The refittable ship

A method for modular design of a ship's power supply

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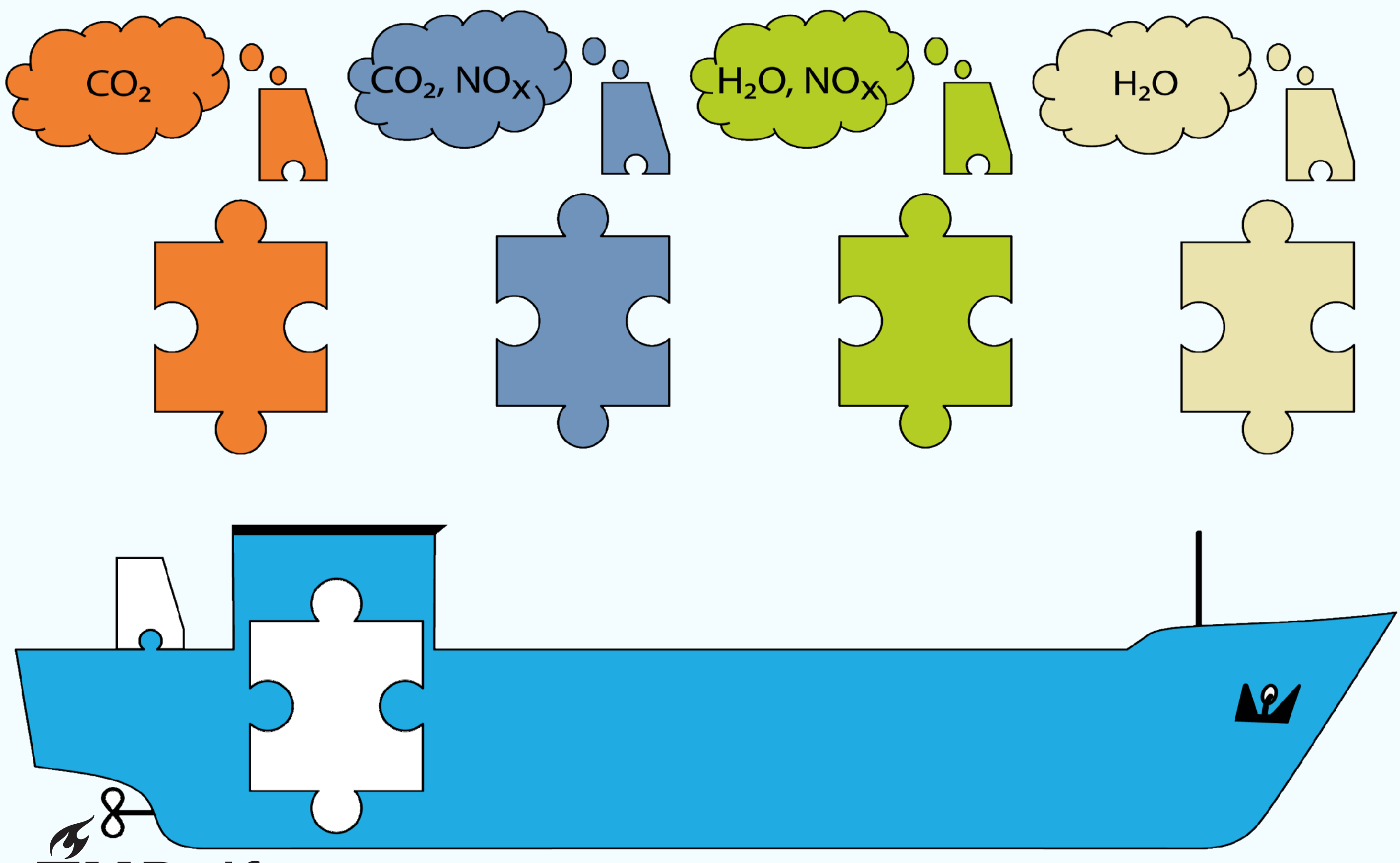

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The refittable ship

A method for modular design of a ship's power supply

by

J.W.J. Benedictus

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Preface

The world is changing continually, including the weather, the climate, and the available techniques. These changes continually introduce a range of engineering challenges to see how we can make the world a better place. This thesis is written in the context of such an engineering challenge, and to obtain my master's degree.

Conoship International is a company that likes to take up engineering challenges, including those that come with using alternative fuels. My introduction to this company was the start to an intense and enlightening period. It was a period in which I developed myself, I was taught about real ships, I learned about virology and home schooling, and I developed a way to make a ship into a puzzle.

In this report you can find the development of a method for designing a ship, that allows a ship to be renewed with a 'green' installation halfway its life. For readers who want to know more about these 'green' installations instead of the method, some basic information about available energy carriers and power supply units can be found in 2.3, the components of alternative installations of the case ship can be found in chapter 4 and the effect of those installations on the design to be found in section 5.3.

Without the guidance, help and support of others I could not have delivered the project as I have, so I would like everyone who helped me in any way during the duration of my project.

Firstly, I would like to thank Guus van der Bles and Harald Rugebregt of Conoship for their supervision throughout the project. Your input, comments and support are very much appreciated, especially since you gave me the opportunity to use information on real ships. I would also like to thank everyone else at Conoship for allowing me to have a nice workplace in your office and giving me advise and support.

Secondly, I would of course also like to thank Peter de Vos and Robert Hekkenberg of the TU Delft for their supervision. I had to learn how to manage the project, and I was spoiled with having a daily supervisor in the office in Groningen, but without your comments on my approach and presentation, and without your discussions I could not have finished the project as I have now.

I would also like to thank my family for their encouragement and help. I would especially like to thank my parents, parents-in-law and my husband for not only encouraging me, but also in taking over other tasks that come with motherhood, to free me the time to study. Finally, I would like to thank my children for their patience and being a motivation to persist.

Julia Benedictus-Kortenhorst
Garyp, December 2020

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Summary

In this report a method for modular design is developed, with the aim to design a ship for a low-impact refit of its power supply system. Traditionally, ships are powered by fossil fuels in combustion engines, causing 3% of global greenhouse gas emissions. Alternative installations have yet to prove their reliability and are currently not as cheap.

To enable ship-owners to prepare their ship for the future, but postpone their decision on which alternative installation to choose, **it is the objective of this research to develop and validate a method for modular design of the power supply system of a ship, that allows a low-impact refit to lower the ship's greenhouse gas emissions when the alternative power supply technology is ready**.

This method is developed within the scope of short-sea dry cargo vessels with little auxiliary power (<20%) that is to be refitted before 2050. The studied background information includes greenhouse gases, possible alternative installations, low-impact refits, and modularity. Furthermore, the method is verified and validated using two different case ships.

In this research it is expected that it is important to reduce acquisition and labour cost during the refit of a short-sea dry cargo ship. Therefore, it is assumed that only a minimal amount of structural work should be necessary, that no components should be moved that are not to be refit and that the number of components to be refit should be kept low.

Modularity is a design form in which parts of the system can be changed, without having to change the rest of the system. As cited: “Modularity is a special form of design which intentionally creates a high degree of independence or 'loose coupling' between modules by standardizing module interface specifications” [1]. It is found that modules are relatively independent subassemblies with standardised interfaces, that can be exchanged so the system can take on different forms.

Instead of using an existing modularity method, a method was developed to fit the objective, because not suitable existing method was found. In literature, modularity in shipping is used mainly for large section-block modules and operational modules. For this research, a modularity method was required that looks at a ship in a higher level of detail and recognises all the small interactions between the components.

