for Marine Diesel Category 1 commercial engines

Power (P)	Displacement (D)	NOx+HC	PM	Date
kW	*dm^3 per cylinder*	*g/kWh*	*g/kWh*	
P < 19	D < 0.9	7.5	0.4	2009
19 ≤ P < 75	D < 0.9[a]	4.7	0.3	2014
75 ≤ P < 600	D < 0.9	5.4	0.14	2012
	0.9 ≤ D < 1.2	5.4	0.12	2013
	1.2 ≤ D < 2.5	5.6	0.10	2018
	2.5 ≤ D < 3.5	5.6	0.10	2018
	3.5 ≤ D < 7	5.8	0.10	2018
a - < 75 kW engines ≥ 0.9 dm^3/cylinder are subject to the corresponding 75-3700 kW standards.				

Table D-10: Tier 3 Standards for Marine Diesel Category 2 commercial engines

Power (P)	Displacement (D)	NOx+HC	PM	Date
kW	*dm^3 per cylinder*	*g/kWh*	*g/kWh*	
P < 600	7 ≤ D < 15	6.2	0.14	2013
	15 ≤ D < 20	7	0.34	2014
	20 ≤ D < 25	9.8	0.27	2014
	25 ≤ D < 30	11	0.27	2014

Table D-11: Tier 4 Standards for Marine Diesel Category 1/2 commercial engines

Power (P)	PM	NOx	HC	Date
kW	*g/kWh*	*g/kWh*	*g/kWh*	
P ≥ 3700	0.06	1.8	0.19	2016
2000 ≤ P < 3700	0.04	1.8	0.19	2014
1400 ≤ P < 2000	0.04	1.8	0.19	2016
600 ≤ P < 1400	0.04	1.8	0.19	2017

In addition to the above NOx, HC and PM standards, the following CO emission standards apply for all Category 1 and 2 commercial marine engines, as presented in Table D-12.

Table D-12: Tier 3/4 CO emission limits for Marine Diesel Category 1/2 commercial engines

Power (P)	CO
kW	*g/kWh*
P < 8	8.0
8 ≤ P < 19	6.6
19 ≤ P < 37	5.5
P ≥ 37	5.0

EU regulations

Similarly to the EPA regulations, CO_2 emissions targeting tugboats are not regulated in the European Union, while SO_x emissions are indirectly regulated through limiting the sulphur content on marine fuel oils, by obligating all vessels berthed or anchored at European ports to burn marine fuel with a sulphur content not exceeding 0.1 per cent by mass. Furthermore, the rest of the combustion-related emissions are also not regulated for harbour tugboats. Nonetheless, as explained in Chapter 3, the emission standards applied to EU inland vessels are adopted for harbour/terminal tugboats' emission compliance verification. This assumption is deemed reasonable, since tugboats intended for use in inland waterways are indeed regulated by the EU 2016/1628 regulation, and in the future it is anticipated that the same might be applied for sea-going tugboats, in order to harmonize EU emission standards with the US regulatory Tiers. The standards and implementation schedules applied to marine engines, for use as main and auxiliary power applications in newly-built Rotortugs are shown in Table D-13 through Table D-14.

Table D-13: EU 2016/1628 (EU Stage IIIA) Standards for marine engines

Category	Displacement (D)	Date	CO	Nox + HC	PM
	(dm3 per cylinder)		g/kWh	*g/kWh*	*g/kWh*
V1:1	D ≤ 0.9, P > 37 kW	2007	5	7.5	0.4
V1:2	0.9 < D ≤ 1.2		5	7.2	0.3
V1:3	1.2 < D ≤ 2.5		5	7.2	0.2
V1:4	2.5 < D ≤ 5	2009	5	7.2	0.2
V2:1	5 < D ≤ 15		5	7.8	0.27
V2:2	15 < D ≤ 20, P ≤ 3300 kW		5	8.7	0.5
V2:3	15 < D ≤ 20, P > 3300 kW		5	9.8	0.5
V2:4	20 < D ≤ 25		5	9.8	0.5
V2:5	25 < D ≤ 30		5	11	0.5

Table D-14: EU 2016/1628 (EU Stage V) Standards for marine engines

Category	Net Power	Date	CO	HC[a]	NOx	PM	PN
	kW		*g/kWh*				*1/kWh*
IWP/IWA-v/c-1	$19 \leq P < 75$	2019	5	4.7[b]		0.3	-
IWP/IWA-v/c-2	$75 \leq P < 130$	2019	5	5.4[b]		0.14	-
IWP/IWA-v/c-3	$130 \leq P < 300$	2019	3.5	1	2.1	0.1	-
IWP/IWA-v/c-4	$P \geq 300$	2020	3.5	0.19	1.8	0.015	1×10^{12}
a - A = 6.00 for gas engines b - HC + Nox (combined)							

It must be highlighted that there are no Stage IV emission limits for inland vessels, thus not included. Furthermore, engines below 19 kW are not regulated. EPA Tier 3 and 4 are the equivalent emission standards to the EU Stage IIIA and V. However, at EU Stage V, an additional limit of $1x10^{12}$ #/kWh, on the number of solid particles emitted for engines rated at ≥ 300 kW, has been introduced. The introduction of more stringent emission limits for PM emissions and especially the inclusion of a PN limit, is widely considered from industry-experts that will mandate installation of DPFs. Moreover, the HC limits differ for gaseous fuelled engines. An “A” factor is defined, set equal to 6, and the HC limit for the corresponding engine categories is calculated using the formula HC = 0,19 + (1,5 x A x GER), where GER is the average gas energy ratio. The upper limit of this formula is set to 0,19 + A = 6,19, which is adopted for simplicity, as the required HC limit, instead of the limit derived by the aforesaid formula. Finally, regarding the engine category nomenclature, followed under EU Stage V, IWP/IWA stands for Inland Waterway vessels Propulsion/Auxiliary engines respectively and v/c stands for variable/constant -speed.

D.6 ISO 8178 test cycles

For verification of compliance of marine diesel engines with combustion-related emission limits, a standardised test procedure prescribed in ISO 8178 is performed. The used test cycles, according to the envisaged application, are presented in Table D-15.

Table D-15: Test cycles according to ISO 8178

Application	Test Cycle
Constant-speed marine engines for ship main propulsion, including diesel-electric drive	E2
Variable-pitch propeller sets	E2
Propeller-law-operated main and propeller-law-operated auxiliary engines	E3
Constant-speed auxiliary engines	D2
Variable-speed, variable-load auxiliary engines, not included above	C1

Each test cycle consists of a number of distinct operating modes, with differing weighting factors, under which emission measurements are performed in steady-state condition. As explained in Chapter 4, all prime movers envisaged for use as main engines are “propeller-law operated”, while all prime movers envisaged for use as auxiliary engines are “constant-speed”. For this reason, they are tested according to the E3 and D2 ISO 8178 test cycles respectively. To this end, the relevant test cycles are presented in Table D-16 and Table D-17 below.

Table D-16: Test cycle for propeller-law-operated main engine application

Test cycle type E3	Speed	100%	91%	80%	63%
	Power	100%	75%	50%	25%
	Weighting factor	0.2	0.5	0.15	0.15

Table D-17: Test cycle for constant-speed auxiliary engine application

Test cycle type D2	Speed	100%	100%	100%	100%	100%
	Power	100%	75%	50%	25%	10%
	Weighting factor	0.05	0.25	0.3	0.3	0.1

D.7 Transmission losses derivation

A synoptic presentation of the candidate drivetrain transmission losses is given below together with the rationale behind the conversion of power demand to required brake power. The values for the apparatus efficiency losses are taken by the “Equipment efficiency losses” section of the database. It has to be highlighted that the number and rated power of the selected main and auxiliary engines has been selected, for each candidate propulsion configuration, so as to sufficiently meet the maximum propulsion and electrical power demand anticipated, as provided in the “Duty Cycle” block. The maximum propulsion power demand is experienced during the BP condition, while the maximum electrical power demand during transit condition.

Conventional propulsion configuration

Each azimuth stern drive thruster is driven mechanically by a main engine via a clutch and an intermediate shaft. These means that the propulsion transmission losses consist of the losses in the shaft line η_{shaft}, the clutch η_{clutch} and the Z-drive gear box $\eta_{Z\text{-}drive}$. Therefore, the propulsion transmission efficiency η_{TRM} would be:

$$\eta_{(TRM)CONV} = \eta_{Shaft} \cdot \eta_{Clutch} \cdot \eta_{Z-drive} \tag{66}$$

The required main engine brake power $P_{B,prop,req}$ is a function of the delivered engine power to the thruster’s propeller Pp and the transmission efficiency η_{TRM}:

$$P_{(B,prop,req)CONV} = \frac{P_p}{\eta_{(TRM)CONV}} \tag{67}$$

In terms of estimating the electrical distribution losses the generator’s nominal efficiency η_{gen} and the AC switchboard efficiency $\eta_{AC\ SB}$ have to be taken into account. Therefore, the electric distribution efficiency would be

$$\eta_{(el\ dis)CONV} = \eta_{Gen} \cdot \eta_{AC\ SB} \tag{68}$$

The required auxiliary engine brake power $P_{B,aux,req}$ is a function of the electrical power demand P_{el}, as estimated in the Electrical Load Analysis, depending on the mode of operation and the electric distribution efficiency $\eta_{(el\ dis)CONV}$:

$$P_{(B,aux,req)CONV} = \frac{P_{el}}{\eta_{(el\ dis)CONV}} \tag{69}$$

Diesel-electric propulsion configuration (DEP)

In contrast with the conventional propulsion configuration the total energy demand both for propulsion and auxiliary needs is satisfied from the installed generator sets. The transmission losses would be the product of both electrical and mechanical losses incurred between the diesel engines driving their respective alternator and the thrusters' propellers. Specifically, the nominal generator's efficiency η_{gen}, the AC switchboard efficiency $\eta_{AC\ SB}$, the frequency converter (VFD) η_{VFD} efficiency, the electric motors η_{EM} efficiency, connected to their associated propeller's shaft and the Z-drive gearing $\eta_{Z\text{-}drive}$ efficiency have to be taken into account. Thus, the propulsion transmission efficiency η_{TRM} would be:

$$\eta_{(TRM)DEP} = \eta_{Gen} \cdot \eta_{AC\ SB} \cdot \eta_{VFD} \cdot \eta_{EM} \cdot \eta_{Z-drive} \tag{70}$$

As a consequence, the propulsion transmission losses would be bigger in comparison to the conventional drivetrain, thus more power is required to deliver the same amount of power to the propeller.

$$P_{(B,prop,req)DEP} = \frac{P_P}{\eta_{(TRM)DEP}} \tag{71}$$

In addition the electrical power demand for auxiliary consumers has to be added in the total electrical power to be satisfied by the connected diesel generators. The electrical distribution losses for these auxiliaries and the brake power required for auxiliaries would be

$$\eta_{(el\ dis)DEP} = \eta_{Gen} \cdot \eta_{AC\ SB} \tag{72}$$

$$P_{(B,aux,req)DEP} = \frac{P_{el}}{\eta_{(el\ dis)DEP}} \tag{73}$$

The required brake power $P_{(B,req)DEP}$ is the sum of the of the required brake power for propulsion and electric needs.

$$P(B,req)DEP = P_{(B,prop,req)DEP} + P_{(B,aux,req)DEP} \tag{74}$$

Hybrid propulsion configuration (Hybrid)

The hybrid concept layouts chosen to be investigated is one that combines the conventional technology as described in the DDP layout and the use of separate electric motors installed between each of the main engines and the Z-drives, so that they are in series with the main engines. Power to the thrusters is provided either from the main engine or the electric motor, depending on the operating mode, but not simultaneously from both. Two options are investigated. The first option is based on an AC topology, while the second on a main DC topology utilizing a secondary AC distribution switchboard supplemented by batteries. Depending on the operating mode under investigation the propulsion and electrical transmission losses will differ, since the power flow changes. A separate energy management strategy algorithm is developed for the two Hybrid propulsion configurations variants, which take into account the differing energy efficiency losses. The machinery configuration power utilization for the transit and tow pull services is in principle the same. They differ for stop and idle services. Particularly, in the "Hybrid based on DC topology" the batteries power utilization has to be taken into account. The total transmission efficiency between the AC and the DC topology variants will be different however.

Since it is not the goal of this section to analytically explain step by step the transmission efficiency derivation for each operating mode, rather provide the principles governing the estimation procedure, only the transit mode of the "Hybrid based on an AC topology" will be explained. This mode is considered an indicative example of demonstrating the varying transmission losses incurred throughout the power flow. The VBA code is governed by confidentiality closure agreement and therefore is not available to the reader.

For the reader's convenience the operating matrix per task/service for the Hybrid configuration based on an AC topology, is once again depicted in Table D-18, as presented in Appendix C.3.3.

