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Author: Harmen Pik - 4064801

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TU Delft
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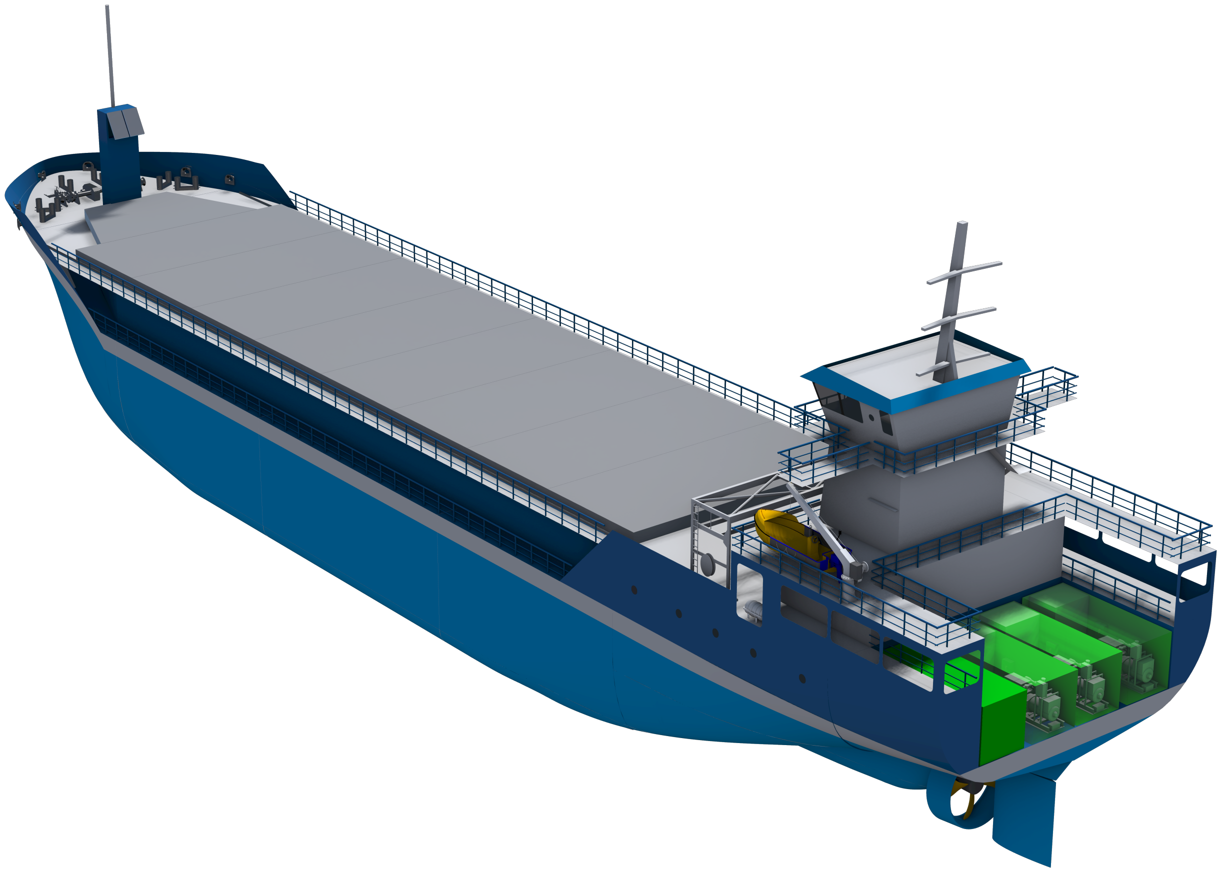

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Applicability of a modular power plant with alternative fuels

A case study to determine the impact on ships operation capabilities and power plant performance, when using a modular power plant for a 2999 gross tonnage general cargo concept ship.

by

Harmen Wieger Pik

Performed at :

DEKC Maritime

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Thesis committee:	Dr. ir. R.G. Hekkenberg,	TU Delft, Chairman thesis committee
	Dr. ir. P. de Vos,	TU Delft, Supervisor
	Dr. ir. S.A. Miedema ,	TU Delft, Independent committee member
	H. Linskens, MSc,	DEKC Maritime, Supervisor

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Abstract

This thesis examines a case study to determine the effects on system performance of the power plant and ship operational capabilities, this case is a ship designed by the company DEKC. It is a small general cargo vessel of 2999 GrT (Gross Tonnage) called the Future Trader. The ship design is finished and the ship will be equipped with a modular power plant and fuel storage on the aft of the ship. Different mathematical models are created for three modular power plants and as a base line a single engine non modular power plant was modelled. With those models the effects on the Future Traders, range, fuel costs and emissions (operational capabilities) are researched.

The research starts with the frame of reference for the study. In the design of the vessel a space of four Twenty foot Equivalent Unit (TEU) on the aft of the ship is reserved for the modular power plant, resulting in the instalment of the systems in standardised containers. Doing so results in a power plant which uses the concept of Distributed Generation (DG). The fuel storage is done in four TEU on top of the power plant, this has as consequence that a limited amount of fuel can be stored and this in combination with the use of different power plants and power plant components will result in different ranges. To research the effects on the operational capabilities of the ship, the efficiencies and fuel consumption of each power plant need to be known.

In total four different systems will be designed and compared as seen in table 1. The first is used as a base line and is not modular, the three other systems are modular. The systems are all simulated for a couple of voyages. After the simulations all data is normalised to the base line system and conclusions about the system performance and their effect on the ships capabilities are drawn.

Engine Type	Number of engines	Fuel
Internal Combustion Engine (CE)	one	MDO
Internal CE (DG)	three	MDO
Proton Exchange Membrane (PEM) Fuel cell	two	liquid hydrogen
Solid Oxide Fuel Cell (SOFC)	two	liquid ammonia

Table 1: Systems taken into account in the study.

For each modular power plant with its one fuel, the efficiencies of the systems and volume based fuel consumption are modelled to find the effects on the Future Traders' range. The efficiencies (power delivered, divided by heat flow of the fuel) of both the fuel cell systems are better than the base line. The ammonia fuel cell system is most efficient (+28%), after that a hydrogen fuel cell system will gain +5%. The three engine MDO power box solution will be less efficient (-9%) than the base line system.

There is looked at the fuel consumption for each system (volume of a TEU used per voyage), all with respect to the fuel consumption of the base line (100%). The MDO system will use 109%, ammonia will use 279% and hydrogen will use 357% of the fuel storage in TEUs compared to the base line. In the storage capacity of a TEU for each specific fuel a suitable storage method is selected [1]. In short sea shipping ammonia and hydrogen can supply a good range but for longer voyages the range of those systems is too small and a MDO DG setup should be placed on the Future Trader.

Besides the range the fuel costs are also of importance in practice. For hydrogen the fuel costs will be 10.8 times that of MDO and for ammonia the cost will be 3.7 time that of MDO. Since hydrogen is lower in range and has a large increase in costs ammonia will be a better alternative at this moment, the costs are still high but if grey ammonia (produced with fossil fuels) is used the cost can be reduced to 1.4 times that of MDO at this moment. Currently the use of a modular power plant on the Future Trader will always be an increase in costs. Even for the MDO DG setup the costs will still be 1.09 times higher compared to the base line. When

[1] e.g. For the storage of hydrogen a cryogenic system is needed that is cylindrical and under high pressure. This results in a specific amount of fuel that can be stored inside the dimensions of a TEU. This is referred to as one TEU of fuel storage for hydrogen. For MDO far more of the space of a TEU can be used for fuel storage.

CO_2 taxes are introduced or ammonia and hydrogen are widely used the difference in costs will get smaller for those fuels.

When considering the emissions a clear answer is that both fuel cell systems are better solutions than the base line, since both have no harmful emissions. The MDO DG setup has higher (9%) fuel related emissions (CO_2, SO_x) than the single engine configuration. However, most engine related emissions (NO_x, CO_e , PM, HC) are lower in comparison to the base line (single engine MDO) when looking at the emitted emission per burned kg of fuel. If the emission per sailed mile is considered the advantages are reduced due to the higher fuel consumption.

It can be concluded that a modular system with the concept of DG using MDO as a fuel will reduce the ships overall performance in comparison to the single engine diesel electric system (base line). When reviewing the DG fuel cell systems with respect to the base line system it is found that the ammonia fuel cell system has zero emissions and still offers a sufficient range. The increases in fuel cost are lower than that of the hydrogen fuel cell system. Hydrogen will also reduce harmful emissions to zero but the reduction in range is more severe. The increase in fuel costs is also significantly higher than for the base line. Overall ammonia seems the most promising of the non hydrocarbon fuels. The DG system is also useful as long as emission regulations remain unchanged. The MDO DG system can be loaded for large distance voyages and hydrogen can be loaded for short voyages if desired.

Acknowledgements

This thesis will end my time at the Delft University of Technology. It was a long journey in which I developed as an engineer but also in my personal development. The choice to leave Groningen for a study Maritime technology in Delft is one I never regretted. I had a great time in Delft and made great connections. For the thesis I moved back to Groningen since I missed the countryside and prefer to start my professional career over here.

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Also a great thanks to Harry Linskens, the company supervisor from DEKC. You really helped me out when needed with the right balance between the expectations from both the academical and business world. For every small question I could call you, sometimes resulting in a push in another direction as I was thinking, this all really helped!

A special thanks to Robert Hekkenberg for your input in the beginning and end of the thesis. Despite this being the only contact moment, you were great in pointing out the details that were needed to push the thesis and me to the next level.

Finally I would like to thank the company of DEKC for giving me a working place and professional help to finish my thesis and discover how working at the office works. Unfortunately due to corona my office hours were less then hoped. Still I felt at home and respected by colleagues. The family like working environment really helped to ask others for help and input.

On a personal note, I would like to thank my girlfriend, family and friends who have supported me during this thesis. With a big shout out to my girlfriend who helped correcting my English within this thesis. This I could never have done without you due to my dyslexia. I am looking forward to the opportunities that lie ahead!

H.W. Pik
Kantens, February 2021

Nomenclature

$\dot{E}$	Energy flow	J/s
$\dot{m}_f$	Mass flow fuel	kg/s
$\dot{m}_{pe}$	Mass flow pollutant emission	kg/s
η	Efficiency	
μ	Fuel utilisation coefficient	-
ρ	Density	kg/m^3
ρ_m	Mass energy density	MJ/kg
ρ_v	volume energy density	MJ/m^3
Θ	Temperature	°C
h^L	Lower heating value	kJ/kg
v	Velocity	m/s
V_c	Cell voltage of a fuel cell	V
c	Specific heat constants	kJ/(kg*K)
D	Diameter	m
E	Energy	J
h	Specific enthalpy	kJ/kg
I	current	A
j	current density	A/m^2
LHV	Lower heating value	MJ/kg
m	Mass	kg
P	Pitch	
P	Power	kW
Q	Heat	J
r	Evaporation heat	kJ/kg
T	Temperature	°C
W	Work	J
We	watt electric power	W, J/s

Abbreviations (Alphabetical)

AC Alternating Current

AMFC Alkaline Membrane Fuel Cell

ANT Antwerp Port

CE Combustion Engine

CHP Combined Heat and Power

CNG Compressed Natural Gas

CSR Continuous Service Rating

DC Direct Current

DG Distributed Generation

DP Dynamic Positioning

DSM Design Structure Matrix

DWT Dead Weight Tonnage

ECA Emissions Controlled Area

ECTS European Credit Transfer System

EEDI Energy Efficiency Design Index

EFD Energy Flow Diagram

EM Electric Motor

FC Fuel Cell

FiFi Fire Fighting

FMEA Failure Mode and Effects Analysis

FN Froude Number

GDA Gdansk Port

GHG Green House Gasses

GT Gas Turbine

GrT Gross Tonnage

HAM Hamburg Harbour

HFO Heavy Fuel Oil

HHV Higher Heating Value

IPS Integrated Power System

LHV Lower Heating Value

LNG Liquid Natural Gas

MAR Marseilles Port

MCR Maximum Continuous Rating

MCFC Molten carbonate Fuel Cell

MDO Marine Diesel Oil

MSc Master of Science

mt Metric Ton

nm Nautical Mile

ORC Organic Rankine Cycle

OWD Open Water Diagram

PAFC Phosphoric Acid Fuel Cell

PEBB Power Electronic Building Blocks

PEM Proton Exchange Membrane

PER Pollutant Emission Ratio

PM Particulate Matter

PoA Plan of Approach

RPM Rounds Per Minute

RTD Rotterdam Port

SFC Specific Fuel Consumption

SOFC Solid Oxide Fuel Cell

SPE Specific Pollutant Emission

TEU Twenty foot Equivalent Unit

TU University of Technology

WHR Waste Heat recovery

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1. Introduction

To obtain the degree of Master of Science (MSc) a graduation research needs to be performed, which needs to be documented in a MSc Thesis. This document is the final document for the thesis with the following topic: System performance of a modular power plant running on an alternative fuel, for a concept ship. The author chose to preform graduation outside of the University of Technology (TU) Delft at a company. In May of 2019 the researcher was introduced to one of the employees of DEKC Maritime, a company specialised in marine engineering located in Groningen in the Netherlands. In March 2020 the thesis was started at DEKC. After approval of the Plan of Approach (PoA) the literature study of this thesis was started, after that the development of systems and models was started. The way models are developed and the results and conclusions are shown within this thesis.

The thesis report will be structured in the following way. Within this chapter (1) the problem will be introduced and the concept vessel called the Future Trader will be discussed. This vessel is designed by DEKC to be a possible solution for the problem, this vessel will be used as a case study in this thesis. After the problem and the Future trader are discussed the research question and scope will be reviewed in chapter 2. In chapter 3 the frame of reference will be discussed, in this chapter the definitions used in this thesis and system boundaries are presented. The sailing profile and emission regulation for the ship are also presented in chapter 3. If those are clear a first step in the description of the modular power plant is taken in chapter 4. Here Distributed Generation (DG) will be introduced and explained, this is done because the Future Traders power plant uses DG for the power generation. In chapter 5 there will be looked into possible alternative fuels and their specifications. The fuels which will be selected for use in the Future Trader are also presented in this chapter. As this is completed there can be looked into the system descriptions and the power requirements for the Future Trader, this is done in chapter 6. To determine the power a system breakdown is done to find the energy consumers within the ship. After the total power output for the modular power plant is determined the result are combined with the fuel selection and those together will be used to determine suitable power converters and the number of installed power plant for the Future Trader. The results of this are presented in chapter 7. After this selection is completed all the information is known for the system design of the power plant and power packs. How this is done and whether it is plausible to fit all systems in the power packs is discussed in chapter 8. After finishing the general system design different mathematical models, each for a specific power plant, will be created using Matlab Simulink. How this is done is reviewed in chapter 9. In chapter 10 the used voyage for the Future Trader will be presented and the results from the mathematical models will be determined. With the results from the mathematical models known, there can be started with stating conclusions and answering the research questions, this will be done in chapter 11. Finally the research will be reviewed and future research will be discussed in chapter 12.

Background

The last couple of years climate change becomes more and more visible, the effects are more extreme and more common now than they were a few decades ago. Due to the effects of climate change there is a global discussion about the use of fossil fuels. Besides this discussion a lot of companies and governments are performing research on the effects of climate change and how we (humans) can solve the problems that come with climate change (KNMI, 2014). One of the fields of research is focused on finding a replacement fuel for fossil fuels, these replacement fuels are so called "alternative fuels". However, it is hard to predict the fuel that will be used in the future.

The uncertainty of which fuel will be used in the future brings a challenge for engineers. This challenge is that they do not know which power plant should be selected for a vessel since different power plants, or power plant components (e.g. internal combustion engines and fuel cells), require different fuels. Therefore it is challenging to select engines that are available now and will still be suitable for the fuel of the future. This is a complex challenge for the shipping industry, due to the fact that the economic lifespan of ships is a couple of decades. Therefore choices made today need to still be suitable choices in 10 to 20 years from now. For new build ships that need to be developed now this is a difficult situation, engineers need to be ready for the fuel and power plant of the future today. Since it is uncertain what this fuel will be, other solutions to counter this problem are explored.

One of the possible solutions to deal with the inherent uncertainty of the energy transition is a modular power plant that can be removed and added to a ship. Such a ship is designed by the company DEKC (see figure 1.1). Using a modular power plant results in a ship that can be upgraded or adapted to other fuels and engines by only changing the power plant. This will make ships developed at the moment suitable for future fuels and engines. However, this strategy brings a couple of challenges that will be addressed later in this study. On top of those challenges a power plant of a marine vessel has to perform well on many criteria such as: fuel consumption, emissions, radiated noise, propulsion availability, manoeuvrability, comfort due to minimal noise, vibrations and smell, maintenance cost and purchase cost. (Geertsma et al., 2017).

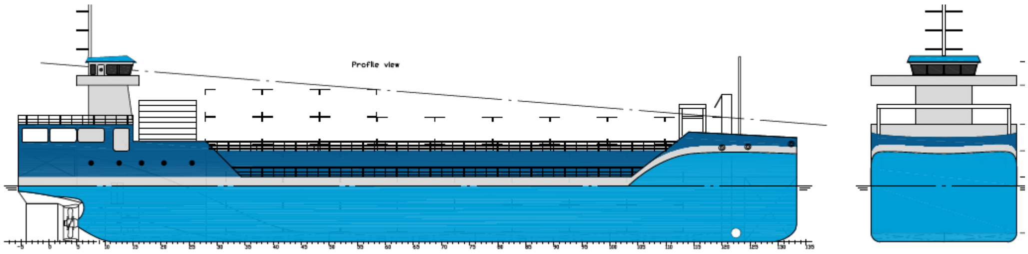


Figure 1.1: Side and front view of the Future Trader by DEKC Maritime

The ship that is designed by DEKC is called the Future Trader. This ship is used in this study as a case study and no changes to the ship design will be made, i.e. this study fully focuses on the design of the power plant of the Future Trader, not on other ship design aspects. The Future Trader is a general cargo vessel. The vessel has an overall length of 83.30 meters and has a Gross Tonnage (GrT) of 2999. The ship has a design speed of 10 kn and the resistance characteristics of the ship are known. The installed power of the ship is not decided and will be a result of the present study.

The Future Trader is designed so that the power will be supplied to the propeller using a full electric propulsion, this can be found inside the ship close to the propeller. The electric power needed to drive this motor and other on-board systems needs to be generated by a modular power plant, which will be designed in this thesis. For this modular power plant a space is reserved by DEKC on the stern of the ship. The space has the following dimensions: 6058 mm x 10310 mm (length x width). This is equal to four Twenty foot Equivalent Unit (TEU) next to each other. The space reserved for this can be seen in figure 1.2. On top of these four TEU an extra row of TEUs can be added in which the fuel is stored. This study analyses the effects on system performance of the power plant and ship operational capabilities when using the modular power plant concept of the Future Trader.

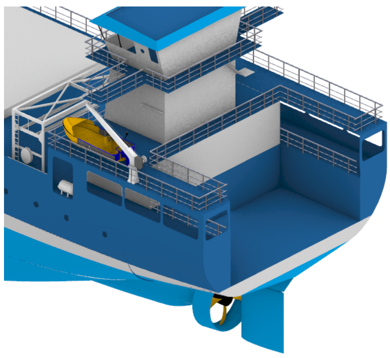


Figure 1.2: 3D stern of the Future Trader

2. Research questions and scope

Now that the problem is introduced and the general arrangement of the used concept ship is given, the research question are presented in this chapter. After the main research questions the sub question will be introduced, those help to find the answer to the main question, both will be addressed in chapter 2.1. After the questions the scope of the research will be narrowed in chapter 2.2.

2.1 Research questions

In this thesis the main research question is the following:
What are the effects on system performance of the power plant and ship operational capabilities when using different power plant concepts and different fuels in the Future Trader concept ship?

To help answer the main research question the following sub questions are formulated:

1. What are the system performance parameters of interested in this study?
2. What are the ship operational capabilities of interested in this study?
3. Which alternative fuels will be used for the modular power plant?
4. Which systems of a ship its power plant will be placed in the modular power plant?
5. What energy converter types for the power generation will be used?
6. How many power boxes (sub systems of a power plant) are desired to power the ship?
7. Which models are used to find the effects on the selected performance parameters and ship operational capabilities of the designed system with the alternative fuel(s)?

2.2 Scope of the thesis

Within the topic of the application of modularity in Maritime Technology (MT) there are many aspects to be researched within a large variety of disciplines. This thesis is focused on the discipline of marine engineering. More specifically, the scope of this thesis is bound by the modular power plant design as foreseen for the DEKC Future Trader ship concept. This means that the following aspects are out of the scope:

- In the design of DEKC a full electric propulsion is installed i.e. the propeller is driven by a single Electric Motor (EM) only. Since no changes will be done in the design of the ship, ships with directly or indirectly mechanically driven propellers (i.e. propellers driven by internal combustion engines through a mechanical transmission system consisting of shafts, gears, etc), in combination with a modular power plant will be out of the scope.
- Due to the fact that the ship has a full electric propulsion the decision is made that the module only needs to deliver electric power. Hydraulic power and mechanical power will be converted outside the module. How this is done is left out of the scope. The reason to only have electric power as an output is made to keep the number of connections from the module to the ship as low as possible.
- The location of the modular power plant is at the stern of the vessel since there space is reserved there in the design for the modular power plant. Whether this is the best position on the ship is open for discussion, but that discussion will be out of the scope. So, effects on the trim or stability of the ship will be neglected.

- For each power plant concept considered only one engine type will be installed in the modular power plant. In a DG setup, a couple different engine units with different power ratings and/or operating on different fuels may be considered, but these types of combined systems are left out of the scope. This is done for a number of reasons:
  - To limit the number of power plant concepts and fuels under consideration to a reasonable number, since considering all possible configurations of different power plant components and fuels will result in a number of possibilities that is too large to research within this research (Georgescu et al., 2017b). Therefore a reduction in possible layout needs to be done to keep the options within reasonable numbers.
  - Practical considerations with regard to maintainability (e.g. exchange-ability of spare parts) and costs are in practice often reasons to select only one engine type. A detailed operational profile for the Future Trader is not available, making optimisation of power ratings impossible (e.g. it is impossible to select the power rating of a dedicated generator unit for operation in ports when power consumption in ports is unknown).
  - Comparing the effects on system performance for a small number of well-selected power plant concepts in combination with well-selected fuels provides sufficient insight to answer the main research question. Furthermore, note that the utilised models are set up generically, making it possible to analyse more complex, combined power plant concepts with these models in later design stages as well when more information on e.g. the operational profile is available.
- The working principles and challenges of advanced electronics are left out of the scope as they will have little influence on the system parameters analysed here.
- The thesis will be focused on one modular plant at a time for one journey. In theory it could be possible and it may be desirable to switch between plants. For example, when the voyage is partly trough an Emissions Controlled Area (ECA) where more strict emissions regulations are enforced. Changing systems during voyage is however left out of scope for similar reasons as the ones provided for selecting only one type of engine for each modular power plant concept.
- At last, the results of interest in this thesis are seen from tank to wake. However for some green fuels are cheaper when those are produced in grey manner, if this is done there are harmful emissions within the production process of the fuels. Therefore it can be argued if a well to wake approach is not a more suitable way to look at harmful emissions. However, in this thesis modular power boxes are used for a ship that needs to comply with upcoming regulations. Those regulation are mostly based on emissions of the ship, therefore there is looked into the tank to wake only since those will be measured for regulation purposes. Note: when the costs are mentioned the prices are based on green fuels, in this way there will be no harmful emissions in the well to tank part.

3. Frame of reference

In this chapter the overall frame of reference will be discussed. Chapter 3.1 will introduce the definitions of modular power plant and modular power pack. In this chapter the difference between the two concepts will be presented. Thereafter the question which system performance aspects are of interest in this study will be answered in chapter 3.2. Next, the area of operations and the incomplete sailing profile of the Future Trader are presented in chapter3.3. In chapter 3.4 the regulations that are applicable on the performance parameters are discussed. In the last chapter 3.5 the modularity of the power plant will be addressed.

3.1 Modular power plant and power pack definitions

The Future Trader designed by DEKC is a concept ship that should provide ship owners with a ship of which the power generation can easily be altered. This is done by making the power plant modular, in this way the uncertainty of what fuel would be used in the future is reduced since the ships powerplant can be changed easily. Due to the design and to created an easy transportable solution multiple smaller power pack will be installed (this will be explained in chapter 4 in depth). Doing so relates to two concepts that look and sound similar but there is a fundamental difference between them. Those concept are power plant (modular engine room) vs power pack, the definitions are:

- Power plant: this refers to the complete power generation system. Which can consist of multiple power packs. This is without the propulsion engine and systems. In the Energy Flow Diagram (EFD) of the ship this can be found on the left side, see figure 3.1.
- Power pack: This is a single smaller (sub)system of the power plant with one energy converter which is installed in a single TEU. Multiple of those power pack will form the power plant (modular engine room).

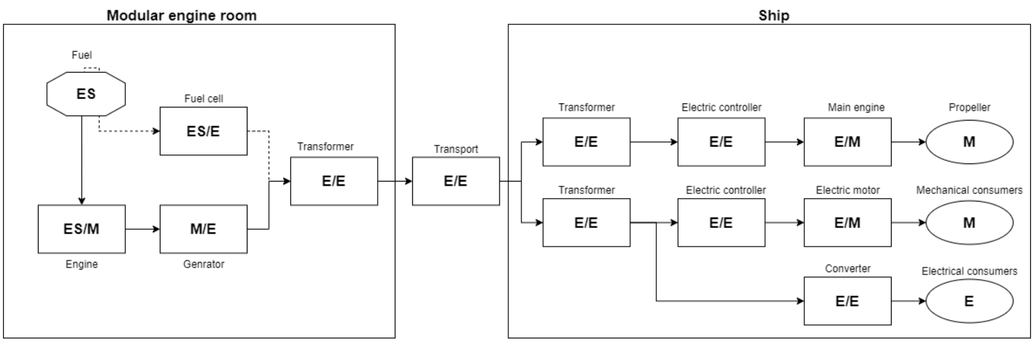


Figure 3.1: The modular power plant on the left (2 different systems, Fuel cell or generator set) and power consumers at the right

3.2 Power plant performance parameters and ship operation capabilities

Since the goal of the thesis is to find the effect on the performance parameters of ships power plant when this will be modular and to see how those effect the ships operations, those need to be described.

One of the ships operational capabilities is the range of the ship. Since the design of the ship is fixed and four TEU of fuel can be loaded the range is limited and is one of the important operational capabilities. The range of the vessel will depend on some performance parameters, those are the amount of fuel that can be stored within those containers and the fuel consumption. The amount of electric energy that can be converted from the chemical energy of the fuel will also be of importance, meaning that the overall system efficiency of the power plant is of importance. When the fuel consumption is combined with the exact amount of fuel stored the range can be found for the Future Trader.

Besides the range of the ship another important parameter of the power plant is the emissions that will be produced by the power plant. Since the Future Trader is designed to be a solution for the uncertainly that comes with the selection of future fuels, the ship should also compile to the upcoming regulations and therefore should reduce the polluting emissions. More about this will be discussed in chapter 3.4.

The last ships operational capabilities is a more practical one. Since ships need to be economical beneficial for the owners the cost of the ship are of interest. This thesis is focused on the power plant and fuel consumption of the ship. Therefor there will be looked into one of the operational costs for the ship, this is the difference in fuel cost when using different power plants.

3.3 Sailing profile

All ships have a sailing profile, this profile is used to design the ship and its systems. However the Future Trader of DEKC does not have a complete sailing profile. The millage range and days at sea are not given by DEKC and are flexible. This choice was made to be able to explore as many options as possible for the Future Trader. However to be able to design a suitable power plant some of the characteristics of the ship need to be set.

Some features of the ship are known. The ship is a general cargo vessel that will be active in short sea shipping. The main area of operation will be around European water where no ice class is needed. The assumption is made that most voyages of the Future Trader will be similar. A voyage profile will look similar to other short sea vessels, meaning there is time spend at the quay, then the ship will sail to its destination with a almost unchanged speed. When it arrives, some waiting time can occur before it can enter the port. A typical voyage can be found in figure 3.2. However other sailing profile data as maximum range are not fixed, and this will be a result of the study. In figure 3.2 seen is that for around 80% of the time the speed is constant with some peaks of a couple of hours. In addition to the figure assumed is that the ship is entering port and leaving port with a speed of 7 kn, based on maximum speed in the port of Rotterdam.

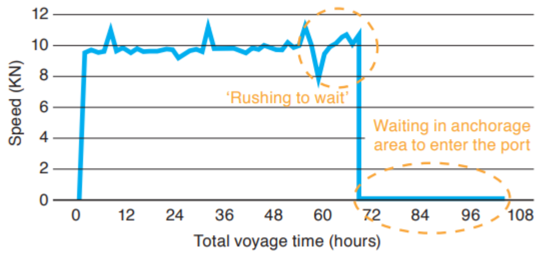


Figure 3.2: Typical voyage around Baltic sea (Gustafsson, Magnus et al., 2018)

3.4 Emission regulations

The regulations addressed here are applicable to power generation systems on board of ships. They are therefore shortly reviewed in this section, to ensure a proper power box that could be used in the shipping industry. In practice each power box needs to comply to a lot of rules, here the emissions regulations are discussed. There are many other regulations which are applicable on the ships however those are not of interest in this study. The emission regulation are presented for completeness. The result of the study do not have to compile to those regulations since the regulations are applicable on ships in practice and this is a academical research.

3.4.1 Emission Control Area (ECA)

First since the Future Trader operates around Europe were ECA are found thos will be presented. The ECA areas are described as follows (definition is from MARPOL Annex VI (IMO, 2019)):

- The North American ECA, which means the area described by the coordinates provided in appendix VII to this Annex.
- The United States Caribbean Sea ECA, which means the area described by the coordinates provided in appendix VII of annex VI of the MARPOL.
- The Baltic Sea ECA as defined in regulation 1.11.2 of Annex I of the MARPOL.
- The North Sea ECA as defined in regulation 1.14.6 of Annex V of the MARPOL.

3.4.2 Emissions

In this section the regulations for air pollution will be presented. The most commonly known emission is that of CO_2, however in the shipping industry there are three major groups of area polluting emissions, those are CO_2, NO_x and SO_x. For those there are air polluting regulations. In general the IMO wants to reduce the Green House Gasses (GHG) emissions to 50% in 2050 compared to that of 2008 (IMO, 2018). Those emissions are applicable on a global level. However in ECAs, more strict rules for emissions are enforced. The rules are applicable in practice and will not be strictly followed for the Future Trader. Also as result of the IMO its wish to reduce emission drastically in 2050 most of the regulations will change in the future. For this uncertainty the Future Trader is a solution since in this ship concept the power plant can be changed in the future when regulations are changed. For every new build ships (from 01-07-2015) the following rules are applicable. Some of these rules are also applicable on major conversions, meaning that the ship is substantially altered in dimensions carrying capacity or engine power or which substantially alters the energy efficiency of the ship and includes any modifications that could cause the ship to exceed the applicable required Energy Efficiency Design Index (EEDI). However the Future Trader is a 2999 GrT general cargo vessel and therefore there are no specific rules with respect to the EEDI.

The rules which are stated by the IMO in MARPOL Annex VI with respect to the air polluting emissions are discussed below for the major groups of emissions. The regulation that is pressented is the regulation that would be applicable of the Future Trader ship as it was build today. All are found in Annex VI - Regulations for the Prevention of Air Pollution from Ships (IMO, 2019).

For a conversion with respect to the engine and changing it the rules state the following. *A marine diesel engine with a non-identical marine diesel engine, or the installation of an additional marine diesel engine, the standards in this regulation at the time of the replacement or an addition of the engine shall apply. In the case of replacement engines only, it is not possible for such a replacement engine to meet the standards set forth in paragraph 5.1.1 of this regulation (Tier III, as applicable), then that replacement engine shall meet the standards set forth in paragraph 4 of this regulation (Tier II), taking into account guidelines developed by the Organisation.* This is mentioned since the Future Trader in designed to swap easily between power packs and therefor other engines or even power plant with complete other energy converter types.

Nitrogen oxides
Looked to the Nitrogen oxide emission, those are stated in regulation 13 of the MARPOL annex VI. The rules are for different tiers, the rules are applicable on marine diesel engines.

Tier II
The emission of nitrogen oxides (calculated as the total weighted emission of NO2) from the engine is within the following limits, where n = rated engine speed, the ship needs to be at least a Tier II:

- 14.4 g/kWh when n is less than 130 rpm,
- 44 · n(-0.23) g/kWh when n is 130 or more but less than 2,000 rpm,
- 7.7 g/kWh when n is 2,000 rpm or more.

Tier III
However due to the area of operation is within a ECA the ship should also comply with Tier III emissions.

- 3.4 g/kWh when n is less than 130 rpm,
- 9 · n (–0.2) g/kWh when n is 130 or more but less than 2,000 rpm,
- 2.0 g/kWh when n is 2,000 rpm or more.

Sulphur oxides
Sulphur oxides are a emission which is reduce more and more. At the moment applicable rules are state in regulation 14 of the MARPOL annex VI. The rules are for different tiers. In general the sulphur content of any fuel oil used on board ships should be below the 0.50% m/m on and after 1 January 2020. However in an ECA the emissions should be lower then 0.10 % m/m. Here already seen is that regulations will change overtime, ship need to compile to the new rules in ECA. A ship as the Future Trader would have less trouble to compile with new regulation since only a different power plant needs to be installed, which is an easy alternation to the Future Trader.

Carbon oxides
For carbon oxides there are no specific rules for ships at this moment. However the IMO has started with monitoring all ships that load and unload cargo in Europe above 5000 Dead Weight Tonnage (DWT). The emission of CO_2 is measured and probably regulation will follow in upcoming years. The IMO already has published a strategy that should reduce the GHG to 70% in 2050 compared to the emission of 2008 (IMO, 2018). In the spring of 2021 the IMO aspires to publish data that is collected in 2019 and this will probably result in regulations for carbon oxide emissions. Those could have drastically effect on the shipping industry, only time will tell in what magnitude, this is one of the insecurities for which the Future Trader concept is designed to counter.

3.5 Modular systems

The focus of the Future trader its concept is that it should be possible to change the power plant configuration in a short amount of time when laying at a quay. So when and if desired power boxes should be load on and of of the Future trader at the quay. Therefore transportation and handling of the modular power boxes should be as easy as possible. Since the space available in the design has the same dimensions as four TEU. The choice is made to keep the power boxes within this standardised TEU.

This can lead to one big system that needs to be put together at the stern of the ship or multiple individual smaller systems that are self supporting. In chapter 4 there will be looked at a suitable option for the ship.

First a definition of modularity will be given. In the literature there are many definitions and types of modularity found. This definition is based on the definition of Erikstad for modular design. He described the following:
The opposite of an integral architecture is a modular architecture. Here, the different functions of the product are, to the extent possible, allocated to separate product modules, and the interaction between these modules is small or non-existent.(Erikstad, 2019).
This definition is used as a base and some constrains are added for the use in this thesis. The definition used in this study is as follows.

Definition modularity: *The whole power plant or a power box can be added and taken off the ship in a harbour, without docking or major work. So the power plant or box is swapped easily on and off the vessel.*

Now the definition of modularity is given there is looked to the benefits modularity has for the Future Trader. Using modular systems can bring benefits and challenges, in the area of engineering, design and production, both for builder and client. The benefits(+) and challenges(-) that are applicable on the Future Trader are [1] (Largiader, 2001), (Erikstad, 2019):

+ Give flexibility in use. If multiple power packs are available the ship can be equipped with different energy converter for each voyage.

[1]Many of the benefits and challenge will be applicable when the modular power boxes are used on a wide scale in the industry.

+ Result in a design that is ready for the future today, since refitting can be done more easily as on a non modular system.
+ Improvement of availability due to pre-applied parts. The impact of failure can be reduced since the ship can be equipped faster with a new power pack.
+ Increase in automation in production process. Due to standardised units.
+ Improvement in production quality, when modules are used on a large scale.
+ Reduction of maintenance time, due to easy access or swapping modules.
+ Supporting innovation by using a combination of modular systems.
− Increase complexity.
− Too many modules can reduce performance.
− Swapping modules for new systems can lead to under educated personal. If a combustion engine maintenance expert has to work on a fuel cell he/she could be under educated.

Modular design is an adoption from other industries. Here instead of the one of a kind design which shipping mostly is, there is a product platform strategy. This allows to reduce cost of engineering and also provides lower maintenance costs due to the use of standardised systems. However, the platform design strategy is limited in shipping, especially for complete vessels due to the previous mention of a one of a kind design. A lot of ships and their owners have a request for a high degree of customisation (Erikstad, 2019).

However using it on only a power plant leave the rest of the ships design process the same, in this way still a high degree of customisation can be achieved. Using modularity for power plants, there could be a reduction in maintenance and production time and costs. Using a modular plant, the plant itself can be customised not only during building but also years after that new technology can be fitted on the vessel. This can optimise the ship for now and in the future to still be able to keep up with regulations.

When looking at engine technology this can lead to changes in efficiencies and emissions. Research should be done to determine the possible scale of the effect doing this. However this depends on the fuel, engines and systems used in the modular plant. Modularity can be used in a power plant, but the effects of a modular power plant need to be studied (as done in this research).

4. Distributed Generation systems

In the design of the Future Trader there is a space reserved at the aft in which the complete power plant should be installed, the dimensions of this space equals that of four TEU. This in combination with the demand of DEKC to easily swap the powerplant (or parts) for a new one in port means that the powerplant should be installed in an easy way and handling needs to be simple. Therefore using power packs in TEU size could be a suitable option. This is called Distributed Generation (DG). For the maritime industry there is little representative literature regarding the subject of DG since the concept is mainly used in onshore systems. However since a ship's electrical system can be compared to a small stand alone land based grid (Skjong et al., 2016), the benefits and challenges of those land based systems can be applied on the Future Trader. Therefore a study is done to see the effect of DG in a land based system.

The differences between land based systems and a ship system are: the transported distance, frequency planning of power generation distribution distance, system size, single fault lines, environmental loading effects and load effects. The fundamental difference between the systems will not be discussed, those can be found in (Skjong et al., 2016). The differences are however taken into account in the comparison made in this chapter.

There is started with the definition of DG in chapter 4.1. When a clear definition is presented for DG, there will be looked at the applicable benefits and challenges for DG on a more general level in chapter 4.2. Since DG is not widely adapted in the marine industry in the chapter 4.3 there will be looked at the application of DG within the maritime industry and why this is done. All is concluded in chapter 4.4.

4.1 Definition of DG

For the definition of DG there is no general accepted definition and there are a number of other names for DG, such as 'embedded generation', 'dispersed generation','decentralised generation' and 'distributed energy resources' but they all mean more or less the same. (Morren, 2006). The small differences between those are not discussed in this thesis. For this thesis DG means that smaller electrical generation units are connected to a large distribution network (Morren, 2006). The modular power plant of the Future Trader represent this large distribution system and the smaller generation units are the power packs.

4.2 General benefits and challenges of DG

Due to the lack of literature on DG systems aboard of ships. Looked is which literature about land based systems could be applicable for shipping. e.g. a common benefit for DG is to reduce transportation cost or grid cost, this will not be the case for shipping because the used grid is a lot smaller than the power grid of a country. However other benefits and challenges are applicable and those are presented in this section.

Benefits (El-Khattam & Salama, 2004)

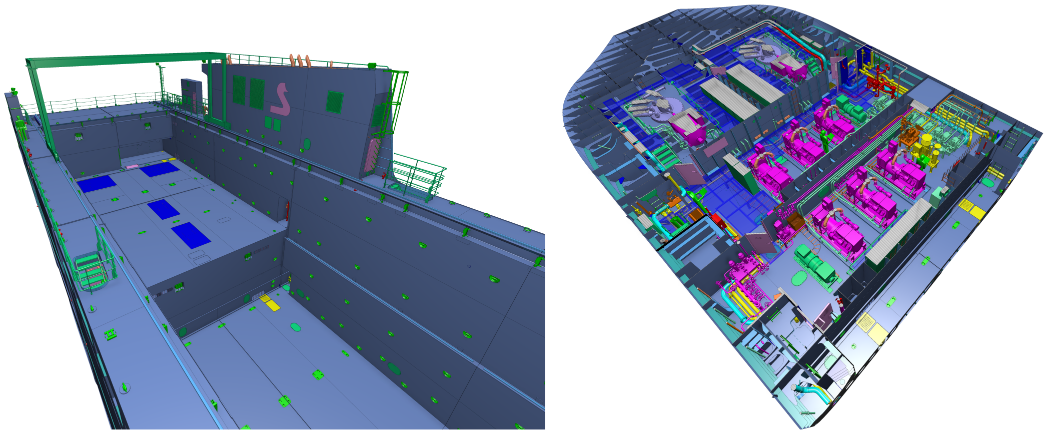
- DG can provide the required load increases by installing them in certain locations, so they can reduce or avoid the need for building new systems.
- DG can be easily assembled anywhere as modules.
- DG can be assembled is a short time.
- DG are not restricted by the centralisation of the power as they can be placed anywhere.
- DG are well sized to be installed in small increments to provide the exact required customer load demand.
- According to different DG technologies, the types of energy resources and fuels used are diversified. Therefore, there is no need for certain types of fuels more than others.

- Savings into port and maintenance cost can be gained. Since in a DG system power generating units can be switch off when partial load is needed.

- Using a DG setup increases the redundancy of a vessel.

Another advantages of DGs is that installing DGs reduces the construction schedules of developing plants. Hence, the system can track and follow the market's fluctuations and/or the peak-load demand growth.(Silvestri, Berizzi & Buonanno, 1999) In this formulation this is true for the power grid, but for shipping this not entirely true. However if used in combination with modularity of the power plant it can be possible to engineer one DG system that could be placed on different vessels, this can result in savings in design costs.

For shipping the use of a DG system can result in an increase in cargo space. Due to smaller engines especially the height dimensions can be smaller. The engine can be placed in locations where a larger diesel can not be placed. For example, multiple smaller engines can be placed in the stern of the vessel. Due to the height savings extra cargo space can be created, see figure 4.1. The total space needed for a DG system is larger due to multiple smaller systems that all need their own equipment. But due to the flexibility in placement the space aboard of a ship could be better used.