The method was developed by identifying possible steps from the found theory and constraints, and verifying if those steps were suitable by applying them to the first case ship. The developed method exists of three phases:

1. Demarcation: To find where the modular power supply system ends
2. Finding suitable repeatable subsystems: To identify the overlap between the systems and to find the subsystems' dependencies
3. Designing modules: To design the ship, by grouping the repeatable subsystems so they can be exchanged as subassemblies, whilst respecting the assumptions of a low-impact refit

From the design of the case ship that was developed during the verification of the steps, and from the design that was developed during the validation of the method, it could be concluded that the method fits the research objective. The method resulted in designs that met the low-impact refit constraints and the modularity definitions. The method did not require that the space available for power supply components had to be enlarged, but some power supply components required additional space because of their size. The designs had a clearly demarcated power supply system. This specified interface is expected to make it easier to design a new installation that was not considered.

It is recommended to further validate the method, for different ship types and to see if installations that were not considered are also easier to refit when the ship is designed with the method. Also, the assumption on the definition of the low-impact refit should be verified. In general, it is expected the method will help in effectively enable a ship-owner to make its ship more climate-friendly halfway the ship's lifetime, instead of scrapping it or remaining to emit more greenhouse gases.

Nomenclature

Chemical compositions

C_2H_6O	Dimethyl Ether
CH_4	Methane
CH_3OH	Methanol
CO	Carbon Monoxide
CO_2	Carbon Dioxide
$NaBH_4$	Sodium borohydride
$NaBO_2$	Sodium metaborate
NH_3	Ammonia
NO_x	Nitrogen Oxides
SO_x	Sulphuric Oxides

General

CNG	Compressed Natural Gas	CO_2e	Emission equivalent to CO_2 emission
CPP	Controllable pitch propeller	DME	Dimethyl Ether
DWT	Deadweight, or available payload	EM	Emergency generator
FAME	Fatty Acid Methyl Ester	FC	Fuel cell
FPP	Fixed pitch propeller	GB	Gearbox
GHG	Greenhouse Gas	GT	Gross tonnage
GT	In appendix B: gas turbine	HFO	Heavy Fuel Oil
HT	High temperature	HT-PEM	High temperature protone exchange membrane
ICE	Internal Combustion Engine	IMO	International Maritime Organisation
LFL	Lower flammability level	LHV	Lower heating value
LOHC	Liquid organic hydrogen carrier	LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas	LT	Low temperature
LT-PEM	Low temperature protone exchange membrane	MCA	Multi Criteria Analysis
MDO	Marine Diesel Oil	MeOH	Methanol
MGO	Marine Gas Oil	MPS	Modular power system
NMSS	Non-modular ship system(s)	NMVOC	Non-Methane Volatile Organic Compounds
PM	Particulate Matter	PTO	Power Take-off
PPO	Pure plant oil	RS	Repeatable subsystem
SCR	Selective catalytic reduction	SOFC	Solid oxide fuel cell
UFL	Upper flammability level	VOC	Volatile organic compounds

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1 Introduction

Imagine yourself being a ship-owner, that needs a new ship to stay in business. You just found out that regulations to reduce greenhouse gas emissions are in the pipeline and that the consumer wants to go 'green'. Now, you also heard the current prices of alternative propulsion compared to your traditional diesel set-up and you realise that it will cost significant money to go 'green'. You are facing a dilemma.

This dilemma is actuality for ship-owners. As the world realises that fossil fuels as power source might not be sustainable because of their contribution to greenhouse gas (GHG) emissions, the maritime sector is also pushed to reduce its 3% share of the global GHG emissions[2]. Over 99% of the maritime fuel consumption consists out of marine gas oil (MGO) and heavy fuel oil (HFO) [2], collectively called 'diesel'. Other power sources are rare [2], which means that virtually all ships sail on fossil fuels.

There are many ways to emit less or no GHG emissions in comparison to traditional diesel installations (see 2.3), but diesel is cheap, reliable, and familiar. Other ways of powering a ship typically are not familiar, have yet to prove their reliability and are currently also not as cheap [3]; hence the dilemma.

To enable ship-owners to prepare their ship for the future, but postpone their decision on which alternative installation to choose, this research is aimed at finding a way to design a refittable ship. A low-impact refit can postpone the choice of the alternative installation, whilst the installations and the infrastructure are developed further. The ship can initially profit from the cheapness, reliability, and familiarity of diesel, whilst it can later install a reliable and (more) affordable alternative installation. This prevents early scrapping and enables a ship owner to switch to a low carbon power supply sooner compared to when the ship would be replaced completely. Such refit is only feasible if the conversion between the installations can be so smooth that the cost of the conversion can be earned back in the remaining lifetime of the ship after the conversion.

1.1. Objective: A refittable ship by modularity

The problem central to this research lies within the smooth conversion that can be earned back. Shipping is a low margin business and therefore ships are designed to be optimised for maximum profit in their business case. This design strategy would not specifically be aimed at allowing for conversion during the lifetime of a ship. However, when the traditional diesel set-up would no longer be viable because of market or regulation changes whilst the ship is still young, a conversion is necessary, and conversions can be expensive. The installation will cost a significant amount of money, but if the ship is not designed with a conversion in mind, the conversion could demand an even larger investment.

In enabling a low-impact refit it was requested to investigate how modularity could help. Modularity accommodates uncertainty and it allows to change pieces of a system without redoing the whole system [4]. This seems to fit the problem at hand very well, but it would require further work to apply modularity to ship design. Some literature can be found to adapt ships for different missions (e.g. [5] and [6]) and on how to apply modularity to ship design [7], but to incorporate modularity in the initial design to allow a power generation conversion is under-exposed. This means that even though modularity might allow conversion without significant negative impact, a method for this specific purpose is not developed and therefore currently cannot be used to solve the ship-owners dilemma. Therefore, **it is the objective of this research to develop and validate a method for modular design of the power supply system of a ship, that allows a low-impact refit to lower the ship's GHG emissions when the alternative power supply technology is ready.**

To reach the objective, several questions should be answered:

1. How can modularity be defined in the light of ship design?
2. How are methods for modular design currently applied in the maritime field?
3. What power plant components can be expected to be exchanged in a refit from diesel power to a less GHG emitting solution in the upcoming 30 years?
4. How can the relevant aspects from modularity in the maritime and other fields be used to form a suitable method for modularity in ship design to enable a low-impact refit from diesel power to a less GHG emitting solution in the upcoming 30 years on board a short-sea dry cargo vessel?

This means that not only should the method be investigated, but also the necessary background information should be collected and a case is required to verify and validate the method. An approach for the development of the method is to be presented once the necessary background information is collected.

1.2. Research scope

The method will be developed within a certain context, that should receive further attention. Also, the necessary background information should be gathered, and an approach should be established.

Context The method will be developed within the limited context of short-sea dry cargo vessels with little auxiliary systems (<20% of installed power) that are built before approximately 2050. This ship type is chosen because of the available data on this kind of ships. The conversion should be for techniques that might come up the next 30 years, because only within this period it is expected that a switch from fossil diesel will be made. Fossil diesel fuel is expected to become less important in the upcoming decades [8] and it might well be possible to new-build a ship with a 'green' installation after 2050.

Background information Background information is necessary on GHGs, alternative propulsion, low-impact refits, and modularity:

- Of GHGs it should be determined why they are thought to be problematic, what they are and what can be done about it for ships.
- It should be investigated which alternative installations can be expected to be realistic options within the context of the research
- A solid basis should be developed on what a low-impact refit is, and how this can be obtained in ships
- It should be thoroughly investigated what modularity is, and how to apply it to a ship

Approach After investigating the background, a case will be developed to verify the method with. A clear approach on how to develop the method can only be made after existing methods have been investigated, as it is yet unknown if any existing method can be (partially) used for the low-impact refit, which can change the way the method should be developed. The steps of the method will have to be verified with the first case ship, and the result of the method should be validated using a second case ship. It is not expected that the validation will give a complete quantitative overview of all influenced parameters, but it should give a view on whether modularity can bring the desired improvement on the conversion.