Table D-18: Hybrid based on AC electric distribution equipment utilization level per operating mode

Task	Service	Device							
		ME 1	**ME 2**	**ME 3**	**Gen 1**	**Gen 2**	**M/G 1**	**M/G 2**	**M/G 3**
Shore Power	**Cold Ironing**	Off	Off	Off	Off	Off	Off	Off	Off
Dock	**Stop**	Off	Off	Off	Off	On	Off	Off	Off
Standby	**Idle**	Off	Off	Off	Off	On	On	On	On
Low Transit	**Transit**	Off	Off	Off	On	On/Off	On	On	On
High Transit	**Transit**	On	Off/On	Off/On	Off/On	Off/On	(On/PTO) Off*	On/PTI (On/PTO)*	On/PTI (On/PTO)*
Assist	**Tow pull**	On	On	On	On/Off	On/Off	On/PTO	On/PTO	On/PTO

In each of these modes, the resources that might be used to support vessel services and propulsion are different. It can be observed that two conditions have been established for the transit mode, the low and high transit condition.

Low transit conditions

In low transit modes there is no need for starting a main engine. The propulsion and electrical power is satisfied by the auxiliary engines, and the thrusters' propellers are driven by their respective motor, according to the throttle position in the wheelhouse. The MCD clutches remain in the fully open position. Priority has been set on the C18 generator to be started first. If additional power is required, the C9 generator will come on-line. In such conditions the propulsion transmission losses as well as the electrical distribution losses will be the same as in the DEP case.

$$\eta_{(TRM)HYBRID} = \eta_{gen} \cdot \eta_{AC\,SB} \cdot \eta_{VFD} \cdot \eta_{EM} \cdot \eta_{Z-drive} \tag{75}$$

$$\eta_{(el\,dis)HYBRID} = \eta_{Gen} \cdot \eta_{AC\,SB} \tag{76}$$

Therefore, the required brake power $P_{(B,req)HYBRID}$ is the sum of the of the required brake power for propulsion and electric needs.

$$P(B,req)HYBRID = P_{(B,prop,req)HYBRID} + P_{(B,aux,req)HYBRID} = \frac{P_P}{\eta_{(TRM)HYBRID}} + \frac{P_{el}}{\eta_{(el\,dis)HYBRID}} \tag{77}$$

High transit conditions

In high transit conditions a plethora of energy sources combination might be utilized depending on the transit speed and thus the power requirement. Three basic scenarios are developed for this purpose in the EMS strategy employed. In the first scenario the center main engine is started to drive its thruster. The center M/G acts as a shaft generator, providing power to the AC bus. The energy produced, is sufficient to support electric propulsion on the outboard thrusters (the center thruster is driven by its main engine), as well as for vessel services. For higher transit speed bands, which is the second scenario, the auxiliary generators will need to come on-line to support the AC bus. Finally, in the third scenario, in which the power demand cannot longer be supported by the aforementioned energy sources, the other two main engines will start running, driving their respective thrusters with the clutches fully engaged. In this case the motor-generators of the outboard thrusters will also operate in PTO mode, contributing to the electrical power demand. The auxiliary engines will stay off-line, since the required power will never be bigger than the available power reserve. For each case the transmission losses will differ.

Scenario 1

If the centre main engine is able to meet the total power demand, then the transmission losses would be

$$\eta_{(TRM)HYBRID} = \eta_{Shaft} \cdot \eta_{Clutch} \cdot \eta_{Z-drive} \tag{78}$$

$$\eta_{(el\,dis)HYBRID} = \eta_{Shaft} \cdot \eta_{Clutch} \cdot \eta_{EM} \cdot \eta_{VFD} \cdot \eta_{AC\,SB} \tag{79}$$

Therefore, the required brake power $P_{(B,req)HYBRID}$ of the center main engine is the sum of the of the required brake power for propulsion and electric needs.

$$P(B,req)HYBRID = P_{(B,prop,req)HYBRID} + P_{(B,aux,req)HYBRID} = \frac{P_P}{\eta_{(TRM)HYBRID}} + \frac{P_{el}}{\eta_{(el\,dis)HYBRID}} \tag{80}$$

Scenario 2

In this scenario the propulsion power demand of the center thruster will still be satisfied by the center main engine, but the remaining electrical power demand, both for propulsion and auxiliaries will be satisfied partly by the remaining main engine's power capability and the rest by the auxiliary diesel generators. It has to be highlighted that, in order for prime movers to operate in an efficient power range, in terms of SFC and SEF, the desired maximum load has been set at 85% MCR, for prime movers used as main engines and at 90% for prime movers used for auxiliary purposes. Therefore, the power flow will be subject to the following transmission/distribution losses

$$\eta_{(TRM)HYBRID} = \eta_{Shaft} \cdot \eta_{Clutch} \cdot \eta_{Z-drive} \tag{81}$$

$$\eta_{(el\ dis)HYBRID} = \eta_{(el\ dis)ME} + \eta_{(el\ dis)AUX\ ENG} \tag{82}$$

$$\eta_{(el\ dis)ME} = \eta_{Shaft} \cdot \eta_{Clutch} \cdot \eta_{EM} \cdot \eta_{VFD} \cdot \eta_{AC\ SB} \tag{83}$$

$$\eta_{(el\ dis)AUX\ ENG} = \eta_{Gen} \cdot \eta_{AC\ SB} \tag{84}$$

Therefore, the required brake power $P_{(B,req)HYBRID}$ will be the sum of the of the required brake power for propulsion provided by the centre main engine and the remaining combined propulsion and auxiliary electric needs, satisfied partly from the centre motro-generator and partly from the auxiliary diesel generators.

$$P(B,req)HYBRID = \frac{1/3 * P_P}{\eta_{(TRM)HYBRID}} + \left\{ \frac{(x * 2/3) * P_P}{\eta_{(el\ dis)ME}} + \frac{[(1-x) * 2/3] * P_P + P_{el}}{\eta_{(el\ dis)AUX\ ENG}} \right\} \tag{85}$$

Where x is the percentage (%)

Scenario 3

In this scenario, the propulsion power is satisfied exclusively by their respective main engine, similarly to the Conventional case. However, the electric needs are satisfied by the three motor-generators, operating in PTO mode. The transmission losses for propulsion and auxiliaries would be:

$$\eta_{(TRM)HYBRID} = \eta_{Shaft} \cdot \eta_{Clutch} \cdot \eta_{Z-drive} \tag{86}$$

$$\eta_{(el\ dis)HYBRID} = \eta_{Shaft} \cdot \eta_{Clutch} \cdot \eta_{EM} \cdot \eta_{VFD} \cdot \eta_{AC\ SB} \tag{87}$$

Therefore, the required brake power $P_{(B,req)HYBRID}$ is the sum of the of the required brake power for propulsion and electric needs.

$$P(B,req)HYBRID = P_{(B,prop,req)HYBRID} + P_{(B,aux,req)HYBRID} = \frac{P_P}{\eta_{(TRM)HYBRID}} + \frac{P_{el}}{\eta_{(el\ dis)HYBRID}} \tag{88}$$

Cold ironing

Finally, the power management for cold ironing mode has also been developed. The tugboat will be connected to shore power only when secured at the dock and the shore power cable is connected to the vessel. The shore power will be conventionally using the AC switchboard for all candidate propulsion configurations. When the tugboat is on cold ironing mode, all energy sources are off and the vessel is powered using shore-based electricity. However, transmission and distribution losses in the system must be considered in order to compare emissions at the point of consumption. The electricity power demand when at dock has to be converted in required brake power. The power flow comprises of the power transformer, the connecting cable socket (shore supply jb) and the AC switchboard. Therefore, the electric distribution losses and the required brake power would be:

$$\eta_{(el\,dis)COLD\,IRONING} = \eta_{TF} \cdot \eta_{Shore\,JB} \cdot \eta_{AC\,SB} \tag{89}$$

$$P_{(B,aux,req)COLD\,IRONING} = \frac{P_{el\,STOP\,MODE}}{\eta_{(el\,dis)COLD\,IRONING}} \tag{90}$$

D.8 Grey Relational Analysis (GRA)

According to [88] the required number of steps of the proposed framework are summarized below. Let the number of candidate propulsion configuration variants under consideration be m, and the number of valuation metrics be n. It is reminded that bunkering availability, as inserted in the Input spreadsheet by the user initially, is used as a cut-off criterion; thus, m will equal the number of fuels that can be bunkered in the designated area of intended operation

Step 1 : Generate reference data series x_0

$$x_0 = (\mathrm{d}_{0,1}, d_{0,2}, \dots, d_{0,m}) \tag{91}$$

In general, the x_0 reference data series consist of the optimal values depending on the valuation metric under consideration. These data are established from the comparison of the individual values assigned for each performance metric for the available alternatives taking into consideration the relevant decision rule, as discussed in the three (3) individual "technical-evaluation" sub-blocks. The aforesaid data are used as input in tabulated format, for step 1.

It is stressed that the model formulation process of GRA at step 1 is taking into consideration the decision rules for generating the reference data series x_0**.** Specifically, when competing options are judged on their economic performance, there is an elimination process, for alternatives that score worse than the baseline case for all cash flow metrics.

Step 2: Normalization of data set

The criteria matrix was normalized using two approaches: For criteria if the larger value is better, the matrix can be normalized using larger the better concept using equation (92), while for a criteria if the smaller value is better, the matrix can be normalized using smaller the better concept using equation (93).

$$x_{ij}^* = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \tag{92}$$

$$x_{ij}^* = \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \tag{93}$$

Where, i=1,2,…,m (Alternatives); j=1,2,…,n (Criteria)

Then the absolute difference was calculated between the normalized cell value and the corresponding referential series value by using equation (94).

$$\text{Absolute difference} : \Delta_{ij} = \left| x_{0j}^* - x_{ij}^* \right| \tag{94}$$

Where x_{0j}^*= referential series value of j^{th}criteria; x_{ij}^*= normalized cell value of j^{th}criteria

Step 3 : Calculation of the grey relational coefficient $\gamma(x_{0j}^*, x_{ij}^*)$

Grey relational coefficient is calculated to express the relationship between the best and the actual results, by using the following equation (95).

$$\gamma(x_{0j}^*, x_{ij}^*) = \frac{\Delta_{min} + \zeta * \Delta_{max}}{\Delta_{ij} + \zeta * \Delta_{max}} \tag{95}$$

Where $\Delta_{min} = \min_{i,j} \Delta_{ij}$; $\Delta_{max} = \max_{i,j} \Delta_{ij}$ and ζ = distinguishing coefficient, $\zeta \in [0,1]$

The distinguishing coefficient ζ is used to compensate the effect of Δmax. In general the value of ζ can be set as 0.5. [86]

<u>Step 4</u> : Calculation of the grey relational grade Γ(X0,Xi) using the equation (96)

$$\Gamma(X_0, X_\iota) = \sum_{j=1}^{n} w_j * \gamma\left(x_{0j}^{*}, x_{ij}^{*}\right) \tag{96}$$

Where w_j = weightage of criteria j. It applies that $\sum_{j=1}^{n} w_j = 1$ και $w_j \geq 0 \; \forall \, j$.

The result obtained by using equation (96) can be applied to rank the available alternatives. The option with the highest grey relational grade would be also the preferred solution.

In this work the weights are assigned to valuation metrics using a rank order weighting formula, which is a ranking method of weights determination, included in the category of weight approximation techniques. Rank ordering the importance of performance attributes is easier than directly determining the exact weights, so it was preferred in this research. The rank order weight determination involves two steps, first the performance attributes are ranked according to their importance by the decision-maker and secondly the selected rank order weighting formula, Rank Reciprocal given by equation (97), is used for deriving the final weighting. This specific formula was preferred among others, because the performance attribute with the biggest importance gets a higher weighting score compared to the other available methods.

$$w_j(RR) = \frac{1/r_j}{\sum_{k=1}^{n} 1/r_k} \tag{97}$$

Where rj is the rank of the j-th criterion, j=1,2,…,n.

Appendix E Decision-support tool results

The results for the two case studies are summarized below.