(a) engine room

(b) vessels engine layout

Figure 4.1: A vessel (designed by DEKC) with a DG system at the stern.

A last argument for DG systems is that the polluting emissions are lower than traditional plants (El-Khattam & Salama, 2004),(Silvestri et al., 1999). However, this could not be said for the maritime industry because this strongly depends on the sailing profile of the vessel, the fuel type used in the DG setup and before a DG was used. To claim that DGs can reduce polluting emissions within the maritime industry still needs to be proven.

Challenges

- Using a DG system makes the systems more complex.

- A DG system has multiple inputs for power, those need to be controlled and combined to be able to power one grid.

- DG systems also have multiple links to each other which need to be designed (Daly & Morrison, 2001)

- A DG system costs more to produce due to the larger number of parts. (Daly & Morrison, 2001)

- Safety of the system is of importance (Grigsby, 2016), what happens when a part of the DG system breaks down?

Within the maritime industry other challenges need to be taken into account. For example: the location where the DG system will be installed needs to be considered, in this thesis the system is at the stern of the ship. The system needs to be resistant to sea water and needs to be attached properly to the rest of the ship, to prevent losing part of the system in fierce sea states. Also the robustness of the DG systems aboard of a ship need to be better in comparison to the same system on land. Due to the rough environment and the fact that a ship is moving a DG system will experience force due to ship movement and wave impact (Diab et al., 2016). When DG is used it is often combined with an electric propulsion system. Doing this results in an extra energy conversion in comparison to a mechanical driven ship. The extra conversion will result in extra losses in the system. However, depending on the operation profile of the ship it is possible that this loss could be reduced or even transformed into a profit when using a DG.

4.3 Marine application of a DG system

In this section the DG implication within the shipping industry is reviewed. Within the shipping industry a DG system is not new. In a lot of ships there are a couple of diesel generators sets installed next to a main engine. Those are to provide electricity in case the main engine is shut down, this type of setup is already a small DG system.

In the more recent years there are more ships with a DG setup to deliver power to all of the ship its systems. In those ships a couple of generator sets are installed to provide the ships with power not only for auxiliary users but also for the propulsion. This type of system is mostly found in ships in the offshore branch, those ships are often equipped with Dynamic Positioning (DP) capabilities. In other ship types those systems are seldom used, due to higher building and design costs. However, the use in DP ships can be seen as a proof of concept, but why is was for this setup chosen for those ships?

An often mentioned reason is the increase in efficiency but also the flexibility in energy supply and the capability of adding energy storage aboard are reasons to opt for a DG system (Tang et al., 2015). However, there are challenges to overcome while a DG setup has a lot of potential. Another reason for a DG system in DP ships is the response time of this setup. Often DP ships have thrusters located at the far end of the ship. This location makes a mechanical drive unpractical. So, often those ships have engines that generate electric energy that is used for the propulsion (Veksler et al., 2012). To make DP effective those thrusters need to give a lot of power in a specific direction almost instantly. If a large diesel engine was used for a DP task, the engine can not keep up with the quick change in power demand due to slow turbo response. Therefore smaller and more engines can be used to keep up with the fast change in power demand (Veksler et al., 2012). Also a reason for the use of a DG system in DP ships is the increase in redundancy. When a single engine fails the other generators are capable of picking up the loss in power and therefore the ship can continue the operation at least for the time needed to stop working in a safe manner (Tang et al., 2015) (Patsios et al., 2012).

4.4 Conclusion about DG systems in shipping

To install a DG system challenges need to be countered. In the long run there are multiple benefits to gain, this makes a modular DG power plant a suitable option for a ship. In a DG system there can be an increase in losses so they will be less efficient than others, when running at their design point. However, a DG setup can be more efficient in partial load due to the capability of switching single generators on and off, if this gives an increase in ship and powerplant performance for the modular power plant on the Future Trader needs to be proven.

The use of DG setups is seen in ships and increases the redundancy of the vessels and therefore reduces the risk of a complete break down of the vessel (dead ship). This is a major advantage for ships with DP capabilities who are close to other structures or connected to the bottom. For other ship types the use of a DG system can be beneficial, but due to higher investment costs and due to the lower risks when a dead ship occurs the use of this system is not often found. However, there is a lot of research done regarding the use of DG system with alternative fuels and the use of power storage, this to keep up with upcoming emission regulations.

The final and most important reason for the use of a DG system in this study is the size. Due to the fact that in this thesis the power plant needs to be modular and that it should be able to be transported from and to a harbour, it is practical that this could be done in standardised form (container size). As mentioned before this can be realised when multiple smaller engines are used and that each of those can be fitted within the size of a container.

So due to the increase in redundancy, the potential to reduce fuel consumption, the flexibility in in-/decreasing the installed power and the ability to make smaller sized unit for easy transportation a DG system can offer advantages for the Future Trader. Therefore this type of system will be used. The exact size and systems needed will be research later on in the project (see chapter 8). Before there can be started with the system engineering of multiple power plants, first suitable fuels need to be determined.

5. Alternative fuels

In the near future new fuels will become more needed to keep up with regulations and to reduce polluting emissions. This results in a insecurity around what power plant types should be installed in new build ships. The Future Trader counters this by using a modular power plant that consists of a DG power box concept, this power plant can be replaced by a power plant with other power plant components and other fuels. To find the effect of the ships operational profile several of those modular systems will be modelled, as a reference a single marine diesel engine will be used as a baseline. Before the system design of the other power boxes can be done suitable fuels need to be selected, this will be done in this chapter. There will be looked at different fuel types in chapter 5.1 e.g. hydrocarbon, chemical fuel or electric power storage. When the general description of fuel types is explained a research is done based on the fuel properties in chapter 5.2. This will be done with respect to the storage volume, mass and possible range, those criteria are chosen since the storage space is limited to four TEU on-board of the Future Trader. After selecting suitable fuels, the chemical properties and properties of the selected fuel are reviewed in chapter 5.3. At last all is summarised and concluded in chapter 5.4

Note that there is a small selection of fuels taken into account for this thesis. There are many other alternative fuels or combinations of fuels available or researched but in this thesis only the fuels that are often discussed in literature are taken into account (Pik, 2020).

5.1 Fuel type

In this section there will be looked into the non carbon fuels. This is because they are very promising with respect to emissions. First the chemical fuels will be addressed, afterwards electric power storage is discussed. Hydrocarbon fuel will not be explained, since those are widely used in different industry it is assumed that the general fuel properties are known. The used chemical formulas of diesel are found in chapter 5.3.

5.1.1 Chemical fuels

From an environmental point of view it is interesting that a fuel does not have a carbon fraction within the molecules. If this is the case no CO_2 will be present in the emissions. Besides the positive environmental impact of non-carbon fuels, those fuels are often more future proof because they will be more suitable for upcoming regulations (Hansson et al., 2019). Hydrogen and ammonia are free of carbon elements, so those could be interesting and based on literature both could be a suitable option (Pik, 2020),(Hansson et al., 2019). Both fuels need to overcome some challenges but both can be a suitable fuel for this project. To be able to make a choice for this study both will be researched, see chapter 5.3.

5.1.2 Electric power storage in batteries

Besides chemical fuels batteries are becoming more common aboard of ships. Every ship has an energy storage aboard, most of the time this energy is stored in a chemical way as fuel (e.g. diesel, LNG, hydrogen and many more). The energy can also be stored in a electrical form, in batteries. However a full electric ship (the size of the Future Trader) with only batteries as energy storage is not designed yet, this due to the draw back of modern batteries (see chapter 5.1.3). Having an electric power storage aboard of the vessel can offer benefits, such as more redundancy, reduced generator maintenance, better emissions and fuel saving (Johansen et al., 2014).

Within a DG system there is another reason to equip a ship with batteries. This is due to the pulse loads that are experienced in a DG system, which can bring the reliability of the system in danger. To overcome this a dynamic energy storage is needed. Ways to store energy are by flywheel, capacitors or batteries. A flywheel is an easy to realise system, batteries or capacitors are more complex but suitable for most systems. Capacitors have a high power density but are limited in storage capacity. For pulse loads however capacitors and inertia systems (like the flywheels) are suitable due to the short discharge time when a peak load occurs (Tang et al., 2015). Batteries have a longer discharge time so will perform less, however they store a lot more energy.

Nonetheless Li-ion batteries are still capable of peak shaving and have a great power quality (IRENA, 2017).

In recent years the use of battery packs aboard of DP vessels is explored to reduce the effect of power variations (Veksler et al., 2012). This is done especially in ships with DP capabilities, where peak loads are more frequent than in non-DP ships. This use of batteries for peak shaving is not seen in short sea shipping. However, batteries are seen more often to keep up with regulations, in addition to the use of a DG system this is not often done. If batteries are beneficial for the Future Trader will be researched later (chapter 8.1). First there will be looked into batteries.

5.1.3 Mass and volume of batteries

Batteries are often compared based on power and energy density. It is important to mention that power density and energy density are two different characteristics. Where for fuel energy density is the important value to compare in MJ/m^3. This is different for batteries. The power density of a battery in W/m^3 is the amount of power a battery is capable to deliver (Sinovoltaics, 2019). This can be compared to the break power of the engine. The power density says nothing about the amount of energy stored in the battery, just as the break power of a engine can not tell how much energy is stored in the fuel tank. The energy density of a battery is like the energy density of the fuel itself and gives the amount of energy that can be stored in the battery. For batteries this is often given in Wh/m^3 or kg (same units as J/m^3, however 1 Wh equals 3600 J) (Sinovoltaics, 2019).

There are a lot of different types of batteries available these days, all with other advantages and disadvantages. In figure 5.1 the most common types of batteries are shown with their power and energy density. Seen in the figure is that capacitors have a high power density and are therefore suitable as a solution for pulse loads. But for energy storage Li ion batteries are one of the best batteries.

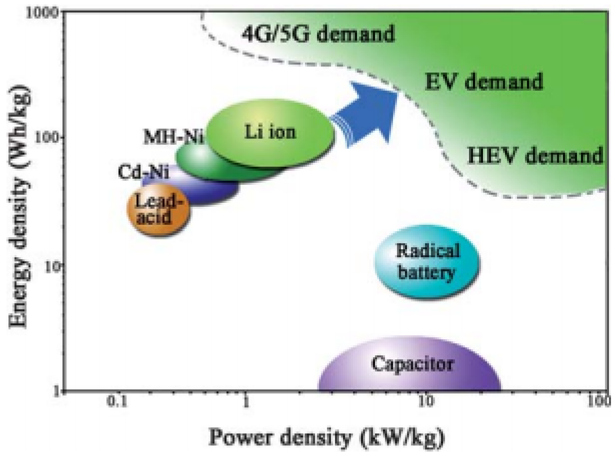


Figure 5.1: Battery types and their mass power and energy density. (Gao & Yang, 2010)

In the figure the demand for future EV is also shown and this already shows the problem with the battery technology of today. The performance can not match the demand. Still a lot of research is done to enlarge the performance of batteries, also for applications within the shipping industry (Peralta P. et al., 2019).

Where the Li ion battery can provide an energy density of 150 Wh/kg, new batteries should be able to reach far more. Especially redox based batteries are promising (Gao & Yang, 2010). For now it is assumed that batteries used in shipping will be Li ion based. Also because Li ion based batteries will be installed often (97% in Germany in 2017) and therefore will have lower costs for instalment in the future, due to the economy of scale effect those batteries will be around for a while (IRENA, 2017).

For the first estimation of the mass and amount of energy stored a volumetric energy density of 315 Wh/L will be used, this is the main value of different common options (IRENA, 2017). The energy density mass is assumed to be around 100 Wh/kg as seen in figure 5.1. In section 5.2.3 the range in miles will be calculated when one TEU is used.

5.2 Fuel properties

Before there is looked at the applicability of batteries in the Future Trader there will be looked into possible fuels. There are a lot of different fuels available nowadays. However in the Future Trader there is limited space available for fuel storage, the energy density is therefore of great importance. This will be used as a starting point to see which fuels are not only promising, based on the chemical formula, but also suitable for the Future Trader ship with respect to storage space and mass.

Using other fuels and other energy converter will result in a other necessary energy flow as for diesel with a Combustion Engine (CE). This is due to other efficiencies in the power plant, in this chapter the comparison will be made with respect to the properties of MDO in combination with a CE. The real range will depend on the exact systems in the power plants and the amount of fuel that can be stored in the four TEU. Not all of this is already known so a more general way is used to narrow down the fuel options.

First the density (kg/m^3) and the Lower Heating Value (LHV) of different fuels are given in table 5.1 below (Wild, 2015), (ToolBox, 2003) and (GIIGNL, 2009). Using the LHV gives a moderate number of available energy in storage. When calculating efficiencies the Higher Heating Value (HHV) can also be used since this results in lower efficiencies. In this thesis the LHV will be used everywhere to be consistent and to make sure that the amount of energy in storage is not overrated. When combining the LHV with the density of a fuel the amount of space needed can be found. The table below shows the LHV and the density of different fuels. The pressure that is needed for storage is kept out of the comparison for now.

Table 5.1: Fuel properties

Fuel	**Temperature** [°C]	**LHV** [MJ/kg]	**Density** [kg/m³]	**Energy density** [MJ/m³]
Marine Diesel Oil (MDO)	15	43	900	38700
Heavy Fuel Oil (HFO)	15	40	1010	40400
Ethanol	20	27	789	21303
Liquid Natural Gas (LNG)	-162	49	430	21070
Methanol	20	20	792	15840
Amonia (liquid)	-50	19	702	13338
Hydrogen (liquid)	-253	121	69	8349
Compressed Natural Gas (CNG)	20	54	0.9	48.6

5.2.1 Storage volume

From table 5.1 it can be deducted that the volume energy density of MDO and HFO are much higher than those of many other fuels. As mentioned before, promising alternative fuels will be compared to diesel fuels. In this case the diesel fuel used is MDO because this has a wide application in ships that have a similar size as the Future Trader.

Next a comparison between the energy densities will be made. In this comparison MDO will be used as the 'base' fuel, this means that division of energy density will be done with the energy density of MDO as numerator. The result of this division can be found in table 5.2. This is called the volume factor, to calculate this equation 5.1 is used. In this equation n equals a fuel in the first column from table 5.1 (E.q.: n = 1 is MDO).

$$VolumeFactor = \frac{\rho_{v,MDO}}{\rho_{v,Fuel\_n}} \quad (5.1)$$

Table 5.2: Volume factor compared to MDO

Fuel	Volume factor
MDO	1.00
HFO	0.96
Ethannol	1.82
LNG	1.84
Methanol	2.44
Amonia (liquid)	2.90
Hydrogen (liquid)	4.64
CNG	796

The volume factor of the fuels shows us the multiplier that is needed to store the same amount of energy with a fuel in comparison to MDO. In this comparison there is looked to the volume factor of the fuel. So the net fuel properties are used, this is without the packaging factor for tanks or tank weights. In chapter 8 were the actual fuel storage is calculated those will be taken into account. For now those are not needed.

It is shown that the volume needed to store hydrogen is at least 4.6 time higher than the volume needed for MDO. Based on this and to reduce changes in the design of the ship hydrogen and CNG could be considered less suitable as a fuel for this study. HFO will be eliminated because this will not be an improvement environmentally. Also according to DEKC, because the regulation for emissions in Northern European waters are getting more strict, HFO is seldom used nowadays for small coasters like the Future Trader. CNG needs too much room for fuel storage and is similar to LNG when looking at the emissions, therefore CNG will be left out. Hydrogen also requires more space and is harder to store but has other major benefits as discussed in chapter 5.1, therefor hydrogen will not be eliminated.

5.2.2 Storage mass

Beside the volume needed for storage the mass of the fuel is also of importance, since every kg of fuel needed is a kg of cargo less. To get an idea of the mass factor, table 5.1 is used. Only in this comparison the mass of the fuel that is needed to get the same amount of energy in comparison to that of the mass of one cubic meter MDO is considered.

To get the mass factor for the remaining fuels the equation 5.2 is used. Here the amount of energy that is given by one cubic meter of MDO is used as a reference, this equals 38700 MJ. Then there was looked into the multiplier for the mass with respect to MDO. The results can be found in table 5.3. From the table it can be concluded that Hydrogen and LNG will require less mass than MDO, with the note that storage in this case should be done at a low temperature to keep them liquidised.

$$massFactor = \frac{38700}{LHV_n * \rho_{m,MDO}} \tag{5.2}$$

Table 5.3: Mass factor compared to MDO

Fuel	Mass factor
Hydrogen (liquid)	0.36
LNG	0.88
MDO	1.00
Ethannol	1.59
Methanol	2.15
Amonia (liquid)	2.26

It can be seen that methanol and ammonia are both more than twice as heavy as MDO, therefore if the same amount of energy needs to be transported those are less ideal. If we look at LNG this outperforms ethanol in both the mass and volume factors, for this reason ethanol will not be used as a fuel in this project. However ammonia as a fuel could still be interesting because ammonia is like hydrogen a non carbon fuel and therefore it can have major environmental benefits.

5.2.3 Fuel range

Besides the storage volume and mass of the fuels the range of the ship is also important. In this section there will be looked into the range the ship can reach when using a different fuel with respect to MDO. To determine the range, an engine efficiency is used based on one engine type. To be able to make a comparison between all fuels, it is assumed that the power requirement when sailing at a design speed of 10kn will not change. Therefore no changes in mass and resistance are taken into account.

As calculated in chapter 6.2.1 the engine brake power needed is 734 kW (80% mcr). Using this number and the engine efficiencies shown in table 5.4, the heat input from the fuel can be calculated (Stapersma, 2010b), (Woud & Stapersma, 2002b). Note that some of the fuels can also run on different engines. For example LNG can be used in a Combustion Engine (CE) with a starter fuel or spark ignited combustion. The optimal choice of engine type will be addressed later. Also there will be looked into the range that can be reached with batteries.

Table 5.4: Engine efficiencies

Fuel type	**Engine type**	η_{engine}	Needed energy flow from fuel [kJ/s]
Diesel	CE	0.35 (Woud & Stapersma, 2002c)	2096
Hydrogen	Fuel Cell (FC)	0.5 (Willis & Scott, 2000)	1467
Ammonia	CE	0.45 (Zamfirescu & Dincer, 2008)	1630
LNG	Gas Turbine (GT)	0.3 (Woud & Stapersma, 2002c)	2446
Batteries	Li ion	0.9 (Willis & Scott, 2000)	815

Now that for every type of engine the heat flow is known, the volumetric density of all the different fuels is considered. In table 5.5 the amount of energy that is available is shown. For the batteries the 315 Wh/L is rewritten to 1134 MJ/m^3 (315 *3,600 *1,000 / 1,000,000) (Corvus, 2020). It is seen that hydrogen and batteries represent a rather small amount of energy, this is as expected when looking at the volume factor presented in chapter 5.2.1.

Fuel type	**Volumetric energy density**[MJ/m^3]
MDO	38700
Hydrogen	8349
Ammonia	13338
LNG	21070
Batteries	1134

Table 5.5: Available energy is a TEU

Now the last step is combining the heat flow needed for each engine to sail at 10 kn with the amount of energy available and the range can be calculated using equation 5.3. The results are found in table 5.6.

$$Range = \frac{E}{\dot{E}} * \frac{v}{0.514 * 3600} \tag{5.3}$$

Fuel type	**Needed energy**[MJ/s]	**E density**[MJ/m^3]	**Range [nm]**
MDO	2.1	38700	51
Hydrogen	1.5	8349	15.5
Ammonia	1.6	13338	23.2
LNG	2.4	21070	24.4
Batteries	0.8	1134	3.9

Table 5.6: Range on a cubic meter fuel at 10 kn

Table 5.7: Range factor compared to MDO

Fuel	**range factor**
MDO	1.0
LNG	0.5
Ammonia	0.5
Hydrogen	0.3
Batteries	0.1

As seen in the table 5.7 using only batteries will not be a possible solution based on its range. As an additional system for sailing short distances or manoeuvring batteries may be suitable. When looking into the other systems ammonia and LNG are similar in performance and could both be an option. However, due to the fact that ammonia is a non carbon fuel ammonia is preferred above LNG. Hydrogen as a fuel is relatively low on range and due to the storage this looks like a less suitable option. However, a lot of promising research is done and engine manufactures are developing hydrogen systems. It can be concluded that transatlantic sailing on hydrogen would be too optimistic. For sailing around Europe hydrogen could be a suitable fuel option due to the shorter distances. Nonetheless the storage of hydrogen would still be a big challenge. After combining the mass, volume and range factors there are three fuels left that will be taken into account those are: MDO, Hydrogen and ammonia. The following section will look closer into their chemical properties.

5.3 Chemical fuel properties of the selected fuels

In this section the fuel properties and availability will be discussed for each fuel that is selected. In this section the focus is on the fuel's safety and the emissions that will be produced, the rules for emission were discussed in chapter 3.4.2. In this thesis there will be looked into the emissions from tank to wake for the fuels, the part from well to tank will be out of the scope. The reason for this is that there are many ways to produce some fuels, ammonia for example can be produced from hydrocarbon fuels or in a way that no CO_2 is produced(Duynslaegher et al., 2010), the same can be done for hydrogen. Due to the large and fast technological progress it is hard to predict in which way those fuels will be produced in the future.

There is briefly looked into the availability of a fuel. This means, if the fuel is renewable (or limited) and the impact on the infrastructure for transportation of the fuel to ports. This last point will not be taken into account for the fuel selection, this is because the main goal is to make a system that is technical feasible.

For the hydrocarbon fuel (MDO) a C/H ratio is given, equation 5.4 is used to calculate this number. This shows the mass amount of carbon compared to hydrogen. Each carbon molecule has a molecular mass of 12 g/mol (M_C) and a hydrogen atom has a mass of 1 g/mol (M_H), p is the number of carbon atoms in the fuel and q the number of hydrogen atoms. This ratio can also be calculated using the mass fraction of the elements present in a specific fuel, see equation 5.5 (Stapersma, 2010b).

$$\frac{C}{H} = \frac{p}{q} * \frac{M_c}{M_h} \tag{5.4}$$

$$\frac{C}{H} = \frac{X_C^f}{X_H^f} \tag{5.5}$$

MDO

MDO is an often used fuel. This fuel is used as a benchmark within this research. Therefore in this section MDO is not explained as a fuel and working principles of the engines are not discussed. Instead the emission values and fuel composition is given. This is done, so that it can be used later on in the study. The properties here are of the fuel itself, the effect of the engine is not taken into account. Typical 30% of the energy from the fuel is transformed to useful energy for the ship (Woud & Stapersma, 2002b). In the research an engine will be selected and then the efficiencies and emissions will be compiled for that specific setup.

MDO is a fuel that is specified as MDO by the ISO standards, a typical composition for this type of fuel is as follows (in mass fractions), C: 87% H: 12% and S: 1%. This means that the c/h ratio is 7.25. This is the bench mark, lower numbers will mean that there is more hydrogen in the fuel and less carbon. This will reduce the CO_2 emissions when the fuel is burned. This can be said because the chapter ratio is linked to the LHV of the fuel. (Stapersma, 2010b) Besides the carbon fraction the most important fraction to look at is the amount of sulphur in the fuel, this because this will react to SO_x. ECA regulation are strict on this and are getting even stricter.

Hydrogen

Hydrogen as a fuel is a promising alternative for MDO, especially the environmental impact and the ability to be able to meet regulations look promising. Due to the fact that hydrogen only emits water, it is a clean fuel to use (Hansson et al., 2019). However, it can happen that NO_x is also formed in the combustion of Hydrogen. This is due to the fact that on high temperatures the nitrogen from the incoming air will react. This is only the case when hydrogen is burned.

For hydrogen there are two main options during the energy transition, hydrogen can be used in a fuel cell or can be burned. Which system will be used will have an impact on the performance of the fuel. Still the emissions will be only water. Both systems have their advantages and are promising due to their size and the relatively high efficiencies with the usage of a fuel cell. With a fuel cell up to 60% of the energy from the fuel can be used. For a CE this will be around 40 till 50% maximum (Willis & Scott, 2000), (Stapersma, 2010b).

The storage of hydrogen is one of the most challenging parts of the fuel. Hydrogen is promising and has a lot of benefits, however the infrastructure and storage of the fuel have to be developed and this will be expensive. As discussed before the storage aboard of the vessel will be one of the biggest challenges. Because the volume energy density of hydrogen is 4 times as low in liquidised form and 16 times less if stored at 25 degrees at 200 bar (Duynslaegher et al., 2010). This high pressure and low temperature in combination with the low flash point of hydrogen gives some concerns about the safety of the fuel (Hansson et al., 2019). When looked into the emissions hydrogen is the cleanest fuel available.

Ammonia

Ammonia can be seen as a hydrogen vector or a carrier of hydrogen. Similar to hydrogen, ammonia can be used as a clean energy carrier and storage medium because it can potentially be burned in an environmentally friendly manner, exhausting only water, nitrogen and nitrogen oxides (Duynslaegher et al., 2010). The storage of ammonia when pressurised is around 8 bar and at a temperature around -50 degrees which makes it easier to store than hydrogen.

An advantage of ammonia is that ammonia is already produced and therefore the investment costs for creating the fuel are lower. Also there already is an infrastructure for this fuel, this infrastructure will need modification and needs to be scaled up to make it suitable for ammonia as a fuel. In the future ammonia can be created from sunlight, water and air which also makes it a carbon free fuel in the process of making it (Li et al., 2014).

A challenge that comes with the use of ammonia as a fuel can be the formation of NO_x. Due to the molecular structure of ammonia nitrogen mono oxide can form in a spark ignition engine (Duynslaegher et al., 2010). This will also be the case in a non-spark combustion engine. However it is shown in studies that it is still possible to reduce the NO_x emissions with ammonia as a fuel (Li et al., 2014). The study of Li also shows that a combination of hydrogen and ammonia can further increase the benefits from those fuels, however before this can be used in the industry this should be researched further. A challenge for ammonia as a fuel is the ignition of ammonia because ammonia has to be sparked or needs a starter fuel to burn (which could be hydrogen). Also a small amount of diesel oil can be injected to start the ignition. By doing this ammonia is capable of burning and can be used in a spark engine. This combination can be beneficially from an environmental point of view. Besides that there are tests done to show that a power increase from the engine can be generated up to 32 % (Reiter & Kong, 2011). However there is little known and no research done if and how ammonia and a starter fuel can be used in a diesel engine or how ammonia can be used as a single fuel. (Dimitriou & Javaid, 2020). Ammonia is less suitable as a single fuel in a compression ignition engine, due to the high compression needed to auto ignite ammonia. In a dual fuel engine ammonia is a feasible option but more research is needed on this part if a dual fuel should be selected in combination with a compression ignition engine. A good option is the use of ammonia in combination with a spark ignited engine. In those systems ammonia can increase engine power and reduce emissions (Reiter & Kong, 2011). As mentioned before ammonia as a fuel itself has some challenges but in combination with another fuel as a dual fuel ammonia can offer a good alternative for diesel fuels. Beside the combustion of ammonia it can also be used in a FC this can be in a direct way were ammonia is fed into the fuel cell directly. Or ammonia can be cracked in to hydrogen and nitrogen and the fed in to a fuel cell. Using a fuel cell has as a benefit that there is no need for a extra conversion step from mechanical to electrical power.

5.4 Conclusion fuel selection

As discussed there are many alternative fuels and there is a lot of research available about this topic. LNG and hydrogen are often found in the top predictions (Hansson et al., 2019). However Ammonia is less common in the shipping industry, it a upcoming fuel and found often in resent researches (amoniaenergy, 2020), (Afif et al., 2016). First lets look into LNG, this is the most promising fuel of all the carbon based fuels and is already used in the shipping industry today. This shows that it is not only technical possible but also economical. LNG can be a good alternative for fuels like MDO. However, LNG is able to conform to tier III regulations of MARPOL, it can be challenging to conform to even stronger regulations in the future without the use of additional systems. So for the fuel of the future LNG can be less suitable than carbon free fuels. Still due to low costs and new techniques like a lean CE, LNG could be around for a while. Hydrogen and ammonia both outperform LNG when looked into the emissions. Hydrogen has better efficiencies and Ammonia is like LNG also widely available and has better storage pressure and temperature compared to LNG or Hydrogen, also ammonia is similar in range compared to LNG. For those reasons LNG will not be used as a fuel for the Future Trader. It still is a good alternative for MDO but it is less promising as a sustainable solution for the future.

Ammonia has promising features like the fact that it is carbon free. However there are challenges that need to be overcome when using ammonia as a single fuel in a ship, those challenges are mostly focused on the combustion of ammonia. In the present when ammonia is used as a fuel it is often used as a dual fuel (starter fuel) to make ammonia suitable. If this starter fuel is diesel this makes it less interesting due to the emissions of diesel fuel. Especially since diesel can be a major part of the fuel mix. For many other fuels combinations such as hydrogen and ammonia engines need to be developed before this can be used in practice. To combine ammonia and hydrogen can result in a promising fuel. Ammonia provides a good range for a ship and using hydrogen as starter fuel can keep emissions very low. Also a spark ignition engine can be an outcome for ammonia. There are also fuel cells with sufficient power output in development which can use ammonia as a fuel e.g. the ship Viking Energy will be equipped with a ammonia fuel cell system. Ammonia therefore be used as a fuel in this project.

The last option is hydrogen. For hydrogen there is a difference in the engine that is used to transform the power from chemical to electrical. There are two main options, hydrogen can be used in a fuel cell or can be burned in a combustion engine. Where the fuel cell seems to be the most promising when looking into the potential of hydrogen and at the fact that the emissions of hydrogen are mostly water. This fuel has a great potential to keep up with all the future regulations, as long as it is produced in a green manner (this is out of the scope).

The challenge of storage and safety needs to be countered and respected. The range of hydrogen is rather low in comparison to other fuels. However it is suitable for the Future Trader. This is mainly due to the fact that in the short sea shipping industry distances are small in comparison to other shipping industries. Due to this relative short distances the limited range could be less of a issue for the Future Trade. Therefor hydrogen is a suitable and promising fuel for a small general cargo ship.

However there are a lot of fuels found not suitable. The fuels that are used in this project are MDO, ammonia and hydrogen. Also a combination with a small battery pack can be used. Especially for peak shaving and for sailing in harbour areas or as a power supply for auxiliary systems when the ship is in port. If this will be used for ammonia, hydrogen or the DG MDO will be discussed later. If there are additional batteries installed this will be discussed in chapter 8.1. Now the used fuels are known a system description for the Future Trader needs to be made.

6. System description

After the selection of fuels that will be used in this research is know, the next step is looking into the system which will be researched. The system is the power plant of the Future Trader. This is a modular power plant that consist of multiple smaller power packs. Using a modular system results in a hard line between ship and power plant systems. This means that for each system in the ship its location needs to be determined, by looking at if a system is needed on the ship or for the power plant or for both. Making this division results in a list of components needed for the power plant and the location of those. First in chapter 6.1 a system breakdown of a general cargo ship is performed to find the energy users on board of the ship. The engine room is also divided in smaller systems. Those together with the Energy Flow Diagram (EFD) results in the system locations. When all the systems are known there is looked into the energy consumption of those systems. This is combined with the resistance data from DEKC and results in the total power, this is described in chapter 6.2. A recap of all of this is given in chapter 6.3

6.1 System breakdown

In this chapter the ship is decomposed in smaller systems and after that the connection between systems is shown. This is done using a top down method, meaning that it is started with the ship as a system and then it is broken up in smaller systems and parts until a certain detail level is reached. This is a frequently used method for system decomposition. In this thesis a functional decomposition is used to develop a top down hierarchic decomposition. (Komoto & Tomiyama, 2011). Then the decomposition will be presented in a Design Structure Matrix (DSM). By doing this a good overview of the system and the system interactions can be shown (Baldwin & Clark, 2006). However a DSM is not a fixed representation and can change over time. It it a good tool to get an understanding of complex systems and the relations within a system. (Chiriac et al., 2011)

6.1.1 Decomposition of a ship

As a start a functional breakdown is made for the ship, see figure 6.1. This system breakdown is on a general level and is made in cooperation with colleagues from DEKC. Due to the fact that the focus of this study is on the engine room, this decomposition will be used for the electric load balance as a starting point for determining system interactions between the engine room and other parts of the ship.

The decomposition is made so that the power flow to specific systems in a ship can be seen. A functional decomposition can also be used for ship design, but this is not of interest in this thesis. So is in figure 6.1 the branch of crew accommodation specified as supply of air, water and electricity. The electricity can be used in the galley or to charge a phone but where and how is not of interested. The functional break down is also used as structure for the electrical load demand that can be found in table D.1. Because the goal of this thesis is related to the engine room of the ship a more detailed decomposition will be made for this part. The rest, like cargo holds, structure and crew facilities, will not be addressed in more depth. The decomposition of the engine room will be addressed in the following section.

6.1.2 Engine room decomposition

To be able to determine which systems should be simulated an engine room decomposition is done, see figure 6.2. This decomposition is done in a general way for common systems aboard a ship (Woud & Stapersma, 2016). This can result in the fact that there are systems in the breakdown that are unnecessary for a specific engine type and systems. Also some engine types need a couple of other systems that are not presented in the breakdown. Still most system will be needed for a good working ship and engine room, therefore this breakdown is used as a starting point to determine the needed systems. Depending on the engine type and fuel used specific systems will be deducted or added to the system as shown in figure 6.2. Additionally the engine unit can differ in the example shown in the figure an CE is decomposed.

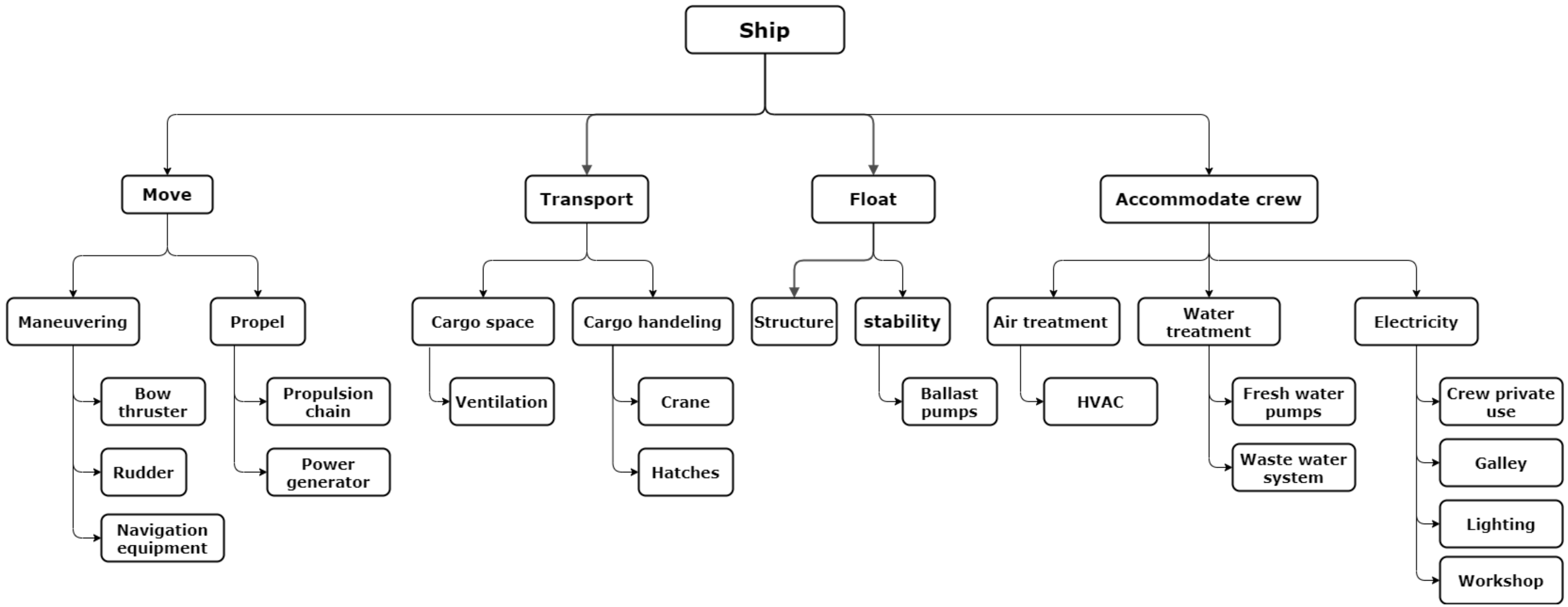


Figure 6.1: Functional breakdown of a ship, focused on energy consumers

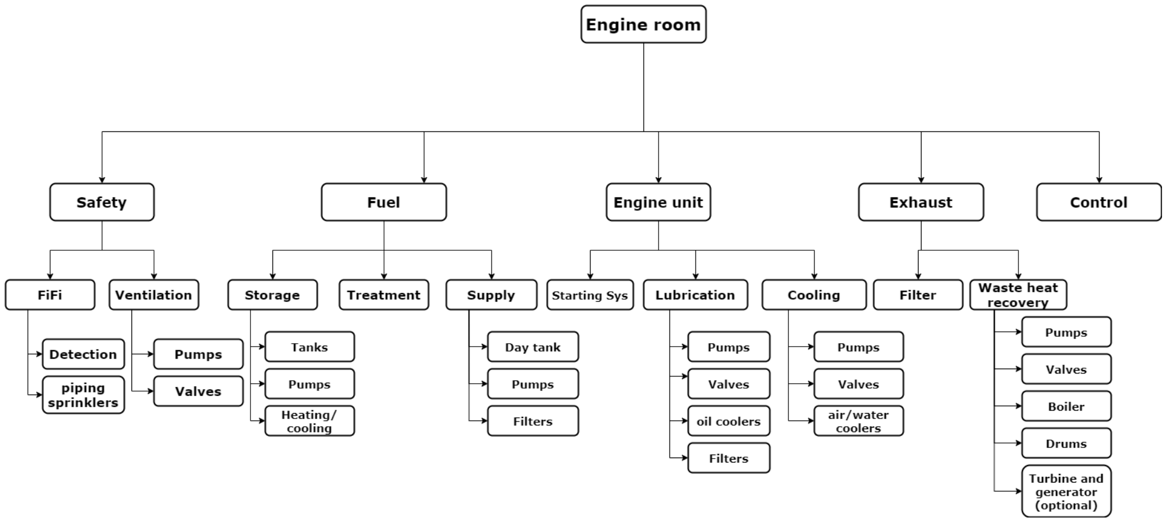


Figure 6.2: General engine room systems decomposition

6.1.3 Ships systems and power plant systems

To be able to determine the connection between components in- and outside the engine room a more detailed system decomposition for the engine room needs to be made. For each system a decision is made whether the system is linked to the ship or to the engine. All systems that have a close relation to the ship are placed outside of the modular power plant.

As discussed before, the power leaving the modular power plant exists of only electric power. So aboard of the ship the conversion and the power distribution will be done. To be able to provide a stable output a converter should be stationed in the modular power box. Meaning that the EFD of the engine room is as shown in figure 6.3. In this figure the two engine types that will be used are both shown (see chapter 7 for the engine type choice). There is a dotted line for a fuel cell system and a system for a combustion engine. Now that the energy flow is known there will be looked into the ships systems.

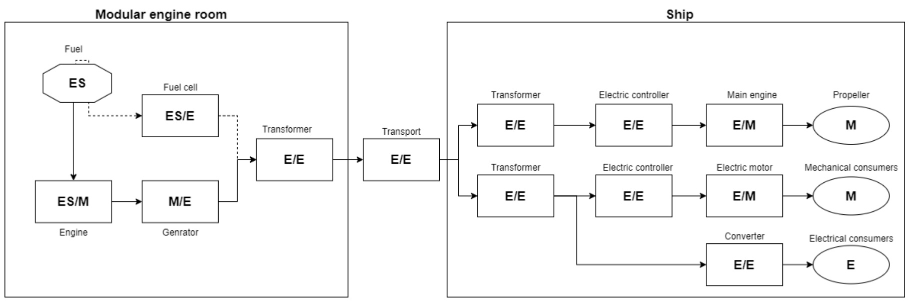


Figure 6.3: EFD of a ship with a modular engine room.

By combining the system breakdown of the ship with the system found in *chapter 5 of Design of Auxiliary systems, shafting and flexible mounting*, the engine room and auxiliary power systems are determined (Woud & Stapersma, 2016). Then, for every system the interaction is given a value between 1 and 4 in a DSM (the DSM can be found in appendix B). This results in a list of all systems and the connections between them. Meaning that the important connections are now visible, e.g. the connection to the power distribution is an important one and a lot of information needs to be transferred from and to the bridge. The systems that have no or little interaction with the engine room will be taken out of the modular engine room and therefore will be left out of the simulation. Based on those connections it is determined which systems are crucial to install within the modular power plant (packs) systems. In table 6.1 it is given whether the systems are in the ship (s) or in the modular power plant (pp).

Besides the system in the table the fuel storage and all fuel systems will be modular. This due to the fact that different fuel types should be loaded. When using another fuel the fuel treatment and storage system also need to be changed. Systems related to the engine or the fuel systems need to be placed within the modular power box, the fuel storage will be a separated system.

Table 6.1: System locations

System group	System	Location	System group	System	Location
Cargo	Cargo vent	s	**Engine systems**	Water cooling HT	pp
	Crane	s		Water cooling LT	pp
	Hatches	s		Lube oil cleaning	pp
Hazard systems	FIFI system	s/pp		Fuel supply	pp
	Detection systems	s/pp		Fuel treatment	pp
	Bilge pumps	s		Fuel transport	pp
Hotel	Accommodation	s		Air supply	pp
	Food prep and storage	s		Exhaust systems	pp
	Fresh water	s		Engine start system	pp
	Waste water	s		Engine room ventilation	pp
	Electric	s		Acoustic enclosure	pp
	HVAC	s		Mounting system	pp
Float	Ballast pumps	s	**OtherPower systems**	Hydraulic power	s
Move	Propulsion chain	s		Mechanical power	s
	Radar	s		Compressed air system	s
	Navigation lighting	s		Waste heat system	s/pp
	Winches	s	**Control systems**	HVAC Control	s
	Bow thruster	s		Vent control	s
	Steering pumps	s		Eng vent control	pp
	Shaft bearing lubrication	s		Fuel system	pp
	Gearbox lubrication	s/pp		Power distribution	s
	Lube oil cleaner	s/pp		Bridge	s
Tanks	Day tank	pp			
	Lubrication oil	pp			
	Bilge tank	s/pp			
	Oil leakage	pp			

6.2 Installed power calculation

Now that the systems needed and the locations are known, a next important step needs to be taken and that is the calculation of the power demand of the Future Trader. The power demand is split into two categories. Those are the propulsion power and the auxiliary power. When both are added together the total installed power is known.