The method should become a set of guidelines and boundary conditions to which the design should be made to reach the desired effect. Even though the method will be developed for the short-sea vessels mentioned earlier, the method will be as generic as possible, only making specific choices if necessary.

1.3. Report outline

In this report the development of the method will be described. First the background information can be found in chapter 2 and 3. In chapter 2 information will be given on GHG emissions, GHG emission reduction and alternative power supplies. In chapter 3 it will be established what the relevant aspects of a refit are, including the application of modularity.

In chapter 4 the case ship is presented used for the verification of the steps. This includes the technical information on its installations.

The method will be developed in chapter 5. This chapter will include a wordlist and the design of the first case ship, including the findings on its technical installations. The validation of the method is described in chapter 6, using a second case ship.

Conclusions on the effectiveness of the method are finally presented in chapter 7. This is also where it is indicated how the method can be improved further.

2
Greenhouse gas emission reduction in ships

Since the objective of this research is to develop a design method that should enable one to design a ship that will be refit to emit less GHG, it is important to have some background information on what these gases are and how to reduce them.

In this chapter it will first be explained what is meant by GHG and how they are produced by ships. The second part of this chapter will be about why and how reduction is ought to take place, and in which parts of the process the balance between different emissions and pollutions is most precious. The final part of this chapter will be about how a ship can be powered, as there is a broad selection of options available, besides the standard of using fossil fuels.

2.1. Introduction in ship greenhouse gas emission

In this section, it will be explained how ships typically cause certain emissions. It has been stated before that the transition to emitting less GHG's is the ground for this research, so it is important to know where these gases come from and how large this effect is. For more in-depth information on GHG's and other emissions from ships it is advised to read the book 'Shipping and the Environment' [9]. First it will be explained what emissions form during combustion of fuel, secondly which of those are GHG's and how much of those GHG's are produced by ships.

2.1.1. Emissions from combustion of fuel

Over 99% of all ships are sailing by using fossil fuel oils [2]. Combustion or oxidation of fuel will lead to several emissions from the exhaust pipe. The emissions are dependent on the fuel and the process of the reaction. Based on [10] the following three categories are identified and explained for combustion of diesel: Air related emissions, fuel related emissions and cylinder process related emissions.

The air related emissions in the exhaust gas is the part of the unaltered air intake which is emitted after having passed through the engine. The utmost part of this air will consist of nitrogen (N_2) and Argon (Ar). A small amount of oxygen (O_2) will also be present in the exhaust gas, the fraction of the oxygen from the inlet air that has not been used in combustion.

From complete combustion of diesel several fuel related emissions will occur. This is dependent on the fuel; pure hydrocarbon fuels only contain hydrogen and carbon atoms, but marine fuel may also contain sulphur and nitrogen, as well as other trace elements. Combustion will therefore mainly lead to the emission of carbon dioxide (CO_2) from the carbon atoms and water (H_2O) from the hydrogen atoms. From burning sulphur during the combustion this will also form sulphur oxides (SO_x), existing of sulphur dioxide (SO_2) and sulphur trioxide (SO_3). The nitrogen bound to the fuel will create nitrogen oxide (NO) and nitrogen dioxide (NO_2) in the combustion process, of which the NO will mostly convert to NO_2 later on. The weight of the emissions will exceed the weight of the burnt fuel, because of the addition of oxygen from the air; for a fuel with 86% carbon, the production of CO_2 will be 3.15 kg/kg fuel.

Finally, the engine's cylinder process causes incomplete combustion of part of the fuel and unintended combustion of part of the nitrogen present in air. The incomplete combustion will lead to carbon (C), carbon monoxide (CO), gaseous (unburned) hydrocarbons (Volatile Organic Components or VOC) and particulate matter (PM). The unintended combustion of air will lead to nitrogen oxides (N_2O, NO and NO_2) which are normally grouped as NO_x.

From all these emissions only the unaltered fresh air components and water are harmless[10]. A remark should be made about the used fuels; if a fuel has a different composition, it will also produce different emissions, because the chemical composition determines which atoms will oxidise into which molecules. Also, the type of fuel-user makes a different, as not all of them will produce as much NO_x as a diesel engine.

2.1.2. Greenhouse gas emissions from ships

Greenhouse gases are gases that insulate the earth's atmosphere to maintain the Earth's temperature at a reasonable temperature to sustain life [9], which also means that not all GHG's are harmful. However, GHG's emitted by human actions are thought to increase this greenhouse effect [11], leading to a global increase in temperature, called global warming [9]. Currently the international maritime organisation (IMO) has indicated that the maritime sector is to pursue reduction of those GHG reductions in several stages [12]. Even if according to some global warming cannot be doubtlessly blamed on GHG, it is not circular to use high amounts of fossil fuels. This makes it at least a sensible idea that using high amounts of fossil fuels could disturb the natural equilibrium on earth and should be prevented. The rest of the text is written under the presumption that the cited theories surrounding global warming are true.

The largest contributor to anthropogenic climate change is carbon dioxide (CO_2), but there are many other gases that cause global warming[11]. The IMO has described the most important contributions of GHG's originating from combustion of fuel; CO_2, methane (CH_4), N_2O, other NO_x, CO and non-methane volatile organic compounds (NMVOC). These six types of emission from combustion will also be the ones that will be considered in this research. Other sources of GHG's are refrigerant and air conditioning gas releases.

All emissions from fuel combustion and the use of refrigerants are combined to calculate the total equivalent CO_2-emissions of the shipping trade annually [12]. In a prior IMO study annual CO_2 and CO_2e emissions of shipping and globally have been found to be as shown in table 2.1. CO_2e-emissions are a way to account emissions of other GHG's than CO_2, expressed in the equivalent amount of CO_2e that would have to be emitted to reach the same effect over a certain time period, in the IMO study a time period of 100 years. According to the same study it can be expected that these shipping emissions will grow between 50% and 250% in 2050, if no measures are taken.

	Global emissions	Total shipping	International shipping
CO_2 emission relative to global	100%	3.1%	2.6 %
CO_2 emission in million tonnes annually	33,273	1,013	846
CO_2e emission relative to global	100 %	2.8 %	2.4%
CO_2e emission in million tonnes annually	36,745	1,036	866

Table 2.1: Overview CO_2 and CO_2e emissions of shipping, based on the average between 2007 and 2012[2]

2.2. Greenhouse gas emission reduction

As has been explained in the previous section, the emission of GHG increases global warming and therefore is to be reduced. The IMO has decided to address this issue in global shipping and therefore it has set up a future vision of the pace to reduce the GHG emissions in the upcoming years. This vision will be outlined in the following part of this section. The next step is to investigate ways to reduce GHG emission on board. First it will be explained how in general GHG emissions from a ship can be reduced and afterwards some thought is given about other pollution or emission that could be related to the reduction of GHG's on board.

2.2.1. Incentives to reduce greenhouse gas emissions

Even though many ship-owners might feel some pressure to reduce their GHG emissions, the costs prevent them from doing so and nobody forces them to do so yet. But where does this pressure come from? One of the reasons ship-owners reconsider their fuel is the fact that the IMO has shown an ambition to reduce the GHG emission of the global shipping fleet.