E.1 Case Study 1 – Terminal tug

Table E-1: Mission profile for case study 1 (terminal tug)

Mode	Utilization rate (%)	Duration [hours/year]
Standby	17%	245
Transit low (6.6 knots)	12%	173
Transit light (8.5 knots)	25%	360
Transit high (12.5 knots)	5%	72
Assist low 10 % BP	20%	288
Assist medium 40 % BP	15%	216
Assist high 75 % BP	4%	58
Bollard Pull (100%)	2%	28

E.1.1 Economic performance results

Table E-2: Results summary for case study 1 (terminal tug) based on economic performance decision criterion from a ship-owner perspective

ID	Nomenclature	Candidates	Combustion fuel	GRA	IMO
1	CONV-S2	LBSI (LNG)	LNG	0.950	yes
2	CONV-S1	LPDF (LNG)	LNG	0.877	yes
3	HYBRID-S2	LBSI (LNG)	LNG	0.813	yes

Table E-3: Part 1/4 of financial valuation metrics results for case study 1(terminal tug)

Cash flow metrics results	CONV-S2	CONV-S1	HYBRID-S2	HYBRID with bat-S2	HYBRID with bat-S1
Net Investments	$677,148	$865,860	$2,661,285	$3,640,305	$3,830,925
NPV	$-148,675	$-516,345	$-854,125	$-1,531,088	$-1,721,708
IRR	5.92%	1.38%	0.41%	-1.76%	-2%
Payback period	15.6	25.5	26.7	No	No

Table E-4: Part 2/4 of financial valuation metrics results for case study 1(terminal tug)

Cash flow metrics results	HYBRID-S1	HYBRID with bat-S6	CONV-S6	HYBRID with bat-S4	HYBRID-S6
Net Investments	$2,846,655	$4,440,794	$1,174,686	$10,021,257	$3,498,731
NPV	$-1,089,000	$-1,793,896	$-460,962	$-3,521,696	$-1,139,748
IRR	-1%	does not exist	does not exist	does not exist	does not exist
Payback period	No	No	No	No	No

Table E-5: Part 3/4 of financial valuation metrics results for case study 1(terminal tug)

Cash flow metrics results	HYBRID with bat-S3	HYBRID-S3	CONV-S4	HYBRID-S4	Diesel Electric-Base Case
Net Investments	$3,698,925	$2,716,905	$6,829,230	$9,051,083	$1,696,740
NPV	$-1,946,076	$-1,283,243	$-2,212,103	$-2,857,848	$-394,007
IRR	does not exist	does not exist	does not exist	does not exist	-3%
Payback period	No	No	No	No	No

Table E-6: Part 4/4 of financial valuation metrics results for case study 1(terminal tug)

Cash flow metrics results	HYBRID with bat-Base Case	CONV-S3	HYBRID-Base Case
Net Investments	$2,951,065	$739,860	$2,341,898
NPV	$-1,126,364	$-631,484	$-683,995
IRR	does not exist	-4%	does not exist
Payback period	No	No	No

E.1.2 Environmental performance results

Table E-7: Part 1/2 of results summary for case study 1 (terminal tug) based on environmental performance decision criterion

ID	Nomenclature	Candidates	Combustion fuel	GRA	IMO
1	CONV-S2	LBSI (LNG)	LNG	0.88	yes
2	HYBRID with bat-S2	LBSI (LNG)	LNG	0.81	yes
3	HYBRID-S2	LBSI (LNG)	LNG	0.74	yes
4	HYBRID with bat-S1	LPDF (LNG)	LNG	0.67	yes
5	HYBRID-S1	LPDF (LNG)	LNG	0.60	yes
6	HYBRID with bat-S6	4xCI (DME)	DME	0.59	yes
7	CONV-S6	4xCI (DME)	DME	0.57	yes
8	HYBRID with bat-S4	4xCI (Biodiesel)	Biodiesel	0.54	yes
9	HYBRID-S6	4xCI (DME)	DME	0.52	yes
10	HYBRID with bat-S3	LPDF (Methanol)	Methanol	0.51	yes
11	CONV-S1	LPDF (LNG)	LNG	0.49	yes
12	HYBRID-S3	LPDF (Methanol)	Methanol	0.46	yes
13	CONV-S4	4xCI (Biodiesel)	Biodiesel	0.46	yes
14	HYBRID-S4	4xCI (Biodiesel)	Biodiesel	0.45	yes
15	Diesel Electric-Base Case	4xCI (MGO)	MGO	0.43	yes
16	HYBRID with bat-Base Case	4xCI (MGO)	MGO	0.41	yes
17	CONV-S3	LPDF (Methanol)	Methanol	0.40	yes
18	HYBRID-Base Case	4xCI (MGO)	MGO	0.36	yes

Table E-8: Part 2/2 of results summary for case study 1 (terminal duty) based on environmental performance decision criterion

ID	Nomenclature	Endurance	Range	Alternative fuel	MGO	Urea
1	CONV-S2	24.67	4736	89	74	-
2	HYBRID with bat-S2	22.67	4352	95	31	-
3	HYBRID-S2	22.67	4352	94	32	-
4	HYBRID with bat-S1	22.88	4392	95	31	-
5	HYBRID-S1	22.50	4320	102	31	-
6	HYBRID with bat-S6	20.67	3968	86	32	-
7	CONV-S6	22.67	4352	82	68	-
8	HYBRID with bat-S4	34.96	6712	146	31	-
9	HYBRID-S6	20.67	3968	86	32	-
10	HYBRID with bat-S3	17.42	3344	72	31	-
11	CONV-S1	24.75	4752	134	30	-
12	HYBRID-S3	17.13	3288	78	31	-
13	CONV-S4	36.33	6976	131	109	-
14	HYBRID-S4	34.96	6712	145	32	-
15	Diesel Electric-Base Case	42.26	8113	-	141	-
16	HYBRID with bat-Base Case	43.88	8425	-	154	-
17	CONV-S3	18.83	3616	102	30	-
18	HYBRID-Base Case	43.88	8425	-	143	-

Table E-9: Part 1/4 of emission reduction (%) comparison results for case study 1(terminal tug)

Emission output comparison results	CONV-S2	HYBRID with bat-S2	HYBRID-S2	HYBRID with bat-S1	HYBRID-S1
NO_x	-80%	-81%	-76%	-68%	-63%
HC/10	156%	97%	101%	109%	113%
PM	-94%	-97%	-83%	-77%	-62%
CO	179%	69%	93%	62%	86%
CO_2	-16%	-11%	-12%	-11%	-10%
SO_x	-83%	-77%	-77%	-77%	-70%

Table E-10: Part 2/4 of emission reduction (%) comparison results for case study 1(terminal tug)

Emission output comparison results	HYBRID with bat-S6	CONV-S6	HYBRID with bat-S4	HYBRID-S6	HYBRID with bat-S3
NO_x	-39%	-32%	-5%	-35%	-38%
HC/10	-4%	0%	-8%	0%	11%
PM	-99%	-97%	-79%	-84%	-78%
CO	-42%	0%	-58%	-18%	-12%
CO_2	-4%	-8%	6%	-4%	-2%
SO_x	-77%	-83%	-76%	-78%	-77%

Table E-11: Part 3/4 of emission reduction (%) comparison results for case study 1(terminal tug)

Emission output comparison results	CONV-S1	HYBRID-S3	CONV-S4	HYBRID-S4	Diesel Electric-Base Case
NO_x	-42%	-34%	7%	-1%	-27%
HC/10	83%	15%	-6%	-4%	-1%
PM	-20%	-63%	-56%	-64%	-70%
CO	76%	12%	-27%	-34%	-43%
CO_2	-10%	-2%	2%	5%	5%
SO_x	-55%	-70%	-82%	-77%	5%

Table E-12: Part 4/4 of emission reduction (%) comparison results for case study 1(terminal tug)

Emission output comparison results	HYBRID with bat-Base Case	CONV-S3	HYBRID-Base Case
NO_x	-11%	-20%	-7%
HC/10	-4%	11%	0%
PM	-52%	-21%	-37%
CO	-42%	22%	-18%
CO_2	-3%	-4%	4%
SO_x	-3%	-55%	4%

In addition, the comparison results for the emission reduction per year, in kilos, for all 18 alternatives are presented in the tables below.

Table E-13: Part 1/4 of emission reduction per year (in kilos) comparison results for case study 1(terminal tug)

Emission output comparison results	CONV-S1	CONV-S2	CONV-S3	CONV-S4	CONV-S6
NO_x	-5643	-10801	-2707	948	-4329
HC	6989	13186	935	-528	0
PM	-161	-760	-167	-453	-785
CO	2418	5713	685	-859	0
CO_2	-113422	-171496	-43955	18419	-83034
SO_x	-375	-567	-376	-562	-569

Table E-14: Part 2/4 of emission reduction per year (in kilos) comparison results for case study 1(terminal tug)

Emission output comparison results	HYBRID-Base Case	HYBRID-S1	HYBRID-S2	HYBRID-S3	HYBRID-S4
NO_x	-946	-8566	-10336	-4601	-122
HC	-24	9509	8541	1252	-367
PM	-296	-504	-667	-511	-517
CO	-562	2737	2956	372	-1091
CO_2	41433	-110959	-127024	-17624	59526
SO_x	26	-478	-531	-479	-526

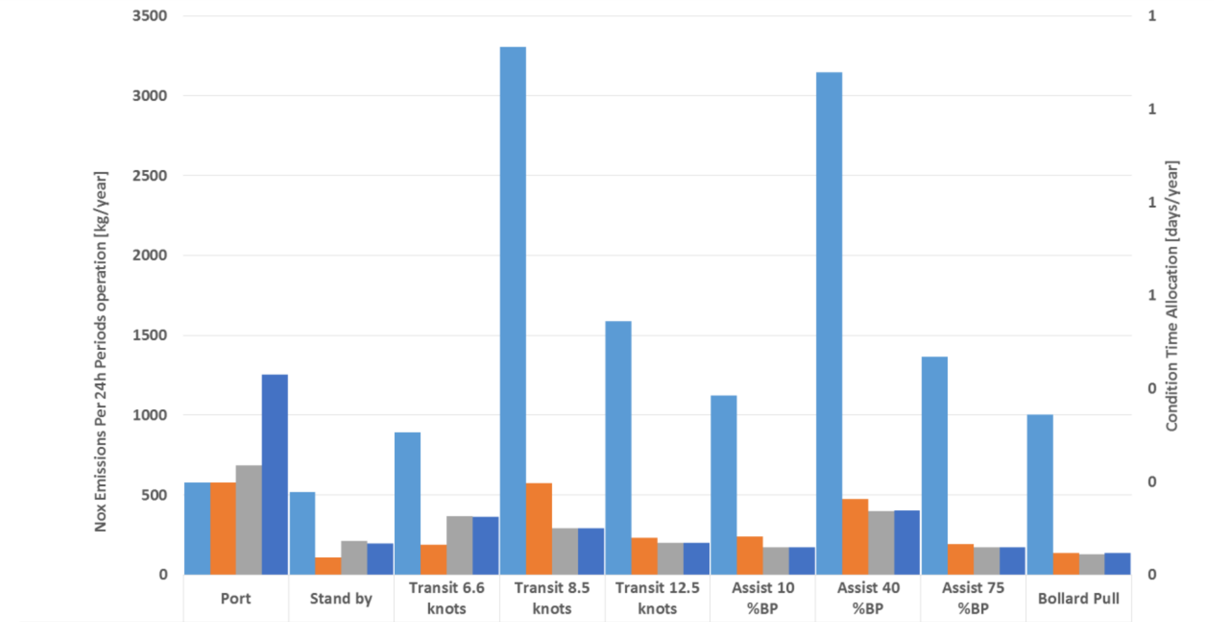
Table E-15: Part 3/4 of emission reduction per year (in kilos) comparison results for case study 1(terminal tug)

Emission output comparison results	HYBRID-S6	HYBRID with bat-Base Case	HYBRID with bat-S1	HYBRID with bat-S2	HYBRID with bat-S3
NO_x	-4709	-1542	-9142	-10898	-5187
HC	-24	-324	9182	8201	948
PM	-679	-416	-623	-785	-631
CO	-562	-1324	1976	2185	-389
CO_2	-40130	-37426	-123474	-123474	-20812
SO_x	-533	-23	-526	-526	-528

Table E-16: Part 4/4 of emission reduction per year (in kilos) comparison results for case study 1(terminal tug)

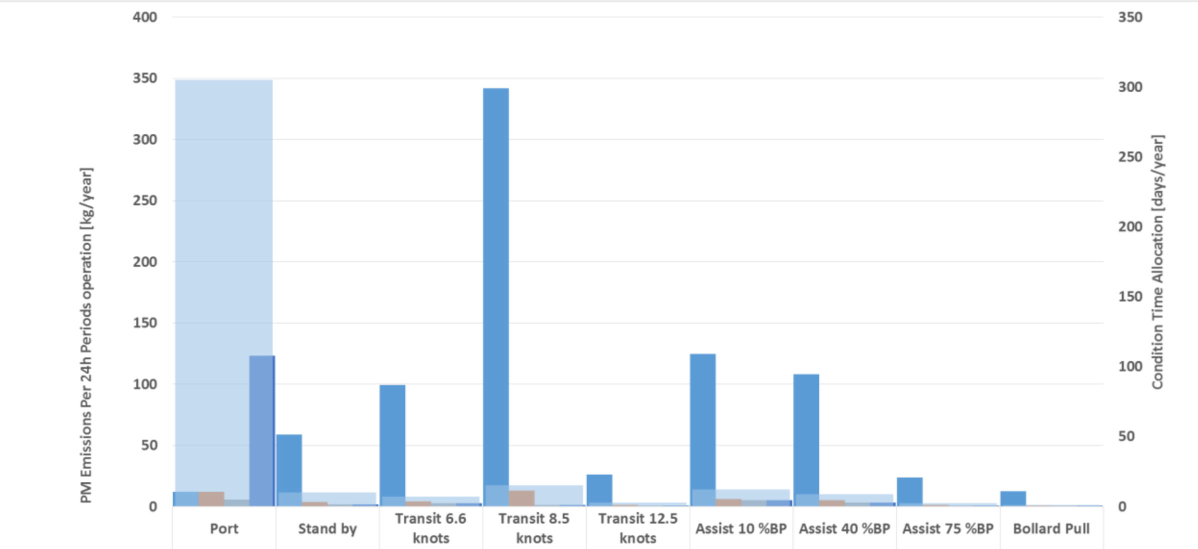
Emission output comparison results	HYBRID with bat-S4	HYBRID with bat-S6	Diesel Electric-Base Case
NO_x	-721	-5317	-3681
HC	-666	-325	-52
PM	-636	-797	-561
CO	-1852	-1327	-1355
CO_2	62149	-43462	58172
SO_x	-522	-532	36

In addition some indicative diagrams for the top three ranked alternatives of case study 1 (terminal duty) are presented below.