6.2.1 Propulsion power demand

The power calculation is done following the procedure presented in "Design of Propulsion and Electric Power Generation Systems" chapter 3 (Woud & Stapersma, 2002b). In table 6.2 the given information from DEKC is shown, this information is based on the Open Water Diagram (OWD) of the vessel on which the future trader is based.

Table 6.2: Resistance data DEKC

Name	**Data**	**Unit**
Speed	10	kn
	5,14	m/s
Resistance	80	kN
Wake	0,20	
Trust	94	kN
η_o	0,607	
Draft	6,00	m
Installed power	-	kW
Propeller type	KA 4-70 nozzle 19A	
Propeller P/D	1,30	
Propeller diameter	3,00	m
Water density	1,026	t/m3

The power calculation is done from outside of the ship to the heat input of the fuel (see figure 6.4 for a graphical representation). The calculation is started with the resistance and by using estimations with respect to the efficiencies of some of the propulsion components. With those values the power of the propulsion engine (electric motor) is calculated. The diagram that was followed is shown in appendix C. The results and values of the calculation can be found in table 6.3. From the calculation it can be concluded that the electric motor needs to deliver 650 kW of power.

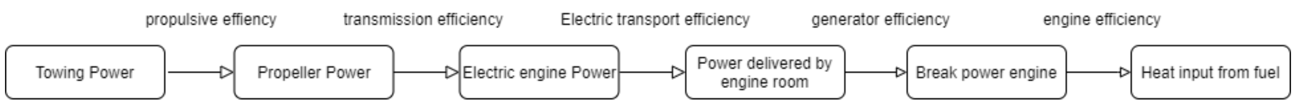


Figure 6.4: Power flow diagram from water to tank.

The power that is needed to propel the ship is 650 kW from the electric motor. The total propulsion power that needs to be installed is larger due to losses in transportation, conversion and generators. Those are addressed and the total power that needs to be generated in the modular power plant needs to be 697 kW. The used efficiencies are shown in table 6.4, those efficiencies are given by DEKC based on past experiences and the book "Design of Propulsion and Electric Power Generation Systems" (Woud & Stapersma, 2002b). The calculation of the needed power is done following a similar procedure as in figure 6.4, for an example see formula 6.1.

$$P_{engineroomout} = \frac{Pb_{electric}}{\eta_{conversion} * \eta_{transport} * \eta_{electricengine}} \tag{6.1}$$

Now the total power out of the modular power plant is known, the break power of the engine(s) in the modular power plant are calculated. Those combined need to be 734 kW at 80% MCR (see last part of table 6.4). The total installed power can be calculated, by DEKC a sea and engine margin of 20 % is set. Meaning the total installed break power is 918 kW at 100% MCR.

Table 6.3: Break power calculation electric motor.

Name	**Data**	**Unit**
Speed	10	kn
	5,14	m/s
Resistance	80	kN
Wake	0,20	
Trust	94	kN
η_o	0,607	
va	4,112	m/s
Pe	411	kW
PT	387	kW
η_{Hull}	1,064	
Trust reduction	0,149	
Po	637	kW
$\eta_{rotative}$	0,99	
Pp	643	kW
η_{shaft}	0,99	
Ps	650	kW
η_{gb}	1	
Pb	650	kW

Table 6.4: Propulsion power engine room.

Name	**Data**	**Unit**
$Pb_{electric}$	650	kW
$\eta_{electricmotor}$	0,98	
$\eta_{transport}$	0,97	
$\eta_{conversion}$	0,98	
$P_{engineroomout}$	697	kW
$\eta_{conversion}$	0,98	
$\eta_{generators}$	0,97	
$Pb_{mainengine}$ (80% MCR)	734	kW

6.2.2 Auxiliary power demand

In this section all the auxiliary components found in the decomposition (see chapter 6.1) will be powered and summed to get the necessary auxiliary power demand. Based on the functional decomposition as seen in figure 6.1 a load balance of a similar vessel and a load balance for the Future Trader is made. The main focus of the load balance is to determine the installed power of the modular power plant. From the load balance (D) it is seen that the auxiliary system need a power of 399 kW when manoeuvring, 262 kw during sailing and at a quay a power of 147 kW is required.

However, when manoeuvring the total power needed for propulsion should be lower than the 734 kW needed for sailing at 10 kn. Assuming that in port the maximum speed is 7 kn (like in Rotterdam) the power needed for propulsion is max 252 kW (see equation 7.1 with c1[1] = 5.405). Meaning that there is a large amount of power available for manoeuvring. Lets use the 80% MCR level of 734 kW for propulsion, if we reduce the 252 kW needed when sailing around port this means that 482 kW is available for auxiliary systems. This is more power than needed (443 kW) so in this case no extra power needs to be installed.

When the ship is sailing at sea there is also a need for auxiliary power. At sea the propulsion power of 734 kW is assumed to be used by the engines. The 20% margin is also assumed to be needed for propulsion in case of harsh sea conditions. The auxiliary power at sea is 262 kW, see appendix D. In this case all the power installed for propulsion is used so an extra power of 262 kW is needed. Next, the efficiencies need to be taken into account. The efficiencies are used the same as for the propulsion power, as seen in table 6.4. This results in table 6.5. Therefore the total installed auxiliary power is 290 kW, this is when the ship is at sea. Due to the

[1] c1 is assumed to be constant (only applicable for low fn numbers) and is calculated using the design speed of 10 kn and a power requirement of 734 kW

use of the DG concept in the modular power plant this power can be delivered by the same engine type and engines as the propulsion power.

Table 6.5: Auxiliary power needed in engine room.

Name	Data	Unit
$\mathbf{P}_{aux-electric}$	262	kW
$\eta_{transport}$	0,97	
$\eta_{conversion}$	0,98	
$P_{engineroomout}$	276	kW
$\eta_{conversion}$	0,98	
$\eta_{generators}$	0,97	
$Pb_{main-engine}$	290	kW

6.2.3 Power demand difference for engines producing electrical power

Since both the auxiliary and the propulsion power are known now, they are summed together. This brings the total power needed in the vessel to 1208 kW, this is the power needed at the axle(s) of the power generating engines. A small difference can be present due to the engine type. Engines that deliver mechanical power to a generator will need 1208 kW of power (GT and CE). However for fuel cells this power is slightly different, because a FC delivers electrical power directly. Meaning that conversion from mechanical to electrical power is not needed. This means that the power needed from the fuel cells is 1171 kWe, as seen in table 6.6.

Table 6.6: Power needed form modular power boxes Fuel cell

Name	Data	Unit
$\mathbf{P}_{aux-dem}$	276	kW
$\mathbf{P}_{Prop-dem}(100\%MCR)$	871	kW
$\mathbf{P}_{powerbox-out}$	1147	kW
$\eta_{conversion}$	0,98	
$\mathbf{Pb}_{fuelcell}$	1171	kW

6.3 Conclusion system description

There was started with the system decomposition of the Future Trader to determine which systems will be located inside of the ship and which system will be modular and are placed within the modular power box(es). This analysis resulted in table 6.1. After the required power is calculated, the mechanical power at the shaft of a CE is 1208 kW. However if no generator is needed to transfer mechanical to electrical power, as is the case when using fuel cells, the total power needed is somewhat lower and should be 1171 kW. Now that the power is known, in the following chapter during the engine selection and design of the power boxes those power values are used as a reference point and it will be used to select engines that are close to this power demand.

7. Engine selection

Now that it is known which systems would be in- and outside of the modular power boxes a decision about the engine type needs to be made. For every fuel type an engine option will be discussed. The number of engines (power boxes) will also be discussed for every engine and fuel type. The number of engines is determined by: system reliability, system efficiency and available space. In the first section (chapter 7.1) there will be looked into engine availability and efficiencies. In the next sections for every fuel type (MDO chapter 7.2, hydrogen chapter 7.3 and ammonia chapter 7.4) a suitable engine will be selected. After this selection the number of power pack systems will be determined.

7.1 Engine efficiencies and availability

To determine the number of engines or power boxes aboard of the ship there are three main factors taken into account. The first one is the availability (reliability and maintainability) and the second one is based on efficiency and the third is the efficiencies over power range .

7.1.1 Engine availability

A dead ship should always be avoided and prevented. To prevent this there should always be power aboard of a ship, so the engine(s) aboard should not fail all at once. To achieve this and to make the ship more reliable multiple engines could be installed. However increasing the number of engines to infinity is useless and there will be a point where adding an extra engine will not result in a significant increase in redundancy. What the best number of engines is for this ship based on availability will be discussed below.

To determine the amount of engines a risk analysis should be done for a couple of key components within the engine room. A Failure Mode and Effects Analysis (FMEA) is a frequently used method to analyse the risk of components. However, for a good FMEA a detailed system needs to be developed and a lot of failure modes need to be known. Since this type of information is not known for the Future Trader, in this thesis FMEA is not suitable for a risk analysis. Another method is making a fault tree analysis. This method gives a good insight in the system and is also capable of detecting a combination of failures. However this method needs a lot of time to develop and to provide numbers to work with, it also needs modelling and computational power (Lee et al., 1985). Because FMEA and fault trees both need a high detail level and a lot of data that is not known a more generalised form needs to be found. In the research of Brocken it is tried to improve the ship reliability (Brocken, 2016). In the research a summation is made of all the technical failures for the years 2001, 2002, 2003, 2004, 2010 and 2011. His data is based on the German Ship Safety division, the result are shown in table 7.1.

Table 7.1: Technical failures in the system groups(Brocken, 2016)

System group	Amount [-]	Percentage [%]
Main engine	139	38.7
Steering gear	75	20.9
Fuel system	40	11.1
Electrical system	32	8.9
Cooling water system	30	8.4
Shafting	24	6.7
Diesel generator	13	3.6
Other	6	1.7
Total	359	100

In the table it can be seen that the component that fails most often is the main engine itself where the diesel generator seldom fails. This can be due to the running hours of the main engine. However the table shows that there is a big gain to earn in the reliability of the main engine. Note that in this system a turbo charged CE is used and that a lot of failures (36.7%) are related to starting and reversing (Brocken, 2016). In this thesis there are also other engine types used, for these types the failing percentage can be completely different. Therefore we can only conclude from the table that a lot of failure in a ship with a turbo CE is related to the main engine. Since almost all ships within the ship type of the Future Trader are equipped with this type of system, an advantages can be gained in the reliability of the main engine compared to commonly used systems(Brocken, 2016).

A qualitatively number about the availability of an engine can not be given and a detailed researched will be too time consuming for this thesis. This is due to the early stage and relative new technologies that need to be developed and due to the focus of this thesis on efficiencies and emission of the engine room concepts. However using an engine as a back up or dividing the power over multiple engines should result in a gain for the reliability of the ship (Brocken, 2016). Also Brocken says that a gas/steam turbine or a fuel cell and batteries will improve reliability, so there will be looked into the usages of those motor types. First a decision needs to be made about the definition of fatal failure is, this is done together with DEKC. The decision is made that if the speed of the ship is less then 7 kn (harbour speed) the ship has to abort its voyage and it is assumed to be a fatal failure.

To couple this to a power demand the cubed relationship is used between ship speed and power demand as seen in formula 7.1. However c_1 is dependent on the Froude Number (FN) and therefore on the ships speed, therefore the cube law is only applicable for ships with a FN between 0.10 and 0.20 (Woud & Stapersma, 2002b). Using formula 7.2 the FN is 0.18 for the Future Trader at design speed (10 kn), so the cubed law can be used. Meaning that a reduction to 7 kn max in ships speed results in a power drop, the power for propulsion needs 252 kW at full load.

$$P_e = c_1 * v_s^3 \tag{7.1}$$

$$FN = \frac{v_s}{\sqrt{g * L}} \tag{7.2}$$

In conclusion using a FMEA or fault tree are ways to determine the reliability of the ship. Only for this thesis there is not enough data or time available for this type of analysis. Therefore more general rules are used, for example: two engines are more redundant as one. It is also known that the main engine is a component that is often a cause of failure in a ships system. The reliability can be improved when using multiple engines. This information in combination with the minimum power available of 252 kW for propulsion, the availability of space and the efficiencies will be leading in the decision of the number of engines used in different concepts. This number of engines will be greater than one to give a better reliability.

7.1.2 Engine type efficiency

The amount of installed power is based on a ships propulsion and auxiliary systems. However the power demand of the ship is not a fixed amount and will variate in time. Therefore the installed power aboard of a ship will be used partially. Using a DG system as discussed in chapter 4 has the benefit of switching engines on and off.

For each engine there is an optimal running point (highest efficiencies), this in combination with the sailing profile of a ship result in a engine selection. Due to the fact that the Future Trader does not have a specific sailing profile at the moment another method is used to determine the number of engines installed. The percentage of power demand vs the optimal running point is considered for one or more engines.

Before this can be done there was looked into the maximum number of engines installed, this is based on the total power that is needed. The power installed with the auxiliary power is a total power of 1208 kW. The maximum number of engines is determined by the fact that if one engine is running and it solely propels the ship the power needs to be above the 252 kW mark, this is the point where the ship is in fatal failure. This means that the maximum number of engines is 4 (see equation 7.3). Meaning that the ship can run on one engine before it is in fatal failure. One engine has a power of 302 kw in that case and should be capable to propel the ship up to 7.4 kn at full power. To keep the system as simple as possible the engines will all be of the same type and have the same power output. This means that all the spare parts can be used on all the engines, and therefore less parts need to be present on the ship. The connections to all the engine rooms can also be the same because the same amount of power is delivered. This is in line with the idea of easily exchangeable modular engine rooms.

$$n_{eng} = 1208/252 = 4.8 = rounddown 4.8 = 4 \quad (7.3)$$

Now that it is known that at least two engines and a maximum of four engines should be installed. The information about specific energy converters (engine types) needs to be found before the 'optimal' number of engines for the Future Trader can be determined. In the rest of the section for the three most common energy converters (internal combustion engines, fuel cells and turbines) the efficiencies at partial load will be given. Note that each individual system has another optimal running point. The system eventually used in the modular system can therefore differ from those seen in the figure but the overall trend will be similar.

For most internal combustion engines (diesel) the optimal load demand is around 70 % of Maximum Continuous Rating (MCR) as seen in figure 7.1(Jalkanen et al., 2011). The total efficiencies around 40 % can be reached for (diesel) combustion engines.

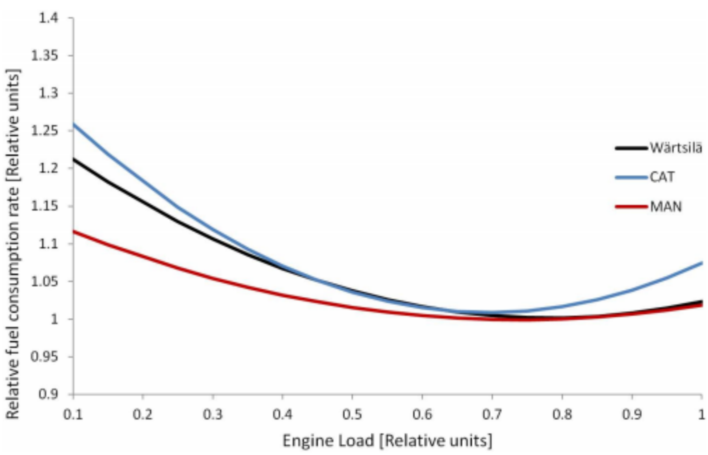


Figure 7.1: SFC different diesel engine. Caterpillar are four stroke engines, MAN is a large 2 stroke engine and Wartsila is from the 467 family (Jalkanen et al., 2011)

For fuels cells the efficiencies are low until 10% load then up til 100% the efficiency are almost the same. The optimal lays around 60%. In figure 7.2 it can be found where the optimal efficiency can be reached for fuel cells with different system efficiency factors. The overall system efficiency factor runs form 58.3 up to 100%. If 100% is reached the efficiency of a fuel cell system is at 80% at most. However this is a theoretical value and will probably not be reached soon in practice. The total system efficiencies for fuels cells can be higher than those of a combustion engine between 45 to 65% (Woud & Stapersma, 2002c), (Larminie & Dicks, 2003). For fuel cells the total efficiency can be calculated using equation 7.4. For the nominator there are two values, one corresponding with the HHV and one for the LHV. The 1.25 used in the formula is according to the LHV of a fuel cell using a fuel that releases 2 electrons per molecule (Larminie & Dicks, 2003).

$$\eta = \mu_f \frac{V_c}{1.25} * 100\% \quad (7.4)$$

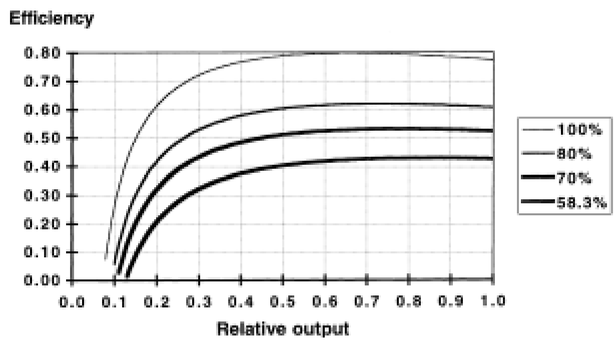


Figure 7.2: Fuel cell efficiency vs relative output for a phosphoric acid fuel cell (legend is the theoretical efficiency factor) (Thorstensen, 2001)

For turbines the efficiencies are highest at maximum load and will drop quickly if a turbine runs at partial load. Besides this the total efficiencies of a turbine are low in comparison to fuel cells or diesel CE. In figure 7.3 the SFC is plotted against % MCR. The overall efficiencies of a turbine are lower than those of the two other systems (around 30%). Turbines are mainly used for their high power density and quick reaction time. Because of this quick response time and the high power density is not of importance for a general cargo ship like the Future Trader, therefore a turbine is not interesting.

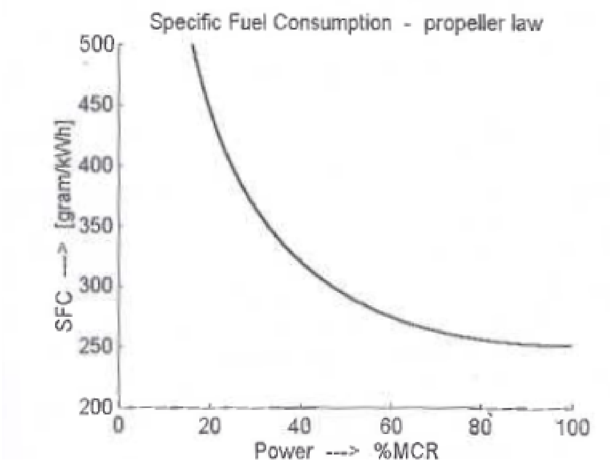


Figure 7.3: Turbine SFC against MCR (Woud & Stapersma, 2002e)

In conclusion, it was seen that the three engine options all have other characteristics when looking at fuel efficiency. For a ship that demands partial load, engines can run inefficient. In the lower range CE and GT and FC engines preform badly. Up from 40% power fuel cells systems have good efficiencies. Where turbines are only efficient in the higher power range. The number of engines that is preferred in the Future Trader is dependant on those optimal efficiency ranges. In the next section there will be looked into suitable engine types and the amount of engines for the fuels left (MDO, hydrogen and ammonia).

7.2 Engine type and number of engine when using MDO as fuel

The first fuel for which an engine type and number of engines will be determined is MDO.

7.2.1 Engine type

If MDO is used as a fuel, like often seen in short sea shipping nowadays, this is almost always in combination with a CE. Therefore this will also be the case for the base line system in this study. For MDO there is also a DG system which uses the same engine type, the number of engines will be determined next.

7.2.2 Engines installed

The number of engines (power boxes) installed depends on the power required and the optimal running point of the selected engine type. With the total power known for the CE engine that runs on diesel, a table is made for multiple optimal engine running points. In this way each running point can be compared. For the MDO DG setup the optimal running point was at 0.75, this results in table 7.2. There are four different setups with one to four engines. Each engine has an own colour and in the columns below for each number of engines the place where an engine is closest to the optimal point is shown in bold and is made larger. For the multiple engine setups this value gives the optimal running point for all the engines in the system when the power is divided equal over the number of engines. So green means that one engine is running and the larger bold number is the optimal running point. Orange means there are two engines running and the large bold number represents the point where both engines are at their optimal point, etc. Each cell represents the index number to provide the needed power with respect to the power of a single engine (see equation 7.5).

$$Index = \frac{P_{total-needed}}{Pb_{one-engine}} \tag{7.5}$$

For a diesel engine the optimal running point is between 0.6 and 0.8 times the maximum load (as seen in figure 7.1), the mean of the curves is 0,75 so this point is used as an optimal point for a diesel CE. In table 7.2 it is seen at which % MCR and speed engines are close to their optimal point of 0.75 (engine point 0.6, 0.7 and 0.8 of MCR can be found in the appendix A). The number of engines was already narrowed down to be at least two and a maximum of four. It can be seen that the optimal engine point for all setups for 1,2,3 or 4 running engines is at 76% MCR as expected (since the optimal point is set at 75%).

If we look at the table (7.2) using one engine is not a suitable option due to the lack of availability. Looking at the lower speeds it can be seen that for a four engine layout two engines will always be running, where the two and three engine layouts are using one engine for the same speed. Always needing two engines will result in higher costs in instalment and in maintenance, meaning that the four engine option is less suitable than the two or three engine option.

Whether to use two or three engines needs an extra iteration step, since both setups are within the range (from 0.6 to 0.85 MCR) where the engine efficiencies are almost constant, meaning that both are suitable options. Therefore there is looked at a second operation, when the ship is manoeuvring in port. The auxiliary power is then 443 kW and the conclusion changes, see table 7.3. The grey rows represent the speed around the port speed, with a maximum speed of 7 kn since this is the maximum port speed. Seen is that the three engine options have an optimal running point within these rows. The three engine option can also run on two of the three engines, which means that one engine could be shut down for any reason e.g. maintenance or back up for higher redundancy in a higher risk operation. Where the two engine setup needs one engine on full power or even both engines up and running. In conclusion, the three setup engines is preferred above the two engine setup due to the extra redundancy of the third engine and the option to sail in port at 6 kn at an optimal running point.

The previous combined with the fact that in the three engine system the optimal running point is at the speeds where the ship will sail most of its time (10kn) and that the three engine setup allows the ship to lose one engine and then it can still sail around 9 kn on two engines. This increases the ships redundancy and provides the opportunity to do repairs and small maintenance at sea. Therefore a three engine setup will be used for the DG diesel system. Meaning that three identical power boxes will be placed on the aft of the Future Trader.

Table 7.2: Optimal engine load over MCR for a optimal engine point of 0.75, with auxiliary power in sailing conditions 290 kW

			Nr of engines installed (running)			
Auxiliary power [kW]	290		1	2	3	4
optimal MCR point	0.75	**Pb [kW]**	1208	604	403	302
Power demand [% mcr]	**Speed [kn]**	**power [kW]**	**index mcr**	**index mcr**	**index mcr**	**index mcr**
32%	5.0	382	0.32	0.63	**0.95**	1.26
37%	6.0	449	0.37	**0.74**	1.11	**1.49**
45%	7.0	542	0.45	0.90	1.35	1.79
50%	7.5	600	0.50	0.99	**1.49**	1.99
55%	8.0	666	0.55	1.10	1.65	**2.20**
61%	8.5	741	0.61	1.23	1.84	2.45
68%	9.0	825	0.68	1.37	2.05	2.73
76%	9.5	919	**0.76**	**1.52**	**2.28**	**3.04**
85%	10.0	1024	0.85	1.70	2.54	3.39
100%	10.8	1208	1.00	2.00	3.00	4.00

Table 7.3: Optimal engine load over MCR for a optimal engine point of 0.75, with auxiliary power when manoeuvring, manoeuvring is within the grey rows

			Nr of engines installed (running)			
Auxiliary power [kW]	433		1	2	3	4
optimal MCR point	0.75	**Pb [kW]**	1208	604	403	302
Power demand [% mcr]	**Speed [kn]**	**power [kW]**	**index mcr**	**index mcr**	**index mcr**	**index mcr**
43%	5.0	525	0.43	**0.87**	1.30	**1.74**
46%	5.5	555	0.46	0.92	1.38	1.84
49%	6.0	592	0.49	0.98	**1.47**	1.96
53%	6.5	635	0.53	1.05	1.58	2.10
57%	7.0	685	0.57	1.13	1.70	**2.27**
61%	7.5	743	0.61	1.23	1.84	2.46
67%	8.0	809	0.67	1.34	2.01	2.68
80%	9.0	968	**0.80**	**1.60**	**2.40**	**3.21**
97%	10.0	1167	0.97	1.93	2.90	3.86
100%	10.2	1208	1.00	2.00	3.00	4.00

7.3 Engine type and number of engine when using hydrogen as fuel

To determine the number of engines installed for hydrogen the same method is used as for MDO (see chapter 7.2.2), but first there will be looked into the type of energy converter used.

7.3.1 Engine type

For hydrogen there are two main options to generate electricity: the hydrogen combustion engine or a fuel cell.

Hydrogen combustion

There is much researches done into the combustion of hydrogen. A couple of large car manufactures are developing different types of combustion engines, v in line and rotary engines are researched (Barbir, 2013). A big advantages is that hydrogen can burn lean, also the hydrogen CE will be more efficient (up to 43%). However, the power density of the engine will lose around 15% due to the lower energy content in the stoichiometric mixture within the engine (Barbir, 2013). This loss can be reduced or be turned into an increase using a direct injection system for hydrogen (Anstrom, 2014).

The downside when using hydrogen is that due to the heat nitrogen oxides are formed from the nitrogen in the incoming air. This chemical reaction is seen in equation 7.6. Another downside for using an CE in this setup is that the engine produces mechanical energy and we need to have electrical energy. So an extra conversion from mechanical to electrical energy is needed and this will result be loses (couple of %), it also takes up space inside the module.

$$H_2 + O_2 + N_2 = H_2O + NO_x \tag{7.6}$$

Fuel cell

A second option is the use of a Fuel Cell (FC). The use of a FC has one major advantage and that is the emission of only water. The working principle is based on the electrons that are released at the anode side of a FC. Those move trough the load that is connected and then go to the cathode and there they will form water with the air that is passing trough. The total reaction is seen in equation 7.7. As a result of the reactions a F will produce electric power, which in the case of the Future Trader is the required type of energy. This means that a generator is not needed. Additionally the efficiency of a single cell system are not different from a complete system. This means that fuel cells have good partial load efficiency as seen in figure 7.2. Partial loads can therefore be demanded from the system without increasing fuel consumption or losses (van Biert et al., 2016). For a fuel cell it is hard to determine the exact efficiencies because the fuel utilisation needs to be designed with care. However a Proton Exchange Membrane (PEM) hydrogen fuel cell system can have an average efficiency of 50% (Anstrom, 2014). This number also depends on the temperature of the fuel cell. When looking at the disadvantages of fuel cells this mostly comes down to the production price. Even though a fuel cell itself is a simple system the total system needed for a effective fuel cell consists of complex components.

$$2H_2 = 4H^+ + 4e^- = 4H^+ + 4e^- + O_2 = 2H_2O \tag{7.7}$$

Conclusion engine type

For the Future Trader of DEKC the selected engine type when using hydrogen as a fuel will be a fuel cell. This is due to the high efficiencies that can be reached and the fact that a fuel cell does not need extra power conversion it generates electrical power. The higher installation cost are unfortunate but if fuel cells will be mass produced the price will probably profit from the scale effect, also production prices are out of scope of the thesis. Lastly, the fact that fuel cells lose very little of their efficiency ,during operations other then design conditions, in partial load is a big advantage.

7.3.2 Engines installed

Now the decision is made for using a fuel cell system the decision for the number of fuel cell systems need to be made. Because a fuel cell system efficiency is less effected by partial loading of the system, above 40 % MCR the system's efficiency is almost the same. Therefore there will be looked at the optimal point of 0.4 and it is assumed that above that point the system runs almost optimal. The results are shown in figure 7.4. In the figure it can be seen that all the optimal running points except for one engine are in the first row. Meaning that when more than one engine is used, the system will preform optimal throughout whole of the MCR range. Due to the high redundancy of fuel cells (van Biert et al., 2016) and to the fact that one fuel cell can deliver a power of more than 252 kW (minimum required, before failure) at a almost optimal running point. This combined with the high instalment costs of fuel cells, the lower power density and the fact that a lot more space is needed for fuel storage, results in the conclusion that there will be two fuel cell systems aboard of the ship.

Table 7.4: Optimal engine load over MCR for a optimal engine point of 0.4, with auxiliary power in sailing conditions 290 kW

			Nr of engines installed (running)			
Auxiliary power [kW]	290		1	2	3	4
optimal MCR point	0.4	**Pb [kW]**	1208	604	403	302
Power demand [% mcr]	**Speed [kn]**	**power [kW]**	**index mcr**	**index mcr**	**index mcr**	**index mcr**
32%	5.0	382	0.32	**0.63**	**0.95**	**1.26**
37%	6.0	449	**0.37**	**0.74**	**1.11**	**1.49**
45%	7.0	542	0.45	0.90	1.35	1.79
50%	7.5	600	0.50	0.99	1.49	1.99
55%	8.0	666	0.55	1.10	1.65	2.20
61%	8.5	741	0.61	1.23	1.84	2.45
68%	9.0	825	0.68	1.37	2.05	2.73
76%	9.5	919	0.76	1.52	2.28	3.04
85%	10.0	1024	0.85	1.70	2.54	3.39
100%	10.8	1208	1.00	2.00	3.00	4.00

7.4 Engine type and number of engine when using ammonia as fuel

In this section the last of the three fuels will be addressed. For ammonia there are multiple options in engine types: dual fuel engines, spark and compression ignition engines. Fuel cells can also be an option for ammonia. In the first part the option will be discussed and a choice for the engine type will be made, after that a suitable number of engines will be selected.

7.4.1 Engine type

Internal combustion engines

Ammonia can be used as a marine fuel. Only most of the marine engines are self combustion engines. Ammonia is a fuel that needs high pressure and temperature before it will ignite on its own. Therefore there is often spoken of a pilot fuel or a starter fuel for ammonia. This makes it possible to use ammonia in a compression ignition engine. Which pilot fuel is used makes a large difference. There are fuel blends with diesel as a pilot fuel as discussed in chapter 5.3 this is not the best option, ammonia can also be used in combination with hydrogen.

Since ammonia is not suitable for a compression ignition engine, but it can run under specific engine conditions and with advanced fuel injection (Dimitriou & Javaid, 2020). Ammonia engines are developed as spark ignition, still a starter fuel is often used in those engines. Results from other studies show that the engines preform best when the fuel contains around 10% of hydrogen, at this point there is an optimal efficiency and mean effective pressure (Mørch et al., 2011). Those efficiencies will be higher than for diesel engines. CE are widely accepted and proven within the marine industry, this could mean that existing engines can be adjust to run on an ammonia fuel mix. A lot of this type of engines are still in development and data of those are difficult to get. A other option for ammonia is the use of a fuel cell.

Fuel cell

Ammonia can be used in fuel cells in two ways. Fist, ammonia can be used as a hydrogen carrier in a hydrogen fuel cell. To achieve this ammonia needs to be cracked to nitrogen and hydrogen, the hydrogen can be used in a hydrogen fuel cell. This looks promising when considering storage systems (Valera-Medina et al., 2018).

A second option is to use ammonia in a direct ammonia fuel cell. Ammonia is tested in a Alkaline Membrane Fuel Cell (AMFC), those operate around room temperature but only the power density is lower. There are also some challenges regarding the anode and cathode materials. A better choice is the use of a Solid Oxide Fuel Cell (SOFC), here the ammonia can be led directly into the fuel cell (Lan & Tao, 2014). The efficiencies of a direct ammonia SOFC fuel cell can be higher as 50% (Cinti et al., 2016). Which makes is not only interesting from a storage point of view but also for efficiency reasons. For marine applications a direct ammonia fuel cell is not yet developed. However, a 2 MW system will be installed in the late 2023 on the Viking Energy (jburke, 2020).

Conclusion engine type

For the ammonia fuel it is harder to chose a specific type of engine. There are CE that offers benefits, like the use of dual fuels systems and easy retro fitting with spark ignition. Those engine are considered to be suitable options for a ship with a mechanical drive or when refitting needs to be done on already existing CE. However for the Future Trader a fuel cell will be a better option.

A fuel cell will have a high potential efficiency (50%). Also the fact that a fuel cell will deliver electric energy makes it suitable for this ship. An ammonia fuel cell has some challenges with respect to anode and cathode material. Also the use of ammonia cracking and using a hydrogen fuel cell is an option. Meaning that an ammonia fuel cell is a promising option for marine application due to the fact that it will be installed on the Viking Energy. This means that the power output of ammonia fuel cells will be in the range needed and therefore an ammonia fuel cell can be used in the Future Trader.

7.4.2 Engines installed

The number of fuel cell systems installed will be two like the hydrogen fuel cell, this follows the same reasoning as for the hydrogen fuel cell (see chapter 7.3.2). However there are no off the shelf or proven systems available with a power output of 604 kW. For hydrogen there are fuel cells that deliver +602 kW of power. Hydrogenics (Hydrogenics, n.d.) claims to be able to deliver systems from 100 kW to 50 MW for hydrogen applications. Ammonia fuel cells of +602 kW will be developed in the near future, as proven by the Viking energy where a 2 MW system will be installed (Brown, 2020). Therefore it is plausible that the Future Trader can be equipped with two ammonia fuel cell systems.

8. System design

In this chapter there will be looked into whether all the systems could be placed in the modular power box. There will be started with the option of adding batteries to the Future Trader's power plant in chapter 8.1. If this is desired there is looked into the fuel and energy storage system for each power pack, this is done in chapter 8.2. Afterwards the components needed for the engine system are discussed for the MDO fuelled systems in chapter 8.3 and for the FC system fuelled by ammonia or hydrogen in chapter 8.4.

The systems fitted in the modular power box ((PP) PowerPack) and the fuel treatment room (FS) are shown in table 8.1, this was already discussed in chapter 6.1. Sound and fire insulation is applied for every engine type and room, it is assumed that these dimensions are equal for all systems. The insulation thickness is based on an of the shelf available insulation panel of 40 mm thick and it is assumed that it will be fitted on every side of the engine room.

Table 8.1: General systems in modular engine room

System group	System	location
Hazard systems	fifi system	s/pp
	Detection systems	s/pp
Engine systems	Engine unit	pp
	cooling	pp
	Lube oil cleaning	pp
	Fuel supply	FS
	Fuel treatment	FS
	Fuel transport	Fs
	Air supply	pp
	Exhaust systems	pp
	Engine start system	pp
	Acoustic enclosure	pp
	Mounting system	pp
	power box ventilation	pp
Tanks	Lubrication oil	pp
	day tank	pp
	oil leakage tank	pp
OtherPower systems	Waste heat system	pp
Control systems	Eng vent control	pp
	Fuel system	pp
	Engine unit	pp

8.1 Additional batteries

Before there is started with the fuel systems, it first needs to be determined whether it is useful to install batteries. As already seen in table 5.6 the range for batteries is too low to use only batteries in the Future Trader. However adding batteries to the system can offer benefits like peak shaving or as an auxiliary power supplier.

Since batteries are not capable of offering a sufficient range there will always be another type of energy source and system installed aboard. Due to this fact batteries will always be an additional system and will mainly be used for peak shaving or for short distance emission free sailing (for MDO engines). When batteries are installed inside of the ship (so outside of the modular power plant) the batteries can also be used as back up power in case of an emergency, how this is done and how many batteries are needed will be outside of the scope of the thesis.

Adding batteries can result in zero emissions for a short period of sailing time. This could be beneficial for the Future Trader in the future. Norway already has zero emission fjords for cruise ships, scrubbers are also not allowed in these areas (DNVGL, 2019). It can be expected that those regulation will become applicable on merchant ships as well. Since Norway is within the operating area of the Future Trader adding batteries gives the ship the opportunity to sail emission free regardless of the rest of the system.

Another benefit of adding batteries is that those can be used when waiting for port entrance. This waiting often occurs in short sea shipping and can be a major part of the total voyage time, typically around 18% in the Baltic sea at a voyage of 100 hours, from Lubeck to Sillamae (800 nm) (Gustafsson, Magnus et al., 2018). During this waiting time outside of a port only auxiliary system will be running. Assumed is that the load of this will be around the same as at sea (290kW) (see table D.1). In traditional one diesel engine setups this power demand is at a poor running point for the IC engine, so peak shaving will improve ship performance. A battery pack can offer a solution in this case, because when using only the battery if the capacity is large enough or offering the flexibility to run at an optimal running point and store the unused power.

However, with the use of a DG setup in the modular power plants peak shaving is already done. For example in waiting conditions using the MDO modular power plant just one engine could be running, which provides 450 kW electric at full power meaning that this engine will run at 0.66 MCR, which is not optimal but rather close to the optimal point as seen in figure 7.1. This means that an additional battery pack only gives a minor advantage.

8.1.1 Peak shaving

Another benefit could be to preform peak shaving during sailing times. To be able to determine the effects on peak shaving during sailing a sailing profile is needed. Using the assumed speed profile seen in figure 3.2 an estimation can be given of the effect of peak shaving. The speed profile is altered in such a way that the required power is shown and with the addition of peak shaving it can be seen which power is represented in those peaks (seen in figure 8.1).

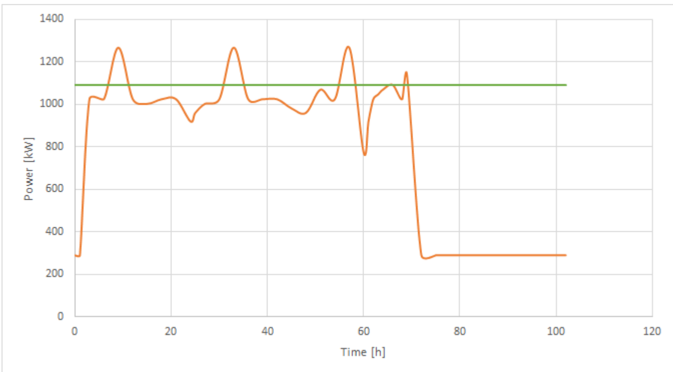


Figure 8.1: Power estimation during voyage (orange) and 0.75 MCR power line (green)

The horizontal line is the optimal engine running point based on the MDO configuration of three 485 kW. The optimal running point is 0.75 of MCR. From the figure it is seen that almost all peaks are relatively close to the optimal power setting. Almost all peaks are within 175 kw from the optimal setting, only the peak at 60 hours is 317 kw below the optimal line. A 175kw peak (or trough) would mean a running point of 0.87 or 0.63, both these numbers are close to the optimal SFC at 0.75 in figure 7.1.

Looking at the 0.87 point this means an increase in fuel consumption of around 2.5% which could still result in a significant saving. However, when looking at the three top peaks a total time of around 15 hours will be at the 0.87 MCR. This is around 21% of the total time (15/70). When multiplying the possible increase in fuel consumption and the time spend in those conditions, there will be 0.5% (0.21 * 0.025) increase in fuel consumption trough the voyage with respect to the optimal line. So when only accounting for the peaks and not looking at the troughs, a maximum of 0.5% will be saved on fuel. This means that the use of batteries for peak shaving in those condition will have a small effect on the fuel consumption and therefore on the emissions and efficiencies. When there is looked into other modular plant concepts the results will be similar or less due to the better partial load performance of a DG MDO setup or fuel cell system (see 7.2). For other engines this optimal line is at a different power amount. So for ammonia and hydrogen in combination with a FC there will be another amount of energy represented by those peaks. Due to the wide range of the optimal running point of a FC system, peak shaving will probably be less effective for fuel cells compared to IC engines. This is because the efficiency is more constant over the MCR range. For fuel cells the batteries can be used to acquire extra range and for better throttle response (out of scope), they will not have an effect on the systems performance and the emissions of the fuel cell itself, therefore this setup is not of interest for this study.

8.1.2 Conclusion about batteries

Since the effect of batteries for peak shaving is limited and also due to the fact that a DG setup is used, which already offers peak shaving, using batteries is not interesting. The benefits of a battery pack to use as auxiliary power give little benefits for the Future Trader. Using batteries could provide a gain in range during off design conditions or when waiting before ports. However, since the Future Trader uses a DG setup those gains would be low and when looking at the emissions this will only be interesting for a MDO plant.

Lastly, it should be mentioned that this study focuses on the effect of using alternative fuels in a different modular system compared to a traditional system. Adding batteries can have small effect on the result of both types of plants, but will affect the results of the data of the chosen engine system and fuel itself. Therefore it will not help answering the research question of this thesis. This led to the conclusion that there will be no batteries installed in the Future Trader. When it is known what the effect of the modular plants and fuels are a following research could be done to investigate the effect of batteries in this type of system. Then there can also be looked into the option to use batteries for pulse load handling from environmental effects on the ship's power.

8.2 Modular fuel system

The modular fuel system is designed in this section and afterwards the available fuel storage and range is given. The actual system design is done on a general level since the study is focused on the effect on the ships operational capabilities when using a modular power plant.

8.2.1 Fuel storage and processing

For the fuel storage there is room on top of the four TEU on the aft of the ship. DEKC stated that there is more room available on the ship for fuel storage. Due to the complexity of other locations and since this will have an effect on storage space those locations will not be taken into account. Therefore the room for the four TEU of fuel is all the available room for fuel storage, meaning that the range will depend on this capacity.