The IMO has indicated an initial strategy on reduction of GHG emissions of shipping. This strategy should lead to a CO_2 emission reduction of the international ship fleet of at least 40% by 2030, and towards 70% by

2050, compared to 2008 [12]. In practice all ships operating internationally must comply to the rules of the IMO, so this ambition shows why ship-owners would feel pressured to seek solutions to reduce their carbon emissions.

Besides the IMO's ambitions there are also several other reasons that might push ship-owners towards renewable fuels, possibly even before the IMO imposes rules. Customer demands, charterer demands, possible CO_2 charges in certain ports or the inaccessibility to fossil fuel oil in certain ports are several of other possible future scenarios that demand a decrease in GHG emissions or a change in fuel for existing ships. So even if the IMO will in the future not push towards forcing rules on existing ships as well, ship-owners might still want to reduce their CO_2 emissions.

This means that it would be useful to develop solutions to convert a ship from a more conventional to a less GHG-emitting power supply system, as this could help both ship-owners and a quick transition in general. Which measures could be taken to pursue those reduction goals will be explained in the next section.

2.2.2. Reduction measures

There are many ways to reduce GHG emissions and these can reduce any amount between 0% and 100% of on-board emissions. As an example, several ways of reducing GHG emissions have been listed and categorised, but there are more measures, especially in operating a ship ([12], [13], general thought):

- Reducing the usage of stored energy
  - Slow steaming
  - Less or shorter voyages (Different planning strategy, higher utility rate, reduced globalisation)[1]
  - Using wind and/or solar power on board
  - Installing a ship to shore power connection to reduce local emissions in port
- Reducing the production of GHG's from stored energy
  - Using a fuel containing less carbon
  - Using a fuel with a closed carbon cycle; no net CO_2 emissions
  - Using an energy carrier that does not produce CO_2 or other GHG's
  - Using a power supply unit that has higher efficiency or improving the current engine efficiency
- Reducing CO_2e-emission from the produced GHG's on board
  - Capturing carbon emissions
  - After-burning VOC's from exhaust or waste gas

It can be seen that the measures have been categorised by the way the emission of GHG is reduced; reducing the necessity of using stored energy, reducing the production from the stored energy or reducing the amount of produced emission leaving the ship. The aim of this research is to develop a method for a refittable ship in the context of reducing GHG emissions. As stated in the introduction, the focus in this research will lie entirely on the measures from the second category. The measures in this second category can of course be combined with measures from the first and in some cases the third category. Especially when using energy carriers with low energy densities the combination with measures from the first category might enable the ship to have a larger range with the energy that can be taken on board, which is better for bunkering or recharging choice or for having to reserve less useful space for the energy carrier. In the last section of this chapter more information will be given on the alternative power supply systems that can reduce production of GHG's on board.

2.2.3. Counting the cost

It is very noble to reduce GHG emissions, but it comes at a price, not only in acquisition and operation cost. Reducing GHG emissions can increase other pollutants, energy consumption and depletion of resources. These facets of reducing the GHG emissions on board will be explained one issue at a time.

Other gas emissions Ships do not only emit GHG's but do unfortunately also produce other emissions. Some of those are fuel based, others are caused by a combustion process and a final category by slipping of chemicals. All of those can be prevented or reduced.

[1] These are measures to be taken on market-level or fleet-level rather than per ship

First, impurities in fuel will also cause impurities in exhaust gas, such as sulphur oxides. Sulphur oxides are formed when sulphur from fuel is combusted. These sulphur oxides can cause local environmental issues such as acid rain and decreased visibility [9] and can cause health issues in people inhaling the gases. Especially heavier fuel oils contain different impurities with different effects [14].

Secondly a combustion process can cause incomplete combustion, or accidental combustion of nitrogen from the air. Incomplete combustion of hydrocarbons can cause other carbon bonds and particulates to form, and this is mainly caused by engine processes. These carbon bonds such as methane and other VOCs are also GHG's. The particulates can cause pollution and airway problems. On the other hand, creating heat in a process can cause the formation of nitrogen oxides (NO_x), as 78% of the air consists of nitrogen and under heat this can react with the oxygen present in the air to form nitrogen oxides. NO_x and CO_2 emissions can be related to each other. NO_x forms under high temperatures and CO_2 forms with complete combustion of carbon-containing fuels, producing heat in the process. Several ways to lower NO_x emissions in a diesel engine lead to higher specific fuel consumption. Therefore, these measures in many cases also lead to a relative increase in CO_2 emissions and sometimes even an increase in PM [10]. In all ways of power generation, it should therefore be recognised that high temperatures could lead to NO_x formation, but that lowering efficiency could lead to an increase in other emissions on board or on land.

Finally, there are gases from refrigeration systems and other systems on board that have a much higher GHG effect than CO_2 [11]. The emission of those refrigerants can be prevented by choosing different working fluids for refrigeration and other systems and by maintaining them. Not many systems within the scope of this investigation are expected to require a refrigerant, but it is something to examine as a spill of refrigerant could reduce the effect of the GHG reduction.

Energy demand and CO2 production for the sourcing and distribution of fuel Nothing comes for free and neither do fuels emitting less GHG's. When looking at the direct emissions of using fuels on board, the image is not complete, as fuels cost energy to source and distribute. More information about alternative fuels can be found in the next section, but it needs to be realised that using alternative fuels could cause an increase in GHG production globally. For example the carbon footprint (the amount of CO_2e produced and transported per standardised unit) of hydrogen and methanol produced from natural gas is actually higher than that of MGO and HFO [3], even though the emissions on board are completely or largely reduced. This is caused by the carbon atoms in the fossil fuels used to produce this hydrogen and methanol. Also, the synthetic production of fuel costs a lot of energy, for a number of fuels it was determined that the fuel costs 170% - 360% of its energy contents on energy to make [15]. It is not something that will be specifically looked at in this research, but it should be considered when a fuel is applied in a practical situation.

Other pollution and ecological damage on shore In general, any material that is used will at some point be discharged to the environment or a recycling process. Any resource that cannot be recycled or reduced to something reusable will be added to the collection of waste and pollution caused by humans. When using special materials for power components that cannot be recycled or neutralised, this might also damage the environment. This is something to study when making up a balance in the total environmental benefit (or harm) of a certain alternative installation. When looking into biofuels, the origin of these biofuels is also very important to keep track of, because there are origins of biofuels that can be disputed [16]. Also, aspects as noise, spills and slip of gases should be considered continuously.

2.3. Ship's power supply

As the purpose of a cargo vessel is to move cargo, it needs propulsion. In the previous section it was explained how fuels are thought to cause problems because of emissions, in this chapter it is explained what the alternative fuels are that could decrease this issue.

Any ship is using power in some sort. Unless a ship solely uses wind and solar power as power sources, it will have some energy storage and power supply unit on board. This power supply unit typically makes use of a fuel but could also use batteries. The prime function of a cargo ship's power supply system is to move the ship with its cargo. Other functions are e.g. to provide electricity, to heat the wheelhouse, to cool the cargo-space or to handle a ballast system. To maximise profit of a commercial ship an installation is required that costs the least money over the life-time of the ship, in which the parameters are capital expense, breakdowns (incurring repair costs and loss of trading time), maintenance, spares and fuel costs [17]. Over a century ago, shipping has started a transition to sailing on diesel and other fossil fuel oils [18] and still over 99% of all ships are currently using fossil fuel oils [2]. Most ships use these fossil fuel oils in a diesel engine: a reciprocating engine according to the diesel process[19]. The costs of a diesel engine are low compared to alternatives, causing them to be the main propulsion method for ships [13]. When looking at maintenance cost and reliability, diesel engines are not the machines with the lowest maintenance requirements, but because many of the maintenance operations are simple enough to be performed on board by the crew and crew is already trained to maintain diesel engines, these life-cycle costs can also be lower compared to other systems. A criterion for shipping that is expected to become more important is the amount of emissions of an installation. This latter factor is not in favour for fossil oil fuelled diesel engines, hence the search for an alternative.