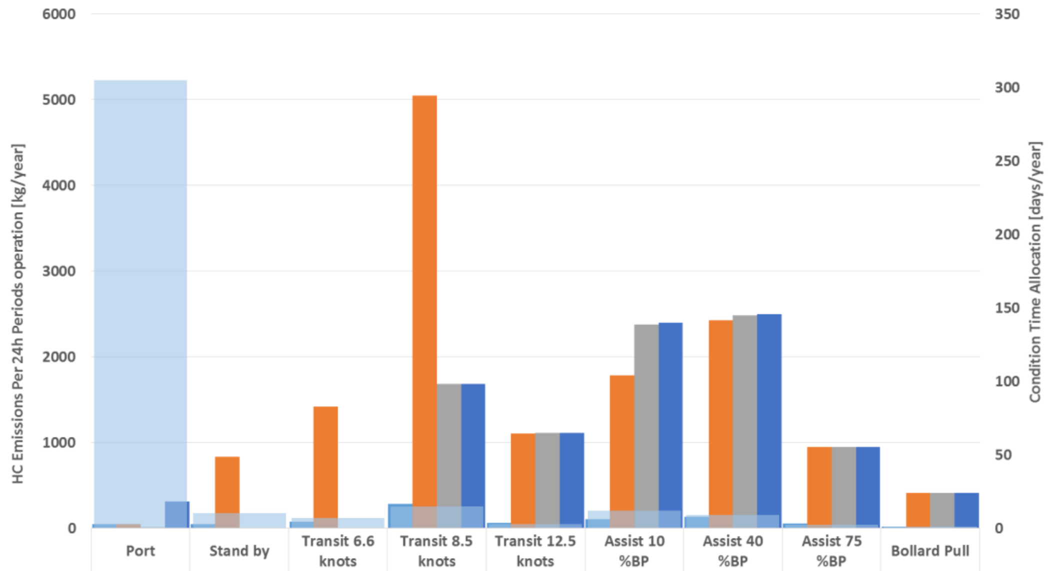
	Port	Stand by	Transit 6.6 knots	Transit 8.5 knots	Transit 12.5 knots	Assist 10 %BP	Assist 40 %BP	Assist 75 %BP	Bollard Pull
CONV-Baseline	578	520	893	3305	1588	1124	3148	1366	1003
CONV-S2	578	109	188	574	232	241	473	193	137
HYBRID with bat-S2	685	212	368	291	198	171	399	171	131
HYBRID-S2	1255	198	363	290	199	173	402	171	137

Figure E-1: Breakdown of NOx emission output results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile



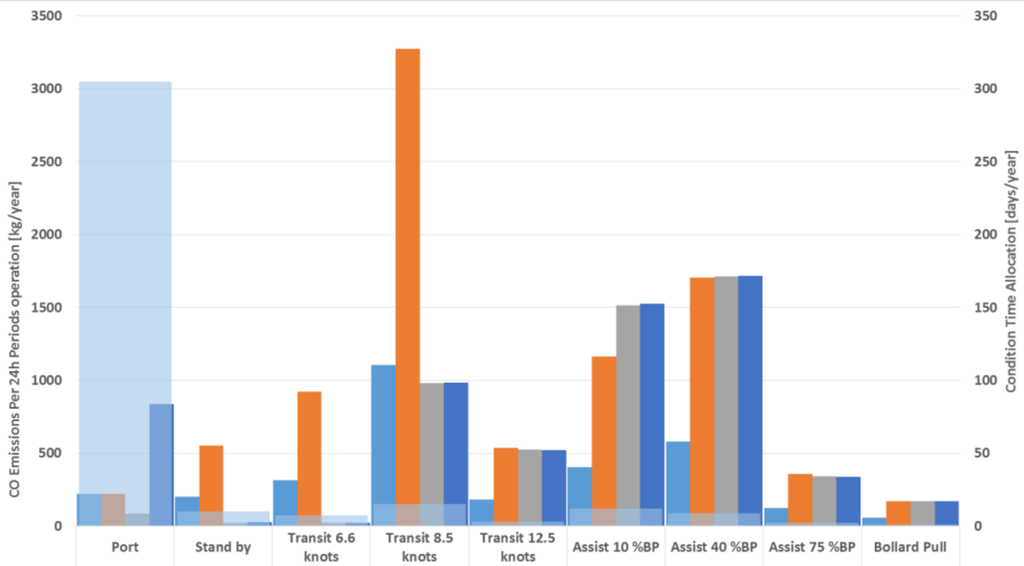
	Port	Stand by	Transit 6.6 knots	Transit 8.5 knots	Transit 12.5 knots	Assist 10 %BP	Assist 40 %BP	Assist 75 %BP	Bollard Pull
CONV-Baseline	12	59	99	342	26	125	108	24	13
CONV-S2	12	4	4	13	1	6	5	1	1
HYBRID with bat-S2	6	2	3	1	1	5	3	1	1
HYBRID-S2	123	2	3	2	1	5	3	1	1
"days per year"	305	10	7	15	3	12	9	2	1

Figure E-2: Breakdown of PM emission output results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile



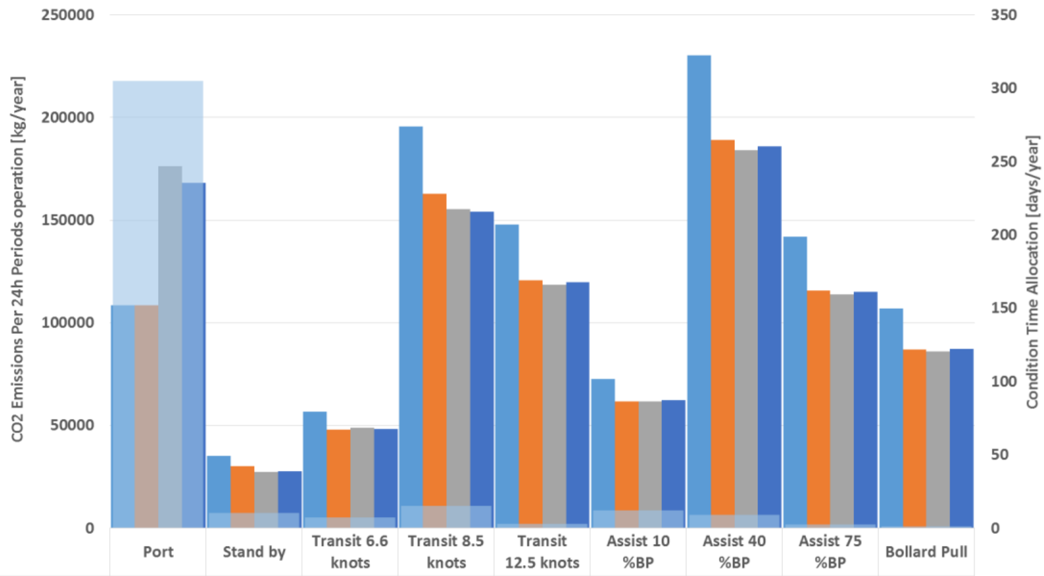
	Port	Stand by	Transit 6.6 knots	Transit 8.5 knots	Transit 12.5 knots	Assist 10 %BP	Assist 40 %BP	Assist 75 %BP	Bollard Pull
CONV-Baseline	47	52	81	283	62	104	138	53	23
CONV-S2	47	834	1422	5049	1104	1782	2428	947	415
HYBRID with bat-S2	13	3	7	1686	1112	2375	2485	948	415
HYBRID-S2	312	4	7	1683	1116	2398	2500	950	415
"days per year"	305	10	7	15	3	12	9	2	1

Figure E-3: Breakdown of HC emission output results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile



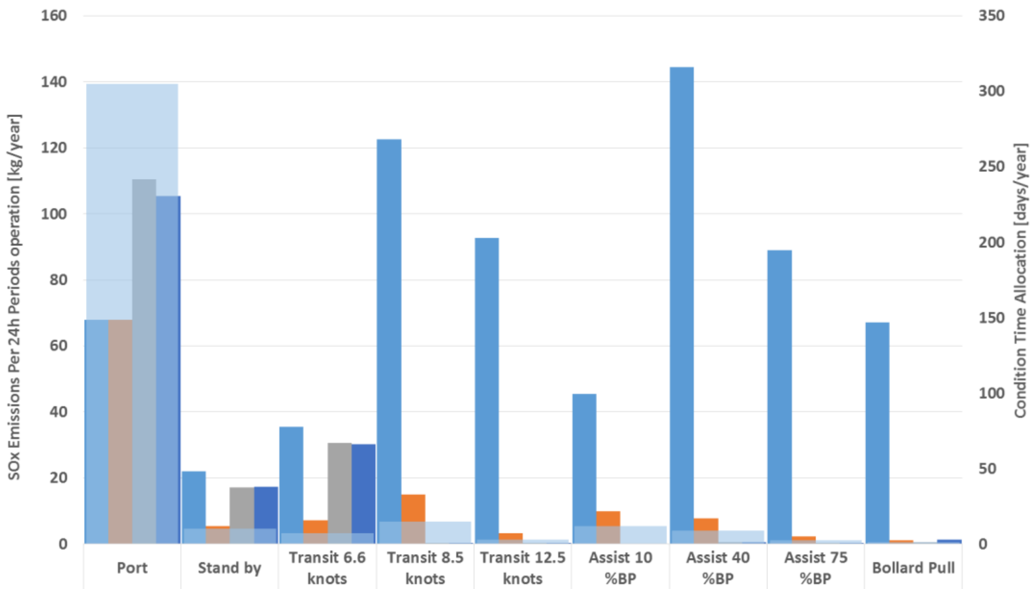
	Port	Stand by	Transit 6.6 knots	Transit 8.5 knots	Transit 12.5 knots	Assist 10 %BP	Assist 40 %BP	Assist 75 %BP	Bollard Pull
CONV-Baseline	219	200	315	1104	182	405	579	122	59
CONV-S2	219	553	920	3273	537	1162	1706	356	171
HYBRID with bat-S2	84	21	21	982	524	1513	1711	343	172
HYBRID-S2	838	25	21	985	520	1527	1718	337	172
"days per year"	305	10	7	15	3	12	9	2	1

Figure E-4: Breakdown of CO emission output results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile



	Port	Stand by	Transit 6.6 knots	Transit 8.5 knots	Transit 12.5 knots	Assist 10 %BP	Assist 40 %BP	Assist 75 %BP	Bollard Pull
CONV-Baseline	108445	35224	56688	195539	147840	72503	230278	141927	106964
CONV-S2	108445	30209	48091	162981	120769	61746	188950	115685	87036
HYBRID with bat-S2	176293	27469	48802	155427	118471	61705	183956	113839	85971
HYBRID-S2	168166	27782	48296	154214	119697	62296	185795	114984	87153
"days per year"	305	10	7	15	3	12	9	2	1

Figure E-5: Breakdown of CO2 emission output results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile



	Port	Stand by	Transit 6.6 knots	Transit 8.5 knots	Transit 12.5 knots	Assist 10 %BP	Assist 40 %BP	Assist 75 %BP	Bollard Pull
CONV-Baseline	68	22	36	123	93	45	144	89	67
CONV-S2	68	6	7	15	3	10	8	2	1
HYBRID with bat-S2	111	17	31	0	0	0	0	0	1
HYBRID-S2	105	17	30	0	0	0	0	0	1
"days per year"	305	10	7	15	3	12	9	2	1

Figure E-6: Breakdown of SOx emission output results for the top three ranked alternatives of case study 1 (terminal duty) based on the environmental performance decision criterion for the complete mission profile

E.1.3 Cost-effectiveness results

Table E-17: Results summary for case study 1 (terminal tug) based on cost-effectiveness decision criterion without the inclusion of external costs

ID	Nomenclature	Candidates	Combustion fuel	GRA
1	CONV-S2	LBSI (LNG)	LNG	0.900
2	Diesel Electric-Base Case	4xCI (MGO)	MGO	0.412
3	HYBRID with bat-Base Case	4xCI (MGO)	MGO	0.398
4	CONV-S6	4xCI (DME)	DME	0.375
5	CONV-S4	4xCI (Biodiesel)	Biodiesel	0.370
6	HYBRID with bat-S6	4xCI (DME)	DME	0.364
7	HYBRID-S2	LBSI (LNG)	LNG	0.364
8	CONV-S1	LPDF (LNG)	LNG	0.364
9	HYBRID with bat-S4	4xCI (Biodiesel)	Biodiesel	0.358
10	HYBRID-S1	LPDF (LNG)	LNG	0.352
11	HYBRID with bat-S2	LBSI (LNG)	LNG	0.350
12	HYBRID-S6	4xCI (DME)	DME	0.349
13	HYBRID-S4	4xCI (Biodiesel)	Biodiesel	0.348
14	HYBRID with bat-S1	LPDF (LNG)	LNG	0.346
15	CONV-S3	LPDF (Methanol)	Methanol	0.346
16	HYBRID-Base Case	4xCI (MGO)	MGO	0.343
17	HYBRID-S3	LPDF (Methanol)	Methanol	0.342
18	HYBRID with bat-S3	LPDF (Methanol)	Methanol	0.340

Table E-18: Cost-effectiveness comparison results summary per exhaust air pollutant for case study 1 (terminal duty) without the inclusion of external costs, using the baseline case as reference