For the power aboard a fuel storage and a fuel system is needed. Earlier in the study the decision was made to make the fuel system a separated modular system. The decision is made (in cooperation with DEKC) to make one module with all the controls and systems needed for fuel handling in a TEU. The fuel storage tanks will be installed and connected to these modular fuel handling systems. This is done so more conventional storage tanks can be used and there is no need for the development of new storage tanks. Another advantage that this setup brings is that fuel tanks can be swapped easily off the vessel and be replaced by a new one. In the TEU for fuel handling the required systems are presented as shown in table 8.2. Those system should be aboard of the ship when using one of the power plant concepts, the TEU is placed next to the power box units on the stern of the vessel. In the table it is seen that for each fuel different systems are needed within the fuel preparation unit. The day tank will be fitted in the power box, the rest of the fuel will be stored in separate TEUs.

For all fuels	additional for: **MDO**	**Hydrogen**	**ammonia**
day tank filters Pumps Controls	Separators	compressor Expansion valve Insulation fans Humidifier (low temp FC)	In addition to Hydrogen Heat exchanger (additional for a high temp FC) Mobile reactor for H2 production (low temp FC) Extra hazard detection

Table 8.2: Additional subsystems needed for a specific fuel

8.2.2 Energy storage system

The fuel storage will be a standardised size, in this way they can be placed on top of the power box itself. Therefore tanks in TEU size will be used on the aft. These tanks are already available and it is known how much fuel they hold (kg or cubic meters). The energy stored in a container is calculated and the amount of fuel stored can be enlarged by installing more of those containers, to a maximum of four. In table 8.3 the energy of a single unit can be found. The range that is shown is based on the energy needed from the fuel as found in table 5.6. This energy represents the energy needed for propulsion and 290 kJ/s for the auxiliary systems, so this comes to a total power usage of 1024 kW.

The fuel stored in the day tank should be enough to sail for 8 hours on 100% MCR as required by SOLAS chII 26.11 (IMO, 1999). The volume of the day tank is considered different for every system and fuel type. The energy that is available for the system is the stored energy in the day tank added together with the energy in a TEU times the energy density. The TEU used are based on of the shelf systems, doing so gives an energy available for the systems that is realistic and also takes the tank factor in consideration. E.g. hydrogen and ammonia are stored in cylindrical tanks and therefore not all the volume represented by a TEU is used in storage. The found amount of energy is compared to that found in other studies like one by TNO (van Kranenburg-Bruinsma et al., 2020), those numbers are similar in size. The heat flow needed is calculated using equation 8.1.

$$[H]\dot{Q} = \frac{P_b}{\eta_{system}} \tag{8.1}$$

Table 8.3: Expected range of the Future Trader on the day tank and one TEU of fuel

fuel	Size day tank [m3]	storage in day tank [m3]	storage in a TEU [m3]	storage in a TEU [kg]	energy density [MJ/kg]	energy density [MJ/m3]	Energy available [MJ]	heat flow [MJ/s]	range [hours]	Range [nm]
MDO	3,0	3,0	25	23500	43	40420	1131760	2,93	107	1075
hydrogen	16,4	770kg		1750	121	8349	304920	2,28	37	372
Ammonia	8,2	7,0	20,83	14620	19	13338	370730	2,28	45	453

Conclusion

There was looked into the fuel preparation and storage systems. The systems needed for the fuel treatment are mentioned in table 8.2. Those system will be installed in a separate modular unit on the ship. Doing this provides the possibility to use of the shelf tanks for the fuel storage itself. The capacity of those tanks is discussed and a first estimation about the fuel range on a single container is done. Later the range of the Future Trader will follow from the simulation (chapter 10), but first the systems that need to be installed inside of the modular power box will be discussed.

8.3 Systems in modular power boxes with an internal combustion engine (MDO)

The first engine system to design is the power box equipped with an internal combustion engine that runs on MDO. This is only done for the DG setup and not for the traditional model with one engine, since this system is commonly used and will function as base line and is not one of the modular power plants.

8.3.1 Modular power system

It is started with the systems needed in the power box as presented earlier in the thesis, those systems are reviewed and adjusted for the application in a modular power box with MDO as a fuel. This is done based on the interaction with other components on the ship as seen in the DSM (see appendix B) and the use of table 8.1.

Hazard systems

The hazard systems in a power box are FiFi and other detection systems. The FiFi systems in the power box will be a pressurised co_2 system. The system will be installed within the modular power box. Due to the fact that this is a pressurised system no power is needed to use the system. The only required power is for the detection and for valves. Those amounts will be small and will be taken from the main power distribution of the modular engine room. Other FiFi systems are portable extinguishers and hoses, those will be placed near the modular power system at the deck of the ship. The power for these items will be deducted from the pumps installed in the ship it self.

The space needed for the co_2 tank is calculated with use of the regulations. Specified is that a gas system should have a capacity of at least 40% of the total protected volume (IMO, 1999). To be able to determine the required amount it is assumed that 1 kg of co_2 equals 500 L of volume (molecular volume of co_2 is 22.4 L/mol). A TEU has a volume of 38,55 m^2 (38550 L). Since 40% needs to be co_2 a volume of 15420 L is needed, this equals roughly an amount of 31 kg co_2. Since co_2 is stored at high pressure this results in a relatively small storage cylinder. For example: a 30 kg version that can be ordered easily, has the following dimensions 590(L)x640(B)x1470(h) mm, the tank is cylindrical. It is assumed that 31kg will fit in a space of (600x700x1500 mm).

Next to the FiFi system a couple of other safety systems are required in the engine room. Those system are a ventilation system with closable valves. These and other systems will be fitted inside the modular plant but will have little impact on the available room inside of the power box. Due to this fact and that they have no impact on the system capabilities those systems will not be addressed in this thesis.

Oil system

To keep the engine running lube oil is needed. This lube oil needs to be stored. The size of this storage is tank is 0.4 m^3, this is a rough estimation based on literature where an engine with twice the power output of the engine in the Future Trader (450 kw) is used (Nitonye, 2017). For the lube oil most of the filters are installed on the engine itself and will not take up extra space.

For engine oil and other fluids an oil leaking tank is installed underneath the engine. This tank needs to have a capacity of $0.21m^3$ on the assumption the ship should be capable of sailing 21 days at sea (see equation 8.2). This equation is used for a main engine power up to 10,000 kW, with D in days at sea and p in kW (IMO, 2018).

$$V[m^3] = \frac{20 * D * P}{10^6} \tag{8.2}$$

The bilge tank is installed inside of the ship instead of in the power box due to the required space of $4m^3$ according to regulations (IMO, 2018). Through the same piping as the bilge system the leakage tank can be emptied in the harbour, meaning that a connection to the bilge system is needed. During a voyage the bilge water and sludge will also be pumped into the tanks that are in the ship itself. The separators and other equipment needed for a good working bilge and sludge systems are all removed outside of the modular engine room since those will be needed for all the different modular power plant systems.

Power generator

For the power generating unit there has been looked into different manufactures and a suitable genset is selected, based on the dimensions and power of the unit. In this thesis a Yanmar engine and generator are used. The dimensions of possible (6N165L-SW) genset can be found in table 8.4. For the height in the table extra space is reserved for removing cylinders. In the section 8.3.2 it can be found that this engine will fit into a TEU.

Table 8.4: System and system dimensions for MDO

			Size (mm)			m3	m2
System group	**System**	**location**	L	B	H	V	A
Hazard systems	fifi system	s/pp	600	700	1500	0,6	0,4
	Detection systems	s/pp	-	-	-	0,0	0,0
Engine systems	Engine unit	pp	3332	1341	2105	9,4	4,5
	cooling	pp	On engine unit			0,0	0,0
	Lube oil cleaning	pp	On engine unit			0,0	0,0
	Fuel supply	FS	unit outside the power plant			0,0	0,0
	Fuel treatment	FS					0,0
	Fuel transport	Fs					0,0
	Air supply	pp	-	-	-	0,0	0,0
	Exhaust systems (SRC cat)	pp	823	425	423	0.1	0,3
	Engine start system	pp	on engine unit			0,0	0,0
	Acoustic enclosure	pp	in plating power box (40mm)			3,0	0,7
	Mounting system	pp	On engine unit			0,0	0,0
	power box ventilation	pp	-	-	-	0,0	0,0
Tanks	Lubrication oi storage	pp	1000	200	2000	0,4	0,2
	day tank	pp	1000	1200	2500	3	1,2
	Bilge	s				0,0	0,0
	oil leakage tank	pp	700	800	400	0,2	0,0
Other Power systems	pp	1096	1396	1982	3,0	1,5	
Control systems	Eng vent control	pp	800	500	250	0,1	0,4
	Fuel system	pp	800	500	250	0,1	0,4
	Engine unit	pp	800	500	250	0,1	0,4
					Total	**20,1**	**10,1**
					TEU	**38,5**	**14,9**

Canals for the exhaust and air intake are assumed to be on top of the engine or directly next to it, and therefore they do not have an area foot print in the table. The out- and inlet of those pipes and also the inlet for cooling is strongly dependant on the way the containers will be placed. When there is a row of 4 TEU wide the inlets and outlets need to be on the front or back sides of the power packs. As example the system of Atlas Sopco is seen in figure 8.2. Here it can be seen that when containers are put side by side the inlet and outlet of the module will be blocked. So the units in this study will be equipped with an inlet and outlet on the front side of the box. This makes it possible to stack them and place them next to each other. Note that it is not possible to place one behind another, this does not matter since there is no room available to set two unit front to back.

Figure 8.2: Atlas Copcos TEU generator unit

8.3.2 Dimension analyses

Whether there is enough floor space and volume in a TEU for the installation of the engine and subsystem will be discussed next. This is done using dimensions given in class regulations and information from Yanmar, which are presented in chapter 8.3. Those dimension and volumes are gathered in table 8.4, it is seen that there is enough floor space and room for all the systems to be fitted. How those systems are arranged into the container is out of scope of this thesis. However it is plausible that all the systems can be fitted and that a modular power box within the space of a TEU is possible. Therefore this system will be used to model a modular power box running on MDO.

8.4 Systems in modular power boxes with a FC installed (hydrogen and ammonia)

Now that the internal combustion system design is finished, a system design is done for the FC modular boxes. It is started with the systems that will be placed inside the power box. After that there will be looked into the space requirements of the system. There are subsystems that are also installed in the IC power boxes. Those systems are already mentioned and explained during the internal combustion engine design, when those are needed for the FC system those subsystems will be mentioned but not explained again.

8.4.1 Modular power system

It is started from the systems needed for the application in a modular power box with hydrogen as fuel. This is done based on the interaction with other components on the ship as seen in the DSM (see appendix B) and the use of table 8.1.

Power generator

For the power generation of the ship when using FC in combination with hydrogen a FC from Nedstack is used as a reference, this is the 13-XXL PEMFC stack. The stack is a low temperature PEM fuel cell. This stack delivers 13.6 kW, has a voltage range from 93.2 up to 58.9 V and a current between 0 and 230 A. The electrical data and power can be seen in figure 8.3. More information about this stack can be found in appendix F. Nedstack has already designed a containerised unit that delivers 500 kWe nominal and 626 kWe peak power, so a fuel system design in a TEU with the power requirements as used on the Future Trader should be technical feasible.

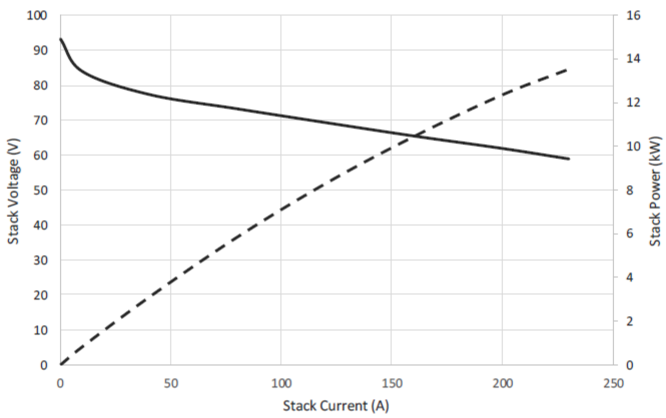
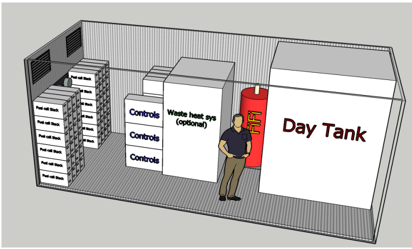


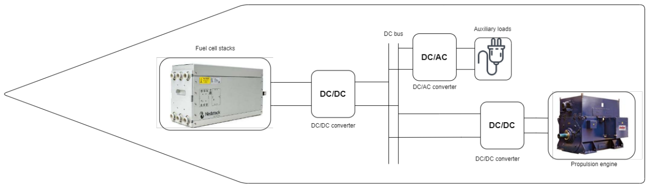
Figure 8.3: 13 XXL stack electrical data sheet (solid line is stack voltage, dotted line is the power curve) (NEDSTACK, 2019)

Control

The controls of the FC plant are similar to the combustion design, only the engine management and hazard controls will be different. Those differences however will be out of scope of this thesis. A ship's power plant can be seen as a mobile isolated micro-grid (Khooban et al., 2019). A problem with a ship is the power fluctuation. Due to the power fluctuation and a slow reacting FC the system could become unstable (Khooban et al., 2019). When using an additional DC/DC buss to which all the power is delivered from both power boxes, the electrical components (voltage and current) and therefore the power becomes more stable (Larminie & Dicks, 2003). Using high tech controllers on both the generating and the consuming side can also minimise power fluctuations, this is schematically presented in figure 8.4b.



(a) 3D impression of a simple FC system layout



(b) basic grid layout fuel cell system (shown systems are only an impression)

Figure 8.4: Fuel cell system layout

8.4.2 Dimension analyses

A dimension analyse is done to show that it is possible to install the required power in a standardised container, this is also proven by Nedstack. An additional waste heat recovery system can be installed, follows out of table 8.5 (this is not done in this research). It is also seen that there is around 6 square meter of floor space left and around 20 cubic meter of volume left. Note that those values are without piping, this should take up some the volume but there should be a sufficient amount of space for that. An impression of a possible layout is made and can be found in figure 8.4a. This layout is a first possibility and will not be altered in this study, it is used to show the plausibility of modular FC systems.

Table 8.5: System dimensions for one modular FC system (two of those will be installed)

System group	System	location	L	B	H	V	A
Hazard systems	fifi system	s/pp	600	700	1500	0.6	0.4
	Detection systems	s/pp	-	-	-	0.0	0.0
Engine systems	Fuel cell stack	pp	604	196	288	0.0	0.1
	total fuel cell system	pp	-	-	-	2.0	1.1
	cooling	pp	On engine unit			0.0	0.0
	Fuel supply	FS	separated unit aboard outside the power plant			0.0	0.0
	Fuel treatment	FS					0.0
	Fuel transport	Fs					0.0
	Air supply	pp	-	-	-	0.0	0.0
	Acoustic enclosure	pp	in plating power box (40mm)			3.0	0.7
	Mounting system	pp	On engine unit			0.0	0.0
	power box ventilation	pp	-	-	-	0.0	0.0
	day tank	pp	1500	2000	2500	7.5	3.0
	oil leakage/sludge tank	pp	700	800	400	0.2	0.0
Other Power systems	Waste heat system	pp	1096	1396	1982	3.0	1.5
Control systems	Eng vent control	pp	800	500	250	0.1	0.4
	Fuel system	pp	800	500	250	0.1	0.4
	Engine unit	pp	800	500	250	0.1	0.4
					Total	**16.7**	**8.0**
					TEU	**38.5**	**14.9**

9. Power plant models

Now that the layout for the different power boxes is known and the power they should generate is calculated, a model can be developed. Those models will provide information about the performance parameters and emissions of each power box concept. This chapter starts with the reasoning why time simulation is used, this is done in chapter 9.1. After this in the following sections the models will be discussed and the similarities and differences will be explained. In chapter 9.2 the part of the mathematical model that is similar for all the four systems will be explained. If this is done the mathematical model for the CE will be explained in chapter 9.3. Then in chapter 9.4 the FC models will be explained, this is the last part of all the models. In the last section (chapter 9.5) the models are all verified and a small model validation is done. Since no real life data is known for the system this validation is based on values found in literature, this is the only step taken in the model validation (Stapersma, 2010a), (Stapersma, 2010b), (Woud & Stapersma, 2002d), (Pik, 2020).

The starting point of each of the models is a speed timetable. This can be a logbook or a possible voyage or sailing profile. In this thesis four (possible) voyages will be used during simulations. This research focuses on the ships operational capabilities (range, emissions, fuel costs). The range is effected by the efficiencies, fuel consummation and fuel storage of the ship. Therefore the systems which will effect efficiencies, fuel consumption and emissions are modelled in more detail. The modelling will be done in Simulink, which is a time simulation program the researcher is familiar with. Why this is chosen will be explained next.

9.1 Time simulation

To be able to predict emissions, fuel consumption and costs at least an approximated operational profile is necessary. This in order to determine whether modern power systems can lead to fuel savings for a specific ship (Georgescu et al., 2017a). A possible voyage as shown in figure 3.2 will be used and altered for the ship, in total four voyage will be created.

For small amounts of data sheets can be used for calculation. However if the amount of data rises it could be desirable to use time simulation. Due to operational profile it is hard to optimise the power and propulsion plant for a specific operating point at a vessel's design stage (Geertsma et al., 2017). Here time based simulation can improve the accuracy of the results by varying some of the variables that would be kept constant in a spreadsheet model. For example: the amount of power needed can be variable in time, accelerating and decelerating can therefore occur more often than with a single time percentage at a specific power output.

In a simulations all the mean components need to be added and simulated. However in a complex system where more smaller components and systems are added to optimise the performance, some of those components can be variable in temperature and working conditions depending on time and system loading. This can be modelled using time domain simulation. E.g. if a large increase in power demand is asked from a diesel engine, it can occur that the diesel can not deliver the asked amount of power in the small amount of time. Therefore the diesel needs more time to speed up to the required power. Due to the occurrence of those type of events within the systems a spreadsheet is not suitable anymore and a time based simulation is more convenient to use. Within this thesis not all of the systems will be modelled into the smallest detail. However, if desired those details can be added later on in an easy way.

Due to the size and number of components in larger systems modelling software can give the designer a graphical interpretation of the system and therefore a better understanding and overview of the system. This helps to keep it logical, more understandable and easier to work with. So besides some technical/mathematical advantages time simulation can give new users an easier understanding of the system. To keep the model easy to understand and accessible, the used model will be time based simulation. This also gives a more realistic result and great flexibility in adding or chancing variables. There will be started with modelling the translation from speed to the power requirement from the power box.

9.2 Fuel/system independent model part

Each modular power plant system has a individual model, these models together will provide the data for answering the research question. Meaning that there are four models developed for this researched, those are the following:

- Diesel electric model with one engine (base line).
- Three modular Distributed Generation (DG) systems:
  - Diesel electric model with three engines.
  - Fuel Cell (FC) model with two PEM fuel cell systems using hydrogen.
  - FC model with two SOFC fuel cell systems using ammonia.

The models have some similarity between them, those similarities will be used in each of the four models and discussed first together with the general layout of the model. This is done to improve the system overview, so it is easier to see the similarities and differences between the models. The general base structure is formed and started is with the explanation of this overall structure, this will be done based on figure 9.1.

It can be seen that there are four main blocks that form the base for each model. Those models will be discussed in more depth, for the blue blocks, see chapter 9.2.1. The yellow engine and red emission blocks are dependant on the selected fuel and engines this will be discussed in chapters 9.3 and 9.4. The explanation of the green efficiencies block can be found in chapter 9.2.1.

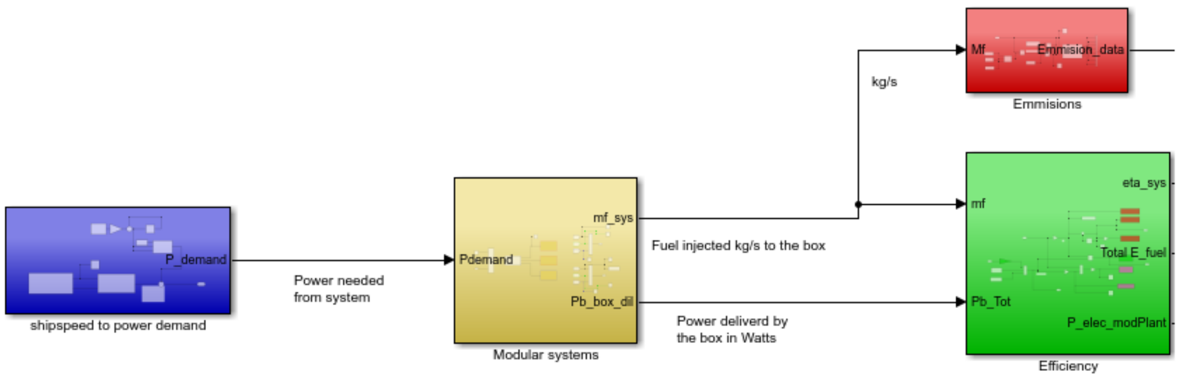


Figure 9.1: General structure of the model

9.2.1 Model similarity

In all four models the ship's speed to power demand (blue block) and the efficiencies (green block) are similar and therefore those will be explained here. The statements are applicable to all the four power plant models.

Speed to power demand

The explanation of the subsystem will be done based on figure 9.2. This figure shows all the Simulink blocks that are used for modelling this sub system. Reasoning will be done in order of appearances from left to right.

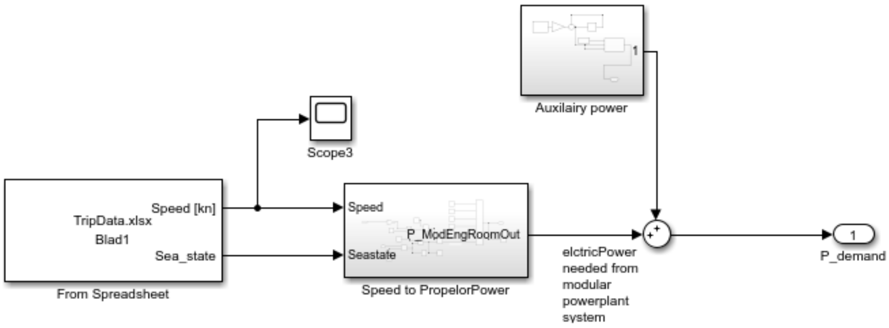


Figure 9.2: Calculation from ship's speed to power demand for the modular system

In figure 9.2 the first block imports the spreadsheet data that is provided by the user trough excel. This should be a matrix with dimension [n X 3], in which the first column is time (s) and the second is the speeds (kn) at that time and the third is the sea state. The block will read the speed at each time and will use linear interpolation between two given set points. It can also hold the last value and a step up when a new value is given, however this is not used. In practice a power (speed)setting is set and will not chance for a certain time. To be able to simulate voyages that take many hours it is easier to only put in the points when the speed setting is changed. If interpolation is used the program will change speeds very slowly. For example: at 60 second a speed of 6 kn is set and at 3600 seconds 8 kn is required, the program now reads this as from 60 up to 3600 seconds 6 kn is required and after 8 kn is required. With interpolation the ship would speed up linear between 60 and 3600 seconds from 6 to 8 knots. This is not what would happen in real life, this acceleration would be done quicker and the limitations are taken into account in the engine model itself. The sailing profiles used in this thesis will use an interpolation between speeds in the excel for a more stable model. To use linear interpolation there will be adjustments for speed settings so this method can be used. This adjustment is a fixed time step of 10 minutes before each new speed setting. In this manner linear interpolation will be used for 10 minutes to change the speed to the new set point.

Next, the speed read from the Excel will be the incoming speed which is translates into the propeller power in figure 9.3 according to formula 9.1. This is applicable on low Froude numbers as explained in chapter 7.1. The difference here is that instead of Pe and c1, c2 is used and gives Pp, meaning that the propulsive efficiency is taken into account (Woud & Stapersma, 2002c).

$$P_p = c_2 * v_s^3 \tag{9.1}$$

In addition to this propeller power the sea state influences are added, as seen in the bottom part of figure 9.3. This is done by simulating white noise and multiply this by the given sea state value read out of the third column in the Excel. The power values of the noise are based on the North Sea where a wave energy of 7-12 kW per meter wave front is found for depths of 25 m with a time of 5-7 seconds (Lavidas & Polinder, 2019). Assuming a heading with head waves, a power around 100 kw can be obtained. When sailing faster this power will increase, therefore the sea state is made a factor of the total power. 100 kW is around 7% of the installed power and therefore the required power will be factored with 1.x were x is the result of the white noise settings. This results in a power factor for the white noise of around 0.005, this is obtained by trail and error. To obtained result that can be compared for all the models. The sea state factor is set to 0 in this thesis. However, if the results of the study are known the influence of this dynamic load could be researched using this part of the model.

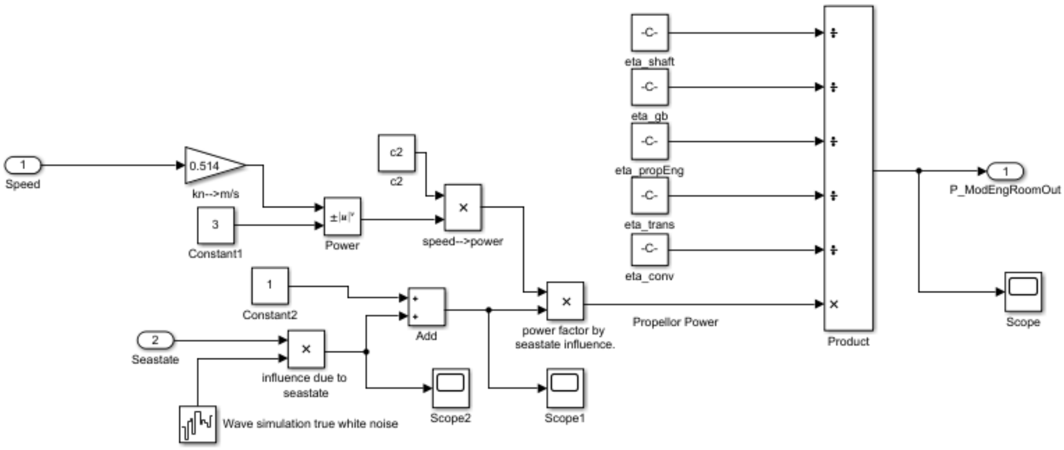


Figure 9.3: Ship speed to propulsion power

The calculated power is the required propeller power. The value goes into the product block and is multiplied by the efficiencies (see formula 9.2 and table 9.1). This results in the power demanded outside of the power box(es) for the propulsion.

$$P_{boxout} = \eta_{shaft} * \eta_{gearbox} * \eta_{EM} * \eta_{conversion} * \eta_{transportation} * P_p \tag{9.2}$$

With:

Table 9.1: Used efficiencies (Woud & Stapersma, 2002c)

η_{shaft}	0.98
$\eta_{gearbox}$	1 (no gearbox installed)
η_{EM}	0.98
$\eta_{conversion}$	0.98
$\eta_{transportation}$	0.97

In figure 9.3 the last part is the top middle part, here the auxiliary power demand is added to the propulsion power. The auxiliary power is added to the set point (sailing at sea 290kw) in the fist 100 seconds. The power of both the propulsion and auxiliary are added together and are leaving the sub systems, the required power is now known. This power will be fed into the modular system box (yellow) in figure 9.1. The other similarity between all the modular power plant models is the efficiencies box (green), so this will be explained next.

Efficiencies

In figure 9.4 the inside of the efficiencies subsystem is shown. Like before it will be explained in order of appearance from left to right in the figure.

There will be started with the two incoming data streams, those are gathered from the engine unit and are the fuel flow in kg/s and the break power of the engine. The power of interest for the comparison is not the engine break power but the power that will be transported throughout the ship. This is the power generated at the modular power plant. The system boundary is shown in figure 6.3. This means that the break power of the engines needs to be multiplied with the shaft-, conversion- and generator-efficiencies. For the FC systems the break power is already electric and will only be multiplied by the conversion efficiency. (Woud & Stapersma, 2002c). The obtained power is the delivered power by the modular plants, this is used for comparisons. The delivered power is set from w to Kw and fed into a division block where the SFC [g/kWh] will be calculated following formula 9.3 (Woud & Stapersma, 2002d)

$$SFC = \frac{36000 * \dot{m}_f}{P_{electric-del}} \tag{9.3}$$

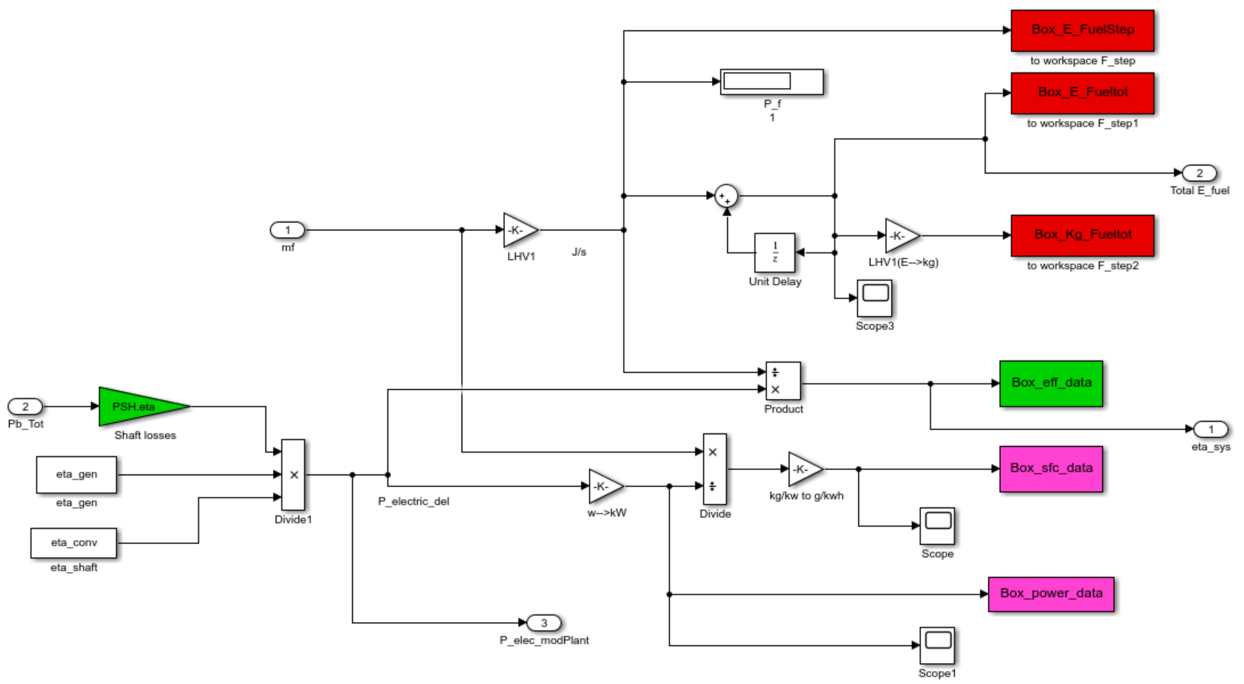


Figure 9.4: Efficiency block

Besides the SFC the total efficiency will also be calculated (Box_eff_data in fig 9.4). This is done by multiplying the fuel flow with the LHV, this results in the energy flow of the fuel in [J/s]. This flow is sent to a division block where the electric power of the modular plant will be divided by the energy flow of the fuel. This gives an efficiency of each time step. The overall efficiency is calculated in the Matlab code following equation 9.4.

$$\eta_{tot-Average} = \frac{\sum(box - eff - data)}{n_{simulations}} \tag{9.4}$$

Left are the red blocks in the top right in figure 9.4, those represent the fuel properties. From top to bottom, the first is the energy flow of the fuel. The next is the total energy needed for the simulated voyage. This data is collected by a time delay loop, in this way the total energy of the fuel is calculated. If we divide this by the LHV the last red box is found, this represents the total fuel mass needed in kg.

Now that the complete green efficiency block is described and going back tot the general model structure (fig 9.1) seen is that the blue and green block have been described. Leaving us with the yellow block called the (modular) engine system and the red emissions block. Those two blocks are dependant on the type of engine and fuel used during the simulation. First the combustion engine will be addressed, this is used for when MDO is used as fuel. Then the FC model will be described which is applied when ammonia and hydrogen are used as fuels.

9.3 Combustion model

In this section the yellow block of figure 9.1 will be explained for the one engine and three engine MDO fuelled systems. It is started with the description of the engine model itself and the emission model, since those are similar for both MDO fuelled models. Next the one engine system that is used as a baseline is explained. Lastly, the modular DG power box system with three engines is explained.

9.3.1 Engine unit

Since the combustion model of a single engine is the same as that of a single engine within the DG setup, the model will be explained in this section for both the single and the DG setup (in which the model is found in each power box).

The model seen in figure 9.5 is the original model as obtained from the department of Design Production and Organisation of Marine Technology at the TU Delft (TU-Delft, 2010). In figure 9.6 the altered version of the Mossel model as used in this thesis is shown. In this section the alterations and the input parameters will be discussed.

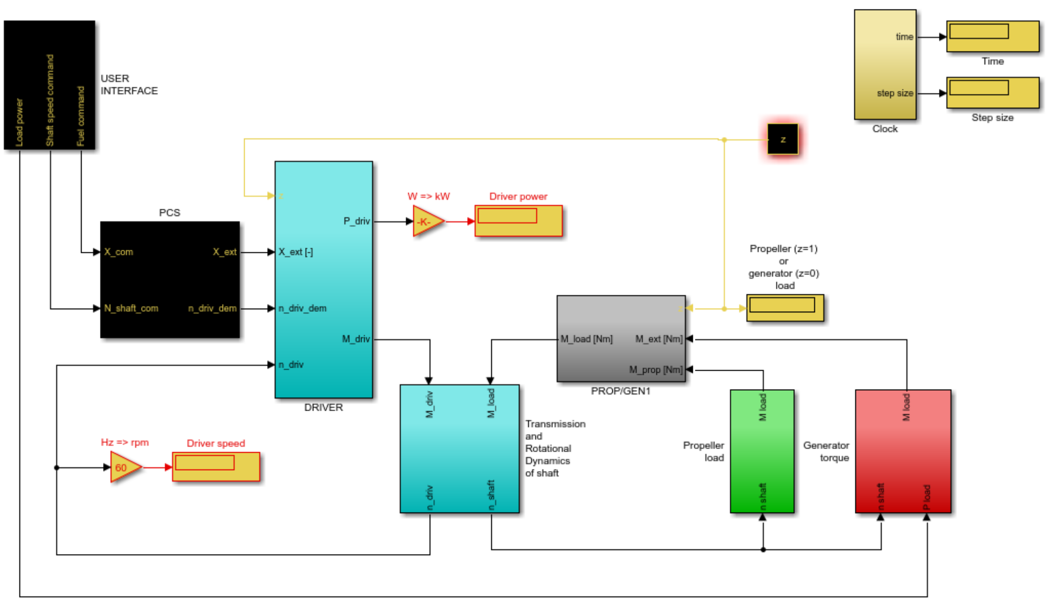


Figure 9.5: Mossel model diesel engine testbed (TU-Delft, 2010)

The first alteration is the elimination of the propeller load and the Prop/Gen block. Since the engines in this thesis are all driving a generator, only the generator torque block (red) and the transmission and rotation block (blue) are of interest. The user interface block and the PCS (both black blocks) are gone since the model input is a generator load that is calculated earlier. The driver block is altered and the result is a rpm set point and a rate limiter for the engine and the engine unit itself. This result in the model as seen in figure 9.6.

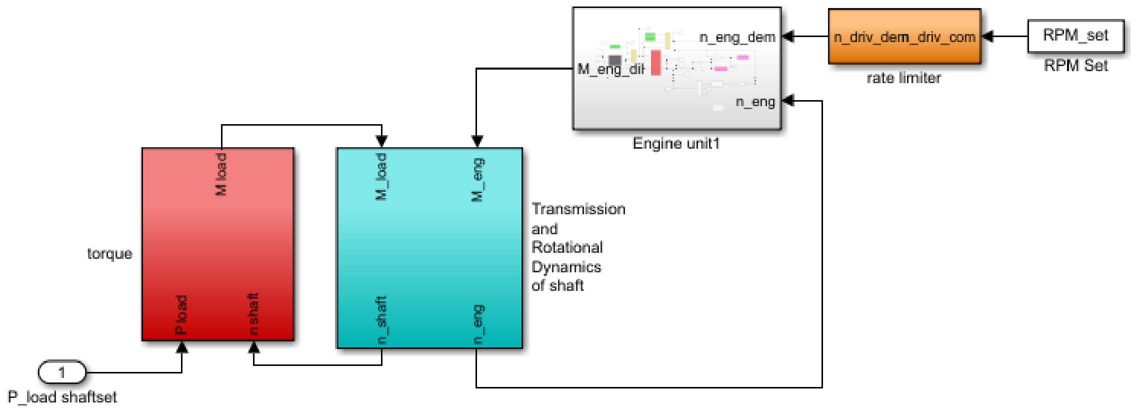


Figure 9.6: Engine model (Mossel based)

Next Within the red block the load is computed to a torque using formula 9.5. The n is the actual shaft rpm, not the demanded set point of the generator. The load torque is send to the blue box in figure 9.6.

$$M_{load} = \frac{P_{load}}{2 * \pi * n_{shaft}} \tag{9.5}$$

In the transmission and rotational dynamics box see figure 9.7, the torque demand (M_load) and delivered engine torque (M_eng) are the inputs. The engine torque is fed into a gearbox and shafting system which gives back the delivered torque. The shaft RPM is also calculated to the engine rpm, in this thesis those are the same since no gearbox is installed. The delivered toque and the torque demand are subtracted, the difference is divided by the rotational inertia and integrated to obtain the shaft RPM which goes to the gearbox and shafting box and is compiled to the engine rpm.

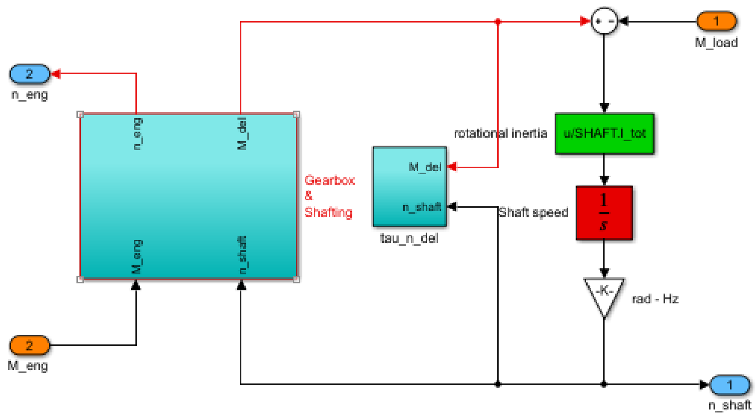


Figure 9.7: Transmission and rotational dynamics (TU-Delft, 2010)

Back to the general engine model as in figure 9.6 where the engine RPM and RPM set points are the parameters for the actual engine unit. The generators used in this thesis are driven on a fixed RPM. This means that this RPM is a constant value that is given to the model, however this is protected by a range limiter that protects the engine from speeding up or down too fast. Since a real RPM and a RPM set point are known we can send those into the actual engine which is the grey block (fig9.6) and this will be explained next.

The inside of the engine model is shown in figure 9.8, for this system only the general working principle will be explained. The inputs for the model are the engine RPM and demanded RPM. Both are put into the governor of the diesel engine where the error between them is calculated and normalised. This error will be proceeded in a PID controller and a X governor will be determined. This is the output of the governor (black), this normalised governor setting will be multiplied with the nominal fuel flow of the engine and this is fed to the diesel engine block (red). Together with the engine RPM and with the use of the Mossel model and an engine specific matrix (will be addressed in chapters 9.3.3 and 9.3.5). The red blocks will deliver the engine torque and the engine brake power.

The fuel flow that is the input for the red diesel engine block is the fuel flow for one cylinder for a complete cycle of the engine. This is multiplied by the number of cylinders and k (cycle type, 2 or 4 stroke) this gives the fuel flow that goes into the engine. The purple part, on the right in the figure, are the SFC and power data from the engine. This is the same for the traditional setup as for the setup in figure 9.4. For the DG setup those numbers are specific for one engine and the data in figure 9.4 is for the complete system. The fuel flow for the engine is followed and an output of the system that will flow into the emission block, the last block that needs to be explained.

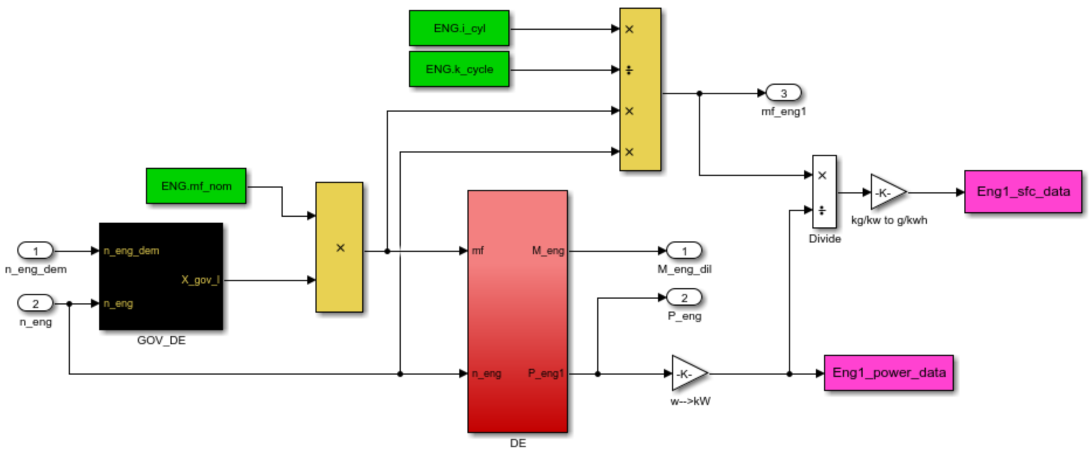


Figure 9.8: Combustion engine from Mossel model (MDO setup) (TU-Delft, 2010)

9.3.2 Emissions

Since the emission model of a single engine is the same as that of a single engine within the DG setup, the model will be explained in this section for both the single and DG setup. There are two types of emissions, engine related and fuel related emissions (Stapersma, 2010b). For the fuel related emission (see chapter 9.3.2) the model is based on the same procedure as described in the book "Lecture Notes WB4408B Diesel Engines Volume 3 Combustion" chapter 13 (Stapersma, 2010b). The engine related emissions are based on the emission simulated by the Mossel model (TU-Delft, 2010). There is started with the emission block red block in figure 9.1, the inside of this block is shown in figure 9.9 and like before the system will be explained from left to right.