This section provides an insight in what kind of installations could be expected in the light of a refit to change ship emissions. First an introduction is given in conventional marine power supply and some definitions that come with it. Secondly the available energy carriers are discussed and finally in the third section of this chapter the power supply means are discussed.

2.3.1. Power supply definitions

As has been stated in the introductory part of this chapter, the main power supply means for ships are currently based on fossil fuel oils in a diesel engine. However, looking at alternatives as well it is important to define a certain lexicon for the rest of this report to have a clear definition of the subject.

A ship powered by a diesel-engine could have the following installation, as pictured in figure 2.1: Tanks containing diesel located in the double bottom or sides of the ship, fed into the diesel engine where the chemical energy from the diesel is converted into heat and rotary kinetic energy. The rotary kinetic energy is fed into a reduction gearbox with two outgoing shafts: one that has a suitable rotary speed for the propeller, providing thrust and the other one at another rotary speed suitable for the power-take-off generator (PTO) which provides electrical power for the rest of the ship during normal operational sailing conditions. Waste heat is mainly lost by cooling water and exhaust gas, a smaller part is lost through engine room ventilation. Some systems can use heat from the cooling water or the exhaust gas, such as freshwater generators, heating systems or fuel treatment systems, which then help reduce heat losses. In situations where the main engine is not delivering suitable rotary power for electricity generation the electricity is provided by one or more auxiliary engines. This installation is only a sketch of the real situation however, where a large amount of auxiliary equipment is necessary to increase performance and lifetime of the system and perform other functions. These include fuel pumps, fuel separators, start air systems, dirty oil drainage, control systems, measuring systems and so on. Apart from the propulsion equipment there is more equipment on board, such as for navigation, cargo heating, cargo handling and accommodating crew. This example is only one possible set-up, there is a wide range of possibilities that include simpler situations without a gearbox or more complex situations with multiple engines or propellers. For more information on the relationships between propeller and engine and on the wide variety of options it is recommended to study the book "Design of Propulsion and Electric Power generation Systems" [19].

With the given example some definitions will be provided. These are the definitions used in this research, to provide a solid base to talk about these subjects. Other texts might have different nuances and not all of these definitions are found in every dictionary, so therefore this research includes its own definitions, with the corresponding components given from the example as an illustration, which is also depicted in figure 2.1

- **Power supply system** The power supply system of a ship in this report is the collection of systems that are taken on board to provide power to the propeller the ship and to all the other users. The power supply system of the example includes all mentioned components excluding the equipment that is not necessary for propulsion or power supply, such as the navigation, cargo heating, cargo handling and crew accommodating equipment.
- **Power supply unit** The power supply system is built around the power supply unit; this is the primary conversion unit within the system, where the energy carrier is consumed or released of its energy to provide power to the rest of the system. In the example this is the diesel engine.
- **Auxiliary equipment/systems** The auxiliary equipment on board is all equipment that does not propel the ship. This can be divided in **propulsion support, general support and operational equipment** [19]. The propulsion support equipment is the equipment necessary to let the power supply unit function; in the example these are e.g. fuel pumps, fuel separators and engine coolers. The general support is everything that is supporting other non-operational functions, such as the accommodation systems and navigation. The operational equipment is the equipment necessary for operational functions such as cargo heating or cargo handling.

- **Energy carrier** & **Fuel** The energy carrier on board is the medium that can be taken on board in which energy can be stored for later usage. In many cases the energy carrier will be a fuel, which is a liquid, gas or solid that can be used as to deliver energy through combustion or a chemical or nuclear reaction. An energy carrier that is not a fuel is a battery. In the example the energy carrier is diesel, which is a liquid fuel.
- **Energy storage** & **Tank** The energy storage actually is the energy carrier storage; it is the unit in which the energy carrier is contained. In the case of a fuel the energy storage is typically a tank; a closed volume in which the fuel can be stored. In the example the energy storage is the tank in the double bottom of the ship.

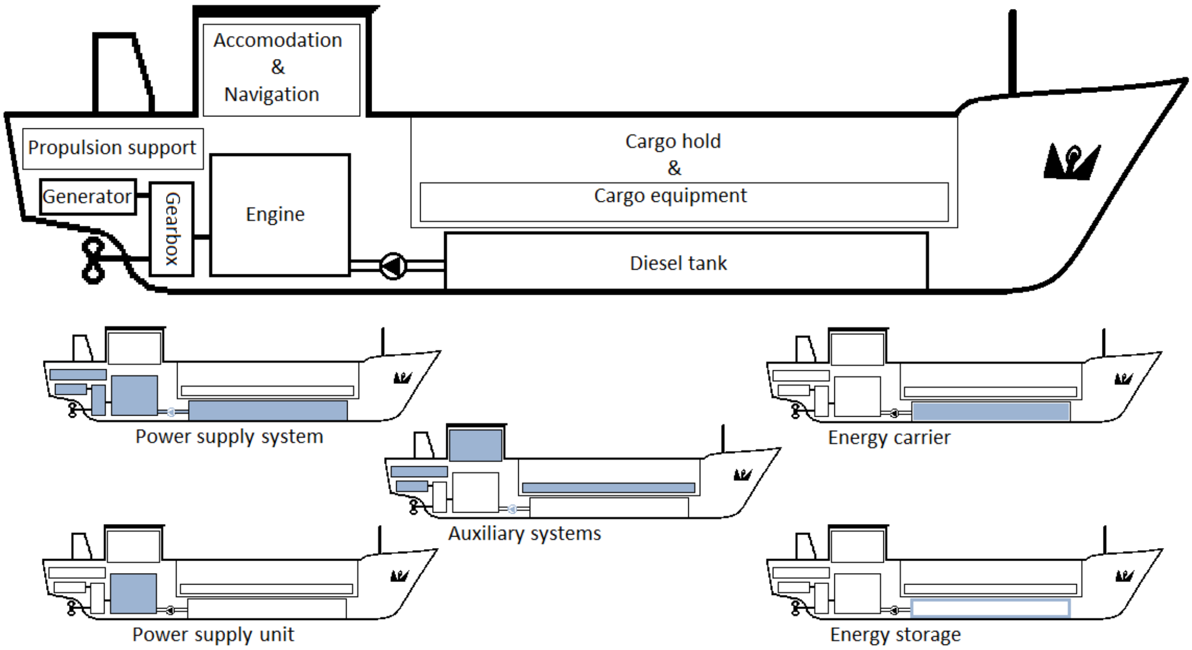

Figure 2.1: Illustration to the definitions used in this report

2.3.2. Available energy carriers

In this section the possible energy carriers for use on board of ships will be discussed. This will be done by starting from what energy carriers could be used, then looking at their most important characteristics, analysing their properties and finally making a smaller selection of fuels which are deemed realistic as candidate for this study.