Configurations	CE-NO_x	CE-HC	CE-PM	CE-CO	CE-CO_2	CE-SO_x
CONV-S2	13.1	#N/A	0.9	#N/A	207.6	0.7
Diesel Electric-Base Case	1.7	0.0	0.3	0.6	#N/A	#N/A
HYBRID with bat-Base Case	0.2	0.1	0.1	0.2	6.0	0.0
CONV-S6	1.7	0.0	0.3	0.0	32.4	0.2
CONV-S4	#N/A	0.0	0.0	0.1	#N/A	0.0
HYBRID with bat-S6	0.5	0.0	0.1	0.1	4.4	0.1
HYBRID-S2	2.2	#N/A	0.1	#N/A	26.8	0.1
CONV-S1	2.0	#N/A	0.1	#N/A	39.5	0.1
HYBRID with bat-S4	0.0	0.0	0.0	0.1	#N/A	0.0
HYBRID-S1	1.4	#N/A	0.1	#N/A	18.3	0.1
HYBRID with bat-S2	1.3	#N/A	0.1	#N/A	14.5	0.1
HYBRID-S6	0.7	0.0	0.1	0.1	6.3	0.1
HYBRID-S4	0.0	0.0	0.0	0.1	#N/A	0.0
HYBRID with bat-S1	1.0	#N/A	0.1	#N/A	12.9	0.1
CONV-S3	0.8	#N/A	0.0	#N/A	12.5	0.1
HYBRID-Base Case	0.2	0.0	0.1	0.1	#N/A	#N/A
HYBRID-S3	0.6	#N/A	0.1	#N/A	2.5	0.1
HYBRID with bat-S3	0.5	#N/A	0.1	0.0	1.9	0.0

Table E-19: Results summary for case study 1 (terminal tug) based on economic performance decision criterion from a societal perspective

ID	Nomenclature	Candidates	Combustion fuel	GRA
1	CONV-S2	LBSI (LNG)	LNG	0.913
2	CONV-S6	4xCI (DME)	DME	0.646
3	CONV-S1	LPDF (LNG)	LNG	0.421
4	CONV-S3	LPDF (Methanol)	Methanol	0.419
5	Diesel Electric-Base Case	4xCI (MGO)	MGO	0.377
6	HYBRID-S2	LBSI (LNG)	LNG	0.376
7	HYBRID-S1	LPDF (LNG)	LNG	0.354
8	HYBRID with bat-S2	LBSI (LNG)	LNG	0.347
9	HYBRID-S3	LPDF (Methanol)	Methanol	0.346
10	HYBRID with bat-S1	LPDF (LNG)	LNG	0.342

Table E-20: Results summary for case study 1 (terminal tug) based on cost-effectiveness decision criterion with the inclusion of external costs

ID	Nomenclature	Candidates	Combustion fuel	GRA
1	CONV-S6	4xCI (DME)	DME	1.000
2	CONV-S2	LBSI (LNG)	LNG	0.525
3	HYBRID-S6	4xCI (DME)	DME	0.454
4	HYBRID-Base Case	4xCI (MGO)	MGO	0.449
5	HYBRID-S4	4xCI (Biodiesel)	Biodiesel	0.442
6	HYBRID with bat-S4	4xCI (Biodiesel)	Biodiesel	0.432
7	HYBRID with bat-S3	LPDF (Methanol)	Methanol	0.431
8	HYBRID with bat-S6	4xCI (DME)	DME	0.423
9	HYBRID with bat-Base Case	4xCI (MGO)	MGO	0.418
10	HYBRID-S3	LPDF (Methanol)	Methanol	0.387
11	HYBRID with bat-S1	LPDF (LNG)	LNG	0.382
12	CONV-S3	LPDF (Methanol)	Methanol	0.378
13	HYBRID-S1	LPDF (LNG)	LNG	0.373
14	HYBRID with bat-S2	LBSI (LNG)	LNG	0.373
15	CONV-S1	LPDF (LNG)	LNG	0.354
16	Diesel Electric-Base Case	4xCI (MGO)	MGO	0.354
17	HYBRID-S2	LBSI (LNG)	LNG	0.335
18	CONV-S4	4xCI (Biodiesel)	Biodiesel	0.333

Table E-21: Cost-effectiveness comparison results summary per exhaust air pollutant for case study 1 (terminal duty) with the inclusion of external costs, using the baseline case as reference

Configurations	**CE-NO_x**	**CE-HC**	**CE-PM**	**CE-CO**	**CE-CO_2**	**CE-SO_x**
CONV-S6	11.56	0.00	2.10	0.00	221.82	1.52
CONV-S2	6.41	#N/A	0.45	#N/A	101.85	0.34
HYBRID-S6	-1.26	-0.01	-0.18	-0.15	-10.75	-0.14
HYBRID-Base Case	-0.26	-0.01	-0.08	-0.15	#N/A	#N/A
HYBRID-S4	-0.01	-0.02	-0.03	-0.07	#N/A	-0.03
HYBRID with bat-S4	-0.04	-0.03	-0.03	-0.10	#N/A	-0.03
HYBRID with bat-S3	-0.63	#N/A	-0.08	-0.05	-2.51	-0.06
HYBRID with bat-S6	-0.76	-0.05	-0.11	-0.19	-6.17	-0.08
HYBRID with bat-Base Case	-0.30	-0.06	-0.08	-0.26	-7.34	0.00
HYBRID-S3	-0.93	#N/A	-0.10	#N/A	-3.56	-0.10
HYBRID with bat-S1	-1.27	#N/A	-0.09	#N/A	-17.14	-0.07
CONV-S3	-1.36	#N/A	-0.08	#N/A	-22.15	-0.19
HYBRID-S1	-2.05	#N/A	-0.12	#N/A	-26.57	-0.11
HYBRID with bat-S2	-2.11	#N/A	-0.15	#N/A	-23.92	-0.10
CONV-S1	-3.52	#N/A	-0.10	#N/A	-70.69	-0.23
Diesel Electric-Base Case	-3.37	-0.05	-0.51	-1.24	#N/A	#N/A
HYBRID-S2	-6.00	#N/A	-0.39	#N/A	-73.76	-0.31
CONV-S4	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

E.2 Case Study 2 – Harbour tug

Table E-22: Mission profile for case study 2 (harbour duty)

Mode	Utilization rate (%)	Duration [hours/year]
Standby	32%	1382
Transit low (6.6 knots)	27%	1166
Transit light (7.8 knots)	3%	130
Transit high (10 knots)	8%	346
Assist low 20 % BP	16%	691
Assist medium 50 % BP	5%	216
Assist medium 60 % BP	4%	173
Assist high 80 % BP	4%	173
Bollard Pull (100%)	1%	43

E.2.1 Economic performance results

Table E-23: Part 1/2 of results summary for case study 2 (harbour duty in Rotterdam port) based on economic performance decision criterion from a ship-owner perspective

ID	Nomenclature	Candidates	Combustion fuel	GRA	IMO	EU
1	HYBRID-S2	LBSI (LNG) + SCRs/DPFs	LNG	0.826	yes	yes
2	CONV-S2	LBSI (LNG) + SCRs/DPFs	LNG	0.665	yes	yes
3	HYBRID-S1	LPDF (LNG) + SCRs/DPFs/Oxicat	LNG	0.509	yes	**no**
4	HYBRID with bat-S2	LBSI (LNG) + SCRs/DPFs	LNG	0.427	yes	yes
5	Diesel Electric-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.395	yes	yes
6	CONV-S1	LPDF (LNG) + SCRs/DPFs/Oxicat	LNG	0.391	yes	**no**
7	HYBRID-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.379	yes	yes
8	HYBRID with bat-S1	LPDF (LNG) + SCRs/DPFs/Oxicat	LNG	0.346	yes	**no**
9	HYBRID-S3	LPDF (Methanol) + SCRs/DPFs	Methanol	0.333	yes	yes

Table E-24: Part 2/2 of results summary for case study 2 (harbour duty in Rotterdam port) based on economic performance decision criterion from a ship-owner perspective

ID	Nomenclature	Endurance	Range	Alternative fuel	MGO	Urea
1	HYBRID-S2	21.50	4128	40	30	30
2	CONV-S2	25.13	4824	35	45	77
3	HYBRID-S1	20.13	3864	45	30	30
4	HYBRID with bat-S2	21.38	4104	40	31	30
5	Diesel Electric-Base Case	42.06	8075	-	61	39
6	CONV-S1	22.08	4240	46	30	68
7	HYBRID-Base Case	43.76	8401	-	64	38
8	HYBRID with bat-S1	21.58	4144	40	31	30
9	HYBRID-S3	15.33	2944	35	30	30

Table E-25: Part 1/4 of financial valuation metrics results for case study 2 (harbour tug in Rotterdam port)

Cash flow metrics results	HYBRID-S2	CONV-S2	HYBRID-S1	HYBRID with bat-S2	Diesel Electric-Base Case
Net Investments	$1,685,289	$184,207	$2,066,709	$2,998,706	$1,436,508
NPV	$1,452,145	$1,239,585	$904,537	$632,436	$491,152
IRR	21.99%	55.79%	14.59%	11.60%	16.18%
Payback period	4.1	1.9	7.3	7.9	5.9

Table E-26: Part 2/4 of financial valuation metrics results for case study 2 (harbour tug in Rotterdam port)

Cash flow metrics results	CONV-S1	HYBRID-Base Case	HYBRID with bat-S1	HYBRID-S3	HYBRID with bat-S6
Net Investments	$548,334	$1,652,429	$3,401,126	$2,164,404	$4,141,495
NPV	$474,097	$416,714	$230,016	$152,741	$-1,139,208
IRR	15.34%	13.69%	9.11%	9.29%	-2.04%
Payback period	7.3	7.4	11.6	11.4	No

Table E-27: Part 3/4 of financial valuation metrics results for case study 2 (harbour tug in Rotterdam port)

Cash flow metrics results	HYBRID-S6	HYBRID with bat-S4	HYBRID with bat-S3	HYBRID with bat-Base Case	HYBRID-S4
Net Investments	$2,908,565	$12,636,267	$3,511,178	$2,988,190	$11,383,087
NPV	$-319,003	$-4,184,284	$-646,991	$-316,476	$-3,367,421
IRR	3.30%	does not exist	4.35%	5.67%	does not exist
Payback period	19.1	No	15.5	14.1	No

Table E-28: Part 4/4 of financial valuation metrics results for case study 2 (harbour tug in Rotterdam port)

Cash flow metrics results	**CONV-S6**	**CONV-S4**	**CONV-S3**
Net Investments	$2,016,138	$12,062,301	$505,060
NPV	$-794,463	$-4,440,550	$-222,611
IRR	does not exist	212.30%	2.88%
Payback period	No	No	18.5

Table E-29: Part 1/2 of results summary for case study 2 (harbour duty in New York and New Jersey port) based on economic performance decision criterion from a ship-owner perspective

ID	**Nomenclature**	**Candidates**	**Combustion fuel**	**GRA**	**IMO**	**EPA**
1	CONV-S2	LBSI (LNG) + SCRs/OxiCat	LNG	0.809	yes	yes
2	HYBRID-S2	LBSI (LNG) + SCRs/OxiCat	LNG	0.792	yes	yes
3	HYBRID-S1	LPDF (LNG) + SCRs/OxiCat	LNG	0.635	yes	yes
4	CONV-S1	LPDF (LNG) + SCRs/OxiCat	LNG	0.582	yes	yes
5	HYBRID with bat-S2	LBSI (LNG) + SCRs/OxiCat	LNG	0.505	yes	yes
6	Diesel Electric-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.499	yes	yes
7	CONV-S4	4xCI (Biodiesel) + SCRs/DPFs	Biodiesel	0.493	yes	yes
8	HYBRID-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.478	yes	yes
9	HYBRID with bat-S1	LPDF (LNG) + SCRs/OxiCat	LNG	0.476	yes	yes
10	HYBRID-S3	LPDF (Methanol) + SCRs/OxiCat	Methanol	0.451	yes	yes
11	CONV-S3	LPDF (Methanol) + SCRs/OxiCat	Methanol	0.428	yes	yes
12	HYBRID-S6	4xCI (DME) + SCRs/OxiCat	DME	0.414	yes	yes
13	HYBRID with bat-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.398	yes	yes
14	CONV-S6	4xCI (DME) + SCRs/OxiCat	DME	0.395	yes	yes
15	HYBRID with bat-S3	LPDF (Methanol) + SCRs/OxiCat	Methanol	0.390	yes	yes
16	HYBRID with bat-S6	4xCI (DME) + SCRs/OxiCat	DME	0.376	yes	yes

Table E-30: Part 2/2 of results summary for case study 2 (harbour duty in New York and New Jersey port) based on economic performance decision criterion from a ship-owner perspective