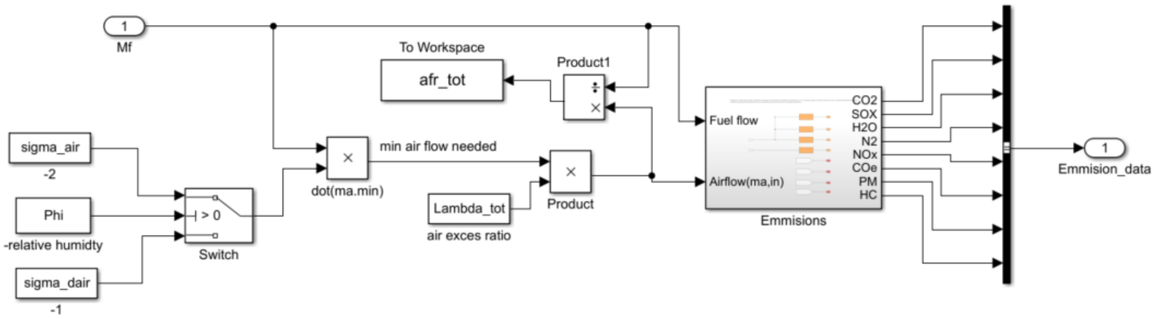


Figure 9.9: Emission sub system (red)

As an input for the model the fuel flow from the engine is used, the σ of the incoming air. In this research the air has a relative humidity of 55% (can be changed within the model). σ air is calculated in Matlab following the next procedure: this is under the assumption of complete combustion of the fuel. Then the amount of (k)mol in the reactions is found with the use of equation 9.6. The n is the amount of (k)mol in a curtain fuel mass, for an example the amount of carbon in the fuel is calculated using equation 9.11.

$$n_c^f \cdot C + n_c^f \cdot O_2 = n_c^f \cdot CO_2 \tag{9.6a}$$

$$n_H^f \cdot H + \frac{1}{4} n_H^f \cdot O_2 = \frac{1}{2} n_c^f \cdot HO_2 \tag{9.6b}$$

$$n_S^f \cdot S + n_S^f \cdot O_2 = n_S^f \cdot SO_2 \tag{9.6c}$$

Since the oxygen needed comes from the air (no bound oxygen in fuel) the oxygen part of equations 9.6 is of interest. If those three are combined this will result in the required amount of oxygen as shown in equation 9.7.

$$n_{O2} = n_c^f + \frac{1}{4} n_H^f + n_S^f = \{\frac{X_C^f}{M_C} + \frac{1}{4} \cdot \frac{X_H^f}{M_H} + \frac{X_S^f}{M_S}\} \cdot m_f \tag{9.7}$$

With the required amount of oxygen the stoichiometric air fuel ratio σ can be calculated using equation 9.8 and combined this with 9.7 where M_A is the molecular mass of the air.

$$n_{O2} = y_{O_2} \cdot \frac{m_{a,min}}{M_A} \tag{9.8a}$$

$$\sigma = \frac{m_{a,min}}{m_f} \tag{9.8b}$$

$$\sigma_{da} = \frac{m_{da,min}}{m_f} \tag{9.8c}$$

$$\sigma = \frac{M_a}{y_{O_2}} \cdot \{ \frac{X_C^f}{M_C} + \frac{1}{4} \cdot \frac{X_H^f}{M_H} + \frac{X_S^f}{M_S} \} \tag{9.8d}$$

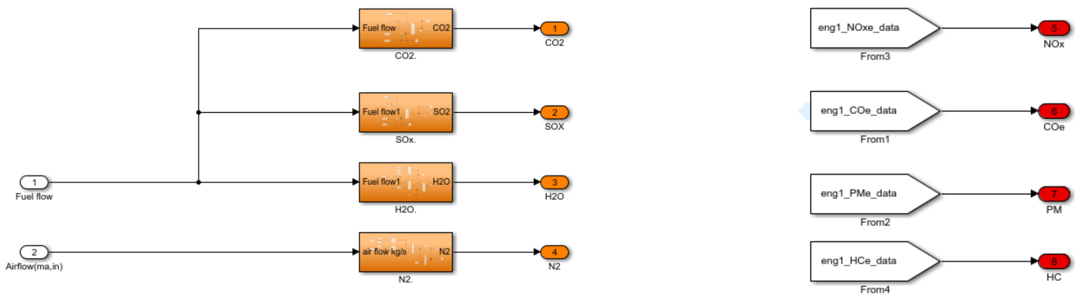
This results in a σ_{da} of 14.30 and for humid air this is 14.14, when using the following fuel composition X_C^f= 0.87, X_h^f= 0.12 and X_S^f= 0.1. σ is multiplied with the fuel flow from the engine, this result in the minimal air flow needed. Next with a λ of the engine of 2.5 (Stapersma, 2010b), and multiply this with the minimal air needed gives us the airflow that goes into the engine. The air fuel ratio is calculated according to formula 9.9

$$AFR = \frac{\dot{m}_{air-in}}{\dot{m}_{fuel}} \tag{9.9}$$

The fuel and air flow are the inputs for the emission block seen in figure 9.9. With this block the two emission types are computed as described next.

Fuel related emission

To determine the emission in the model it is assumed that the fuel completion is known in mass fractions. For MDO the mass fractions as described in chapter 5.3 are used. Meaning the composition is as follows X_C= 0.87 X_h= 0.12 X_S= 0.1 those are used in the orange block of figure 9.10. The fuel related emissions are CO2, SOx, H2O and N2.



(a) Emission sub system (fuel related part)

(b) Emission sub system (engine related part)

Figure 9.10: Emission sub system, representing the fuel and engine related emissions

Each of the mentioned emissions will be calculated using the same procedure, this procedure is based on the fuel flow and assuming complete combustion. By using chemical formulas the emissions are calculated. The whole procedure is explained for CO2, for the other emissions the model overview is presented in appendix G. For CO2 there is started with the reaction equation when complete combustion is assumed (eq. 9.10). It can be seen that the amount of mol carbon dioxide in the exhaust equals the amount of mol carbon within the fuel. This means that if the amount of mol in the fuel is know we can compute the amount of CO2 in the exhaust. The amount of mol in the fuel can be calculated using equation 9.11 (Stapersma, 2010b). Only the fuel flow is missing here, this will gained from the model. So the faction (mol ratio) out of equation 9.11 will be used.

$$n_C^f * CO_2 = n_C^f * C + n_C^f O_2 \tag{9.10}$$

$$n_C^f = \frac{X_C^f}{M_C} * m_f \tag{9.11}$$

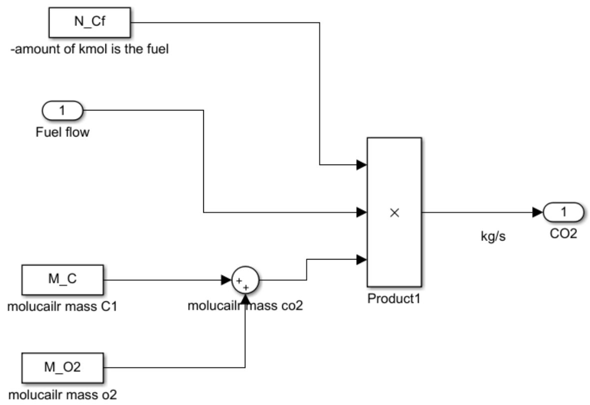


Figure 9.11: Fuel related CO2 emissions

With the ratio of mol carbon in the fuel known and knowing that this equals the produced CO2, the amount of CO2 can be calculated according to equation 9.12. This equation is modelled within Simulink, see figure 9.11. The other fuel related emissions as represented in figure 9.10a equal procedures are followed. The models for those are found in appendix G. For the engine related emissions this procedure can not be followed, so this is done using the following procedure.

$$\dot{m}_{CO_2} = M_{CO_2} * \frac{X_C^f}{M_C} * \dot{m}_f \tag{9.12}$$

Engine related emission

The engine related emissions are emissions which can be related to the engine process. Those emission can be different for every engine and are also not constant for every power output of the engine.

The engine related emission in figure 9.10b shows that a NOX emission is given within the fuel emission, a N2 emission is also mentioned. This is the amount of nitrogen that is fed into the engine and measured in the exhausted. When nitrogen bound fuel (not the case here) reacts to NO2 emissions then it is a fuel related emission. The nitrogen in the incoming air can also react to NO or NO2 or N2O, those are called NOX emissions and are engine related (Stapersma, 2010c). For those engine related emissions like NOX measured engine data is needed.

Since no real data can be found from the Yanmar engine within this research the values that are present within the Mossel model are used (TU-Delft, 2010). Within this model different emission values are represented. Since no real data is avialle the same data set will be used as for the DG setup. This data is a matrix in which engine RPM and power are related to emissions in a normalised way. For each NOx, COe, Particulate Matter (PM) and HCe a matrix is presented, e.g. the ,matrix of PM is given in table 9.2.

engine speed	1.00	1.00	1.00	0.80	0.63	0.63
engine Power	1.00	0.50	0.25	0.50	0.25	0.00
Pme	1.00	0.36	0.18	0.24	0.15	0.25

Table 9.2: Emission matrix for particle matter

All the emissions for the diesel models are known at this moment. So it is time to look at the whole system and the differences in it, starting with the DG engine diesel system since this is the most complex part of the two MDO systems.

9.3.3 DG setup three engines diesel electric

Since the combustion model of a single engine is the same as that of a single engine within the DG setup, those are represented by the yellow modular engine sub systems in figure 9.12. This block contains the same model as explained in chapter 9.3.1. The difference is the power output of the engine and the SFC, so those will be explained in this section together with the rest of the blocks seen in figure 9.12.

The first part is a multiplier block with efficiencies, since the power need is converted and generated by a generator. The generator efficiencies are calculated from the data from Yanmar see equation 9.13, the generator power and the break power of the engine at nominal power were found in the data sheet of Yanmar (YANMAR, 2020).

$$\eta_{gen} = \frac{p_{gen}}{p_b} = \frac{450}{485} \tag{9.13}$$

Multiply this generator efficiency with the conversion efficiency results in the total needed power from all the engines (this can be done because all the efficiencies are identical for the 3 engines), this power is send to the power division block which will be explained next.

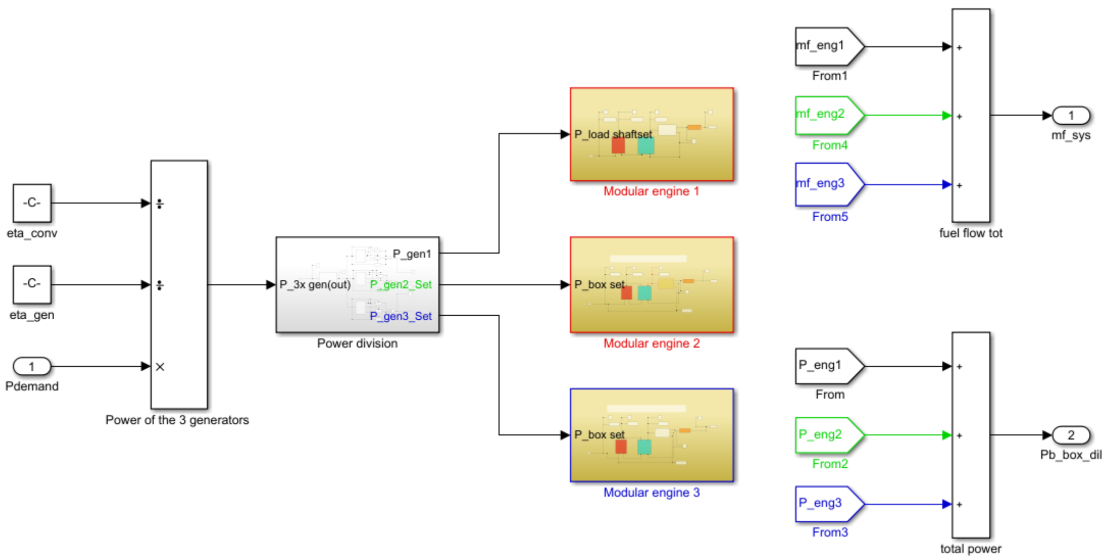


Figure 9.12: Modular power box model for the DG setup

9.3.4 Power division

The power division of the power demand is done within the power box model. Since in the DG setup 3 engines are represented a sub model is made to determine the power demand of each individual engine. This is done based on the power factor. Figure 9.13 shows this model.

There is started with the power demanded by the generators [1] of the three engines. This power is divided by the shaft efficiency times the sum of nominal powers of all the engines. In this way a value (u(1)) is given between 0 and 3 based on the MCR of one engine. This value is given to 3 if blocks. Each of the blocks represents one engine. There are three conditions which can be true, those three condition are the following.

- u(1) is smaller or equal to 1
- u(1) is smaller or equal to 1.8
- u(1) is above the 1.8

If a u(1) meets one of the 3 requirement the signal is passed to the corresponding if action subsystem. Each block has its own function, which can be found in table 9.3. It can be seen that engine one is always running, and engine 2 is running when u is larger than 1.8. This is based on the optimum working point of the selected engine (see figure 9.15) this is at 60 % of MCR. It is seen in the figure that the SFC rapidly increases if engines are loaded below 60%. Three engines at 0.6 of MCR is 1.8 MCR total, so therefor the number 1.8 is used. The point at which a second engine is switched on is when the power is larger than 1.0, meaning that one engine is just not powerful enough. The optimal point would be at 1.2 which is more than an engine can deliver, therefor engine one is switched on when the power demand (u(1)) exceeds 1.0. Switching before engine one is at MCR, lets say at 90%, will not be better since the SFC at (90/2=) 45% is higher than on MCR. The values about when to switch engines on and off are dependant on the SFC (efficiency) curve of each specific engine. For the DG setup with three engines this curve is specific for the selected Yanmar engine.

Table 9.3: Functions corresponding to u(1) values per engine

	U(1) value	**function P_{dem}**
engine 1	≤ 1	$u(1) * ENG.P_{nom} * \eta_{shaft}$
	≤ 1.8	$u(1) * ENG.P_{nom} * \eta_{shaft}/2$
	else	$u(1) * ENG.P_{nom} * \eta_{shaft}/3$
engine 2	≤ 1	$u(1) * 0$
	≤ 1.8	$u(1) * ENG.P_{nom} * \eta_{shaft}/2$
	else	$u(1) * ENG.P_{nom} * \eta_{shaft}/3$
engine 3	≤ 1	$u(1) * 0$
	≤ 1.8	$u(1) * 0$
	else	$u(1) * ENG.P_{nom} * \eta_{shaft}/3$

[1] There are 3 engines each with their own generator but since they are identical the generator efficiency is already taken into account

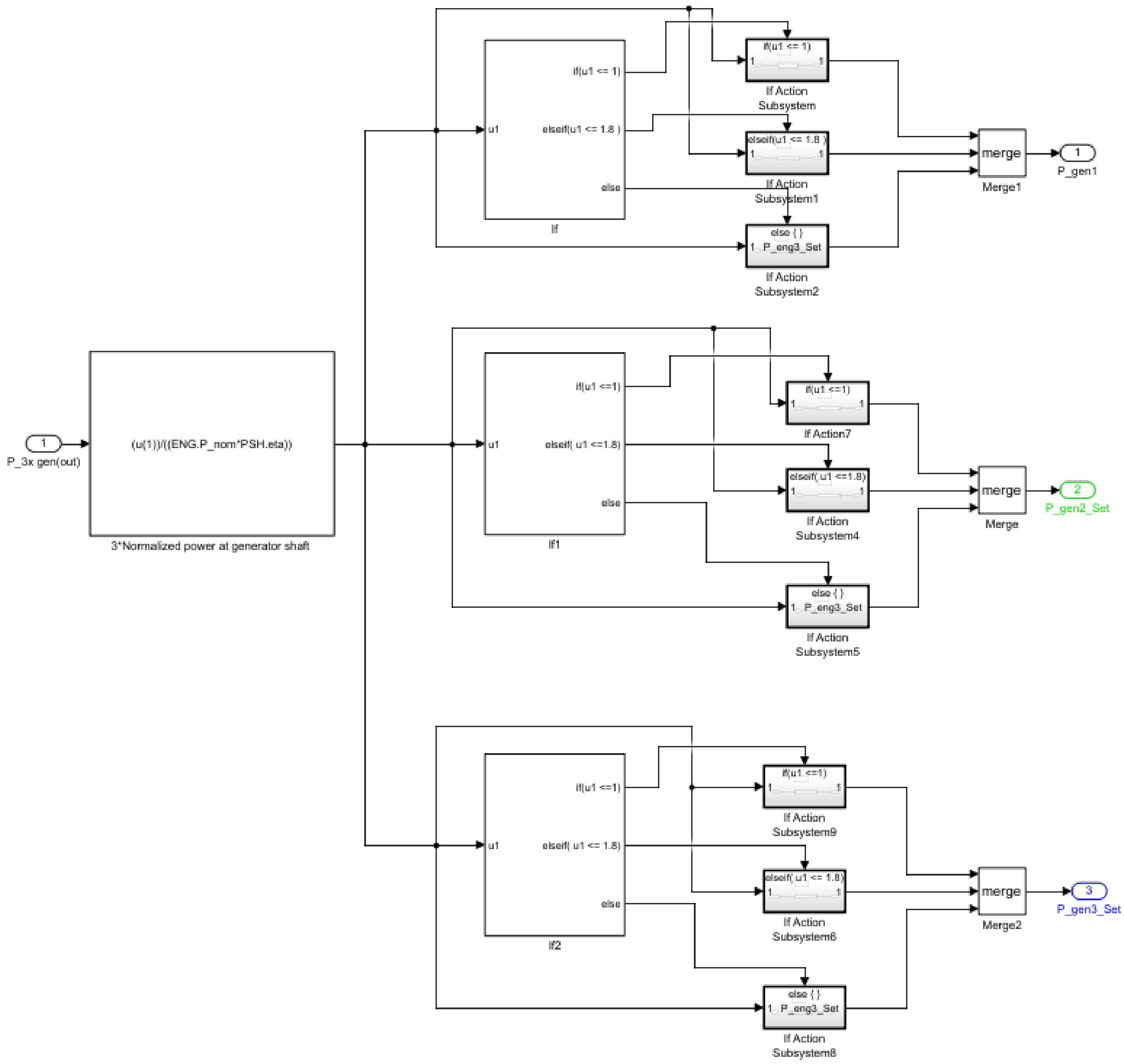


Figure 9.13: Power division for DG setups

Fuel consumption curve

From the data sheet of Yanmar (6AYmWST) the power and torque curves are used to determine the specific fuel consumption of the engine in % of MCR, the curve is shown in figure 9.15, for the data sheet see appendix E. This is another engine than used in the dimension analyses, due to the lack of data of generator sets and since a similar propulsion engine is used for which the fuel consumption data is available on the propeller curve, it is assumed is that this engine can also drive the generator from the gen-set(6n165L-sw) used in the dimension analyses. [2].

The fuel consumption curve of the engine follows the propeller curve and therefore it can not be used directly for this model, since the engine drives a generator and not a propeller. There are two options for generators: a constant speed or variable speed generator. The second type is an upcoming technology, but it is not often

[2]The RPM however will be different but there are generators who are able to run on higher RPMs

used currently. Companies are developing variable speed generator sets because those can reduce the fuel consumption when the ships often sails in partial load conditions (Habermaas & Thurner, 2020). Since the Future Trader is a general cargo ship, its time in partial load will be limited. Additionally due to the DG setup the power needed can already be regulated by turning engines on and off. Due to these two reasons the benefits gained by variable generators are small. This in combination with the lack of data for variable speed generators results in the decision to use a constant speed setup for the Future Trader.

For the modelling of the engines the SFC curve needs to be adjusted to be able to use it for a constant speed engine. In general a constant speed engine has a somewhat higher (1-5%) SFC (Woud & Stapersma, 2002a). The calculated SFC curve based on the data of Yanmar is adjusted to make is more suitable to use in a constant speed engine model. The correction factor is based on figure 9.14, this is taken from the book of Design of Propulsion and Electrical Power Generation Systems. The Yanmar is a high speed diesel engine, so the curves for a fixed speed and propeller law are considered and the same difference is assumed to be true for the Yanmar engine. This results in figure 9.15, this figure represents the fixed engine speed SFC curve. Those data will be used in the model in a normalised way. The speed of the engine is 1900 RPM, in this case the maximum power of the engine is 485 KW. The SFC curve is calculated based on the propeller curve that has a set point at MCR, so this will be used in the model and this is at 1900 RPM.

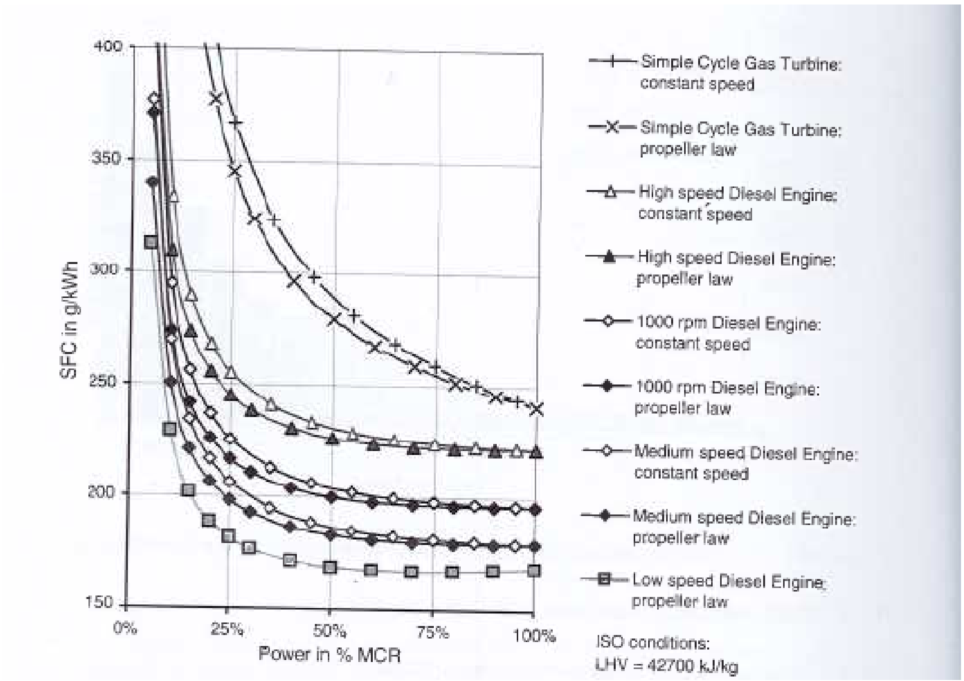


Figure 9.14: SFC of primemovers (Woud & Stapersma, 2002a)

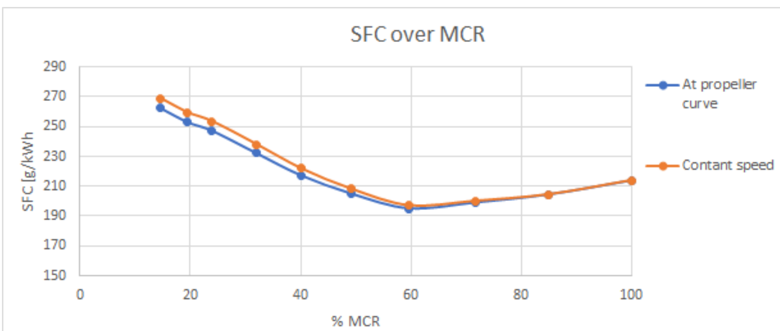


Figure 9.15: SFC over MCR at constant speed

The power torque matrix for the Mossel model is based on the curve as seen in figure 9.15 . This matrix is shown in table 9.4. The matrix represents the engine speed torque dynamics of the engine. Those are based on the data found in the Yanmar fact sheets and the altered SFC curve as seen in figure 9.15. For each MCR and SFC the fuel injection is calculated (by using equation 9.14) and for each power the torque is calculated for a constant speed (ω = 1900 RPM see equation 9.15). Those values are computed to a relative number with respect to the maximum value. Those are loaded into the engine matrix in the Mossel model and result in the SFC curve as seen in figure 9.16, it is tried to get as close as possible to the curve based on the Yanmar data. However, the curve is not a smooth curve and therefore there is a difference between the two. Additionally the used points are read from a graph so there are possible errors already in the points. With some tweaking of the numbers the SFC curves of the model are matched with those of the found engine data.

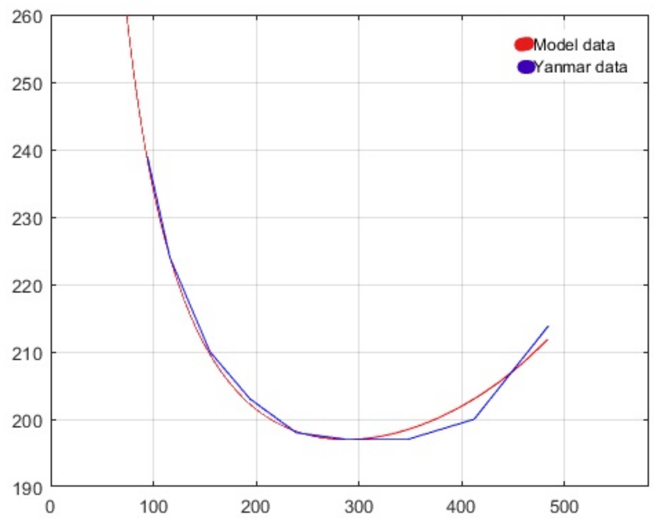


Figure 9.16: SFC curve of the model in comparison to the Yanmar calculated SFC curve

$$m_{fuel} = \frac{SFC * P_b}{3,600,000} \tag{9.14}$$

$$M_{eng} = \frac{P_b}{\omega} \tag{9.15}$$

engine speed	1.00	1.00	1.00	0.75	0.55	0.50
injected fuel	1.00	0.62	0.08	0.56	0.25	0.05
engine torque	1.00	0.65	0.0	0.56	0.20	0.00

Table 9.4: Relative engine speed vs power vs Torque

9.3.5 One engine diesel electric

For the baseline one engine set up a SFC curve is also formed. How those are used and put into the model is already explained in chapter 9.3.3, so here only the values and curves will be presented.

Model parameter difference from DG setup

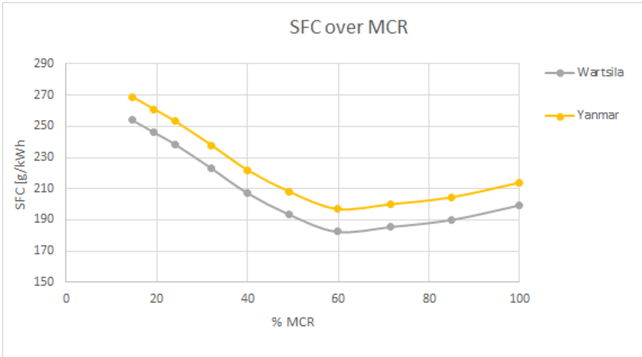


Figure 9.17: Both SFC vs. MCR curves of the Yanmar and Wartsila engine.

For the traditional diesel electric setup with one engine a Wartsila (8L20) engine the specific fuel consumption is 190 g/kWh at 85% MCR (Wartsila, 2017). The assumption is made that this engine has a similar SFC over MCR curve as the Yanmar, meaning that the shape is the same. This is probably not true in real life but manufacturers can tune engines in such a way that the optimum point is at a desired MCR. Therefore the shape would be equal but the values of the SFC would be different and adjusted for the Wartsila engine. The used curve is seen in figure (9.17) below. The SFC of 190 is adjusted for a constant running engine as is done for the Yanmar engine, the same procedure is used as described in chapter 9.3.4. The settings that are different from the DG setup are: RPM is 900, the number of cylinders is 8, the nominal power is 1480 kW and the SFC nominal is set to 200 g/kWh at MCR. This results in the SFC curve as seen in 9.18

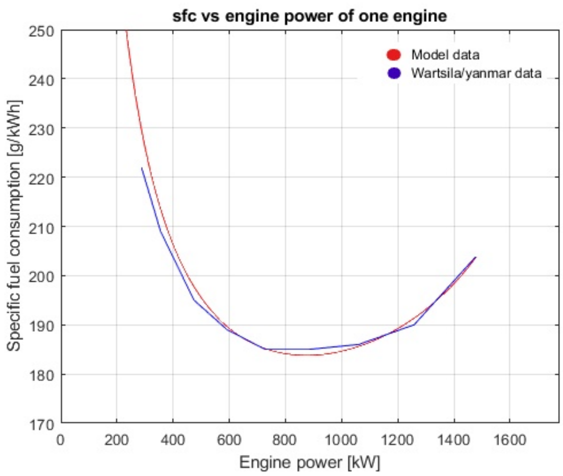


Figure 9.18: SFC curve of the model in comparison with the Wartsila calculated SFC curve

Model differences from DG setup

The major difference between the DG setup and the one engine diesel electric system is the absence of the power division. Since only one engine is installed all the power needs to be delivered from that engine, therefore no power division is needed. This means that the power demand (blue block in figure 9.1) is given to the modular system (yellow, same figure). The inside of this block can be seen in figure 9.19, it is seen that the efficiencies of the conversion and the generator are now taken into account in this block instead of going through the division block first. All the other components of the model are the same as in the DG setup. In chapter 9.5 the verification and validation of all the models will be done. First the fuel cell models need to be constructed before this validation can be done.

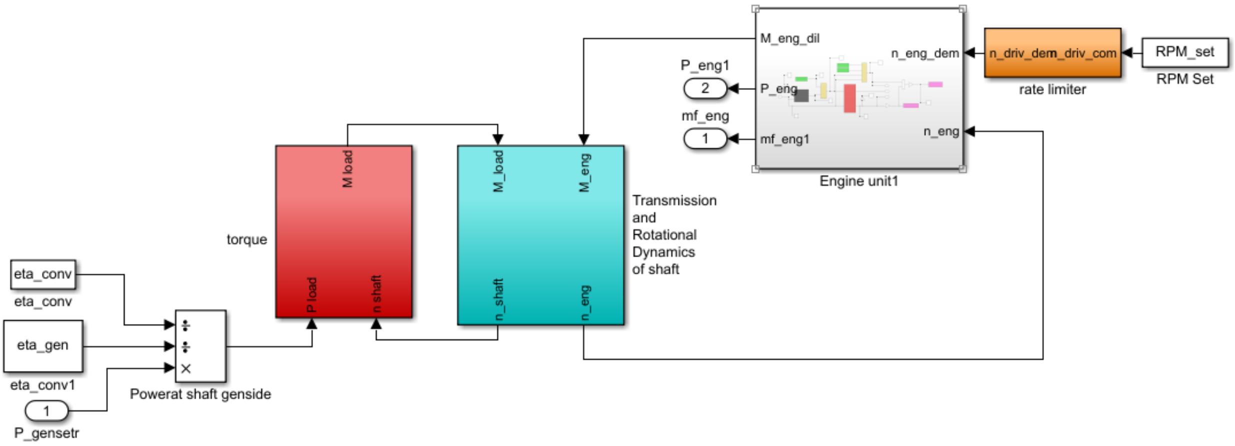


Figure 9.19: Engine model one engine system

9.4 Fuel cell models

Now that the MDO model is complete and ready to use, the FC model will be presented. A large part of the model will be the same as in the MDO models. Those are already explained in chapter 9.2.1. The parts that are changed or added will be explained in this section. There is started with the FC model, which can be found inside the yellow block in figure 9.1. The inside of the modular model is shown in figure 9.20, this part is used for both ammonia and hydrogen. When the models are done the validation is presented in chapter 9.5, the results will be given in chapter 10.

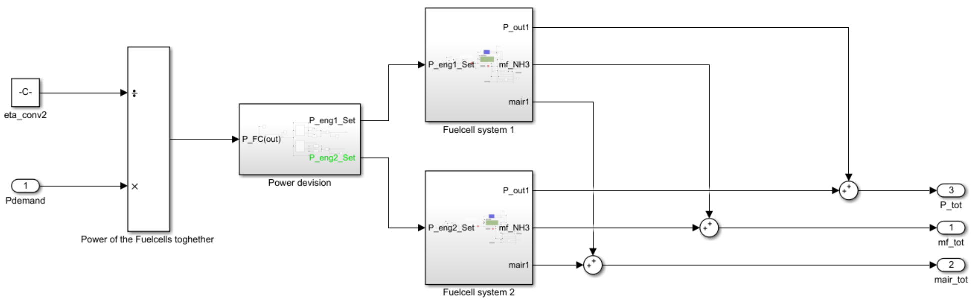


Figure 9.20: Modular engine system FC models

9.4.1 Power division

As seen in the modular engine block of the FC systems, a power division is also used for the FC model this because two systems will be installed. The division is done as shown in figure 9.21, the working principle of the model is explained in chapter 9.3.4.

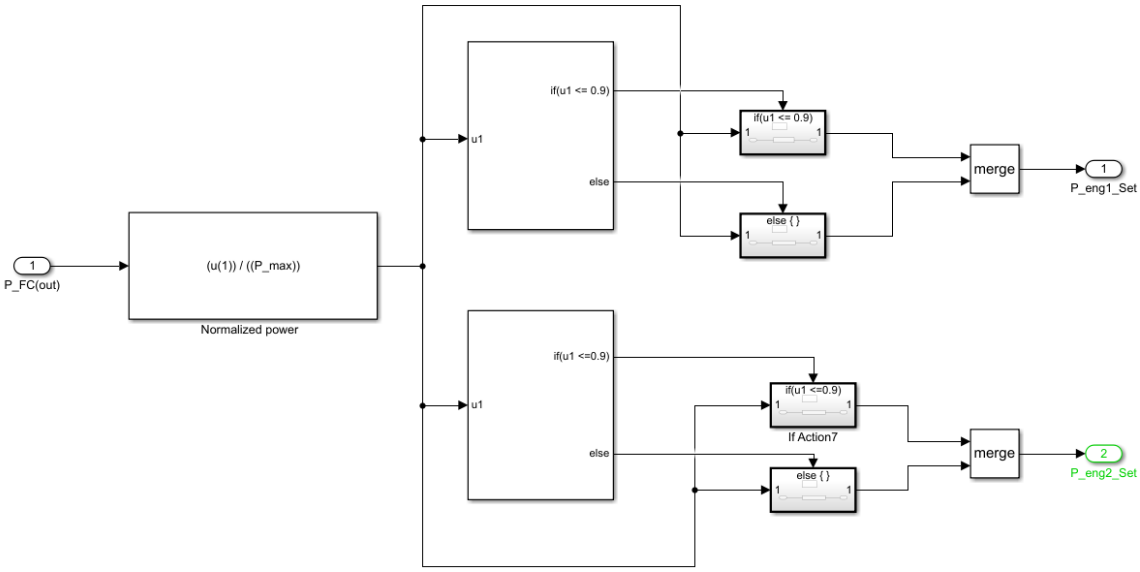


Figure 9.21: Power division for the FC models

The difference is that instead of three blocks used in the MDO DG system now two blocks are used. The incoming power will be divided by the total power of all FC systems and so a u(1) is compiled. This is fed to the if else blocks and to the corresponding subsystems, equations are used to determine the output power of the FC system see table 9.5 for the corresponding functions for each u(1) value.

The point at which a second system needs to be started is determined by using the efficiencies curve. As seen in figure 7.2 a FC has an optimum working point around 0.7, since the efficiency at 90% almost equals that at 45% and the efficiency decreases after 90%. The second FC will be activated at a point at which both systems run at 45% MCR. So the critical value for u(1) equals 90% (0.9) (Welaya et al., 2011), (Thorstensen, 2001). Now that the power asked for each system is known, it is send to the FC systems. Here a FC is modelled, for hydrogen a PEM cell is used and for ammonia a SFOC cell.

Table 9.5: Functions corresponding to u(1) values per fuel cell

	U(1) value	**function P_{dem}**
FC 1	≤ 0.9	$u(1) * ENG.P_{nom}$
	else	$u(1) * ENG.P_{nom}/2$
FC 2	≤ 0.9	$u(1) * 0$
	else	$u(1) * ENG.P_{nom}/2$

9.4.2 Hydrogen FC model explained

For hydrogen the general FC model is shown in figure 9.22. The working principle will be explained form left to right. This model is also used for the SOFC model with ammonia as fuel. The model will be explained once in this section for hydrogen and in the following section the adjustments done for ammonia and why this model can be used for ammonia will be explained.

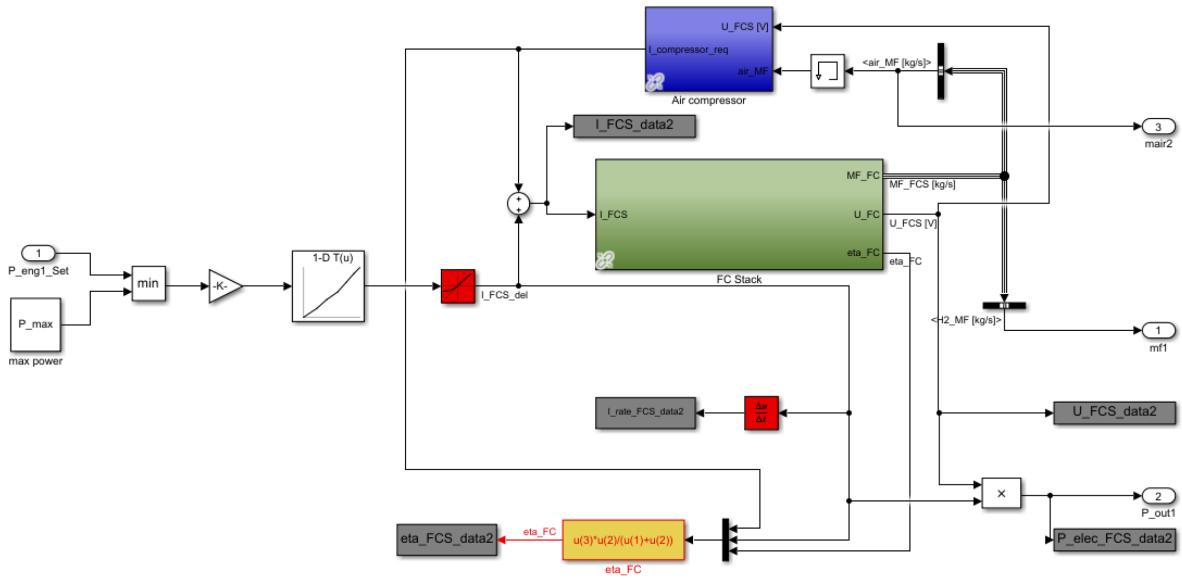


Figure 9.22: Fuel cell model fuel by hydrogen

The model as a whole is obtained from the TU Delft, it was engineered by the department of Design Production and Organisation at the faculty of Marine technology. Alteration are made in the front of the model to make it suitable for use within this thesis. Additionally the parameters of the PEM FC of Nedstack are loaded into the model (NEDSTACK, 2019).

Looking at figure 9.22, the first step is to make sure the power demand will not exceed the power of the system. Therefore both the power demand and the maximum power are send to a minimise block. After this step the power of the total system needs to be divided by the amount of cells in the FC system. Then the power demand of one cell is obtained, however the FC model needs a current as an input and not a power demand. Therefore a look up table is used to transform the required power in a current demand.

This lookup table needs to be addressed in more detail, this because the Nedstack data is implemented here. Instead of assuming a linear curve for the current power graph the data from Nedstack (NEDSTACK, 2019). The curve is presented in figure 9.23. The total current of 230 amps is equal for all the cells present in the stack. The voltage is divided over all the cells, since all cells in the stack are connected in series. Since there are 96 cells in each stack, the voltage is divided by 96 and the amps is constant for all cells. The power can be calculated by using equation 9.16, resulting in table 9.6. This table is used as a lookup table to determine the cell current in the model.

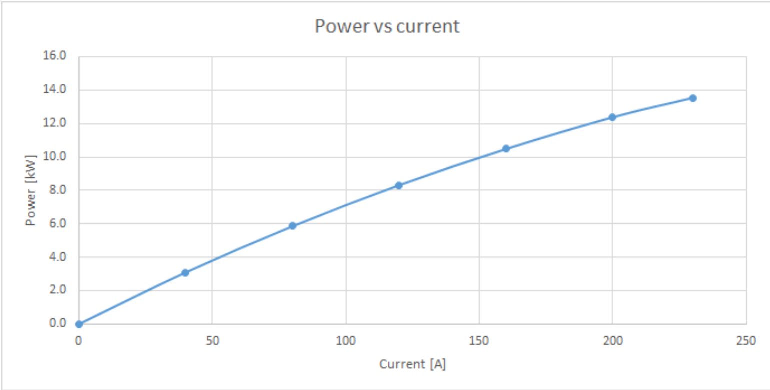


Figure 9.23: Power vs. current curve from Nedstack data (NEDSTACK, 2019)

$$P_{electric} = I * U \tag{9.16}$$

Table 9.6: Look up table for the hydrogen PEM fuel cell based on the Nedstack 13XXL

I(A)	0.00	40	80	120	160	200	230
voltage(V)	0.97	0.81	0.76	0.72	0.68	0.64	0.61
P(kw)	0.00	0.032	0.061	0.087	0.11	0.13	0.1411

This current is send to a rate limiter since a FC can only reacted at a certain rate to changing amps. The obtained current is send to the green FC stack before it enters this block, the required current for the compressor (blue) is added. The obtained data from the FC (top to bottom) is an air and fuel flow for the whole system, the generated system voltage and the efficiencies of a single fuel cell. This efficiencies are fed to a function in which the system efficiencies are calculated. The signals leaving the block and that are used in the rest of the model are: the air flow, fuel flow and the power generated by the FC system.

As seen in figure 9.20 the data is collected from both the systems and added together. The three outputs are the outputs of the modular system (yellow block in figure 9.1). The fuel and air flow are sent to the emission block and the power and fuel flow are sent to the efficiencies block as explained before in chapter 9.2.1.

The emission block is almost similar to that of the diesel engines as seen in figure 9.24. The difference is that emissions of the FC will be water and nitrogen from the air, this will reduce all the polluting emissions to zero.