Current and alternative fuels As stated before, currently the main energy carriers used in shipping are fossil fuel oils such as marine diesel oil (MDO), MGO and HFO, which account for over 99% of maritime fuel consumption [2]. Other energy carriers used in operating ships or ships under order are LNG, batteries, liquefied petroleum gas (LPG), methanol and hydrogen[20]. However, LNG usage accounts for less than 1% of the total fleet and the others have such small share that they have no statistical significance [2]. Some of those are used in a hybrid or flex-fuel configuration, where it is combined with fossil fuel oil, for example LNG powered ships which use diesel as pilot fuel or ships that can sail short times on batteries, but have diesel engines for overseas trips. There are many more available fuels, however, as is shown by the large selection of fuels in figure 2.2, where the possible sources of the fuels are also indicated. Only four of those energy carriers do not produce CO_2 emission when using them; batteries, hydrogen (carriers), ammonia and fissile material. In principle any renewable chemical or bio fuel can be produced in a sustainable and GHG-neutral manner by using renewable electricity and renewable chemicals sources, but this is something to watch closely, just like the production of other emissions such as NO_x, CH_4 or NMVOC. This was already explained in section 2.2.3. The Power to Gas and Power to Liquid fuels come in a variety of forms, currently these processes are already applied in forming a liquid fuel from gas. These fuels can be made from renewable carbon sources (e.g. captured CO_2) and water, closing the carbon cycle.

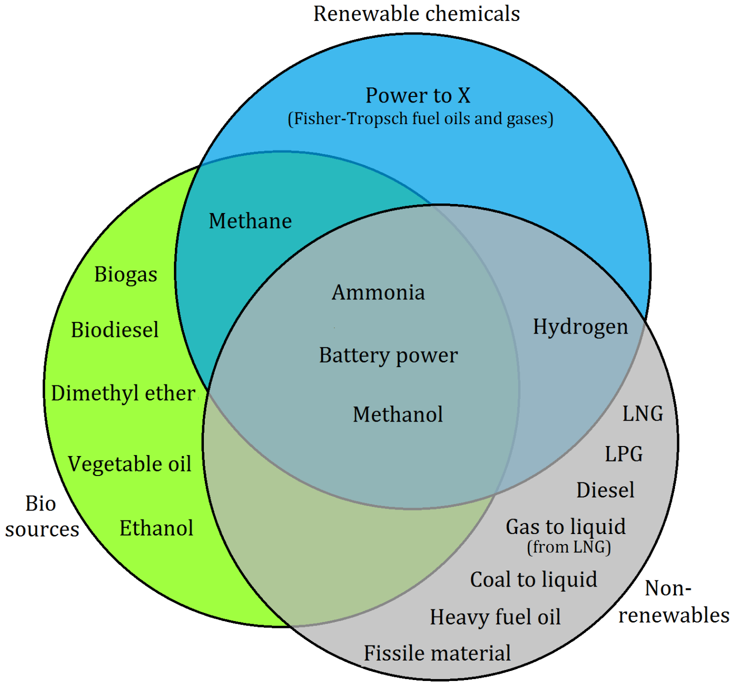

Figure 2.2: Selection of possible marine energy carriers, sorted according to source of energy/fuel (own image, based on common information and [18])

Viable options in the upcoming 30 years It is possible to reduce the number fuels that can be considered as an alternative for the short-sea cargo ship design in the upcoming 30 years by looking at some similarities between them and looking at the restrictions following from the scope of this investigation. First, the selected fuels should reduce the amount of GHG emissions of the ship. This means that any fuel that has CO_2e emissions similar or worse compared to diesel is excluded. From the non-renewables this leaves LNG, LPG, and fissile material. The emission reduction of LNG compared to HFO can be beneficial, as it decreases SO_x by 100%, PM by almost 100%, NO_x by 40-85% depending on the engine type and CO_2 by 25-30% [21]. However, there are more GHG's than CO_2 alone and methane has much higher impact than CO_2. Taking methane slip into account, the CO_2e emissions are about 10.5%[21] up to 20%[22] lower compared to HFO. LPG will have a lower reduction in CO_2 because of the higher carbon content. Neither of these fuels therefore seems to be the answer to large CO_2 reduction, but they are technically ready, and they do contribute. Another advantage of installing these fuels is that in due time the systems could be switched to fuels with the same chemical composition but produced synthetically. All the other fuels are less available yet and some have a lower technological readiness but can be produced circular and therefore reduce net CO_2 emissions completely.

The second restriction is that the power source should be available for operation of a cargo ship within 30 years. For political reasons it is expected that fissile materials are not suitable for international operation the upcoming 30 years. Considering a sea-going cargo ship, this would leave a very small market even if the ship were to operate in national waters in the unlikely event it would become legal to use nuclear power in these waters, so it is decided to not take fissile material further in the investigation.

Looking at the available renewable fuels, a great similarity can be seen between a selection of fuels. These are the carbon-containing gases, such as biogas, dimethyl ether (DME) and some power-to-gas fuels, and the diesel-like fuels such as biodiesel, vegetable oil and power to diesel. Even though these fuels might require different engineering challenges in regards of their corrosion, filtering, pumping, ignition and for the gases also possibly their storage pressure, for the purpose of comparison they are compared as two groups (diesel-like fuels and alternative gases) because of their similar application and necessary fuel containers. It is assumed that the diesel-like bio- and synthetic fuels can be contained in the double bottom or sides of the ship and that no added construction in necessary for them. The considered biofuels are pure plant oil (PPO) and fatty acid methyl esters (FAME). The gases are assumed to be contained in pressurised containers. For synthetic and bio methane the values for LNG are to be used as LNG mainly exists of methane.

Furthermore, batteries as an energy carrier are an option to be used as addition to one of the fuels in a hybrid configuration or as a buffer to serve peak power demands, depending on the power plant configuration. Batteries are currently not suitable to be used as a main power source for cargo ships, because even for inland shipping the sailing range on batteries would not be sufficient [23] and at sea this problem is expected to be worse. Therefore, a small number of fuels remains that are selected to be compared. They can be found in table 2.2. The full table can be found in appendix A, including the sources to the data.

Fuel	Chemical formula	Storage conditions	Energy density [1] [MJ/dm^3]	[MJ/kg]	Possible sources
MDO	Various ±86% C	Ambient	36.0	42.6	Fossil
Diesel fuels [3]	Various	Ambient or heated	34.8	37.8	Bio or synthetic[2]
Ethanol	C_2H_5OH	Ambient	21.1	26.7	Bio or synthetic[2]
Methanol	CH_3OH	Ambient	15.8	19.9	Bio or synthetic[2]
LNG	>87% CH_4	p_0 @ -162 C°	20.6	48.6	Fossil
LPG	C_3H_8,C_4H_{10}	8.8 bar @ 27C°	24.4	45.5	Fossil
DME	C_2H_6O	5 bar @ ambient T	19.2	28.9	Bio or synthetic[2]
Ammonia[4]	NH_3	p_0 @ -34 C°	13.3	18.6	Bio or synthetic[2]
Hydrogen	H_2	p_0 @ -253 C°	8.5	120.1	Synthetic[2]
		700 bar @ 20 C°	7.0	120.1	
		500 bar @ 20 C°	5.0	120.1	
		350 bar @ 20 C°	3.5	120.1	
	$C_{21}H_{38}$ / $C_{21}H_{20}$	LOHC: Ambient	6.7	4.5	Electric[2]
	$NaBH_4$ / $NaBO_2$	Powder	27.3, 26.2[5]	25.6, 14.7[5]	Electric[2]

1: Based on the Lower Heating Value
2: Dependent on the source of the used chemicals and power whether this is renewable
3: Used values are for pure plant oil and fatty acid methyl esters
4: Ammonia can also be stored at 10 bar at room temperature [15]
5: Value for delivered energy per spent fuel ($NaBO_2$), which must remain on board after dehydrogenation

Table 2.2: Characteristics of comparison fuels(Sources: See appendix A)

Storing fuels Liquid fuels at ambient conditions can be stored in any space that is watertight and allowed by class, so the only extra construction necessary for their storage would be outfitting like piping for de-aeration and transport if voids can be used that are there already. In that case the energy density will be in the same range as the liquid without storage. In the case of low flashpoint fuels, such as ethanol and methanol it might depend on the location of voids and the construction around it whether it would require extra construction.