ID	Nomenclature	Endurance	Range	Alternative fuel	MGO	Urea
1	CONV-S2	25.13	4824	35	45	77
2	HYBRID-S2	21.50	4128	40	30	30
3	HYBRID-S1	20.13	3864	45	30	30
4	CONV-S1	22.08	4240	46	30	68
5	HYBRID with bat-S2	21.38	4104	40	31	30
6	Diesel Electric-Base Case	42.06	8075	-	61	39
7	CONV-S4	37.21	7144	52	62	30
8	HYBRID-Base Case	43.76	8401	-	64	38
9	HYBRID with bat-S1	21.58	4144	40	31	30
10	HYBRID-S3	15.33	2944	35	30	30
11	CONV-S3	16.92	3248	35	30	30
12	HYBRID-S6	19.50	3744	37	30	30
13	HYBRID with bat-Base Case	43.76	8401	-	65	37
14	CONV-S6	23.33	4480	32	39	30
15	HYBRID with bat-S3	16.42	3152	31	30	30
16	HYBRID with bat-S6	19.50	3744	37	30	30

Table E-31: Part 1/4 of financial valuation metrics results for case study 2 (harbour tug in New York and New Jersey port)

Cash flow metrics results	CONV-S2	HYBRID-S2	HYBRID-S1	CONV-S1	HYBRID with bat-S2
Net Investments	$62,422	$1,534,017	$1,703,637	$214,749	$2,846,918
NPV	$1,366,166	$1,604,156	$1,268,348	$812,478	$784,447
IRR	158.17%	26.08%	20.16%	35.37%	12.80%
Payback period	0.6	3.7	5.1	3.1	7.5

Table E-32: Part 2/4 of financial valuation metrics results for case study 2 (harbour tug in New York and New Jersey port)

Cash flow metrics results	Diesel Electric-Base Case	CONV-S4	HYBRID-Base Case	HYBRID with bat-S1	HYBRID-S3
Net Investments	$1,407,129	$12,062,301	$1,623,502	$3,037,538	$2,013,133
NPV	$519,914	$-4,440,550	$445,434	$593,827	$304,752
IRR	17.01%	212.30%	14.29%	11.32%	10.85%
Payback period	5.7	No	7.4	8.0	9.1

Table E-33: Part 3/4 of financial valuation metrics results for case study 2 (harbour tug in New York and New Jersey port)

Cash flow metrics results	CONV-S3	HYBRID-S6	HYBRID with bat-Base Case	CONV-S6	HYBRID with bat-S3
Net Investments	$383,275	$2,545,494	$2,959,429	$1,682,553	$3,359,390
NPV	$-96,030	$44,808	$-287,756	$-456,082	$-494,980
IRR	5.30%	9.04%	5.85%	26.35%	5.04%
Payback period	14.9	11.6	13.9	No	15.2

Table E-34: Part 4/4 of financial valuation metrics results for case study 2 (harbour tug in New York and New Jersey port)

Cash flow metrics results	HYBRID with bat-S6	HYBRID with bat-S4	HYBRID-S4
Net Investments	$3,777,907	$12,607,505	$11,354,160
NPV	$-775,397	$-4,155,564	$-3,338,701
IRR	-0.31%	does not exist	does not exist
Payback period	20.0	No	No

E.2.2 Environmental performance results

Table E-35: Results summary for case study 2 (harbour duty in Rotterdam port) based on environmental performance decision criterion

ID	**Nomenclature**	**Candidates**	**Combustion fuel**	**GRA**
1	HYBRID with bat-S6	4xCI (DME) + SCRs/DPFs/Oxicat	DME	0.851
2	HYBRID with bat-S2	LBSI (LNG) + SCRs/DPFs	LNG	0.768
3	HYBRID-S6	4xCI (DME) + SCRs/DPFs/Oxicat	DME	0.720
4	HYBRID with bat-S4	4xCI (Biodiesel) + SCRs/DPFs	Biodiesel	0.715
5	HYBRID-S2	LBSI (LNG) + SCRs/DPFs	LNG	0.714
6	HYBRID with bat-S3	LPDF (Methanol) + SCRs/DPFs	Methanol	0.701
7	CONV-S2	LBSI (LNG) + SCRs/DPFs	LNG	0.691
8	HYBRID with bat-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.665
9	HYBRID-S3	LPDF (Methanol) + SCRs/DPFs	Methanol	0.651
10	Diesel Electric-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.628
11	HYBRID-S4	4xCI (Biodiesel) + SCRs/DPFs	Biodiesel	0.610
12	HYBRID with bat-S1	LPDF (LNG) + SCRs/DPFs/Oxicat	LNG	0.580
13	HYBRID-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.572
14	CONV-S6	4xCI (DME) + SCRs/DPFs/Oxicat	DME	0.534
15	HYBRID-S1	LPDF (LNG) + SCRs/DPFs/Oxicat	LNG	0.492
16	CONV-S4	4xCI (Biodiesel) + SCRs/DPFs	Biodiesel	0.420
17	CONV-S1	LPDF (LNG) + SCRs/DPFs/Oxicat	LNG	0.412
18	CONV-S3	LPDF (Methanol) + SCRs/DPFs	Methanol	0.375

Table E-36: Part 1/4 of emission reduction (%) comparison results for case study 2 (harbour duty in Rotterdam port)

Emission output comparison results	HYBRID with bat-S6	HYBRID with bat-S2	HYBRID-S6	HYBRID with bat-S4	HYBRID-S2
NO_x	-86%	-70%	-85%	-78%	-70%
HC/10	-5%	563%	0%	-6%	568%
PM	-92%	-91%	-60%	-74%	-68%
CO	-52%	97%	-19%	-39%	121%
CO_2	-10%	-18%	-9%	-1%	-18%
SO_x	-76%	-77%	-76%	-74%	-77%

Table E-37: Part 2/4 of emission reduction (%) comparison results for case study 2 (harbour duty in Rotterdam port)

Emission output comparison results	HYBRID with bat-S3	CONV-S2	HYBRID with bat-Base Case	HYBRID-S3	Diesel Electric-Base Case
NO_x	-84%	-57%	-80%	-83%	-83%
HC/10	12%	1035%	-5%	17%	-1%
PM	-67%	-81%	-55%	-35%	-52%
CO	-3%	301%	-52%	30%	-35%
CO_2	-8%	-17%	-4%	-7%	1%
SO_x	-75%	-88%	-5%	-63%	1%

Table E-38: Part 3/4 of emission reduction (%) comparison results for case study 2 (harbour duty in Rotterdam port)

Emission output comparison results	HYBRID-S4	HYBRID with bat-S1	HYBRID-Base Case	CONV-S6	HYBRID-S1
NO_x	-78%	-16%	-79%	-33%	-15%
HC/10	-2%	508%	0%	0%	512%
PM	-41%	-68%	-23%	-82%	-45%
CO	-6%	-14%	-19%	0%	10%
CO_2	-1%	-18%	-3%	-8%	-16%
SO_x	-75%	-77%	-3%	-86%	-65%

Table E-39: Part 4/4 of emission reduction (%) comparison results for case study 2 (harbour duty in Rotterdam port)

Emission output comparison results	CONV-S4	CONV-S1	CONV-S3
NO_x	9%	59%	-4%
HC/10	-3%	591%	21%
PM	-41%	-18%	-16%
CO	26%	47%	80%
CO_2	2%	-12%	-4%
SO_x	-85%	-58%	-56%

Table E-40: Results summary for case study 2 (harbour duty in New York and New Jersey port) based on environmental performance decision criterion

ID	Nomenclature	Candidates	Combustion fuel	GRA
1	HYBRID with bat-S6	4xCI (DME) + SCRs/OxiCat	DME	0.851
2	HYBRID-S6	4xCI (DME) + SCRs/OxiCat	DME	0.723
3	HYBRID with bat-S2	LBSI (LNG) + SCRs/OxiCat	LNG	0.714
4	HYBRID with bat-S3	LPDF (Methanol) + SCRs/OxiCat	Methanol	0.684
5	HYBRID-S2	LBSI (LNG) + SCRs/OxiCat	LNG	0.683
6	HYBRID with bat-S4	4xCI (Biodiesel) + SCRs/DPFs	Biodiesel	0.678
7	HYBRID with bat-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.666
8	HYBRID-S3	LPDF (Methanol) + SCRs/OxiCat	Methanol	0.643
9	Diesel Electric-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.626
10	CONV-S2	LBSI (LNG) + SCRs/OxiCat	LNG	0.626
11	HYBRID-Base Case	4xCI (MGO) + SCRs/DPFs/Oxicat	MGO	0.573
12	HYBRID-S4	4xCI (Biodiesel) + SCRs/DPFs	Biodiesel	0.571
13	CONV-S6	4xCI (DME) + SCRs/OxiCat	DME	0.560
14	HYBRID with bat-S1	LPDF (LNG) + SCRs/OxiCat	LNG	0.522
15	HYBRID-S1	LPDF (LNG) + SCRs/OxiCat	LNG	0.467
16	CONV-S1	LPDF (LNG) + SCRs/OxiCat	LNG	0.403
17	CONV-S4	4xCI (Biodiesel) + SCRs/DPFs	Biodiesel	0.377
18	CONV-S3	LPDF (Methanol) + SCRs/OxiCat	Methanol	0.376

Table E-41: Part 1/4 of emission reduction (%) comparison results for case study 2 (harbour duty in New York and New Jersey port)

Emission output comparison results	HYBRID with bat-S6	HYBRID-S6	HYBRID with bat-S2	HYBRID with bat-S3	HYBRID-S2
NO_x	-86%	-85%	-70%	-84%	-70%
HC/10	-4%	1%	560%	4%	565%
PM	-84%	-52%	-67%	196%	-44%
CO	-44%	-11%	25%	-31%	49%
CO_2	-10%	-9%	-18%	-8%	-18%
SO_x	-76%	-76%	-61%	-75%	-62%

Table E-42: Part 2/4 of emission reduction (%) comparison results for case study2 (harbour duty in New York and New Jersey port)

Emission output comparison results	HYBRID with bat-S4	HYBRID with bat-Base Case	HYBRID-S3	Diesel Electric-Base Case	CONV-S2
NO_x	-78%	-80%	-83%	-83%	-57%
HC/10	-5%	-4%	9%	0%	1028%
PM	-66%	-47%	228%	-44%	-43%
CO	-31%	-44%	2%	-28%	140%
CO_2	-1%	-4%	-7%	1%	-17%
SO_x	-20%	-5%	-63%	1%	-69%

Table E-43: Part 3/4 of emission reduction (%) comparison results for case study 2 (harbour duty in New York and New Jersey port)

Emission output comparison results	HYBRID-Base Case	HYBRID-S4	CONV-S6	HYBRID with bat-S1	HYBRID-S1
NO_x	-79%	-78%	-33%	-16%	-15%
HC/10	1%	-1%	0%	509%	513%
PM	-15%	-34%	-82%	196%	220%
CO	-11%	2%	0%	-7%	17%
CO_2	-3%	-1%	-8%	-18%	-16%
SO_x	-3%	-20%	-86%	-61%	-52%

Table E-44: Part 4/4 of emission reduction (%) comparison results for case study 2 (harbour duty in New York and New Jersey port)

Emission output comparison results	CONV-S1	CONV-S4	CONV-S3
NO_x	59%	9%	-4%
HC/10	591%	-3%	9%
PM	669%	-41%	663%
CO	47%	26%	18%
CO_2	-12%	2%	-4%
SO_x	-45%	-20%	-56%

Appendix F Sensitivity analysis

F.1 Economic performance sensitivity

The results based on economic performance, under the assumed financial parameters for the first case study, have indicated 3 options as viable for investment, based on a positive IRR and payback cash flow metrics. However, none is profitable, due to the negative NPV values. As discussed in section 6.1.1.2, for an alternative to be profitable, the operational savings should outweigh the anticipated net investments, consisting of the initial additional capital expenses and probable cash outflows occurring at different time intervals (i.e. maintenance expenses). Positive $NPV_{financial}$ values indicate that net cash inflows (savings) will offset the net cash outflows (expenses) for the investment horizon. Hence, the impact of varying the aforementioned factors will be explored by investigating the effect on $NPV_{financial}$.

As already mentioned, two are the parameters that characterize a mission profile, the utilization rate and the annual operating hours. To begin with, the effect on NPV by increasing the annual operating hours by 1 hour/day, based on a total of 360 days of operation per year, by keeping the same utilization rate for the central-price scenario is investigated. Part of the results, for certain indicative options, is presented in Figure F-1.