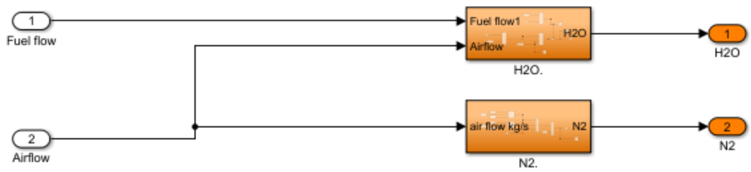


Figure 9.24: Fuel cell emissions

9.4.3 Ammonia SOFC fuel cell

For ammonia the general FC model is shown in figure 9.25, this is similar the model for hydrogen. The working principle therefor will not be explained again (see chapter 9.4.2). However, there are difference between the two and those will be explained. First it is explained why the hydrogen model can be used in an ammonia direct FC.

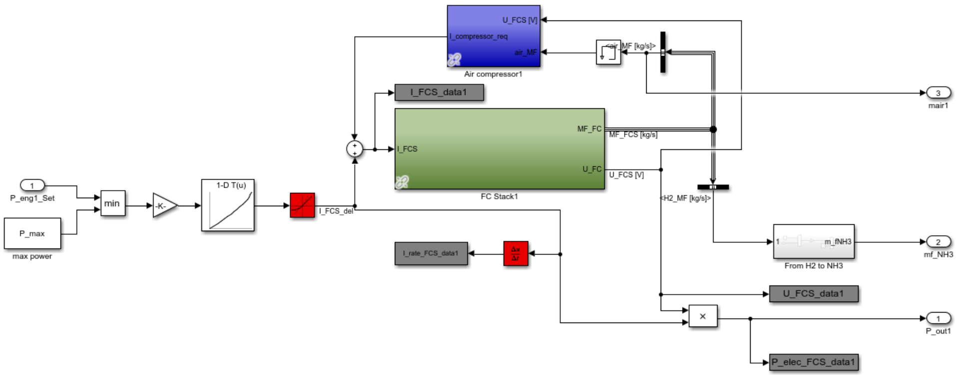
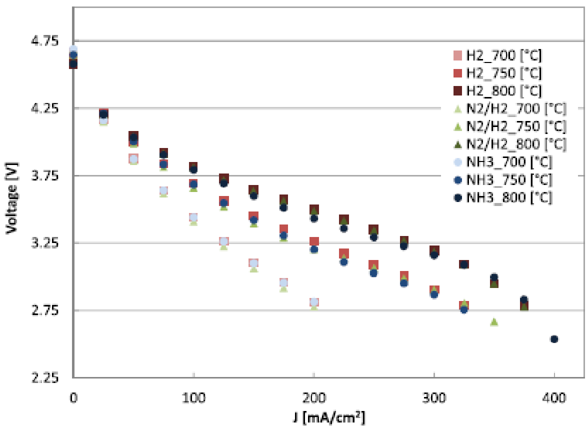


Figure 9.25: Fuel cell model for the ammonia fuelled system

Direct ammonia fuel cells are an upcoming technique and are used in this thesis. It is not a new technique but with the current environmental regulations it is getting more attractive than it was in the past. If ammonia is used directly in a fuel cell, the FC needs to crack the ammonia to obtain the hydrogen that is bounded to the nitrogen. To achieve a complete break up of ammonia a temperature of 1073 K is needed (Ni et al., 2009). If temperatures drops below 673k no NH3 is cracked. The performance of the SOFC ammonia FC is similar to that of a hydrogen fuelled SOFC, this is seen in figure 9.26a (Ni et al., 2009), (Cinti et al., 2016). The power density of the ammonia SOFC is also only slightly different from a hydrogen cell (Afif et al., 2016). Together this means that those cells can be compared in performance. Since a hydrogen FC is already constructed and a SOFC model is present, the choice is made to use the existing model and still get usable results (as long as the temperature is high enough to completely crack the ammonia).



(a) FC polarisation curves of H2 and NH3 (Cinti et al., 2016)

Anode substrate	Ni/8YSZ cermet 1500 μm
Anode functional layer	Ni/8YSZ cermet 7–10 μm
Electrolyte	8YSZ 8–10 μm
Cathode functional layer	LSM/8YSZ 10–15 μm
Cathode current collector	LSM 60–70 μm
Stack design	F-design
Interconnect/cell frame	Crofer22APU
Anode contact layer	Ni-mesh
Cathode contact layer	perovskite type oxide (LCC10)
Sealing	glass-ceramic (87YSZ20)
Number of cells	4
Size of cells	100 × 100 mm^2
Active area per cell	80 cm^2
Total active area	320 cm^2

(b) Fuel cell characteristics fuelled by ammonia

Figure 9.26: Ammonia fuel cell data

As seen in figure 9.26a the difference between H2 and NH3 cells is lowest for a working temperature of 800 degrees Celsius (1073 k), so this is used as temperature. In the model the first step that needs to be taken is the transformation from power to current as for the hydrogen FC, a look up table is created to be able to make this transformation. To use this the ammonia FC characteristic as presented by Cinti are used (Cinti et al., 2016), see figure 9.26b. The total power of a FC is set to 681 kW like for hydrogen. The voltage and current density is gained from figure 9.26a. Together with the FC characteristics this results in table 9.7. It is seen that the maximum cell power is 0.084 kW, a total of 8108 cells is needed to give the required power. The cell current and power from table 9.7 are used in the lookup table in the model.

Table 9.7: Fuel cell characteristic per cell

v stack	vcel	j	1A[cm^{-2}]	I [A]	P [kW]
4.6	1.150	0	320	0	0.000
4.22	1.055	25	320	8	0.008
4	1.000	50	320	16	0.016
3.9	0.975	75	320	24	0.023
3.8	0.950	100	320	32	0.030
3.7	0.925	125	320	40	0.037
3.65	0.913	150	320	48	0.044
3.6	0.900	175	320	56	0.050
3.48	0.870	200	320	64	0.056
3.4	0.850	225	320	72	0.061
3.35	0.838	250	320	80	0.067
3.3	0.825	275	320	88	0.073
3.2	0.800	300	320	96	0.077
3.1	0.775	325	320	104	0.081
2.95	0.738	350	320	112	0.083
2.8	0.700	375	320	120	0.084

The rest of the model is kept the same[3] as for the hydrogen model until the fuel flow out. Since the model gives a hydrogen fuel flow in kg/s this needs to be altered to an ammonia fuel flow. This is done using the LHVs of both hydrogen and ammonia, this is done since all the used hydrogen should be a result of the ammonia cracking. The equation is seen in equation 9.17 and this is used in the model as seen in figure 9.25. On the right just before the fuel flow (middle out flow) is generated to change the fuel flow from hydrogen to an ammonia fuel flow.

$$\dot{m}_{NH_3} = \frac{\dot{m}_{H_2}}{LHV_{H2}} * LHV_{NH3} \tag{9.17}$$

Using ammonia gives the following emissions: N2 and H2O, therefore it gives a possibility of NOx forming. However, those are low to almost not detected in a high temperature SOFC (Ni et al., 2009). This means that the only emissions are water and nitrogen. In comparison to hydrogen there is a larger amount of nitrogen since there is also nitrogen presented in the fuel, therefore the emissions of this FC are also clean.

9.5 Model verification

Now that all the four engine setup models are constructed and explained, the model verification and validation is done starting with the verification. Meaning that there is checked if the model is mathematically correct and reacts as expected the second step is the validation of the model. In this step there will be looked if the data generated is feasible. This second step is done in very general way since the information about the designed system does not exist and and also experimental data of the systems are not available. So there will be worked with general data. Therefore there is a large margin for error in the validation.

9.5.1 Verification

To see if all the models are mathematically correct and react as expect different trials are executed, the results will be discussed below. The criteria and results are shown in table 9.8. Besides those values all the simulations are done 5 times to see if the models gives the same output values. This was found to be true and no differences were obtained, as expected in a mathematical model without a random input (sea state is set to 0). If the sea state is set to another value a difference is sometimes obtained due to the change in power requirements at a certain time.

[3] Meaning that the steps taken in the model are the same, the parameters of a SOFC instead of a PEM cell are loaded into the model

Table 9.8: Model verification steps

Fuel	Diesel		Hydrogen	Ammonia
Requirements Nr engines	**1**	**3**	**2**	**2**
Power demand matches delivered	✓	✓	✓	✓
0 demand 0 delivered	✓	✓	✓	✓
Max power not exceeded	✓	✓	✓	✓
Only auxiliary power (290kW)	✓	318.9	295	✓
Switch in of engine 2 at correct point	x	✓	✓	✓
Switch in of engine 3 at correct point	x	✓	x	x

9.5.2 Validation

The results of the test run are obtained using a sailing profile in which the speed increases from 0 tot 12 knots with the use of linear interpolation. To see if all the models give assumable values for emissions and efficiencies a test run is done the results ar seen in table 9.9. Reference values are shown for the emissions (the references values for MDO are from the diesel engine course books (Stapersma, 2010b), (Stapersma, 2010c)). It can be seen that those match. The engine related emissions are close to the given values. For the fuel cells the difference in N2 emissions for the ammonia cell cause by the fact that within the reference the air consumption is not taken into account, therefore this reference should be ignored. The differences found in the water emissions are the differences in humid or dry air. The reference does not account for the water that is in the incoming air.

The efficiencies should be at a reasonable values, but will be different for the model results as presented in the verification. For the two fuel cells a lower efficiency is expected during the long runs, since the efficiencies of the fuel cells are better at lower MCR values and in the sailing voyages those take up a small part of the total time. In the test case each power is needed for the same amount of time. The one diesel setup should be somewhat lower than in a real situation. This is because in the longer voyages the engine is closer to its optimal MCR point for a longer period. For the DG setup the expectation is that the efficiency is not that different, since the multiple engine setup is expected to perform on a rather steady efficiency number. For the diesel setup figure 7.6 from *Design of Propulsion and Electric Power Generation Systems* (Woud & Stapersma, 2002d) is used. The one diesel engine was expected to have an engine efficiency between 40 up to 45%. For the DG setup an engine efficiency around 37 up to 42% is expected. Since the efficiency calculated in the model gives a system efficiency and the found values are engine efficiencies the range changes because some other efficiencies need to be taken into account, see equation 9.18. The expected efficiencies are 36 - 40% for the one engine setup and 33 - 38% for the three engine layout. As seen in table 9.9 both engines are within this range, so the model results in usable efficiency data. For the fuel cells the system efficiencies are expected to be around 55.9% for the ammonia SOFC system (Fontell et al., 2004) and 40 to 55% (Welaya et al., 2011) for the hydrogen system. The given values of the model's calculated efficiencies as found in table 9.9 are within or close to those values. Therefore the models for the FC systems are also usable.

$$\eta_{system} = \eta_{engine} * \eta_{conversion} * \eta_{generator} * \eta_{shaft} = \eta_{engine} * 0.98 * 0.93 * 0.98 \quad (9.18)$$

Table 9.9: Emission and efficiencies values of the models and a reference

Fuel	**Diesel**			**Hydrogen**		**Ammonia**	
Nr engines emissions	*Reference [kg/kg_{fuel}]*	1 [kg/kg]	3 [kg/kg]	*Reference [kg/kg]*	2 [kg/kg]	*Reference [kg/kg]*	2 [kg/kg]
CO2	*3.19*	3.19	3.19	*0*	0	*0*	0
Sox	*0.02*	0.02	0.02	*0*	0	*0*	0
H2O	*1.47*	1.463	1.463	*8.9*	9.9	*1.587*	1.687
N2	*26.73*	26.67	26.67	*50.29*	50.31	*0.822*	7.401
Nox	*0.056*	0.04	0.07	*0*	0	*0*	0
Coe		0.0033	0.0017	*0*	0	*0*	0
Pm		0.001	0.0011	*0*	0	*0*	0
HC	*0.00195*	0.0026	0.0024	*0*	0	*0*	0
η_{sys}	%	37.8	37.6	45.9		56.6	
AFR_{sys}	kg_{air}/kg_{fuel}	35.7	35.8	67.7		8.9	

10. Simulation results

In this chapter the simulation results will be presented for the three modular power box setups and the one engine diesel system. The results of the efficiency, fuel consumption fuel price and the emissions will be presented. This will be addressed later, first the voyages that are simulated will be given in chapter 10.1. After the voyages are presented the results with respect to the performance parameters will be given in chapter 10.2.1 the fuels consumption result will be given, from those the effect on the ships range can be concluded which is one of the ships operational capabilities. After this the fuel costs are shown in chapter 10.2.2, this will give an insight in the economical side of the ship. At last the results with respect to the emissions will be presented in chapter 10.2.3. When all results are presented conclusions will be drawn from those in chapter 11.

10.1 Simulated voyages

For the simulation four voyages are simulated, the distances and ports can be found in table 10.1 and the figures in appendix H. The voyages are different in length and not all voyages will be achievable within the range of the vessel. Since no sailing profile is given all the voyages are simulated, within the results there will be shown when a voyage cannot be made.

Table 10.1: Simulated voyages for all the models

Departure port	km to sea	Arrival port	km from sea	Open sea	At canal	km total	Max canal speed [kn]
Rotterdam	9.3	Antwerp	16.7	170.1	0	196.0	0
Rotterdam	9.3	Gdansk	7.4	1121.8	98.7	1237.1	8
Rotterdam	9.3	Hamburg	11.1	540.8	0	561.2	0
Rotterdam	9.3	Marseilles	3.7	3827.3	60	3900.3	13

In the table it can be seen that the distance to the harbour is measured. The distances and pictures are all measured and created from searoutes.com. In the harbour the speed is set at 7 kn (as explained before), the distances entering and leaving the harbour area are represented in column 2 and 4 of table 10.1. If a canal needs to be passed the speed will be at the max speed of the canal or 10 kn. For each voyage an excel is created at a hourly base, this is used in the mathematical models and gives the following results.

10.2 Performance parameters

10.2.1 Fuel consumption

To get the range of the Future Trader the efficiencies and the SFC of every system are of interest. Those are calculated using formula 10.1. The formulas in this chapter are from the book *Design of Propulsion and Electric Power Generation Systems* (Woud & Stapersma, 2002d), unless mentioned otherwise.

$$SFC = \frac{\dot{m}_f}{P_b} \qquad [g/kWh] \tag{10.1}$$

The overall efficiency will be calculated using formula 10.2.

$$\eta_e = \frac{P_b}{\dot{Q}_f} \tag{10.2}$$

Besides the efficiencies the amount of fuel needed for the voyage is shown. This can be found in table 10.2. As seen in table 10.2 for hydrogen and ammonia some cells are marked red. This is because those voyages can not be completed with the fuel stored in the four containers aboard.

Table 10.2: Fuel needed

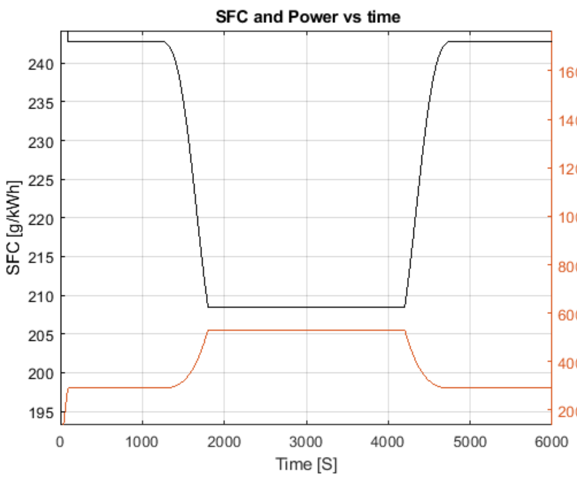
	fuel	**MDO**				**Hydrogen**		**Ammonia**	
	Nr engines	**one**		**three**		**two**		**two**	
Departure port	**Arival port feul needed**	[kg]	**TEU**	[kg]	**TEU**	[kg]	**TEU**	[kg]	**TEU**
Rotterdam Port (RTD)	Antwerp Port (ANT)	2163	0.09	2351	0.10	575.3	0.33	3755	0.26
RTD	Gdansk Port (GDA)	1.345E+04	0.57	1.469E+04	0.63	3572	2.04	2.325E+04	1.59
RTD	Hamburg Harbour (HAM)	6181	0.26	6742	0.29	1646	0.94	1.072E+04	0.73
RTD	Marseilles Port (MAR)	4.216E+04	1.79	4.605E+04	1.96	1.123E+04	6.42	7.31E+04	5.00

The efficiencies and SFC values of all the different systems are found in table 10.3. Those values are the average values across the whole voyage, in appendix I graphs can be found of the SFC and power during each voyage for each power plant type.

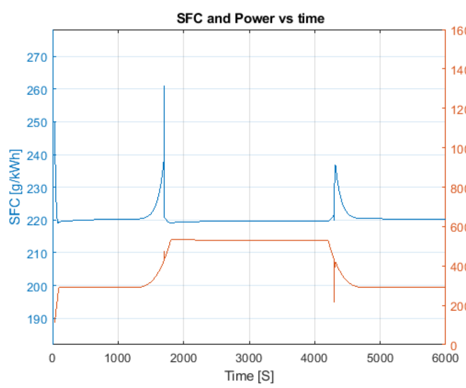
Table 10.3: Average system efficiencies and SFC values

	fuel	**MDO**				**Hydrogen**		**Ammonia**	
	Nr engines	**one**		**three**		**two**		**two**	
Departure port	**Arival port**	η_{sys}	**SFC**	η_{sys}	**SFC**	η_{sys}	**SFC**	η_{sys}	**SFC**
RTD	ANT	41.3	205.8	37.6	222.6	43.2	58.65	52.4	369.8
RTD	GDA	41.2	204.4	37.5	223.0	43.6	58.22	53.1	365.5
RTD	HAM	41.2	204.8	37.6	223.0	43.2	58.63	52.6	369.0
RTD	MAR	41.3	204.3	37.5	223.1	43.2	58.64	52.6	368.7

For the DG MDO it is seen that within the voyage the DG setup seems to keep up with the one engine system when the power is at lower MCR values. To see the effects of this an extra simulation is done where only the last part of a voyage is simulated. The last part consisted of waiting before port entry at 0 speed, sailing to the quay at 7 knots and lying at the quay (only auxiliary). The results of those simulations are found in figure 10.1, as seen during waiting for the harbour entry with only auxiliary power required the DG model has lower SFC values than the one engine setup. However when the speed increases to a speed of 7 knots the one engine system SFC values go to lower values than the modular DG system.



(a) waiting for port to at quay one engine MDO



(b) waiting for port to at quay DG engine MDO

Figure 10.1: Waiting for port and sailing to quay

10.2.2 Fuel cost

Besides the system parameters, the ships operational capabilities are of interest. One of those is the range and the other is the fuel cost. Besides the fuel costs there are many other costs that could be considered, like CAPEX and other OPEX but those are out of scope of the thesis. In table 10.5 the total costs for each fuel and each voyage are seen. The fuel prices of hydrogen and ammonia are based on carbon free production [1]. Grey ammonia and hydrogen are cheaper, however those methods of production will emit a lot of emissions. Since this thesis focuses on reducing emissions the prices of green ammonia and hydrogen are used.

From the table it is seen that a major challenge for the hydrogen and ammonia fuels are the costs of those fuel. Even with better system efficiencies the prices of the fuel for each voyage increases heavily for hydrogen and ammonia. If grey ammonia is used instead of green ammonia (around 250 $/ Metric Ton (mt) (Afif et al., 2016)) the fuel costs will still be higher but the increase with respect to the price for MDO, will be far less. So a reduction in prices of ammonia an hydrogen will be needed. This can be reached when those fuels are widely used, so that they can profit from the scale effect. Another option is the introduction of new regulation e.g. a CO2 tax, this is not yet applicable in shipping but there is already spoken of (Larocca & Nielsen, 2020).

Table 10.4: Bunker prices

MDO	304.5	$/mt
H2 (green)	12,310 (Kayfeci et al., 2019)	$/mt
Ammonia (green)	650 (amoniaenergy, 2020)	$/mt

Table 10.5: Fuel costs per voyage

	Fuel	**MDO**				**Hydrogen**		**Ammonia**	
	Nr engines	**one**		**three**		**two**		**two**	
Departure port	**Arrival port**	**kg**	**$**	**kg**	**$**	**kg**	**$**	**kg**	**$**
RTD	ANT	2163	658.63 $	2351	715.88 $	575.3	7,081.94 $	3755	2,440.75 $
RTD	GDA	13450	4,095.53 $	14690	4,473.11 $	3572	43,971.32 $	23250	15,112.50 $
RTD	HAM	6181	1,882.11 $	6742	2,052.94 $	1646	20,262.26 $	10720	6,968.00 $
RTD	MAR	42160	12,837.72 $	46050	14,022.23 $	11230	138,241.30 $	73100	47,515.00 $

10.2.3 Emissions

For the emissions there are three values that will be used for comparison, the Pollutant Emission Ratio (PER) in kg, PER in mile and Specific Pollutant Emission (SPE) (Woud & Stapersma, 2002d), (Stapersma, 2010b). PER is the pollutant emission ratio and is the amount of polluting emissions emitted per kg fuel (see formula 10.3). Also a PER with respect to distance in nautical miles will be calculated (see equation 10.4). SPE is in g/kWh (see formula 10.5).

$$per = \frac{\dot{m_{pe}}}{\dot{m_f}} \tag{10.3}$$

$$per_{mile} = \frac{m_f}{nm_{trip}} \tag{10.4}$$

$$spe = \frac{\dot{m_{pe}}}{P_B} = per * sfc \tag{10.5}$$

[1] The H2 and NH3 prices are based on literature findings for carbon free production in 2020, where the MDO price is the price of MDO in Rotterdam at 25-11-2020 from https://shipandbunker.com. Especially hydrogen prices have a wide price range depending on the production method. Chosen is to use electrolysis from water with solar panels.

As for the efficiencies, the average emission values can be found in table 10.6, for all the emissions per voyage and for each system see appendix J.

Table 10.6: Average emission values per modular power system

fuel	MDO						Hydrogen			Ammonia		
Nr engines	**one**			**three**			**two**			**two**		
Emissions	**per**	**kg /nm**	**spe**	**per**	**kg /nm**	**spe**	**per**	**kg /nm**	**spe**	**per**	**kg /nm**	**spe**
CO_2	3.19	64.60	652.30	3.19	70.44	711.40	0.00	0.00	0.00	0.00	0.00	0.00
SO_X	0.02	0.41	4.09	0.02	0.44	4.46	0.00	0.00	0.00	0.00	0.00	0.00
H_2O	1.46	29.6	299	1.46	32.3	326	9.96	53.6	1833	1.72	60.4	634
N_2	26.67	539.9	5454	26.67	588.9	5947	50.31	271.0	2947	7.401	259.8	2727
NO_X	0.064	1.29	13.0	0.052	1.1	12	0.000	0.000	0.000	0.000	0.000	0.000
CO_e	0.002	0.047	0.47	0.002	0.049	0.49	0.000	0.000	0.000	0.000	0.000	0.000
PM	0.001	0.017	0.18	0.001	0.020	0.20	0.000	0.000	0.000	0.000	0.000	0.000
HC	0.002	0.050	0.51	0.002	0.049	0.49	0.000	0.000	0.000	0.000	0.000	0.000

11. Conclusions

In this chapter all the data is in comparison to the one engine diesel electric power plant system, this is a non modular system. Using this together with the results from chapter 10 the research question and sub questions are answered. Started is with the recapitulation of the research questions in section 11.1, there the sub questions will also be answered. Then the conclusion drawn from the results with respect to the performance parameters and operational capabilities are presented in chapter 11.2. When those conclusions are presented the general conclusion is drawn, see chapter 11.3.

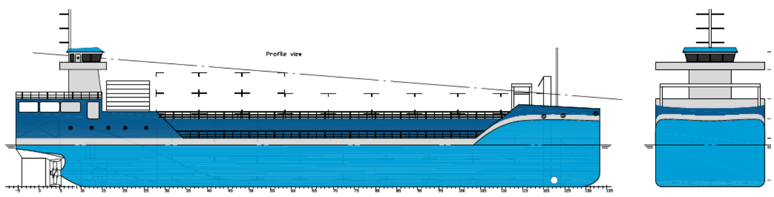
11.1 Recapitulation of ships general arrangement and research question

First the recapitulation of the main research question and the sub questions will take place, the main research question is:
What are the effects on system performance of the power plant and ship operational capabilities when using different power plant concepts and different fuels in the Future Trader concept ship?

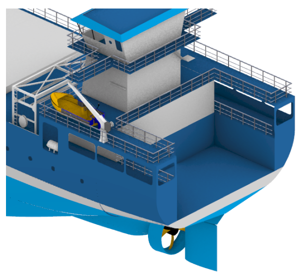
to come to this main research question the following sub questions need to be answered:

1. What are the system performance parameters of interested in this study?
2. What are the ship operational capabilities of interested in this study?
3. Which alternative fuels will be used for the modular power plant?
4. Which systems of a ship its power plant will be placed in the modular power plant?
5. What energy converter types for the power generation will be used?
6. How many power boxes (sub systems of a power plant) are desired to power the ship?
7. Which models are used to find the effects on the selected performance parameters and ship operational capabilities of the designed system with the alternative fuel(s)?

Those question are applicable to the concept ship, designed by DEKC, called the Future Trader. The Future Trader is equipped with a full electric propulsion and the power plant is taken out of the ship and put on the stern. This new power plant will be modular and needs to be easy replaceable by another power plant (see figure 11.1). The Future Trader does not have a range requirement specified, but it is known that it is a small general cargo vessel of 2999 GrT. The main area of operation is in and around Europe, where no ice class is needed.



(a) Side and front view of the Future Trader by DEKC Maritime



(b) 3D stern of the Future Trader

Figure 11.1: The Future Trader

For the answers to the first and second sub question about the system performance the efficiencies fuel consumption and emissions are of interest and are discussed in chapter 3. To find those the ships installed power needs to be determined, this was done in 6.2 and is 1208 kW. The efficiencies and fuel consumption are of interest because they have an effect on the ships operational capabilities. Those capabilities are the range and the fuel cost of the Future Trader. Since four TEU will be used for fuel storage the range of the Future Trader will be limited. The fuel cost will be of interest since shipping needs to be profitable for the ships owner.

What those cost are also depends on the type of fuel used. Which fuels to used is the third question. The fuels used in this study are: MDO as a base line and for a DG system and hydrogen and ammonia as 'future proof fuels'. There are many more options but those are selected for the Future Trader as described in chapter 5.

With the selected fuels chosen there was looked into the system interaction within a ship. This was done to make a division in systems that needed to be within the power boxes that need to be placed on the stern of the Future Trader. This is represented by question four and was answered in chapter 6.1 and for each individual power plant in chapter 8. The results are found in table 6.1.

After each system has a location there needed to be decided which energy converters will be used. For each fuels a suitable energy converter was selected which resulted in the answer of sub question five. For MDO an internal combustion engine was selected and for ammonia an hydrogen fuel cell system was used. This is due to higher efficiencies of fuels cells and technical challenges with a combustion engine for those fuels, as described in chapter 7. In this chapter the answer to question number six is also found.

This question is answered by looking at the optimal engine points of each individual energy converter in combination with the power demand of the Future Trader. For the DG MDO system three engine were desired and for ammonia and hydrogen two fuels cell systems will be used. Since each engine/fuel cell is in its own power pack this means three power packs will be installed.

The data to answer the last question is determined in chapter 10. The conclusion of this will be answered in the next section.

11.2 Performance parameters and operational capabilities

In this section a conclusion is drawn for the system performance parameters and the ships operational capabilities (as described in chapter 3.2 and determined in chapter 10). The conclusions are drawn from normalisation of the model results data. Those conclusions represent the answer to the last sub question of the study. There is started with the emissions since the reduction of Green House Gasses (GHG) brings the uncertainty for which the Future Trader is a solution.

11.2.1 Emissions

In table 11.1 the normalised emission values with respect to the baseline are shown. The cells in red are the so-called harmful emissions, those emissions will be looked into. As expected both the fuel cell systems, hydrogen and ammonia, will reduce those emissions to zero. Therefore those will be a good option to use in shipping.

When looking at the emissions per mile it is seen that the CO2, SOX and COe are increased for the DG setup. This is as expected since the SFC is increased and therefore more fuel is burned for the same amount of energy.

However, the differences in the engine related emissions compared to the base line are different. If we look at the emissions per kg fuel only the PM are increased, the NOx COe and HC are all lower. This has to do with the fact that in the DG system an engine can be switched of when the power is low, doing this reduces the power and lets the engines run at a better point. However more power is then needed since an extra engine needs to speed up and engines are closer to the MCR meaning that more PM is produced. From this data it is hard to draw a conclusion about which systems is better. The increase in PM and COe when using a DG system is unwanted, the reduction in NOx is desired. HC are almost the same and due to the low values this difference can be a result of the model fault margin.

However when looking at the PER emissions only the PM increases and this can be filtered, the reduction in NOx is also very promising. Therefore a slight preference goes to the DG setup. It can not be concluded that this is the better one of the two systems, for a better conclusion a field research with trials should be compiled, but it is clear that the fuel cells both outperform the MDO setups.

Table 11.1: Normalised values per modular power box with respect to the diesel direct setup with one engine

fuel	MDO						Hydrogen			Ammonia		
Nr engines	one			three			two			two		
Emissions	per	kg /nm	spe	per	kg /nm	spe	per	kg /nm	spe	per	kg /nm	spe
CO_2	100%	100%	100%	100%	109%	109%	0%	0%	0%	0%	0%	0%
SO_X	100%	100%	100%	100%	109%	109%	0%	0%	0%	0%	0%	0%
H_2O	100%	100%	100%	100%	109%	109%	682%	181%	613%	118%	204%	212%
N_2	100%	100%	100%	100%	109%	109%	189%	50%	54%	28%	48%	50%
NO_X	100%	100%	100%	81%	89%	89%	0%	0%	0%	0%	0%	0%
CO_e	100%	100%	100%	97%	105%	105%	0%	0%	0%	0%	0%	0%
PM	100%	100%	100%	106%	115%	115%	0%	0%	0%	0%	0%	0%
HC	100%	100%	100%	89%	97%	97%	0%	0%	0%	0%	0%	0%

When looking into the emissions performance parameters, a clear answer is that both the fuel cell systems are the best solutions since both systems have no harmful emissions. The DG setup has a higher fuel consumption which results in more emissions although some engine related emission (NOx,COe looked to PER) are reduced due to the use of DG in comparison to the one engine configuration. Which system performs better is hard to determine from only the emission values, but the reduction in engine related emission seems larger than the gain in fuel related emissions. Since the modular system with two fuel cell units will outperform the MDO combustion engines it can be said that those system are preferable. However there are some draw backs, as seen in the results one is the range of those systems.

11.2.2 Range

Besides the reduction in GHG, the range of the Future Trader is one of the ships operational capabilities of interest. The range of the Future Trader depends on the installed modular systems efficiencies, fuel type and fuel consumption. So to find the range looked there is at those parameters.

As seen in the table 11.2 using a DG setup as described in chapter 8 will result in an average efficiency loss of 9 percent. So if a modular plant with a DG setup of three identical engines is compared to a single engine with the same amount of overall system power a loss will be obtained. An important point to notice is that this efficiency strongly depends on the engine type and SFC curves of the engines. This efficiency increase is also shown in the SFC increase of 9 percent, this is a bigger increase than the difference in SFC of both engines (3% more for the DG setup). Therefore using a modular plant with a MDO DG setup with identical engines will result in a lower efficiency on average than with a traditional setup.

However, for the lower power part of a voyage those result change. As seen in figure 10.1 during waiting for the harbour entry with only auxiliary power required the DG model outperforms the one engine setup. However at a speed of 7 knots the one engine system is already better than the modular system. So for low power operations a DG setup can result in an increase in efficiencies but this setup will quickly be less efficient than a one engine setup. When the modular MDO containers are switched to a DG system with two fuel cell systems, a gain in efficiencies is seen. For the hydrogen PEM system this gain is 5% and for ammonia SOFC this gain is 29% on average.

Table 11.2: Average system efficiencies and SFC values

	fuel	MDO				Hydrogen		Ammonia	
	Nr engines	one		three		two		two	
Departure port	Arrival port	η_{sys}	SFC	η_{sys}	SFC	η_{sys}	SFC	η_{sys}	SFC
RTD	ANT	100%	100%	91%	108%	105%	28%	127%	180%
RTD	GDA	100%	100%	91%	109%	106%	28%	129%	179%
RTD	HAM	100%	100%	91%	109%	105%	29%	128%	180%
RTD	Mar	100%	100%	91%	109%	105%	29%	127%	180%

One of the performance parameters was the efficiencies. When looking into the efficiencies both the modular systems with two fuel cell systems will perform better than the one engine MDO system. An ammonia direct fed SOFC fuel cell will be most efficient (+28%), a PEM hydrogen fuelled fuel cell system will be second (+5%). The three engine MDO power box solution will be less efficient (-9%) than an one engine system.

The SFC values of those systems are hard to compare since these values are related to the amount of grams of fuel needed for each kWh. This is a good comparison if the same fuel is used, however if two different fuels are used this value is less useful. This can also be seen in the table 11.2 where hydrogen needs 28% of the SFC. The SFC of ammonia is 80% higher and the system is 29% more efficient. Therefore it is better to look at the overall system efficiency in this comparison. It is seen that the efficiency of the fuel cell systems increases at lower power.

In conclusion, using a standardised modular MDO DG setup is a suitable system. However, for diesel and with minimal waiting time the traditional system is a more efficient option. At low speed (below 6 kn) or in auxiliary power conditions the DG setup will perform better than the traditional setup. Since the Future Trader is a short sea vessel and it is expected that the ship will often sail close to design speeds a diesel MDO DG setup will decrease the system's efficiency. Both fuel cell systems will outperform the traditional system, when looking at the efficiencies the SOFC ammonia system performs best of both. The systems will both have even better efficiencies when those are at partial load in comparison to the MDO setups. This together makes the SOFC fuel cell system with ammonia the most suitable for the Future Trader, however the range can be a problem.

Using the efficiencies and fuel properties the total fuel consumption is calculated and in table 11.3 the results of the fuel consumption and the TEU fuel storage is shown with respect to that of the base line system. It can be seen that the difference in fuel for the DG setup or the single engine is 9% and in table 10.2 it is seen that both systems always need the same number of TEU aboard to provide the proper range. When looking at the fuel cell systems it can be seen that a major increase in TEU is needed. Looking at table 10.2 it can be seen that during the voyage from RTD to GDA for the one engine system and the DG system only one TEU needs to be loaded onto the ship. When looking at ammonia a second TEU is needed to complete the voyage and for hydrogen a third storage unit is already needed. When looking at the voyage to MAR it is seen that both fuel cell systems will not be able to make this voyage within the set maximum of 4 TEU of fuel. For this voyage more fuel is needed or MDO is the only choice of fuel. In table 11.3 it is seen that on average the hydrogen system needs 357% of the volume of the baseline system and ammonia needs 279% of the fuel volume to complete the same voyage as the one engine MDO system.

Table 11.3: Fuel needed with respect to the base line system

	fuel	**MDO**				**Hydrogen**		**Ammonia**	
	Nr engines	**one**		**three**		**two**		**two**	
Departure port	**Arival port feul needed**	**[kg]**	**TEU**	**[kg]**	**TEU**	**[kg]**	**TEU**	**[kg]**	**TEU**
RTD	ANT	100%	100%	109%	109%	27%	357%	174%	279%
RTD	GDA	100%	100%	109%	109%	27%	357%	173%	278%
RTD	HAM	100%	100%	109%	109%	27%	358%	173%	279%
RTD	MAR	100%	100%	109%	109%	27%	358%	173%	279%

Since the Future Trader will be modular each of the voyages will be achievable, only for the long distance voyages within short sea shipping a fossil fuel like MDO will be needed aboard of the ship. This will result in polluting emissions, however if other smaller voyages will be completed with clean fuels the Future Trader is still able to comply to upcoming regulations and reduce emissions with the fuel cell systems. Besides the range of the Future Trader the fuel cost are also of importance.

11.2.3 Fuel costs

On the emission aspects the FC systems performs better than the (DG) MDO power plants. However the FCs are both limited in range. For a lot of voyages those power plant concept could still be loaded aboard of the Future Trader for the power generation. If we look at the possible range combined with the emissions results, the ammonia SOFC system seems to be the best of the two fuel cell systems.

From table 11.4 it is seen that a major challenge for the hydrogen and ammonia fuels are the costs of those fuel. Even with better system efficiencies, meaning better use of the energy in the fuel, the prices of the fuel for each voyage increase heavily. The fuel costs for a DG system are on average 9 percent more than that of a one engine system. For hydrogen the fuel price is a stunning 1076 percent of the price for MDO, for ammonia the fuel price will be at 370 percent. If grey ammonia is used the fuel costs will be 141 percent of the price for MDO. In that way ammonia comes close to the price of MDO. When using grey ammonia this option could become interesting, especially when a CO2 tax will be introduced. If the prices of green fuels drop in the future ammonia and hydrogen can be competitive. When this will happen is not sure, but the Future Trader can react to this.

Table 11.4: Fuel cost per voyage with respect to the MDO base line system

	fuel	**MDO**		**Hydrogen**	**Ammonia**
	Nr engines	**one**	**three**	**two**	**two**
Departure port	**Arival port feul needed**	**$**	**$**	**$**	**$**
RTD	ANT	100%	109%	1075%	371%
RTD	GDA	100%	109%	1074%	369%
RTD	HAM	100%	109%	1077%	370%
RTD	MAR	100%	109%	1077%	370%

11.3 Overall conclusion

In this section the main research question will be answer based on all the information and results presented in chapter 10 and the conclusions drawn in previous sections.

It can be concluded that a DG setup will reduce the ships overall performance in comparison to the single engine diesel electric system (base line). The fuel costs will be 109% of that of the base line. Also the fuel consumption is 109% of that of the base line. Fuel related emission will rise, however the engine related emission will be lower. Therefore there is no clear answer about the DG systems performance with respect to emissions.

When reviewing the fuel cell systems with respect to the base line system it is found that the ammonia fuel cell system has zero emissions, still offers a sufficient range and causes increases in fuel costs (370% of MDO costs). However this increase is lower than for hydrogen, for hydrogen the cost are 1076% of the MDO costs. Hydrogen will reduce harmful emissions to zero but the reduction in range is more sever than for ammonia. Overall ammonia seems the most promising of the non hydrocarbon fuels. The DG system is also useful as long as the emission regulations remain unchanged. The MDO DG system can be loaded for large distance voyages and hydrogen can be loaded for short voyages if desired.

So using a modular power box for the Future Trader will always bring an increase in costs but with the ammonia fuel cell system the ship has zero emissions. The volume needed for fuel is 2.8 times that of a traditional diesel electric setup. Ammonia still gives a suitable range, so most voyages can be completed. However for longer voyages (e.g. Rotterdam - Marseilles) a MDO DG system should be installed on the aft of the Future Trader since neither of the FC systems could complete those voyages. After the research is finished some new questions are formed for future research and there are some remarks about the thesis that need to be mentioned, this is done in chapter 12.

12. Discussion

Now that the effects of a DG MDO CE, hydrogen and ammonia FC systems are known, it can be concluded that the use of a modular plant has an influence on the ships capabilities and its power plant performance. What the impact is depends on the used system and fuel. Hydrogen and ammonia are both zero emission systems but are limited in range and when a green fuel is used those options give a significant increase in fuel costs. A MDO DG setup with smaller diesel engines is found to be beneficial for ships in the offshore industry. However, if this is used in a ship for short sea shipping this system is less efficient than an one engine setup. Therefore the fuel related emissions of this system also increase. However, it is found that a reduction in engine related emissions can be obtained by using multiple smaller engines. This conclusion is similar to conclusions that can be found in literature about non-modular DG power plants on ships. This suggest that using a modular power plant placed in containers on the aft of the ship will perform similar to the same non-modular systems. If this is true, this means that choosing a modular platform will give the flexibility to switch between systems and fuels with a minimal loss in performance compared to ships with the same platform installed in the heart of the ship. However, this claim needs to be researched in more depth.

As seen from the results, the setup with one MDO engine outperforms the three engine setup. However, it is found that at lower MCR this advantage is lost. A combination of a small and large engine could be a more optimal solution. This is the so-called father-son layout. This layout is left out of scope for this thesis, because it was needed to reduce the amount of possible engine layouts. However if there is looked at the results it could be possible that combining engines with different power ratings can result in a more optimal system. Using such a system results in: running on one less power full engine at low powers, running a bigger one at normal (design) power and when maximum power is required both or even more engines can be on. Leaving those options out of scope early in the thesis seems a bit too harsh now that the conclusions are drawn. Meaning that the effect of this could be interesting and can be researched.

Besides a father-son installation a hybrid electric powerplant solution could be an option, in this thesis only one system type (MDO, hydrogen or ammonia) was installed. However, there are ships with different power supply units aboard, due to the flexibility of the Future Trader it could be possible to install a hybrid power plant in an easy way. In this study the focus was on the effect on the ships performance of different types of power boxes. This resulted in knowledge on the effects of individual systems running on a specific fuel. So the next step could be to research the effect when combing systems. If a MDO and FC system are loaded onto the aft of the Future Trader this could result in a sufficient range for all voyages and still comply to upcoming regulations in ECA. For example, a voyage from Marseilles to a fjord in Norway can then be achieved on the MDO and hydrogen plants combined. MDO has a sufficient range and the last part of the voyage within the fjord can be done on hydrogen, since some fjords already already want to be emission free in 2026 (DNVGL, 2019).

The effects of dynamic loads and how to handle those are not taken into account within the thesis. In literature (Pik, 2020) it was found that those dynamic load changes can have an effect on the ships safety and the power plants stability and handling of power fluctuations. Power electronics and capacitors which can handle dynamic loads are considered in the literature study but are left out of the research scope due to the limited impact on the selected engine performance and the overall ships operational performance. However if you look at a smaller time frame (e.g. minutes) the effects of power electronics can influence and help to solve the challenges of dynamic loading, those in combination with the modular power plant design can be an interesting topic for a future research.