Especially hydrogen has different ways to store it. In the field of hydrogen carriers there is a wide variety of options, but only very few of those material-based hydrogen storage methods seem to be mature enough to be applied in the upcoming decades [24]. A hydrogen carrier is a chemical substance from which hydrogen can be extracted in a chemical process.

Two of those hydrogen carriers are shown in the table, they seem to be most mature based on general perception. Of those two, only the liquid organic hydrogen carrier (LOHC) is already operable on commercial scale, but not yet in marine applications. The big advantage of this LOHC over compressed or liquid hydrogen is ease of handling, as it is a fluid with properties comparable to diesel, instead of a highly flammable gas with high storage demands. When applying the LOHC, a release unit is necessary that can extract the hydrogen from the LOHC, after which the discharged LOHC must be stored on board to be recharged on shore again [25].

The $NaBH_4$, or sodium borohydride, is a light powder which can also be stored as a less energetic slurry, in which with the addiction of pure water hydrogen can be extracted from the $NaBH_4$ and from part of the added water. The process needs pure water, some activator fluid and the $NaBH_4$ itself and produces sodium metaborate ($NaBO_2$), hydrogen and heat (40 MJ/kg hydrogen) [26]. Just like with the LOHC, the discharged $NaBH_4$ ($NaBO_2$) must be stored to be brought back to shore. The $NaBO_2$ molecules are heavier compared to the $NaBH_4$ molecules, so the energy density should be based on the spent fuel rather than the $NaBH_4$ itself and therefore in regards of weight it might not be an issue if the $NaBH_4$ is stored as a slurry instead of a powder. The process of producing hydrogen from the $NaBH_4$ is rather simple, but does nevertheless require a reactor, some activator or catalyst and a supply of pure water. It is suggested that this water supply could be from a fuel cell, which has pure water as emission, but if seawater would have to be desalinated and purified on board this will require part of the produced power on board.

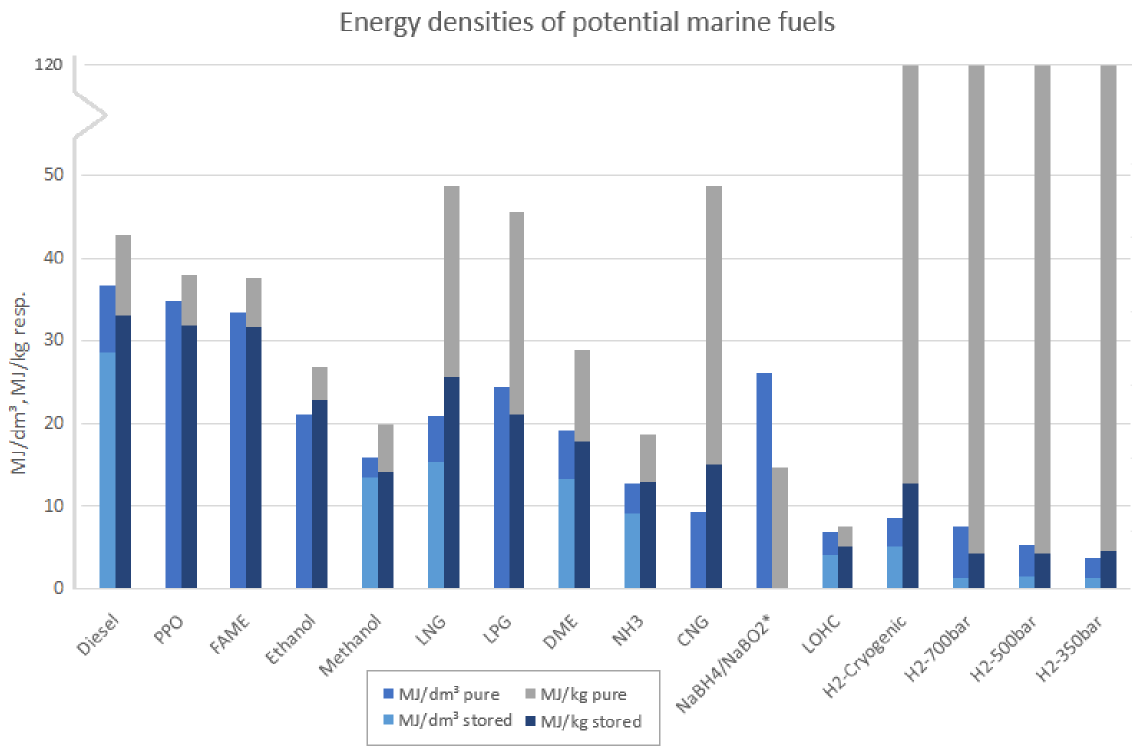

Figure 2.3: Bar graph of the energy density of selected fuels, where data was available the energy density including storage is also shown (Sources, see appendix A)
*Relative energy densities shown for the spent fuel $NaBO_2$

To compare the fuels more easily on the space they might take up on board, a graph is constructed with the energy densities in figure 2.3. For a stored fuel, diesel has the highest value. This is an important reason for the success of diesel as fuel and shows one of the technical disadvantages of alternative fuels. The space a fuel requires, as well as the weight, play an important role in the decision which fuel to choose. In chapter 4, where the case ship is presented a choice will be made in energy carrier.

2.3.3. Available power supply units

The next step taken is to investigate the energy conversion on board. Currently there seem to be mainly 4 options and some combinations, with most (dis)advantages regardless of the fuel used. These options are listed in table 2.3. All comparisons made in the table are done in relation to the internal combustion engine (ICE). These options could either be combined with an electric motor connected to the propeller or, with exception of the fuel cell, with a gearbox connected to the propeller.

Fuel cell systems As a fuel cell system is relatviely new in the maritime field they receive some further attention. A fuel cell system is a system in which a cathode and anode are used to extract the electrons from a chemical process to develop electricity. This typically takes place in a stack of fuel cell plates to develop sufficient power to be processed and multiple stacks form the installation together with many auxiliary components, which take up the largest volume. There are different kinds of fuel cells that have different advantages and disadvantages, but in general the properties from the table apply.

The fuel cells that have had most coverage in the literature up to this point are the low temperature proton exchange membrane fuel cell (LT-PEM FC), the high temperature proton exchange membrane fuel cell (HT-PEM FC) and the solid oxide fuel cell (SOFC). In this research, focussed on short-sea cargo ships, only the LT-PEM FC has been used for three different reasons, based on information from [18], [13] and [29]. First of all, the LT-PEM cell has the advantage to be the smallest and least expensive of the three. Secondly, it is the only type of FC that is able to withstand the fluctuations of the propeller and energy demand of a ship, so it does not demand a buffer battery. Finally, it is the type of FC that most information is available on within this

Internal combustion engine	+ Lot of possibilities in fuel + Well developed + Reliable and familiar technique	- NO_x production - Noise and vibration
Fuel cell	+ Quietest + Fewest non-GHG emissions + High theoretical efficiency	- Voluminous - Slow power in/decrease (some) - Some quite expensive
Gas turbine	+ Low vibrations + Fewer non-GHG emissions + Often in a module + Some: only one moving part [27] Turbine self has high energy density	- Needs large funnel - Needs high quality fuel - High investment cost - Low efficiency - Difficult to repair in situ
Steam turbine	+ Low vibrations + Fewer non-GHG emissions	- Very large machine & funnel - High investment cost - Low efficiency
Combined gas turbine and steam turbine integrated electric drive system	+ Low vibrations + Fewer non-GHG emissions + High efficiency	- Largest equipment & funnel - High investment cost

Table 2.3: Advantages and disadvantages of several power supply units([19], [3], [28] and general knowledge)

research.