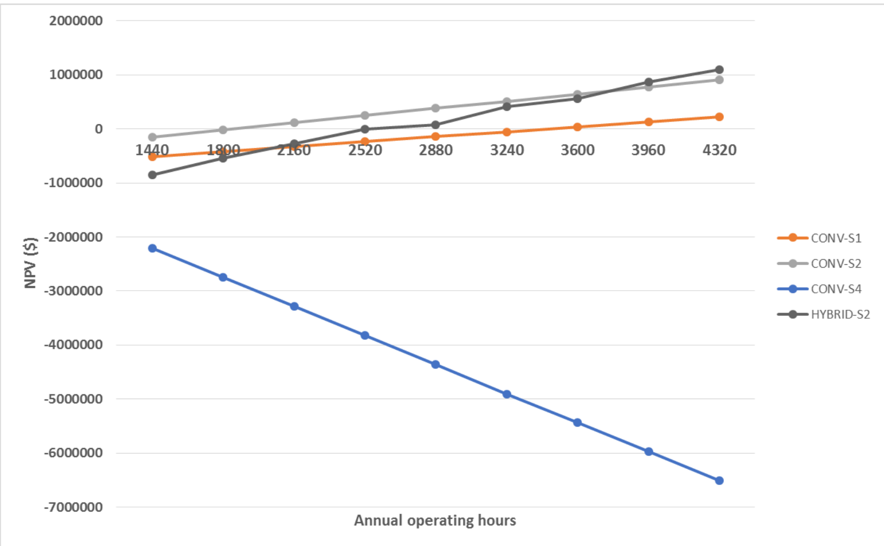


Figure F-1:(NPV)financial as a function of annual operating hours for case study 1 (terminal duty)

As can be observed there are alternatives that show an increase on NPV, while others a decrease. There seems to be a linear relationship between the NPV and the annual operating hours. CONV-S4, a conventional propulsion configuration based on 4*CI engines running on Biodiesel shows a gradual decrease in NPV values, with increasing duration, signifying a worsening effect. The reasons are the higher fuel consumption per operating mode and the higher Biodiesel price compared to MGO. The three initially unprofitable alternatives show an increase on NPV with increasing duration. Hence, as expected, with more operating hours the total fuel savings in the case of the conventional configurations and the total combined fuel and maintenance savings for the hybrid version surpass the initial capital investment, leading to profits. Not only that, but there is also a transition limit, above which the Hybrid-S2 becomes more profitable than the conventional options. This is attributed to the maintenance savings, which become bigger, leading to HYBRID-S2 combined savings to exceed the CONV-S2 fuel savings.

Next, the impact of altering the utilization rate for the initial 1440 annual operating hours, under the same financial parameters is explored. With a utilization rate as summarized in Table F-1, the results for the initial top three ranked alternatives based on economic performance change, as shown in Table F-2.

Table F-1: Mission profile for case study 1 (terminal tug) with different utilisation rate

Mode	Utilization rate (%)	Duration [hours/year]
Standby	7%	101
Transit low (6.6 knots)	6%	87
Transit light (8.5 knots)	30%	432
Transit high (12.5 knots)	10%	144
Assist low 10 % BP	10%	144
Assist medium 40 % BP	21%	303
Assist high 75 % BP	15%	216
Bollard Pull (100%)	1%	14

Table F-2: Results summary for case study 1 (terminal tug) based on economic performance decision criterion from a ship-owner perspective with a modified mission profile

ID	Nomenclature	Candidates	Combustion fuel	GRA	IMO
1	CONV-S2	LBSI (LNG)	LNG	0.967	yes
2	CONV-S1	LPDF (LNG)	LNG	0.437	yes
3	HYBRID-S2	LBSI (LNG)	LNG	0.366	yes

The results continue indicating as the preferred solution CONV-S2. However, the scoring distance between the first and the rest of the viable options has now increased. The reason is revealed by looking at the cash flow metrics results, summarized in Table F-3.

Table F-3: Financial valuation metrics results for case study 1(terminal tug) with a modified mission profile

Cash flow metrics results	CONV-S2	CONV-S1	HYBRID-S2
Net Investments	$677,148	$866,139	$2,464,026
NPV	$154,407	$-197,998	$-524,970
IRR	9.95%	5.83%	4.18%
Payback period	10.7	15.7	20.3

It is evident that CONV-S2 results in positive $NPV_{financial}$, while the other two options continue exhibiting negative $NPV_{financial}$ values. However, for all options the results for NPV, IRR and Payback period are better in comparison with the results, under the initial utilization rate. This means that with the current mission profile alternative options are exploiting better the efficiency gains on the individual operating modes, resulting in more combined cost savings than with the initial mission profile. Particularly, for the CONV-S2 option, the fuel savings alone are enough to outweigh the initial up-front investment, resulting in profits. It was not the point of this example, to delve into comprehensive elaboration for the improvement of the results, rather point out that the mission profile is a decisive factor with regard to the decision-making process.

Secondly, the sensitivity to fuel price is explored by changing the price spread between LNG and MGO based on the initial mission profile of 1440 hours of operation annually. The results for varying the fuel price differential for the central-scenario from 0% to 60%, corresponding to a fuel price difference of 80 $/ton to 128 $/ton are presented in Figure F-2.

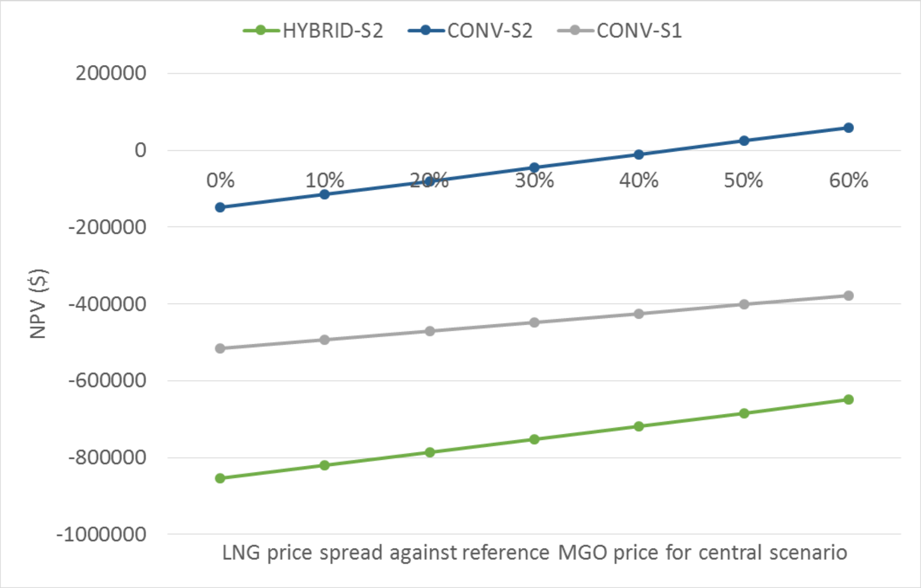


Figure F-2: (NPV)financial as a function of price spread between LNG and MGO for case study 1 (terminal duty)

As can be observed there is a linear relationship between $NPV_{financial}$ and price spread. All options exhibit a linear increase with a higher price differential. However, only the CONV-S2 option is able to reach positive NPV value, at a price differential of 120 $/ton. It is noted that the average price differential from 2014-2019 is estimated to be 188$/ton, 57% higher than the 60% spread scenario. Moreover, the average price differential during 2019, is estimated to be 246 $/ton, more than 100% higher. This means that if the price differential in the next 30 years is kept at levels similar to the average historical price differential, the calculations under the central-price scenario with regard to LNG are conservative. This particular assumption is widely considered probable, attributed to the Sulphur cap phasing in, which is expected to trigger a high demand for premium distillate fuels, leading to a rise in their bunkering prices combined with the steady increase in production of LNG, which will keep the bunkering prices at a constant level. Based on that, CONV-S2 seems like a strong candidate for consideration. Not only that, but more important, the decision-maker should approach results with caution, given the fact that the choice of the MGO price differential scenario will play an important role on the profitability of candidate options.

Thirdly, the financial factors are primary factors which determine the lifecycle costs. A change on the discount and inflation rate or the investment horizon will have a significant impact on the financial evaluation of the candidates. The impact of varying the discount rate, for the same inflation rate and investment horizon on NPV is shown in Figure F-3.

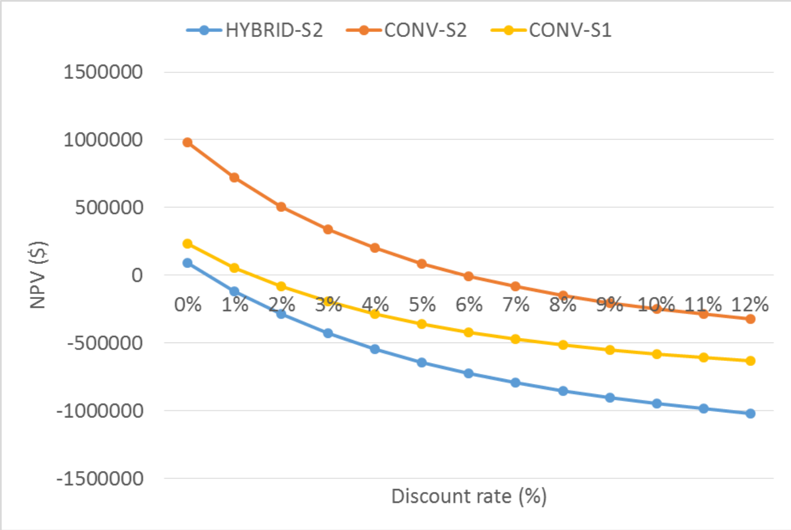


Figure F-3: (NPV) financial as a factor of discount rate (%) for the first case study (terminal duty) with 1440 annual operating hours under the central-price scenario with 2% inflation rate and 30 years investment horizon

For the default discount rate (8%) under the central-price scenario all 3 options exhibited negative NPV values. Looking at the chart it is evident that a decrease in the discount rate has a positive effect on the results, while an increase a worsening result. The relationship between NPV and discount rate is non-linear, indicating that the discount rate has a greater effect on results than the fuel price difference. The point of intersection between x-axis and the NPV curves are specifying the discount rate for which the NPV value becomes zero; this rate is defined as IRR, as discussed in section 5.4.3.2. It gets clear that by knowing the IRR of an option the decision-maker can immediately figure out the maximum discount rate for a break-even point, given a constant inflation rate and investment horizon. For this reason, the impact of inflation on both the NPV and IRR will be explored.

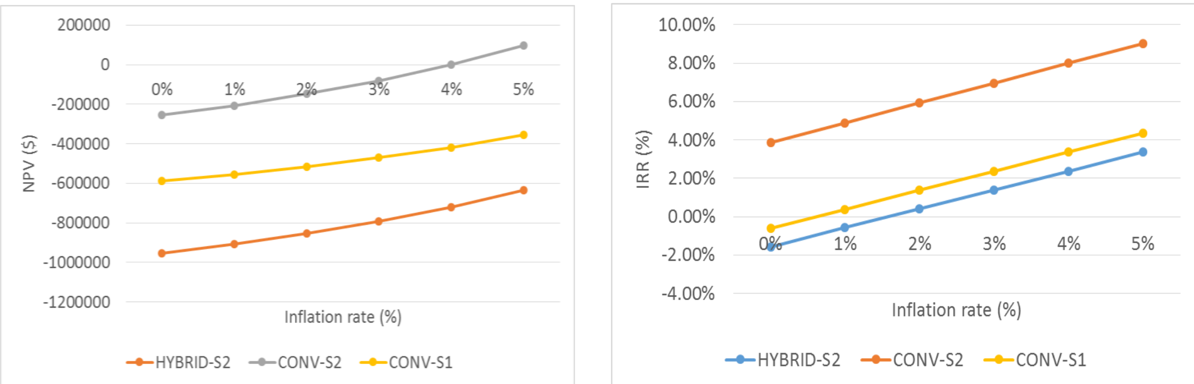


Figure F-4: NPV and IRR as a factor of inflation rate (%) for the first case study (terminal duty) with 1440 annual operating hours under the central-price scenario with 8% discount rate and 30 years investment horizon

As can be observed in Figure F-4 the NPV is a non-linear function, while IRR is a liner function of inflation rate. A decrease in inflation leads to both lower NPV and IRR, while an increase on higher NPV and IRR. A negative IRR indicates a "net loss" result (no profits). On the other hand, for a profitable investment, the IRR should be bigger than the assumed discount rate. For an inflation of 5%, the CONV-S2 option results in an IRR value of 9%, surpassing the default discount rate of 8%, signifying a positive NPV; thus, net profits. The highest the inflation rate, the highest the IRR and thus an alternative becomes more attractive for investment.

With the relationship between discount and inflation rate with NPV already established, it is useful to illustrate how the decision-maker can easily comprehend the usefulness of IRR as a cash flow metric. If the sensitivity analysis of altering the price differential between LNG and MGO was conducted for IRR instead of NPV, then the decision-maker is presented with the maximum required discount rate below which, under the assumed inflation rate and investment horizon, would constitute an alternative profitable. By observing Figure F-5, it can be seen that for a 50% price spread a discount rate of 8.32% would be required for CONV-S2. Since the default discount rate is 8%, profits are anticipated. As can be seen in Figure F-2, indeed this is the case (NPV = 24446 $). It is also evident that for the rest of the alternatives depicted in the graph, a considerably lower discount rate is required in order to become profitable.