Looking at the used model there are some areas which could be refined. The current model has one MCR point for switching extra engines on and off. This results in an even distribution of power along all engines. An optimisation for switching an engine on and off at a certain MCR request can be added. In this way engines can be run at different MCRs which could result in a more optimal system and therefore have an effect on the performance and emissions of the overall system.

Besides this, this research gives the results of a couple of specific power plant concepts in combination with the ship the Future Trader. Since there are many different energy converters, and within each converter type many options for a suitable fuel, for a general conclusion the set of power plant concepts should be widened and the effect needs to be researched for other ships or ship types.

Within the model the power that needs to be generated for a specific power box can change rapidly. This is due to the instant switch in the number of engines running in the power distribution block, this resulted in spikes in the total power graphs around the time an engine is switched on or off. The effects on the results however are rather small because the total simulation time is large in comparison to those small time periods. However, if the engines were turned on earlier and extra time is given to let the engines adjust to a certain set point it is expected is that this results in smaller spikes. For the end result the difference would be small. If the models will be used for simulations to get results for smaller time ranges this needs to be adjusted in the model.

It needs to be mentioned that the found engine related emission values need to be handled with care since the models used for the MDO system are mathematical models that are designed to match measured data. This measured data is not known for a number of the used power plant components. Therefore the discovered values are found using other engine data. Additionally the Mossel model will not model the cylinder processes like cylinder temperature, pressure, scavenging or ignition timing. All of those are determined within the engine design and can have effects on the engine related emissions. The found values in this thesis therefore have a large error margin (e.g. an educated guess is that, for NOx (6.4e-3 kg/kg) in the single MDO engine the error could be in the order of the high 10-percentages and for the HC (2.5e-3 kg/kg) in the high 20s). For a better result a more detailed model and more information of the engine design is needed, or the selected engines need to be measured in real life and the values found need to be used in the Mossel model.

As said in the results a promising system is the ammonia fuel cell system. This system offers a complete reduction in emissions and good efficiencies. An ammonia transport network is already available, so the investment costs for a fuel network could be lower compared to hydrogen (Pik, 2020). However there are some draw backs, one of the most important challenges is the handling and storage in the ship. Since ammonia is toxic extra safety measures need to be taken, e.g. all the piping should be double walled. The SOFC used in this thesis operates at high temperatures, this should also be taken into account when using the system. So before an ammonia modular power box can be designed for use in practice there are some major design challenges which need to researched.

References

Afif, A., Radenahmad, N., Cheok, Q., Shams, S., Kim, J. H. & Azad, A. K. (2016, 1st 07). Ammonia-fed fuel cells: a comprehensive review. *Renewable and Sustainable Energy Reviews*, *60*, 822–835. Retrieved from `http://www.sciencedirect.com/science/article/pii/S1364032116001611` doi: 10.1016/j.rser.2016.01.120

amoniaenergy. (2020, 06). *Industry report sees multi-billion ton market for green ammonia.* Retrieved from `https://www.ammoniaenergy.org/articles/industry-report-sees-multi-billion-ton-market-for-green-ammonia/`

Anstrom, J. R. (2014, 01). 17 - hydrogen as a fuel in transportation. In A. Basile & A. Iulianelli (Eds.), *Advances in hydrogen production, storage and distribution* (pp. 499–524). Woodhead Publishing. doi: 10.1533/9780857097736.3.499

Baldwin, C. Y. & Clark, K. B. (2006). Complex engineered systems:modularity in the design of complex engineering systems. In A. A. Minai & Y. Bar-Yam (Eds.), *Unifying Themes in Complex Systems* (p. 175-205). Berlin, Heidelberg: Springer Berlin Heidelberg.

Barbir, F. (2013, 01). Future of fuel cells and hydrogen ch 12. In F. Barbir (Ed.), *PEM fuel cells (second edition)* (pp. 469–508). Academic Press. doi: 10.1016/B978-0-12-387710-9.00012-6

Brocken, E. M. (2016). *Improving The Reliability Of Ship Machinery: A Step Towards Unmanned Shipping* (Tech. Rep.). Retrieved from `https://repository.tudelft.nl/islandora/object/uuid%3A54a835fe-4b47-4827-8cd3-811b48b5a7ec`

Brown, T. (2020, 23rd 01). *Viking energy to be retrofit for ammonia fuel in 2024* [https://www.ammoniaenergy.org/]. Retrieved 2020-07-21, from `https://www.ammoniaenergy.org/articles/viking-energy-to-be-retrofit-for-ammonia-fuel-in-2024/`

Chiriac, N., Hölttä-Otto, K., Lysy, D. & Suh, E. S. (2011). Three approaches to complex system decomposition. In *Invest on Visualization - Proceedings of the 13th International DSM Conference* (pp. 3–17).

Cinti, G., Discepoli, G., Sisani, E. & Desideri, U. (2016, August). SOFC operating with ammonia: Stack test and system analysis. *International Journal of Hydrogen Energy*, *41*(31), 13583–13590. Retrieved from `http://www.sciencedirect.com/science/article/pii/S036031991630595X` doi: 10.1016/j.ijhydene.2016.06.070

Corvus. (2020). *Corvus Blue Marlin.* Retrieved from `https://corvusenergy.com/products/corvus-blue-marlin/`

Daly, P. & Morrison, J. (2001, April). Understanding the potential benefits of distributed generation on power delivery systems. In *2001 Rural Electric Power Conference. Papers Presented at the 45th Annual Conference (Cat. No.01ch37214)* (pp. A2/1–A213).

Diab, F., Lan, H. & Ali, S. (2016, September). Novel comparison study between the hybrid renewable energy systems on land and on ship. *Renewable and Sustainable Energy Reviews*, *63*.

Dimitriou, P. & Javaid, R. (2020, 02). A review of ammonia as a compression ignition engine fuel. *International Journal of Hydrogen Energy*, *45*(11), 7098–7118.

DNVGL. (2019, 29th 02). *Norway challenges the cruise industry to operate emission free - DNV GL.* Retrieved 2020-07, from `https://www.dnvgl.com/expert-story/maritime-impact/Norway-challenges-the-cruise-industry-to-operate-emission-free.html`

Duynslaegher, C., Jeanmart, H. & Vandooren, J. (2010, November). Ammonia combustion at elevated pressure and temperature conditions. *Fuel*, *89*(11), 3540–3545.

El-Khattam, W. & Salama, M. M. A. (2004, October). Distributed generation technologies, definitions and benefits. *Electric Power Systems Research*, *71*, 119–128.

Erikstad, S. O. (2019). Design for modularity. In A. Papanikolaou (Ed.), *A holistic approach to ship design: Volume 1: Optimisation of ship design and operation for life cycle* (pp. 329–356). Springer International Publishing.

Fontell, E., KIVISAARI, T., CHRISTIANSEN, N., HANSEN, J.-B., PALSSON & MOSELEY. (2004). Conceptual study of a 250 kw planar sofc system for chp application. *Journal of power sources*.

Gao, X.-P. & Yang, H.-X. (2010). Multi-electron reaction materials for high energy density batteries. *Energy Environ. Sci.*, *3*(2), 165–240.

Geertsma, R. D., Negenborn, R. R., Visser, K. & Hopman, J. J. (2017, May). Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Applied Energy*, *194*, 30–54. doi: 10.1016/j.apenergy.2017.02.060

Georgescu, I., Godjevac, M. & Visser, K. (2017a, December). Early Efficiency Estimation of Hybrid and Electric Propulsion Systems on Board Ships. In (pp. 1–5). doi: 10.1109/VPPC.2017.8331005

Georgescu, I., Godjevac, M. & Visser, K. (2017b, 01). A new perspective on the complexity of on-board primary power systems. *Journal of Ship Production and Design*, *35*. doi: 10.5957/JSPD.170014

GIIGNL. (2009, August). *1-lng_basics_82809_final_hq.pdf* (Vol. 1) (No. 1). Retrieved 2020-04-08, from `http://www.kosancrisplant.com/media/5648/1-lng_basics_82809_final_hq.pdf`

Grigsby, L. L. (2016). *Electric Power Generation, Transmission, and Distribution, Third Edition.* (OCLC: 991528469)

Gustafsson, Magnus, Nokelainen, T., Tsvetkova, A. & Wikstrom, K. (2018, December). *Revolutionizing Short Sea Shipping | Global Maritime Hub* (Tech. Rep. No. -). Abo Akademi University. Retrieved from `https://globalmaritimehub.com/articles/revolutionizing-short-sea-shipping`

Habermaas, J. & Thurner, J. (2020, June). VARIABLE SPEED GENERATOR SETS OFFER ADVANTAGES FOR COMMERCIAL SHIPS. -, 4.

Hansson, J., Månsson, S., Brynolf, S. & Grahn, M. (2019, July). Alternative marine fuels: Prospects based on multi-criteria decision analysis involving swedish stakeholders. *Biomass and Bioenergy*, *126*, 159–173.

Hydrogenics. (n.d.). *Fuel cell megawatt power generation platform hydrogenics.* Retrieved 2020-09-26, from `https://www.hydrogenics.com/hydrogen-products-solutions/fuel-cell-power-systems/stationary-stand-by-power/fuel-cell-megawatt-power-generation-platform/`

IMO. (1999). *Solas: International Convention for the Safety of Life at Sea, 1974: Resolutions of the 1997*

SOLAS. IMO Publishing.

IMO. (2018, April). Imo submission talanoa dialogue adoption of the initial imo strategy on reduction of ghg emissions from ships and existing imo activity related to reducing ghg emissions in the shipping sector. *Talanoa dialogue*, -, 1–27. Retrieved from `https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf`

IMO. (2019, 07). *MARPOL international convention for the prevention of air pollution from ships* (Tech. Rep.). London: Author.

IRENA. (2017). Electricity storage and renewables: Costs and markets to 2030. -, 132. (Abu Dhabi)

Jalkanen, J.-P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J. & Stipa, T. (2011, 08). Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. *Atmospheric Chemistry and Physics Discussions*, *11*, 22129-22172. doi: 10.5194/acpd-11-22129-2011

jburke. (2020, January). *2 MW Ammonia Fuel Cell To Be Tested On Ship.* Retrieved from `https://dieselgasturbine.com/2-mw-ammonia-fuel-cell-to-be-tested-on-ship/`

Johansen, T. A., Bø, T. I., Mathiesen, E., Veksler, A. & Sørensen, A. J. (2014, November). Dynamic Positioning System as Dynamic Energy Storage on Diesel-Electric Ships. *IEEE Transactions on Power Systems*, *29*(6).

Kayfeci, M., Keçebaş, A. & Bayat, M. (2019). Chapter 3 - hydrogen production. In F. Calise, M. D. D'Accadia, M. Santarelli, A. Lanzini & D. Ferrero (Eds.), *Solar hydrogen production* (pp. 45–83). Academic Press. Retrieved from `http://www.sciencedirect.com/science/article/pii/B9780128148532000035` doi: 10.1016/B978-0-12-814853-2.00003-5

Khooban, M. H., Vafamand, N. & Boudjadar, J. (2019, 15th 11). Tracking control for hydrogen fuel cell systems in zero-emission ferry ships. *Complexity*, *2019*, 9. Retrieved from `https://doi.org/10.1155/2019/5358316` doi: 10.1155/2019/5358316

KNMI. (2014). *KNMI - Waarnemingen klimaatveranderingen.* Retrieved from `https://www.knmi.nl/kennis-en-datacentrum/achtergrond/waarnemingen-klimaatveranderingen`

Komoto, H. & Tomiyama, T. (2011, September). A THEORY OF DECOMPOSITION IN SYSTEM ARCHITECTING. In (p. 10).

Lan, R. & Tao, S. (2014). Ammonia as a Suitable Fuel for Fuel Cells. *Frontiers in Energy Research*, *2*. Retrieved from `https://www.frontiersin.org/articles/10.3389/fenrg.2014.00035/full` doi: 10.3389/fenrg.2014.00035

Largiader, C. (2001, 02). *Modular platform based surface ship design.*

Larminie, J. & Dicks, A. (2003). *Fuel cell systems explained* (2nd ed ed.). J. Wiley.

Larocca, J. M. & Nielsen, R. B. (2020, 25th 09). Time for a carbon levy on shipping fuel. -, -(-), -. Retrieved from `https://www.ft.com/content/6647bd84-0d2b-4c14-b62c-e6bd80ff40e4` doi: -

Lavidas, G. & Polinder, H. (2019). North sea wave database (NSWD) and the need for reliable resource data: A 38 year database for metocean and wave energy assessments. *Atmosphere*, *10*(9). Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3Ae9cba524-12b1-4d93-8ac4-e0bf4af10cf2 doi: 10.3390/atmos10090551

Lee, W. S., Grosh, D. L., Tillman, F. A. & Lie, C. H. (1985). *Fault tree analysis, methods, and applications a review* (Vol. R-34; Tech. Rep. No. 3). doi: 10.1109/TR.1985.5222114

Li, J., Huang, H., Kobayashi, N., He, Z. & Nagai, Y. (2014). Study on using hydrogen and ammonia as fuels: Combustion characteristics and NOx formation. *International Journal of Energy Research*, *38*(9), 1214–1223.

Morren, J. (2006). Grid support by power electronic converters of distributed generation units..

Mørch, C. S., Bjerre, A., Gøttrup, M. P., Sorenson, S. C. & Schramm, J. (2011, February). Ammonia/hydrogen mixtures in an SI-engine: Engine performance and analysis of a proposed fuel system. *Fuel*, *90*(2), 854–864. doi: 10.1016/j.fuel.2010.09.042

NEDSTACK. (2019, November). *Nedstack fcs 13-xxl pem fuel cell stack.*

Ni, M., Leung, M. K. H. & Leung, D. Y. C. (2009). Ammonia-fed solid oxide fuel cells for power generation—a review. *International Journal of Energy Research*, *33*(11), 943–959. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1002/er.1588 doi: 10.1002/er.1588

Nitonye, S. (2017, June). DESIGN CALCULATION FOR EQUIPMENT AND COMPONENTS SPECIFICATION OF LUBRICATING OIL SYSTEM OF A TUG BOAT. *International Journal of Advances in Engineering & Technology*, *10*, 449–462. doi: 10.7323/ijaet/V10˙iss3

Patsios, C., Antonopoulos, G. & Prousalidis, J. (2012, October). Discussion on adopting intelligent power management and control techniques in integrated power systems of all-electric ships. In *Railway and Ship Propulsion 2012 Electrical Systems for Aircraft.*

Peralta P., C. O., Vieira, G. T. T., Meunier, S., Vale, R. J., Salles, M. B. C. & Carmo, B. S. (2019, January). Evaluation of the CO2 Emissions Reduction Potential of Li-ion Batteries in Ship Power Systems. *Energies*, *12*(3).

Pik, H. W. (2020, 08). Modular power plant, literature study. *TU Delft*, 45.

Reiter, A. J. & Kong, S.-C. (2011, 01). Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel. *Fuel*, *90*, 87–97.

Silvestri, A., Berizzi, A. & Buonanno, S. (1999, August). *Distributed generation planning using genetic algorithms.*

Sinovoltaics. (2019, September). *Energy density and Specific Energy of Battery.* Retrieved from https://sinovoltaics.com/learning-center/storage/energy-density-and-specific-energy-of-battery

Skjong, E., Volden, R., Rødskar, E., Molinas, M., Johansen, T. & Cunningham, J. (2016, April). Past, Present and Future Challenges of the Marine Vessel's Electrical Power System. *IEEE Transactions on Transportation Electrification*, *2*. doi: 10.1109/TTE.2016.2552720

Stapersma, D. (2010a). *A fundamental approach to performance analysis turbocharging combustion emission* *and heat transfer,volume 1 performance analysis , 8th print.*

Stapersma, D. (2010b). *A fundamental approach to performance analysis turbocharging combustion emission and heat transfer,volume 3 combustion, 6th print.*

Stapersma, D. (2010c). *A fundamental approach to performance analysis turbocharging combustion emission and heat transfer,volume 4 emission and heat transfer, 6th print.*

Tang, D., Yan, X., Yuan, Y., Wang, K. & Qiu, L. (2015, November). Multi-agent Based Power and Energy Management System for Hybrid Ships. In *2015 International Conference on Renewable Energy Research and Applications (ICRERA)* (pp. 383–387).

Thorstensen, B. (2001). A parametric study of fuel cell system efficiency under full and part load operation. *Journal of Power Sources*, *92*(1), 9 - 16. doi: https://doi.org/10.1016/S0378-7753(00)00497-3

ToolBox, E. (2003). *Fuels - higher and lower calorific values.* Retrieved 2020-04-08, from `https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html`

TU-Delft, M. t. D. (2010, 17th 08). Mossel model. -(-), -. Retrieved from - doi: -

Valera-Medina, A., Xiao, H., Owen-Jones, M., David, W. I. F. & Bowen, P. J. (2018, November). Ammonia for power. *Progress in Energy and Combustion Science*, *69*, 63–102. doi: 10.1016/j.pecs.2018.07.001

van Biert, L., Godjevac, M., Visser, K. & Aravind, P. V. (2016, 30th 09). A review of fuel cell systems for maritime applications. *Journal of Power Sources*, *327*. Retrieved from `http://www.sciencedirect.com/science/article/pii/S0378775316308631` doi: 10.1016/j.jpowsour.2016.07.007

van Kranenburg-Bruinsma, K. J., van Delft, Y. C., Gavrilova, A., de Kler, R. F. C., Schipper-Rodenburg, C. A., Smokers, R. T. M., … Verbeek, R. P. (2020). E-fuels - towards a more sustainable future for truck transport, shipping and aviation. -, -, -. Retrieved from `https://repository.tno.nl/islandora/object/uuid%3A487a6a47-853d-4a1d-bc2e-dbe21d584cca`

Veksler, A., Johansen, T. A. & Skjetne, R. (2012). Transient power control in dynamic positioning - governor feedforward and dynamic thrust allocation. *IFAC Proceedings Volumes*, *45*(27).

Wartsila. (2017). *Wärtsilä 20 - diesel engine.* Retrieved from `https://www.wartsila.com/marine/build/engines-and-generating-sets/diesel-engines/wartsila-20`

Welaya, Y. M. A., El Gohary, M. M. & Ammar, N. R. (2011, 1st 06). A comparison between fuel cells and other alternatives for marine electric power generation. *International Journal of Naval Architecture and Ocean Engineering*, *3*(2), 141–149. Retrieved from `http://www.sciencedirect.com/science/article/pii/S2092678216302175` doi: 10.2478/IJNAOE-2013-0057

Wild, Y. (2015, September). Dr_wild_report.pdf. -. Retrieved 2020-04-08, from `http://www.effship.com/PartnerArea/MiscPresentations/Dr_Wild_Report.pdf`

Willis, H. L. & Scott, W. G. (2000). *Distributed power generation: planning and evaluation* (No. 10). New York: Marcel Dekker.

Woud, H. & Stapersma, D. (2002a). Ch12 ship fuel consumption and exhaust emissions. In *Design of Propulsion and Electric Power Generation Systems* (p. 471-490). IMarEST, Institute of Marine Engineering, Science and Technology.

Woud, H. & Stapersma, D. (2002b). Ch3 propulsion and electric power. In *Design of Propulsion and Electric Power Generation Systems* (p. 41-88). IMarEST, Institute of Marine Engineering, Science and Technology.

Woud, H. & Stapersma, D. (2002c). Ch4 energy convertions and ch5 power plant concepts. In *Design of Propulsion and Electric Power Generation Systems* (p. 88-130). IMarEST, Institute of Marine Engineering, Science and Technology.

Woud, H. & Stapersma, D. (2002d). Ch7 diesel engines. In *Design of Propulsion and Electric Power Generation Systems* (p. 191-279). IMarEST, Institute of Marine Engineering, Science and Technology.

Woud, H. & Stapersma, D. (2002e). Ch8 gas turbines. In *Design of Propulsion and Electric Power Generation Systems* (p. 281-336). IMarEST, Institute of Marine Engineering, Science and Technology.

Woud, H. & Stapersma, D. (2016). Ch5 overview of auxiliary systems. In *Design of auxiliary systems, shafting and flexible mounting* (p. 127-158). TU Delft reader.

YANMAR. (2020). *6n165lw auxiliary engines product concept marine commercial yanmar.* Retrieved 2020-08-14, from `https://www.yanmar.com/global/marinecommercial/products/auxiliary_engine/6n165lw/index.html`

Zamfirescu, C. & Dincer, I. (2008, October). Using ammonia as a sustainable fuel. *Journal of Power Sources*, *185*(1), 459–465. doi: 10.1016/j.jpowsour.2008.02.097

Appendices

A. Optimal running point of the engine between 0.6 and 0.9 of MCR

Table A.1: Optimal engine load over MCR for a optimal engine point of 0.6, with auxiliary power in sailing conditions 290 kW

			Nr of engines installed (running)			
Auxiliary power [kW]	290		1	2	3	4
optimal engine point	0.60	**Pb [kW]**	1208	604	403	302
Power demand [% mcr]	**Speed [kn]**	**power [kW]**	**index mcr**	**index mcr**	**index mcr**	**index mcr**
37%	6.0	449	0.37	**0.74**	1.11	**1.49**
41%	6.5	492	0.41	0.81	**1.22**	1.63
45%	7.0	542	0.45	0.90	1.35	**1.79**
50%	7.5	600	0.50	0.99	1.49	1.99
55%	8.0	666	0.55	1.10	1.65	2.20
61%	8.5	741	**0.61**	**1.23**	**1.84**	**2.45**
68%	9.0	825	0.68	1.37	2.05	2.73
76%	9.5	919	0.76	1.52	2.28	3.04
85%	10.0	1024	0.85	1.70	2.54	3.39
100%	10.8	1208	1.00	2.00	3.00	4.00

Table A.2: Optimal engine load over MCR for a optimal engine point of 0.6, with auxiliary power in sailing conditions 290 kW

			Nr of engines installed (running)			
Auxiliary power [kW]	290		1	2	3	4
optimal engine point	0.70	**Pb [kW]**	1208	604	403	302
Power demand [% mcr]	**Speed [kn]**	**power [kW]**	**index mcr**	**index mcr**	**index mcr**	**index mcr**
37%	6.0	449	0.37	**0.74**	1.11	**1.49**
41%	6.5	492	0.41	0.81	1.22	1.63
45%	7.0	542	0.45	0.90	**1.35**	1.79
50%	7.5	600	0.50	0.99	1.49	1.99
55%	8.0	666	0.55	1.10	1.65	**2.20**
61%	8.5	741	0.61	1.23	1.84	2.45
68%	9.0	825	**0.68**	**1.37**	**2.05**	**2.73**
76%	9.5	919	0.76	1.52	2.28	3.04
85%	10.0	1024	0.85	1.70	2.54	3.39
100%	10.8	1208	1.00	2.00	3.00	4.00

Table A.3: Optimal engine load over MCR for a optimal engine point of 0.8, with auxiliary power in sailing conditions 290 kW

			Nr of engines installed (running)			
Auxiliary power [kW]	290		1	2	3	4
optimal engine point	0.80	**Pb [kW]**	1208	604	403	302
Power demand [% mcr]	**Speed [kn]**	**power [kW]**	**index mcr**	**index mcr**	**index mcr**	**index mcr**
32%	5.0	382	0.32	0.63	**0.95**	1.26
37%	6.0	449	0.37	**0.74**	1.11	**1.49**
45%	7.0	542	0.45	0.90	1.35	1.79
50%	7.5	600	0.50	0.99	1.49	1.99
55%	8.0	666	0.55	1.10	**1.65**	2.20
61%	8.5	741	0.61	1.23	1.84	**2.45**
68%	9.0	825	0.68	1.37	2.05	2.73
76%	9.5	919	**0.76**	**1.52**	**2.28**	**3.04**
85%	10.0	1024	0.85	1.70	2.54	3.39
100%	10.8	1208	1.00	2.00	3.00	4.00

Table A.4: Optimal engine load over MCR for a optimal engine point of 0.9, with auxiliary power in sailing conditions 290 kW

			Nr of engines installed (running)			
Auxiliary power [kW]	290		1	2	3	4
optimal engine point	0.90	**Pb [kW]**	1208	604	403	302
Power demand [% mcr]	**Speed [kn]**	**power [kW]**	**index mcr**	**index mcr**	**index mcr**	**index mcr**
32%	5.0	382	0.32	0.63	**0.95**	1.26
37%	6.0	449	0.37	0.74	1.11	1.49
45%	7.0	542	0.45	**0.90**	1.35	**1.79**
50%	7.5	600	0.50	0.99	1.49	1.99
55%	8.0	666	0.55	1.10	1.65	2.20
61%	8.5	741	0.61	1.23	**1.84**	2.45
68%	9.0	825	0.68	1.37	2.05	**2.73**
76%	9.5	919	0.76	1.52	2.28	3.04
85%	10.0	1024	**0.85**	**1.70**	**2.54**	**3.39**
100%	10.8	1208	1.00	2.00	3.00	4.00

B. DSM of the ship focused on engine and auxiliary systems

In this appendix the DSM of the ship and the auxiliary engine systems will be given. All the interaction are ranked in the following way.

Legend

1 minor interaction , will function normally without this link
2 interaction will function but not optimal
3 high amount of interaction, will function but poorly
4 lots of interaction will not function without

Please note that there are three tables B.1, B.2 and B.3. Those three tables form one big DSM, due to its size it would be unreadable if it was displayed in one table.

Table B.1: DSM Part 1

		Cargo			Hazard systems			Hotel						Float
	Need of information Supply of information	Cargo vent	crane	Hatches	fifi system	Detection systems	bilge pumps	Accommodated	Food prep and storage	Fresh water	Waste water	Electric	HVAC	Ballast pumps
Cargo	Cargo vent				2	2								
	crane													
	Hatches		1											
Hazard systems	fifi system	1					4							1
	Detection systems	1			3									
	bilge pumps				3									1
Hotel	Accommodated				3	3								
	Food prep and storage													
	Fresh water							3	2					
	Waste water							3	3					
	Electric				3	4		3	4	4	4		4	
	HVAC				3	3		4	4					
Float	Ballast pumps				3		3							
Move	Propulsion chain													
	radar													
	navigation lighting													
	Winches													
	Bow thruster													
	steering pumps													
	Shaft bearing lubrication													
	Gearbox lubrication													
	Lube oil cleaner													
Engine systems	water cooling HT													
	water cooling LT													
	Lubrication oil													
	Lube oil cleaning													
	Fuel supply													
	Fuel treatment													
	Fuel transport													
	Air supply													
	Exhaust systems													
	Engine start system													
	Engine room ventilation				3	3								
	Acoustic enclosure							2						
	Mounting system													
Power systems	Hydraulic power													
	mechanical power									4	4			
	compressed air system													
	Waste heat system													
Control systems	HVAC Control				2	2							4	
	Vent control	2			2	2								
	Eng vent control				2	2								
	Fuel system													
	Power distribution					4	4	4	4	4	4	4		4
	bridge				3	3		2	2				3	3

Table B.2: DSM Part 2

		Cargo			Hazard systems			Hotel						Float	Move									Engine systems												
	Need of information Supply of information	Cargo vent	crane	Hatches	FiFi systems	Detection systems	bilge pumps	Accommodated	Food prep and storage	Fresh water	Waste water	Electric	HVAC	Ballast pumps	Propulsion chain	radar	navigation lighting	Winches	Bow thruster	steering pumps	Shaft bearing lubrication	Gearbox lubrication	Lube oil cleaner	water cooling HT	water cooling LT	Lubrication oil	Lubrication oil cleaning	Fuel supply	Fuel treatment	Fuel transport	Air supply	Exhaust systems	Engine start system	Engine room ventilation	Acoustic enclosure	Mounting system
Cargo	Cargo vent																																			
	crane																																			
	Hatches																																			
Hazard	FiFi system																																			
	Detection systems																																			
	bilge pumps																																			
Hotel	Accommodated																																			
	Food prep and storage																																			
	Fresh water																																			
	Waste water																																			
	Electric																																			
	HVAC																																			
Float	Ballast pumps																																			
Move	Propulsion chain																		2																	
	radar																																			
	navigation lighting															1																				
	Winches																																			
	Bow thruster														3	1																				
	steering pumps														2	2			1																	
	Shaft bearing lubrication														3								3													
	Gearbox lubrication														4								3													
	Lube oil cleaner														3						3	3														
Engine systems	water cooling HT																								2											
	water cooling LT																							2												
	Lubrication oil														4									1												
	Lube oil cleaning														1																					
	Fuel supply																												4	1						
	Fuel treatment																											4								
	Fuel transport																											1	1							
	Air supply																																			
	Exhaust systems																																			
	Engine start system														4											1		3	4	4						
	Engine room ventilation														1																					
	Acoustic enclosure																																			
	Mounting system														3									2	2	2	2	2	2	2	2	2	2	2	2	
Power sys	Hydraulic power																			4																
	mechanical power																																			
	compressed air system																																			
	Waste heat system														3																					
Control systems	HVAC Control																																			
	Vent control																																			
	Eng vent control																																			
	Fuel system														3													4	3	2						
	Power distribution														3	3	4	3	4									2	4	4	4		3	4		
	bridge														4		3	4	4									4	4	4	4		3			

Table B.3: DSM Part 3

		Cargo			Hazard systems			Hotel						Float	Move									Engine systems													Other Power systems				Control systems					
	Need of information / **Supply of information**	Cargo vent	crane	Hatches	FiFi system	Detection systems	bilge pumps	Accommodated	Food prep and storage	Fresh water	Waste water	Electric	HVAC	Ballast pumps	Propulsion chain	radar	navigation lighting	Winches	Bow thruster	steering pumps	Shaft bearing lubrication	Gearbox lubrication	Lube oil cleaner	water cooling HT	water cooling LT	Lubrication oil	Lube oil cleaning	Fuel supply	Fuel treatment	Fuel transport	Air supply	Exhaust systems	Engine start system	Engine room ventilation	Acoustic enclosure	Mounting system	Hydraulic power	mechanical power	compressed air system	Waste heat recovery system	HVAC Control	Vent control	Eng vent control	Fuel system	Power distribution	bridge
Cargo	Cargo vent																																													
	crane																																													
	Hatches																																													
Hazard	FiFi system																																													
	Detection systems																																													
	bilge pumps																																													
Hotel	Accommodated																																													
	Food prep and storage																																													
	Fresh water																																													
	Waste water																																													
	Electric																																													
	HVAC																																													
Float	Ballast pumps																																													
Move	Propulsion chain																																													
	radar																																													
	navigation lighting																																													
	Winches																																													
	Bow thruster																																													
	steering pumps																																													
	Shaft bearing lubrication																																													
	Gearbox lubrication																																													
	Lube oil cleaner																																													
Engine systems	water cooling HT																																							3						
	water cooling LT																																							3						
	Lubrication oil																																													
	Lube oil cleaning																																													
	Fuel supply																																													
	Fuel treatment																																													
	Fuel transport																																													
	Air supply																																													
	Exhaust systems																																							3						
	Engine start system																																													
	Engine room ventilation																																													
	Acoustic enclosure																																													
	Mounting system																																													
Power sys	Hydraulic power																																												3	
	mechanical power																																												3	
	compressed air system																																												3	
	Waste heat system																																												3	
Control systems	HVAC Control																																												3	
	Vent control																																												3	
	Eng vent control																																												3	
	Fuel system																																													
	Power distribution																																			4	4	4		4	3	3	3		
	bridge																																								3				4	

C. Power calculation diagram

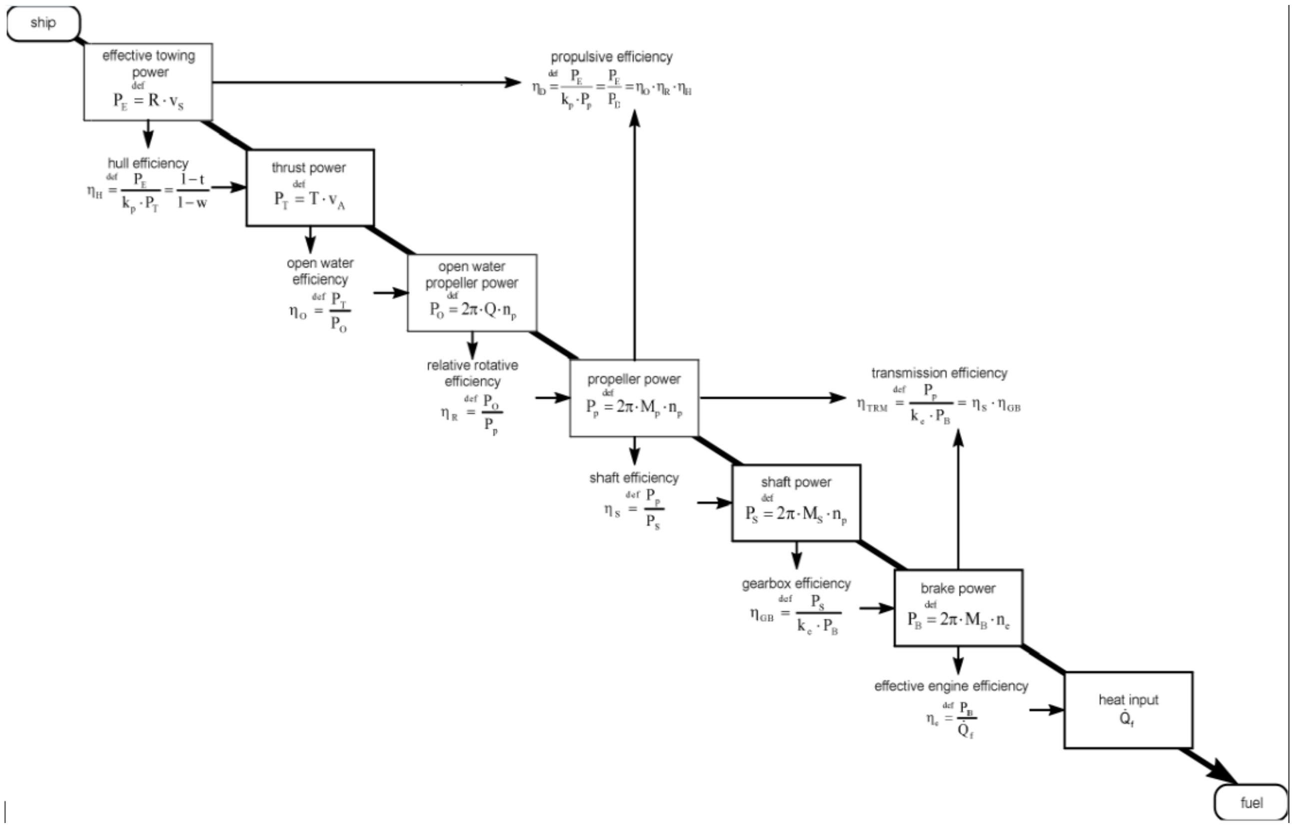


Figure C.1: Schematic representation of the power calculation. (Woud & Stapersma, 2002b)

D. Electric load balance Future Trader

Table D.1: Electric load balance Future Trader

Component			Manoeuvring				At sea				In port			
	Nr installed [-]	Power 100% [kW]	Number in service [-]	Load factor [-]	Simultaneity factor [-]	Average absorbed power [kW]	Number in service [-]	Load factor [-]	Simultaneity factor [-]	Average absorbed power [kW]	Number in service [-]	Load factor [-]	Simultaneity factor [-]	Average absorbed power [kW]
Move														
Bow thruster	1	300	1	0,5	0,8	120	0	0	0	0		0,5	0,8	0
Steering pumps	2	5,5	2	0,1	1	1,1	2	0,15	0,1	0,165	2	0,1	1	1,1
Navigation eq	1	4	1	1	1	4	1	1	1	4	0,5	1	1	2
Winches	2	18,5	2	1	1	37	2	1	0,05	0,925	0	0	0	0
Transport														
Ventilation	2	3,5	2	1	1	7	2	1	1	7	2	1	1	7
Crane	1	15	1	0	0	0	1	1	1	15	1	1	0,5	7,5
Hatches	-	0	0	0	0	0	0	0	0	0	0	0	0	0
Float														
Ballast pumps	4	15	1	0	0	0	0	0	0	0	1	0,15	1	2,25
Crew acomondation														
HVAC	1	75	1	1	1	75	1	1	1	75	1	0,5	1	37,5
Fresh water boiler	1	12	1	1	0,5	6	1	1	0,5	6	1	1	0,5	6
Waste water	1	3,75	1	1	0,15	0,5625	1	1	0,15	0,5625	1	1	0,15	0,5625
Galley	1	37	1	0,4	0,5	7,4	1	0,8	0,5	14,8	1	0,8	0,5	14,8
Workshop	3	20	3	0,3	0,2	3,6	3	0,3	0,2	1,2	0	0	0	0
Lighting & sockets	1	456	1	0,6	0,5	136,8	1	0,6	0,5	136,8	1	0,3	0,5	68,4
Total		**966**				**399**				**262**				**148**

E. Yanmar data sheet

6AYM-WST

H-rating 485kW (659mhp)

MARINE PROPULSION
DIESEL ENGINE

- 6-cylinder, direct injection, heat exchanger cooling.
- Turbocharger + intercooler.
- 4-valves per cylinder for higher combustion efficiency.
- Available either with marine gear or without marine gear.
- Conform to IMO Tier II emissions regulations.