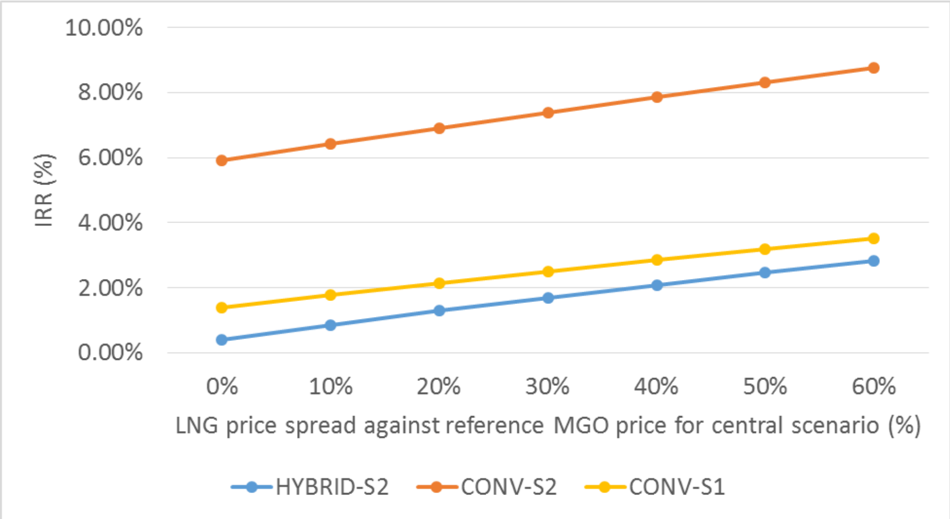


Figure F-5: IRR as a factor of price spread between LNG and MGO for the first case study (terminal duty) with 1440 annual operating hours with 8% discount rate, 2% inflation rate and 30 years investment horizon

Last, the impact of investment horizon in the profitability of a solution, by plotting both the NPV and IRR results is explored. Looking at Figure F-6 it is concluded that with a lower investment horizon less profits are generated, while the opposite happens with a bigger investment horizon. Similarly, for IRR with an increase in number of years the IRR increases, while with a decrease the IRR decreases. It is stressed that for a low investment horizon, certain candidates might result in non-existing IRR. This means that for the assumed mission profile and investment horizon, there is no possible combination of inflation and discount rate, for which the cash inflows can outweigh cash outflows. Hence, no payback period exists within the investment horizon.

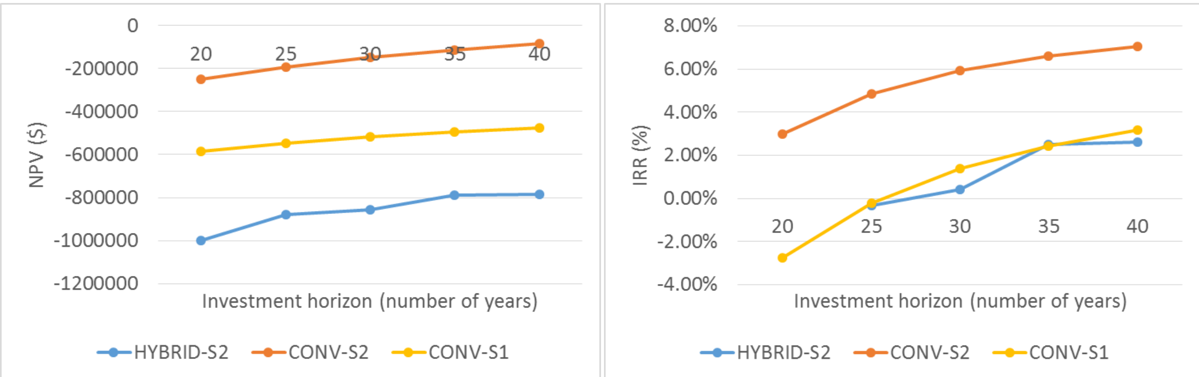


Figure F-6: NPV and IRR as a factor of investment horizon for the first case study (terminal duty) with 1440 annual operating hours under the central-price scenario with 8% discount rate and 2 % inflation rate

Finally, it is stressed that the ranking order will be affected by the preference order of the cash flow valuation metrics. Taking into consideration the definitions of the valuation metrics, as presented in section 5.4.3.2 the competing options are recommended to be rank ordered based on their NPV, which is an indicator of total expected profits, considering the time value of money.

F.2 Environmental performance sensitivity

It became clear from the analysis of environmental performance results for case study 1, as presented in section 6.1.1.2, that the net emission benefits for an alternative have to be examined under the entire mission profile spectrum. This way the potential for emission decrease will be revealed, which could also initiate an exploration on modifying the operational strategy of a tugboat, with the aim of minimizing the exhaust air emission while maintaining the same responsiveness. It is understood that the benefits are anticipated mainly at operating modes, for which prime movers running on alternative fuels are switched on, in order to exploit the emission reduction potential of alternative fuels. Even though, each operating mode will illustrate the same emission reduction potential per exhaust air pollutant, illustrated at Figure 6-7 through Figure 6-12, the change of total annual operating hours will affect each individual mode's total operating duration, consequently the weighting of each emission reduction percentage per mode. Therefore, it is anticipated that the environmental performance of alternative options will be affected. For this reason, the impact of increasing the annual operating hours by keeping the same utilization rate will be explored by investigating the effect on GRA grade on the top three ranked candidates. The results are presented in Figure F-7.

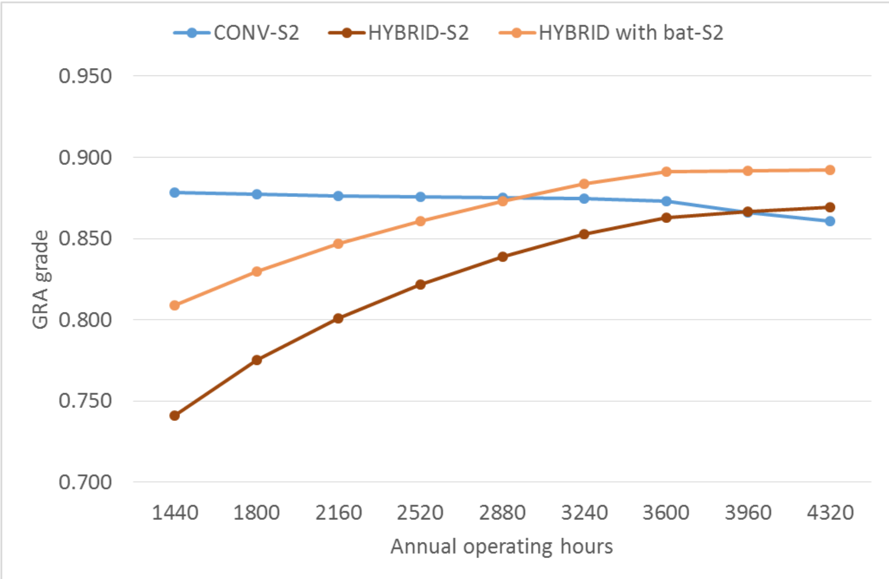


Figure F-7: GRA grade as a function of annual operating hours for case study 1 (terminal duty), assuming the same utilisation rate

As anticipated, it is evident from the above chart that the GRA grade is changing with varying the annual operating hours. The same three options which hold the three top positions based on an annual duration of 1440 operating hours continue to be the preferable ones. However, the ranking order is modified. For the assumed utilization rate, it is evident that there is a crossing point at 2880 hours of operation, after which the most environmentally friendly tugboat becomes one based on Hybrid-S2 with batteries. As already explained, the reason behind this is the effect of increasing duration on the efficient operating modes, leading to higher overall emission reduction for the hybrid drivetrains in comparison to the conventional ones, when compared against the baseline case.

It is also important to note that the duration the tug remains docked, is crucial for its environmental performance. For the majority of the exhaust air pollutants it became apparent that the traditional dedicated harbour diesel generators of the baseline case are the most efficient in harbour mode. Hence, installing auxiliary engines operating on alternative fuels or the use of shore-power should be considered, to eliminate the negative effect observed on that mode and allow the full exploitation of the benefits arising on the other operating modes. Moreover, it is anticipated that changing the utilization rate will further affect the results. Hence, the impact of altering the utilization rate for the initial 1440 annual operating hours, under the same financial parameters, and with a utilization rate, as summarized in Table F-1 is explored. The results for the initial top three ranked alternatives based on environmental performance change, as shown in Table F-4.

Table F-4: Results summary for case study 1 (terminal tug) based on environmental performance decision criterion from a ship-owner perspective with a modified mission profile

ID	Nomenclature	Candidates	Combustion fuel	GRA	IMO
1	CONV-S2	LBSI (LNG)	LNG	0.864	yes
2	HYBRID with bat-S2	LBSI (LNG)	LNG	0.845	yes
3	HYBRID-S2	LBSI (LNG)	LNG	0.781	yes

It is evident that the ranking order for the three candidates remain the same and that CONV-S2 continues to be the preferred solution. However, the difference between the three options has decreased. This signifies an improvement of environmental performance for all three options in comparison to the baseline, attributed to the higher emission reduction potential on the individual operating modes, resulting in less emission output per exhaust air pollutant. Again, it is not the point of this example to investigate the reasons behind the improvement of results. It is evident that the mission profile is a decisive factor also for environmental performance criterion.

It is stressed that neither the financial parameters (investment horizon, discount rate, inflation rate) nor the price scenarios are affecting the results of the environmental performance. Only the technical parameters will influence the environmental performance but have been assumed constant for a certain year of delivery. Finally, it is very important to highlight that the preference order on exhaust air pollutants will determine the ranking order of the options. In addition, candidates can be rank ordered in terms of best environmental performance only on one exhaust air pollutant. For instance, if only CO_2 was chosen as an evaluation metric, the ship-owner would be presented with the most carbon—friendly tug.

F.3 Cost-effectiveness sensitivity

Cost-effectiveness results are also mission profile dependent and subject to the assumptions of the case study as summarized in Table 6-1. It is clear that cost-effectiveness is dependent on the emission abatement potential and the NPV. Consequently, it is sensitive to the same parameters, as the economic and environmental performance. Besides that, also the preference order of the CE index per exhaust air pollutant will dictate the ranking order.

It was shown in section 6.1.1.2, from the analysis of cost-effectiveness results for case study 1, that when internalizing the external costs, there might be a strong case for applying for monetary support from a port-authority, for a specific investment alternative that decreases exhaust air emissions of interest. It is stressed that the TCS results are also sensitive to the external cost factors prices. To account for the effect of this parameter a sensitivity analysis is performed by altering only the shadow price of CO_2 and by plotting the results of NPV_{social} for CONV-S6, for three scenarios; low, central and high CO_2 climate change avoidance costs. The CO_2 emissions are considerably higher than the rest of exhaust air pollutants, thus it is indicative of the expected trend on NPV_{social} results. Usually, the discount rate from a social-economic perspective would be on the order of 4.0 to 4.5 %, according to [127]. For this reason, the discount rate is also varied in order to illustrate the large impact on the results.

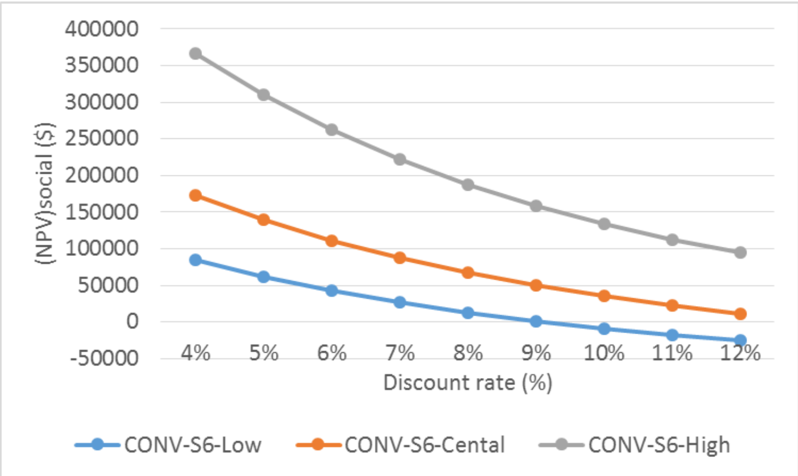


Figure F-8: (NPV) social as a factor of discount rate (%) for the first case study (terminal duty) with 1440 annual operating hours under different MGO price differential scenarios with 2% inflation rate and 30 years investment horizon

As can be observed in Figure F-8, the higher the CO_2 price the bigger the NPV_{social} results. Moreover, there is a non-linear relationship with discount rate, signifying the large effect of discount rate in results, similarly to the conclusion reached from the economic-performance sensitivity analysis. Looking at the same chart it is clear that with an increasing discount rate there is a decrease in NPV_{social}, while with a decrease in discount rate there is an increase in NPV_{social}. This means that with a lower discount rate, for example 4%, more options are expected to yield positive NPV_{social} values and thus be subject to funding relative to the resulting benefit/cost indicators. Indeed, four (4) options in that case, under a central MGO price differential scenario, exhibit positive NPV_{social} value, as summarized in Table F-5.

Table F-5: Societal cash flow valuation metrics results for case study 1(terminal tug) under the central MGO price differential scenario with 4% discount rate, 2% inflarion rate and 30 years investment horizon

Societal cash flow metrics results	CONV-S2	HYBRID-S2	CONV-S6	CONV-S1
Net Investments	\$677,148	\$2,661,285	\$1,174,686	\$865,860
NPVsocial	\$929,309	\$334,451	\$172,546	\$81,510
NPVfinancial	\$199,579	\$-544,519	\$-680,908	\$-286,020
NPVexternal costs	\$729,730	\$878,970	\$853,454	\$367,530
Benefit/cost ratio	-4.66	0.61	0.25	0.28
Benefit/investment ratio	1.37	0.13	0.15	0.09

It is obvious form the results that the CONV-S2 option results in negative Benefit/Costs ratio, indicating a "win-win" situation, where there are both welfare benefits from air pollution reduction and compliance benefits for the ship-owner. Moreover, the benefit/investment ratio is the highest amongst the competing options, meaning that if money is decided to be allocated for investment towards the built of such a Rotortug, this will be the most efficient use of funding resources from the port-authority perspective.

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