Specifications

Model	6AYM-WST H-rating
Number of cylinders	6 in-line
Bore × stroke mm	155 × 180
Displacement lit.	20.379
Rated output kW(hp)/rpm	H : 485(659)/1900
Combustion system	Direct injection
Aspiration	Turbocharger + intercooler
Starting system	Electric starting motor (24V 7.0kW)
Cooling system	Heat exchanger
Size of flywheel housing and flywheel	SAE #0 and 18 in.
Dry mass kg	2365 (without marine gear)
Dimensions (L×W×H) mm	2000×1305×1431

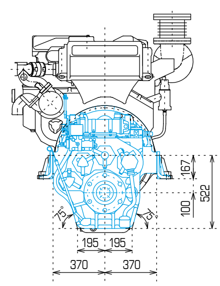
Marine gear specifications

Engine model : 6AYM-WST H-rating			
Model	YX-181	YX-180L	YXH-240L
Type	Hydraulic multi-disc clutch		
Reduction ratio (Ahead)	2.08 2.55 3.03	3.50 4.00 4.54	4.89 5.36 5.91 6.57 6.95
Direction of rotation (propeller shaft)	Clockwise or counterclockwise		
Dry weight kg	560	680	1240

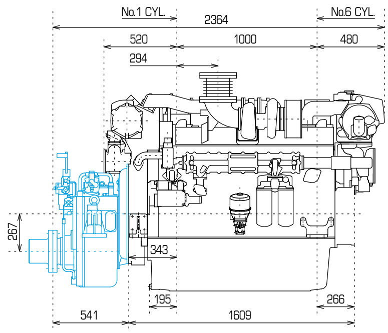
YANMAR

Dimensions Unit:mm

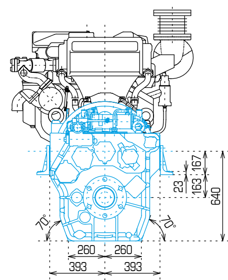
With YX181 gearbox / Rear view



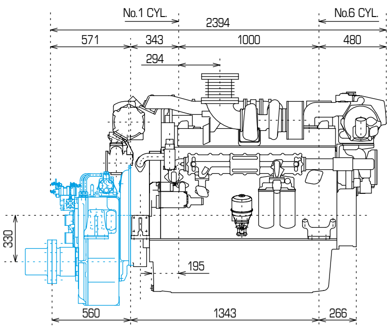
With YX181 gearbox / Right side view



With YX180L gearbox / Rear view

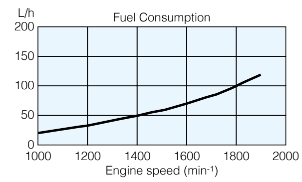


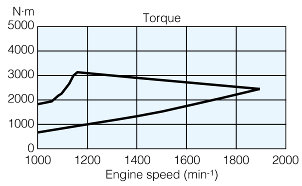
With YX180L gearbox / Right side view

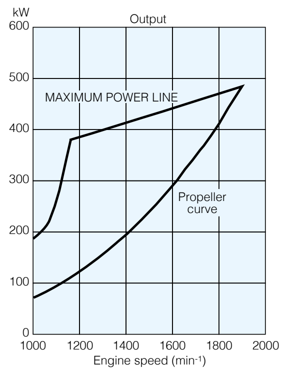


– Marine gear

Performance curves







YANMAR

MARINE DIESEL ENGINES

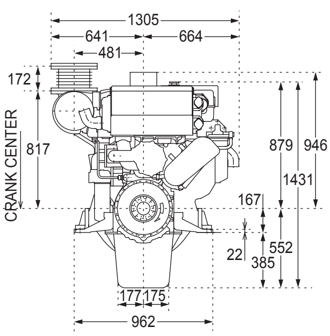
6AYM-WST Series

LONG STROKE | IMO Tier II Compliant I Mechanical Engine Control

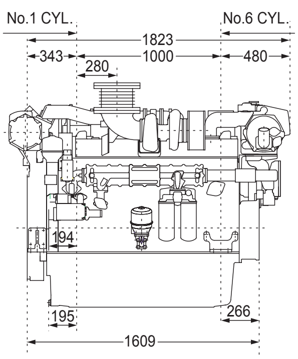
Configuration	4-cycle, Vertical, Turbo-charged with sea watercooled intercooler diesel engine	
Maximum output at crankshaft	H: 485 kW@1900 rpm	[659 mhp@1900 rpm]
Displacement	20.379 ltr	
Bore x stroke	155 mm × 180 mm	
Cylinders	6 in-line	
Combustion system	Direct injection	
Starting system	Electric starting motor [DC 24V-8 kW] [optional airstarting]	
Flywheel housing size	SAE #0 and 18 inch	
Cooling system	With Heat exchanger [optional keel cooling]	
Cooling fresh water capacity	60 ltr	
Lubrication system	Forced lubrication with gear pump	
Lubricating oil capacity	91 ltr	
Lubricating oil grade	SAE40 or SAE15W-40	
Direction of rotation [crankshaft]	Counterclockwise viewed from stern	
Dry weight without gear	2365 kg	
Environmental	IMO Tier II	
Fuel consumption [at rated output]	H: 207 gr/kW hr	

DIMENSIONS [UNIT: MM]

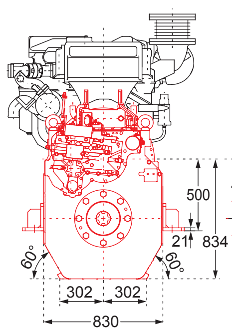
Front view, engine only



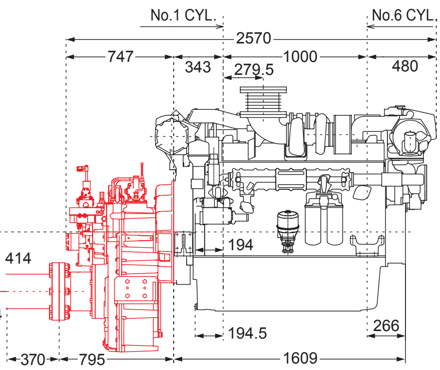
Right side view, engine only



Rear view with gearbox YXH240L



Right side view with gearbox YXH240L



EN_DS6AYM-WST_0215

F. Fuel cell data Nedstack

PRODUCT DATA SHEET

Version: November 2019

NEDSTACK FCS 13-XXL PEM FUEL CELL STACK

SPECIFICATIONS

Electrical - Beginning of Life

Rated power	:	13.6 kWe @ 230 A
Power at lower current	:	see graph

Mechanical

Weight	:	41 kg (approx)
Size	:	604(l)x196(w)x288(h) mm
Cell count	:	96

Hydrogen

Humidification	:	≥ 50% RH at 62 ºC at inlet (75% recommended)
Purity (dry)	:	Grade ≥ 2.5 (max: CO 0.2ppm, CO2 0.5vol%, total sulphur 4ppb, formaldehyde 0.01ppm, formic acid 0.2ppm, ammonia 0.1ppm, total halogenated compounds 0.05ppm, particles 1µg/Nl. Hydrogen specification adapted from ISO 14687-2:2008)
Pressure drop	:	< 0.05 bar at full power
Pressure level	:	0.15 - 0.3 barg
Stoichiometry	:	1.25 - 1.50 for H_2 , minimum flow = 72 Nl/min
Max H2 consumption	:	154 Nl/min at full power

Air

Filtered		
Humidification	:	75% RH at 62 ºC
Purity	:	instrument air quality (max: CO 25ppm, Sulphur 0.01ppm, nitrogen dioxide 0.3ppm, ammonia 0.1ppm, particles 1µg/Nl)
Pressure level	:	Ambient (no backpressure allowed)
Pressure drop	:	< 0.12 bar at max power
Stoichiometry	:	≥ 2.0, minimum flow = 134 Nl/min
Max air required	:	732 Nl/min at full power

MEA

Pressure difference		<0.3 bar

Emissions

Noise	:	0
Water production	:	0.5 l/kWh$_e$(approx.)
H2 respiration	:	60 ml/min (max)

Nedstack
PEM FUEL CELLS

PRODUCT DATA SHEET – NEDSTACK FCS 13-XXL

Cooling

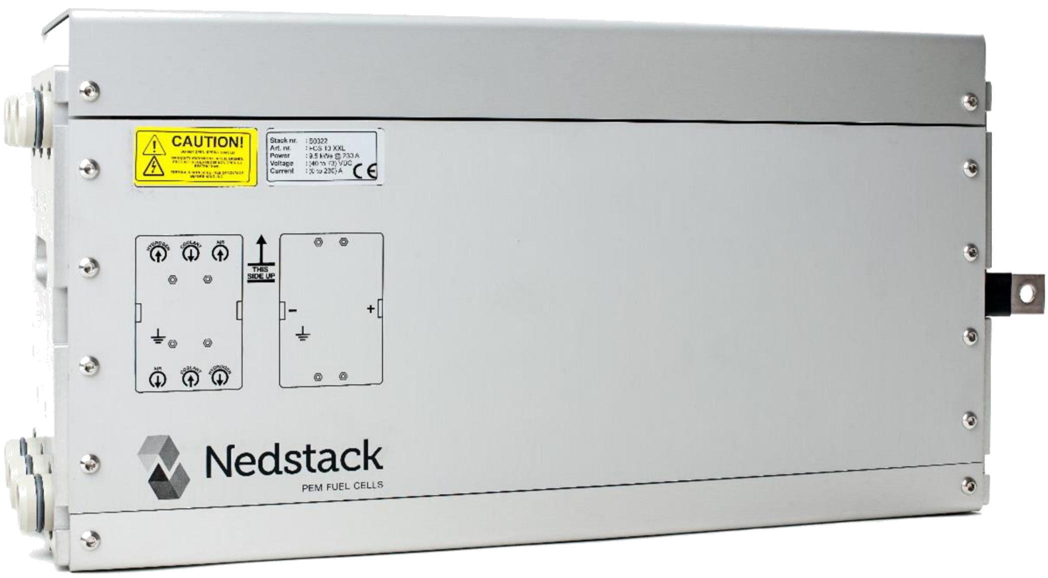
Nominal temperature	:	65 °C
Temperature$_{max}$	:	≤ 70 °C
Capacity	:	< 20 kW$_{th}$ at full power
Medium	:	de-mineralized water or BASF glysantine FC G20
Purity	:	conductivity < 10 µS.cm^{-1}
Pressure difference	:	< 0.15 bar (DI water) or < 0.45 bar for glysantine
Operating window	:	ΔT < 5K

Note that proper material selection in the tempering device is important to avoid release of ions into the coolant

Connectors

Coolant	*standard*	:	Nedstack quick coupling (male)
	optional	:	quick coupling (female)
Hydrogen	*standard*	:	Nedstack quick coupling (male)
	optional	:	quick coupling (female)
Air	*standard*	:	Nedstack quick coupling (male)
	optional	:	quick coupling (female)
Current		:	End contact with 10.5 mm hole (2x)
Cell voltage connector		:	M12 connector (2x)

Appearance Impression



Nedstack
fuel cell technology B.V.

Westervoortsedijk 73
6827 AV ARNHEM

P.O. Box 5167
6802 ED ARNHEM
The Netherlands

Phone +31 (0)26 319 7600
Fax +31 (0)26 319 7601
E-mail info@nedstack.com

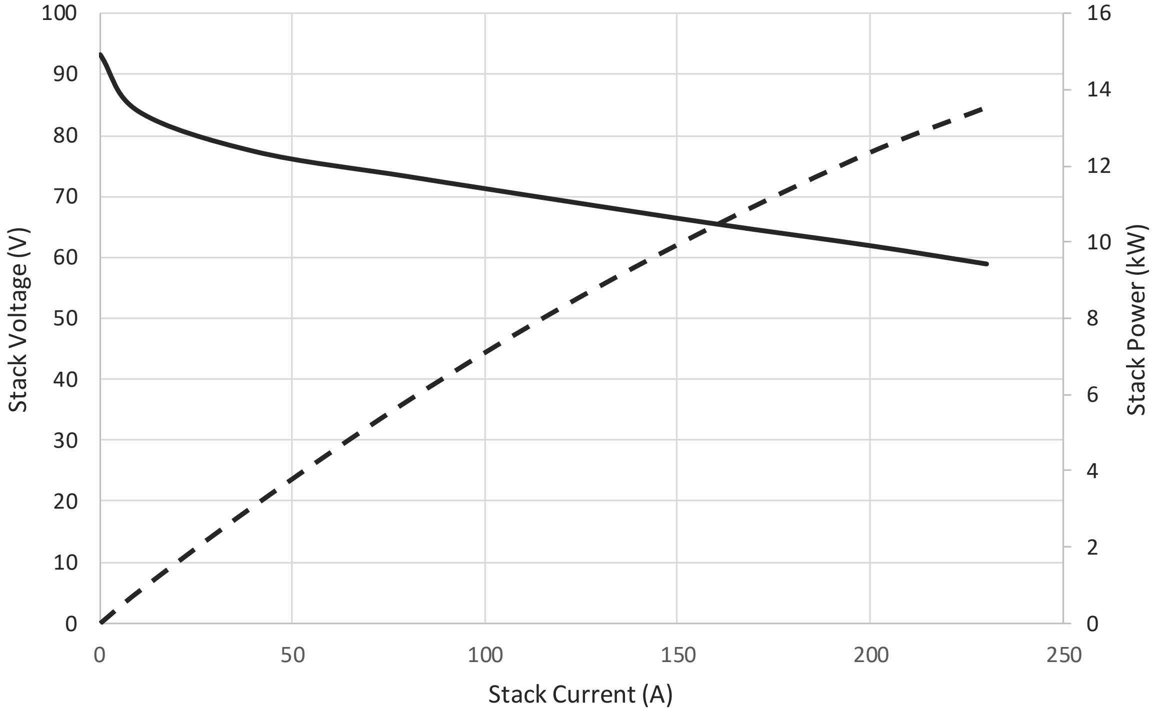
Trade Register Arnhem
nr. 09102161

www.nedstack.com

PRODUCT DATA SHEET – NEDSTACK FCS 13-XXL

Electrical specifications
Beginning of Life stack performance data under standard conditions:

Stack temperature = 62 °C,
Hydrogen: stoichiometry = 1.25; minimum hydrogen flow = 72 Nl/min; RH = 75%.
Air: stoichiometry = 2.0; minimum air flow = 134 Nl/min; RH = 75%



Current (A)	0	40	80	120	160	200	230
Stack Voltage (V)	93.2	77.4	73.2	69.3	65.5	61.9	58.9
Stack Power (kW)	0.0	3.1	5.9	8.3	10.5	12.4	13.6

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fuel cell technology B.V.

Westervoortsedijk 73
6827 AV ARNHEM

P.O. Box 5167
6802 ED ARNHEM
The Netherlands

Phone +31 (0)26 319 7600
Fax +31 (0)26 319 7601
E-mail info@nedstack.com

Trade Register Arnhem
nr. 09102161

www.nedstack.com

Nedstack

PemGen

MT-FCPP-500

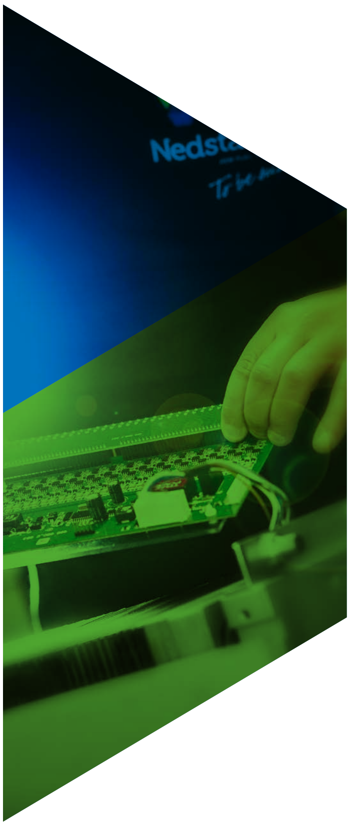
Nedstack Fuel Cell Technology B.V.
Maritime Power Systems
www.nedstack.com

Westervoortsedijk 73
6827 AV Arnhem
The Netherlands

PemGen

MT-FCPP-500

The MT-FCPP-500 is a zero-emission shipping enabler as it offers a containerized LT-PEM fuel cell power supply unit for a variety of large maritime applications both on inland waterways and in the short-sea domain.



GENERAL	Fuel Cell Type	Low Temperature Proton Exchange Membrane (LT-PEM)
	Fuel Cell Model	60 x Nedstack FCS 13-XXL
ELECTRICAL	Peak power	626 kWe
	Nominal power	500 kWe
	Voltage range	560 - 1200 VDC
	Current range	0-1000 A
DIMENSIONS	Weight	Approx. 15000 kg
	Length	6060 mm
	Width	2440 mm
	Heigth	2590 mm
HYDROGEN FEED	Quality	Grade ≥ 2.5 (CO < 0.2 ppm)
	Supply pressure	0.3 – 6 barg
	Max. Consumption	45 kg/h
COOLANT	Medium	DI water or BASF FC G20
	Outlet Temperature	65 – 70 °C
	Max. Heat Output	670 kW
AMBIENT CONDITIONS	Operating Temperature	-10 to 40 °C
	Storage Temperature	5 – 60 °C (optional -20 – 60 °C)
APPLICATION	Intended Use	Main propulsion power for lighter vessel or APU for larger vessel
	Placement	On open deck or integration in vessel
SAFETY	Compliancy	Class approval on request IEC 60092 IEC 60529 IEC 60533 NEN-EN-50110 ISO 13920 NEN-EN 25817 IEC 62282-2
	Enclosure	20 ft ISO Container

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To be sure.

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G. Fuel related emission model

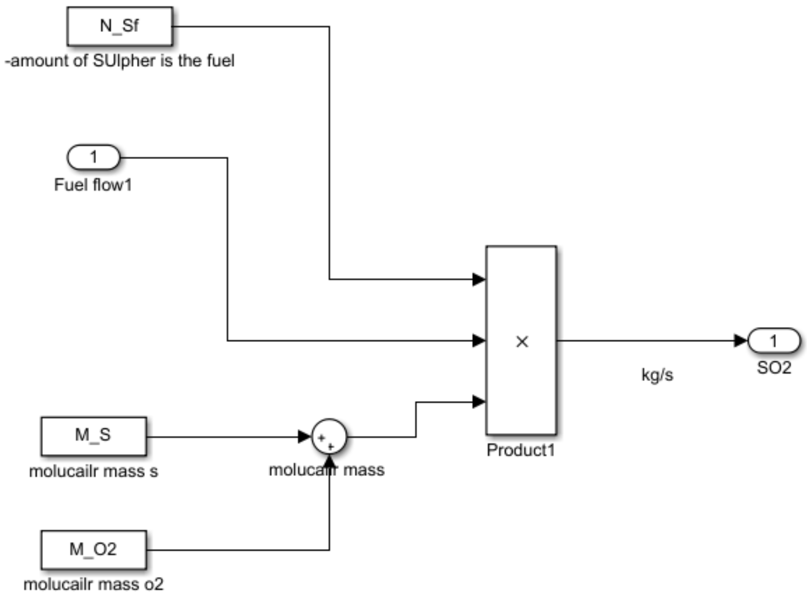


Figure G.1: SO2 emission model

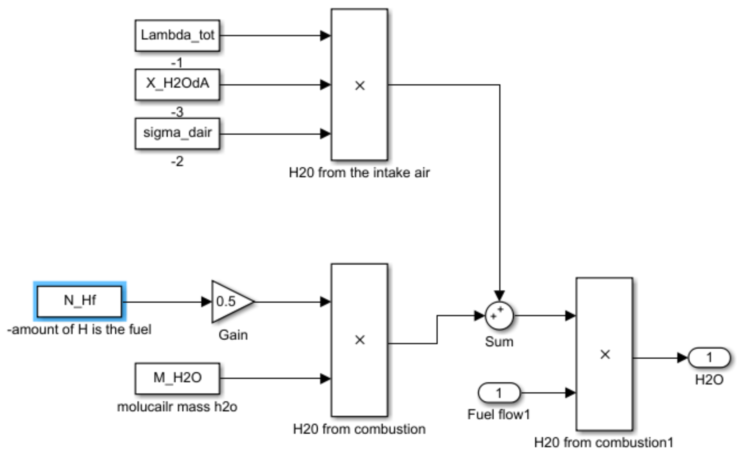


Figure G.2: H2O emission model

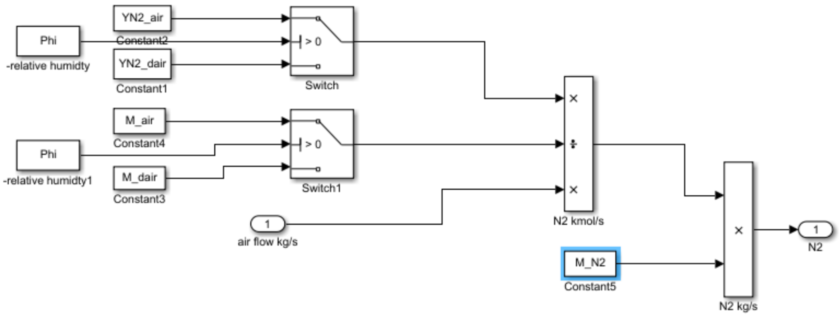
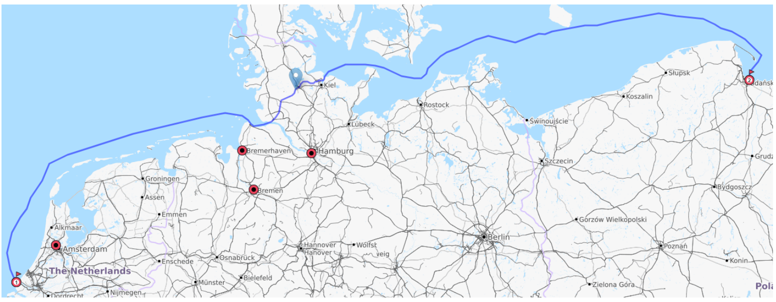
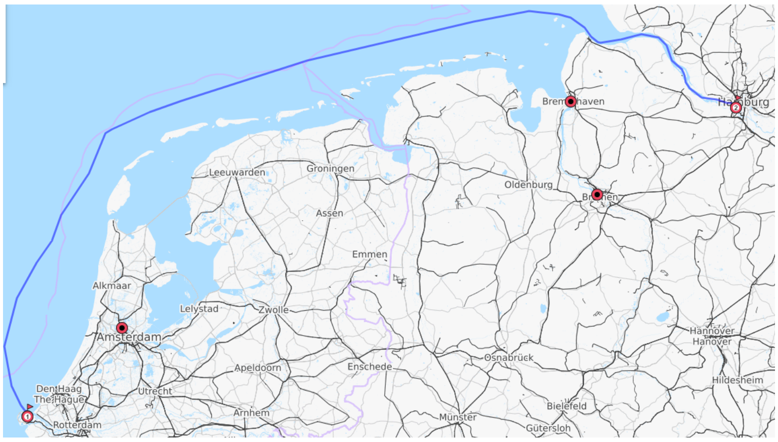


Figure G.3: N2 emission model

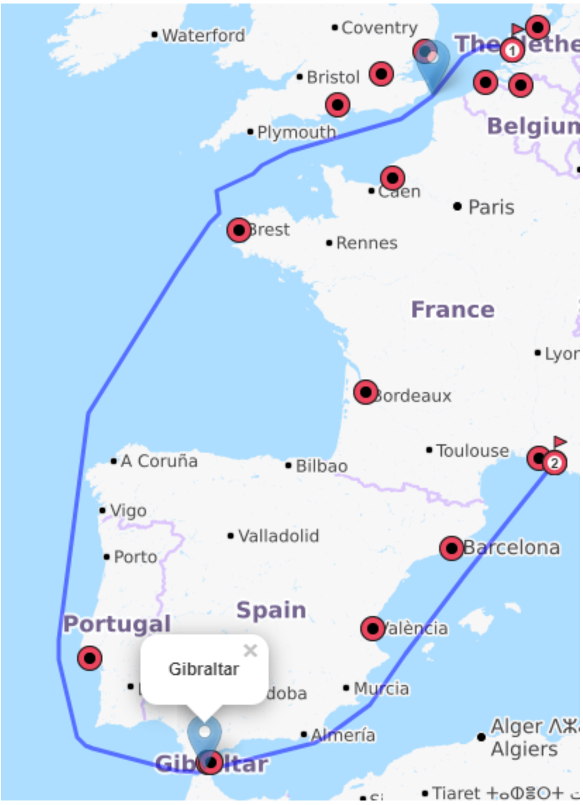
H. Trip routes on world map



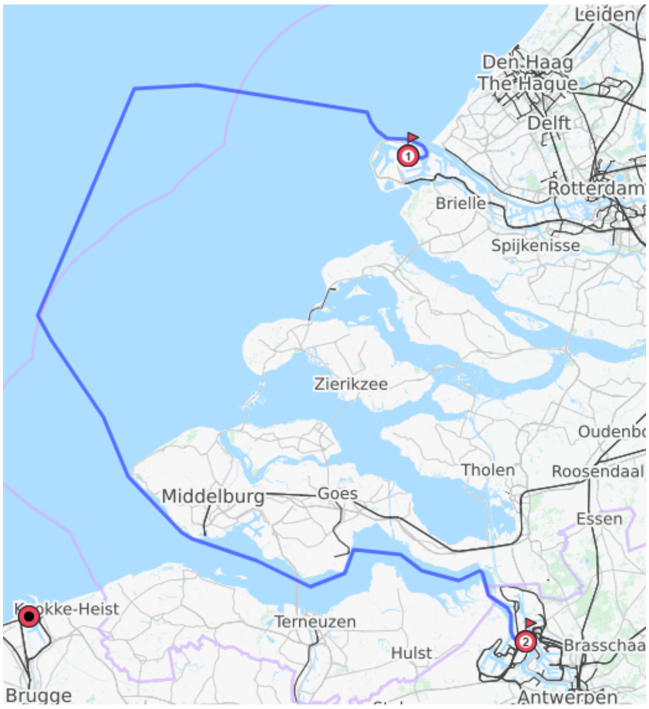
(a) Rotterdam to Gdansk



(b) Rotterdam to Hamburg



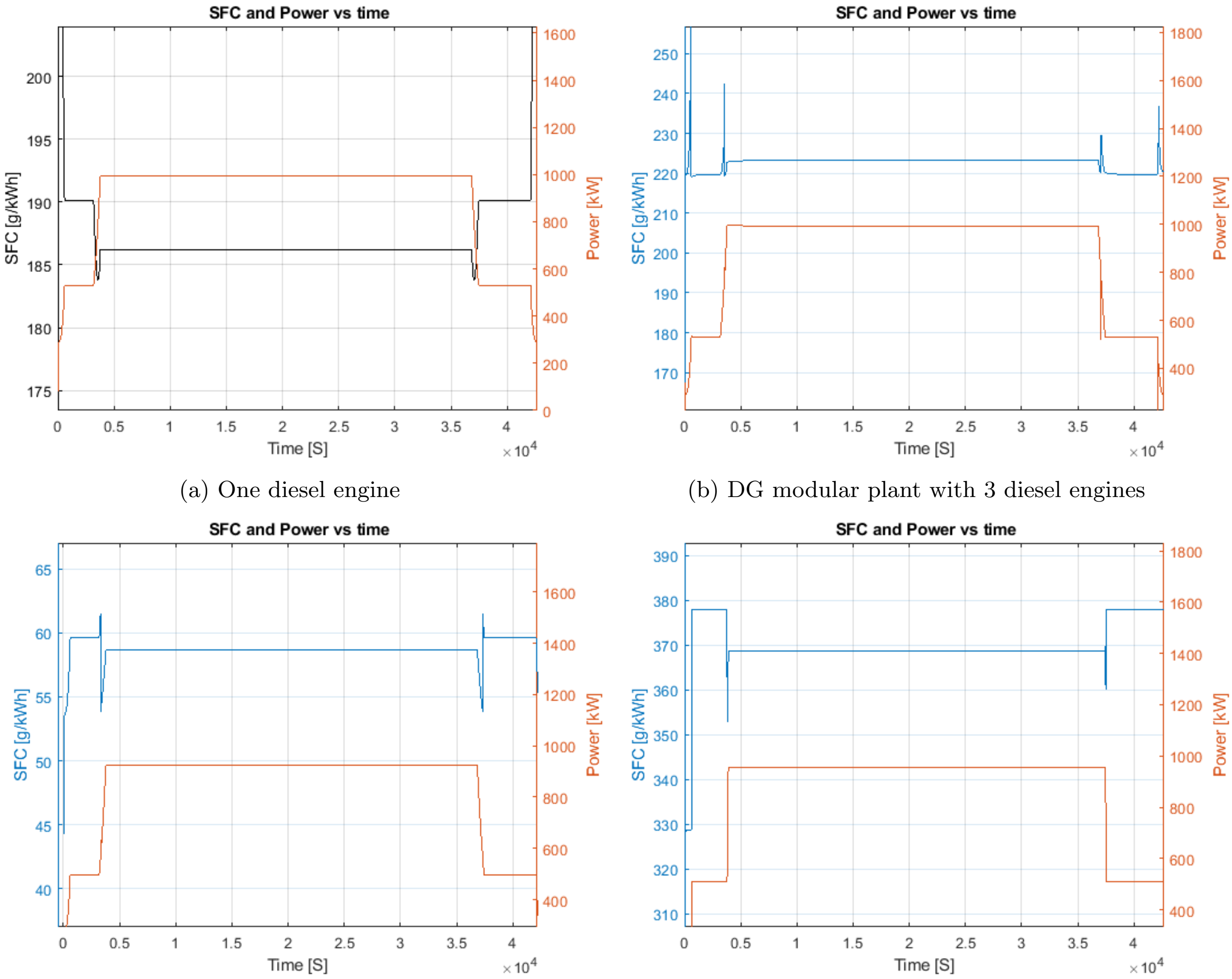
(c) Rotterdam to Marseilles



(d) Rotterdam to Antwerp

Figure H.1: Trips used in simulation

I. Trip SFC and power figures



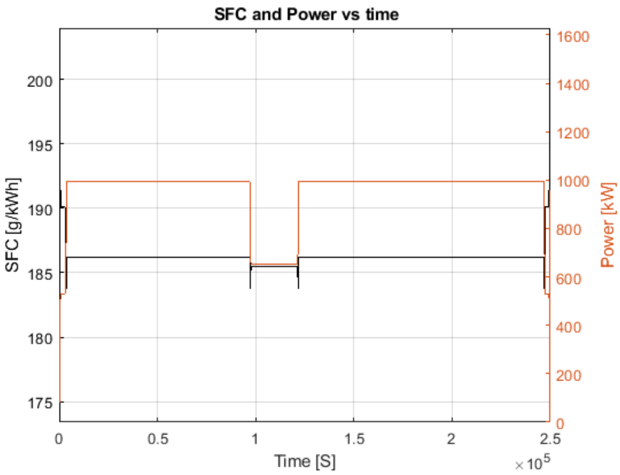
(a) One diesel engine

(b) DG modular plant with 3 diesel engines

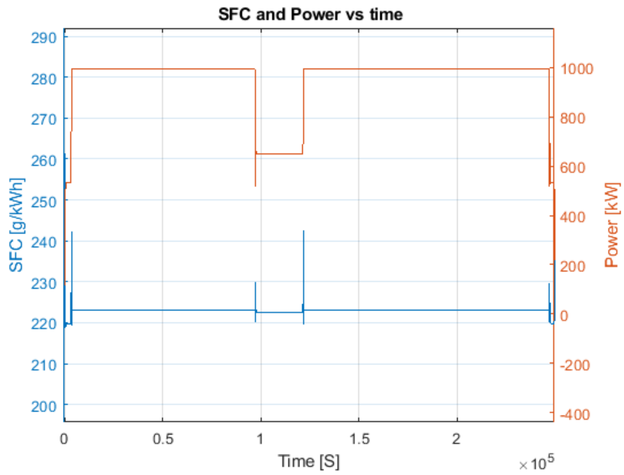
(c) modular hydrogen fuel cell plant

(d) modular ammonia fuel cell plant

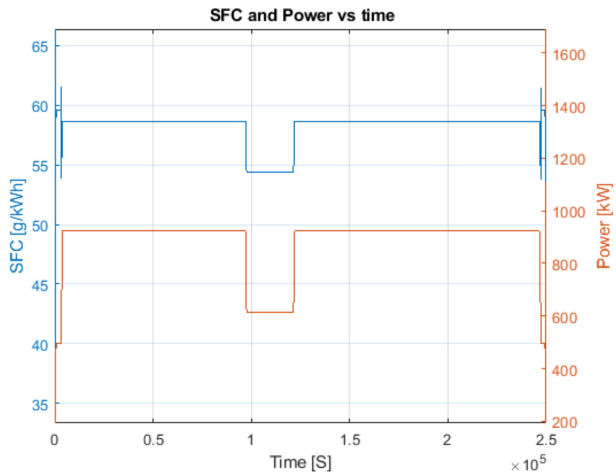
Figure I.1: Rotterdam to Antwerp SFC and power figures



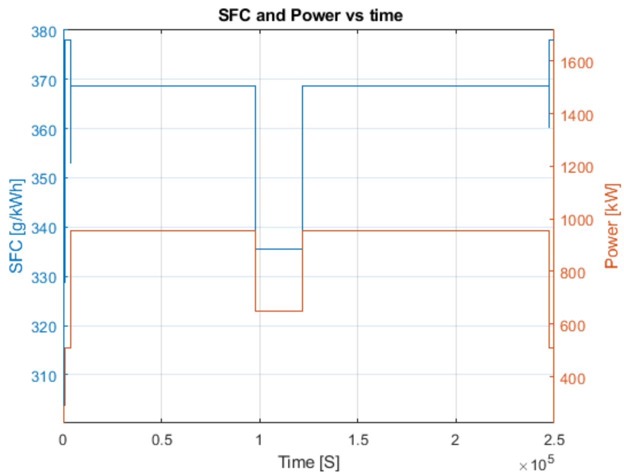
(a) One diesel engine



(b) DG modular plant with 3 diesel engines

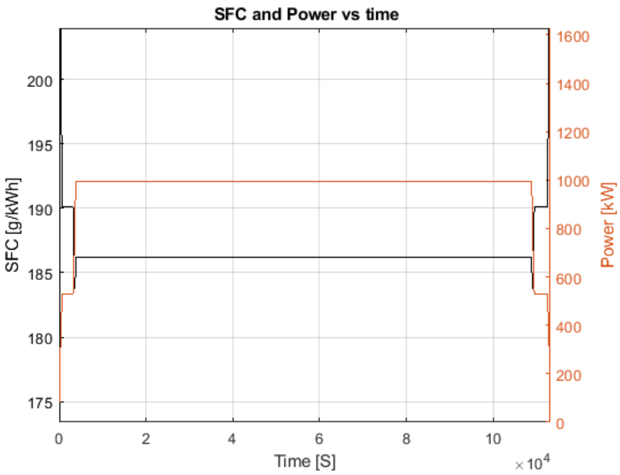


(c) modular hydrogen fuel cell plant

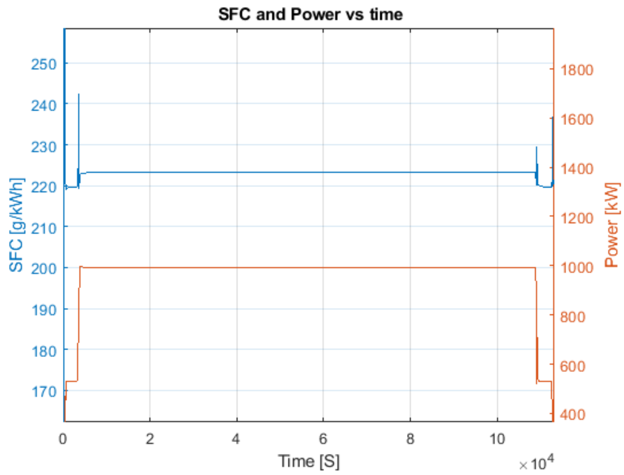


(d) modular ammonia fuel cell plant

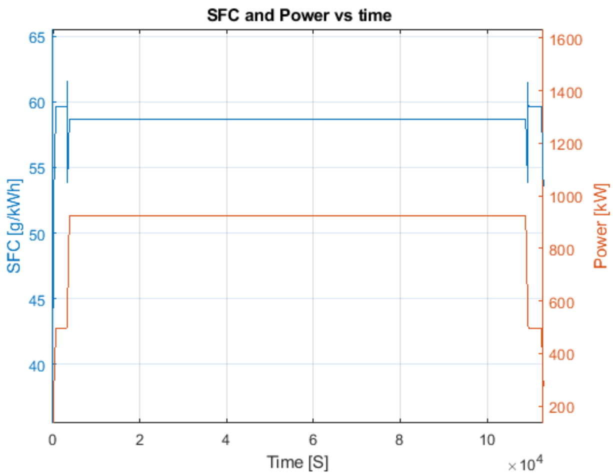
Figure I.2: Rotterdam to Gdansk SFC and power figures



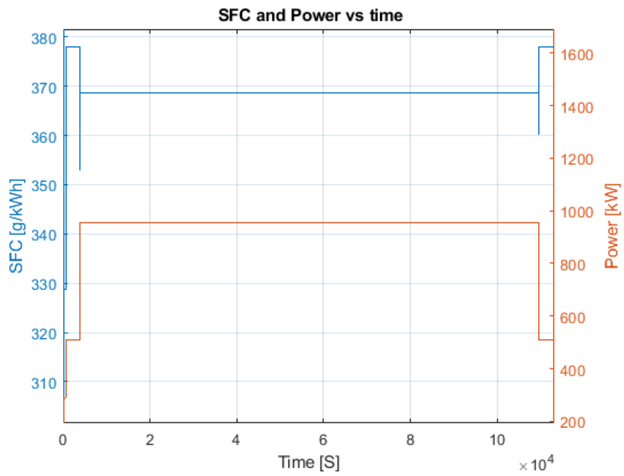
(a) One diesel engine



(b) DG modular plant with 3 diesel engines

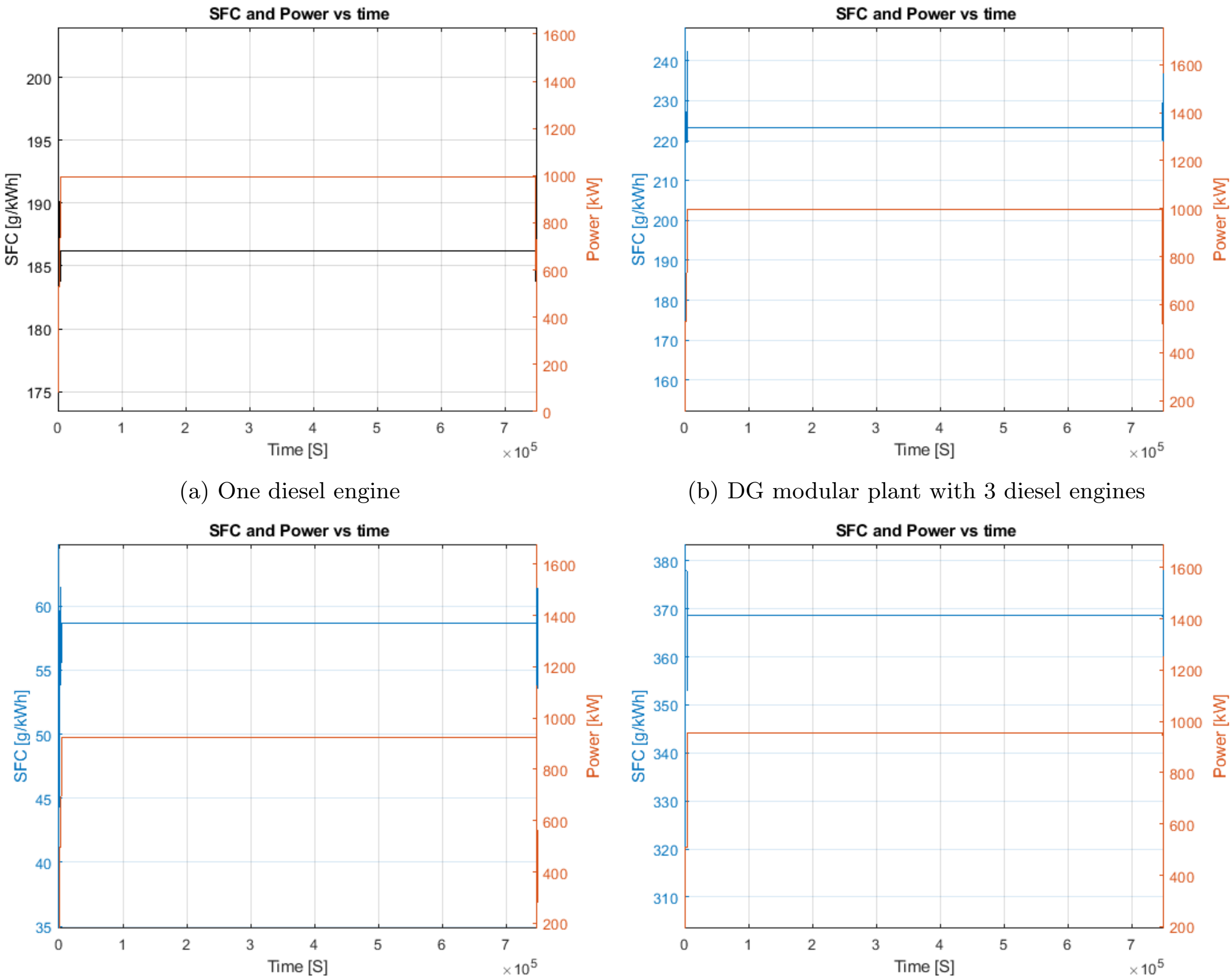


(c) modular hydrogen fuel cell plant



(d) modular ammonia fuel cell plant

Figure I.3: Rotterdam to Hamburg SFC and power figures



(a) One diesel engine

(b) DG modular plant with 3 diesel engines

(c) modular hydrogen fuel cell plant

(d) modular ammonia fuel cell plant

Figure I.4: Rotterdam to Marseilles SFC and power figures

J. Emissions per trip and system

Table J.1: Emission values per trip and system

	fuel	MDO						Hydrogen			Ammonia		
	Nr engines		one			three			two			two	
Emmision	**Trip**	**per**	**kg /nm**	**spe**	**per**	**kg /nm**	**spe**	**per**	**kg /nm**	**spe**	**per**	**kg /nm**	**spe**
CO_2	RTD-ANT	3.19	65.20	653.8	3.19	70.88	710.7	0	0	0	0	0	0
	RTD-GDA	3.19	64.24	651.6	3.19	70.13	711.6	0	0	0	0	0	0
	RTD-HAM	3.19	65.08	652.2	3.19	70.99	711.5	0	0	0	0	0	0
	RTD-MAR	3.19	63.87	651.6	3.19	69.75	711.8	0	0	0	0	0	0
	AVARAGE	3.19	64.60	652.3	3.19	70.44	711.4	0	0	0	0	0	0
SO_X	RTD-ANT	0.02	0.409	4.10	0.02	0.444	4.46	0	0	0	0	0	0
	RTD-GDA	0.02	0.403	4.09	0.02	0.440	4.46	0	0	0	0	0	0
	RTD-HAM	0.02	0.408	4.09	0.02	0.445	4.46	0	0	0	0	0	0
	RTD-MAR	0.02	0.400	4.09	0.02	0.437	4.46	0	0	0	0	0	0
	AVARAGE	0.02	0.41	4.09	0.02	0.44	4.46	0	0	0	0	0	0
H_2O	RTD-ANT	1.46	29.91	299.9	1.46	32.50	325.9	9.956	54.12	584.1	1.721	61.08	636.1
	RTD-GDA	1.46	29.46	298.9	1.46	32.17	326.4	9.956	53.23	581.0	1.721	59.93	630.8
	RTD-HAM	1.46	29.84	299.1	1.46	32.56	326.3	9.956	54.09	583.9	1.721	60.92	635.0
	RTD-MAR	1.46	29.29	298.9	1.46	31.99	326.4	9.956	53.13	5584	1.721	59.73	634.7
	AVARAGE	1.46	29.62	299.2	1.46	32.31	326.25	9.956	53.65	1833	1.721	60.42	634.2
N_2	RTD-ANT	26.67	545.1	5466	26.67	592.5	5941	50.31	273.5	2952	7.401	262.6	2736
	RTD-GDA	26.67	537.0	5448	26.67	586.4	5949	50.31	269.0	2936	7.401	257.6	2712
	RTD-HAM	26.67	543.9	5453	26.67	593.4	5948	50.31	273.3	2951	7.401	261.9	2730
	RTD-MAR	26.67	533.7	5448	26.67	583.1	5951	50.31	268.4	2950	7.401	256.9	2729
	AVARAGE	26.67	539.9	5454	26.67	588.9	5947	50.31	271.0	2947	7.401	259.8	2727
NO_X	RTD-ANT	0.0660	1.3512	13.5700	0.0529	1.17	11.8	0	0	0	0	0	0
	RTD-GDA	0.0640	1.2859	13.0500	0.0516	1.13	11.5	0	0	0	0	0	0
	RTD-HAM	0.0628	1.2822	12.8500	0.0515	1.15	11.5	0	0	0	0	0	0
	RTD-MAR	0.0620	1.2331	12.5900	0.0510	1.12	11.4	0	0	0	0	0	0
	AVARAGE	0.0637	1.2881	13.0150	0.0517	1.14	11.5	0	0	0	0	0	0
CO_e	RTD-ANT	0.0022	0.0452	0.4529	0.00218	0.0485	0.486	0	0	0	0	0	0
	RTD-GDA	0.0023	0.0464	0.4704	0.00222	0.0487	0.494	0	0	0	0	0	0
	RTD-HAM	0.0023	0.0476	0.4765	0.00222	0.0494	0.495	0	0	0	0	0	0
	RTD-MAR	0.0023	0.0475	0.4852	0.00223	0.0489	0.498	0	0	0	0	0	0
	AVARAGE	0.0023	0.0467	0.4713	0.002213	0.0489	0.493	0	0	0	0	0	0
PM	RTD-ANT	0.0008	0.0167	0.1670	0.00090	0.020	0.202	0	0	0	0	0	0
	RTD-GDA	0.0009	0.0171	0.1739	0.00092	0.020	0.204	0	0	0	0	0	0
	RTD-HAM	0.0009	0.0178	0.1780	0.00091	0.020	0.202	0	0	0	0	0	0
	RTD-MAR	0.0009	0.0178	0.1820	0.00090	0.020	0.202	0	0	0	0	0	0
	AVARAGE	0.0009	0.0174	0.1752	0.00091	0.020	0.202	0	0	0	0	0	0
HC	RTD-ANT	0.0025	0.0514	0.5160	0.00222	0.0493	0.494	0	0	0	0	0	0
	RTD-GDA	0.0025	0.0503	0.5100	0.00221	0.0485	0.492	0	0	0	0	0	0
	RTD-HAM	0.0025	0.0507	0.5080	0.00221	0.0492	0.493	0	0	0	0	0	0
	RTD-MAR	0.0025	0.0495	0.5051	0.00221	0.0482	0.492	0	0	0	0	0	0
	AVARAGE	0.0025	0.0505	0.5098	0.00221	0.0488	0.493	0	0	0	0	0	0