The other two mentioned FC types also have advantages however. The SOFC has the highest efficiency and is insensible to fuel impurities, making it possible to fuel it with a multitude of fuels, but is the slowest responding and largest installation. It also has high operating temperatures which can be an advantage when combining it with reforming or other heat demanding processes. The HT-PEM FC is in between the other two with its characteristics. It is equally large and efficient to the LT-PEM FC, and is in between the LT-PEM FC and SOFC in its responsiveness, price, operating temperature and fuel quality.

Meaning of the advantages and disadvantages It cannot be concluded from this information what the best solution is for a ship without the context of a specific ship. All five options are installed on ships and have been chosen based on how their properties fit to a situation. In the PERFECt ship project for example a LNG COGES (Combined gas turbine and steam turbine integrated electric drive system) plant was suggested as an efficient option for ships above 35 MW to reduce emissions [28], but this restriction already shows that below 35 MW this might not be the most suitable option. In most ships an internal combustion engine based on the diesel process is used [19] with the expectancy that it will be the most profitable option. Therefore, only a comparative investigation for a specific case can lead to a realistic estimation of suitable power supply units.

In this research, the available power supply units are only used to come to a case to apply the method to. This can be found in chapter 4. More information on the power supply units can be found in [19], [3] and [13].

This information on the power supply options will be used in section 4.2, where it will be combined with the information on the fuels and information on the verification ship.

2.4. Relevance to the research

The information in the preceding sections are hardly of influence on a method of modular design. It is part of the context for the method, however. In chapter 4 the information will be used to find suitable installations for a case ship, to verify the steps of the method. To perform the analysis of which power supply units and which fuels are suitable as a test case, the information will be used in section 4.2. In case anyone would consider applying the information in this research, the information from section 2.3.2 and 2.3.3 will help them in the overview of what is available for alternative power supply configurations.

3

Reasons and aids to refit a cargo ship

Refitting a ship can be simple. You cut a hole in the hull, remove the old item, and install the new one, after which you repair the hull. The task becomes more complex and consequently more costly, if swapped items are not supposed to perform the same tasks, have different sizes, are blocked by other items or are to be placed in areas where other items are already installed. Considering that for exchanging a whole power supply system, components are in different locations on the ship and engine room in a traditional design, it can be imagined that such refit is not automatically simple. In this chapter the aim is to investigate what information is available on theories and practical approaches that help in making a ship suitable to undergo a refit during its life, with a specific focus on modularity.

The first part of this chapter focusses on different ways of enabling a refit of a ship in general terms. It is first explained why ship-owners would like to refit their ship, to know what aspects of the refit are important to the ship-owner. Secondly the other aspects of the design that could be helpful in designing the ship for a refit are explained. One of these aspects turns out to be modularity, as was expected by the problem owner.

Modularity will therefore be investigated in the remainder of this chapter. First information on modularity in general is collected to find the basic principles. Secondly modularity in shipbuilding is studied and other applications of modularity, deemed of importance for this study.

3.1. Refitting a ship

To design a ship for a refit, first the background of refitting a cargo ship is investigated. Since a refit costs money, it will not take place without a compelling reason. A refit can be costly dependent on the circumstances. Why a refit will or will not take place will be explained first.

Secondly, it will be studied how it is thought refits in naval ships can made easier. The reason this is investigated for naval ships is that it seems to be the only ship type that refits are extensively studied for in detail. The general ways to decrease the impact of a refit that are used in naval ships will therefore be studied in section 3.1.2.

3.1.1. Reasons and important parameters for a refit

The reasons for a refit can be diverse, even when specifically looking at a refit with the aim to reduce GHG production of a cargo ship. A few reasons that might be relevant in the future are:

- Charterers offering better rates for low-carbon or carbon-neutral shipping
- Low-carbon or carbon-neutral shipping becoming a niche market with better prospects for the future
- Regulations coming into place that make fossil-fuelled shipping less attractive in general
- Local legislation reducing the operational possibilities for fossil-fuelled shipping

In short, the reason for a refit is expected to be found mainly in the shipping market or regulations. On one hand this means that in many cases not more money is earned after the refit, and on the other hand this means that not refitting could cost money. Both times the refit should cost as little money as possible, as it is not expected to pay back fast. As the market has high influence on why a refit should occur, it can also be thought that the shipping market has a high influence on which system will be the best solution, as well as the fuel market and regulations.

In deciding whether to refit, there is another parameter that is not market dependent: the remaining lifetime of the ship. This remaining lifetime influences the possible earn-back period of the investment. In a refit some brand-new components are installed that can last several decades. The design of the ship is aimed at an operational time of 25 to 30 years. Fatigue of the hull is one of the factors in the aging of the ship, so the total lifetime of the ship will not be elongated (much) by having a new power supply system. The expense of the refit may be small in comparison to the acquisition of a ship, but the annual cost of the refit will be relatively high, because the remaining lifetime is only a few years. This issue of lifetime may play a big role in the decision what solution fits the ship best. When a new installation is significantly larger or heavier than the initial one this could increase the difficulty earning the refit back even more. Larger or heavier installations can lead to an increase in gross tonnage (GT)[1], a decrease in available payload (DWT), a decrease in available cargo space or even combinations of these disadvantages. This amplifies the difficulty to pay back the investment, as the ship will be able to earn less money in the limited remaining years.

This limited pay-back time may lead to concessions in environment-friendliness. If a zero-emission solution cannot be earned back at all, but a limited emission solution can, the limited emission solution can be justified, as the limited emissions are still more environmentally friendly than continuing to sail in the classical diesel ICE configuration by not refitting at all.

The short remaining lifetime of the ship could also lead to the availability of second-hand environmentally friendly components when the ship's hull needs to be scrapped, but the parts are still young. If the method would lead to standardisation of installations, if would make it easier to re-use the installations which could reduce the cost of the refit further by increasing the second-hand value of parts.

3.1.2. Low-impact refit

In this research, a low-impact refit is assumed to be a refit where it is aimed to have as little construction work and as few new components as practically possible. This is not necessarily true for every ship, however. There are different ways a conversion can be viewed as low-impact, as there are several factors that play a role in the impact of a conversion for the ship owner. The ratio of the costs for a particular ship will determine what a low-impact refit will be for that ship.

Examples of direct costs of a refit:

- Hiring quay or dock of the shipyard
- Acquisition of components and steel
- Labour of construction and installation

Examples of indirect costs of a refit:

- Not earning money because of staying at shipyard, whilst recurring costs continue
- Having to sail empty to/from shipyard

Acquisition cost and labour are thought to be the main direct costs, which depend on the quality of the products and the location of the yard. For a European short-sea vessel the shipyard is most probably in or around Europe where labour is relatively expensive, so extra work by moving components around that can be re-used should be avoided. It is dependent on how much income is lost during the stay whether a lower shipyard-bill or a shorter stay[2] is more important, but it is expected that for a cargo ship the balance lies more towards a low bill because of relatively low margins in cargo shipping. **The focus of the design therefore lies on reducing direct conversion cost in terms of acquisition and labour.**

As demonstrated in figure 3.1 there are more or less rigorous ways of refitting the power supply system. It is expected that the upper kind of rigorous solution will have too high acquisition cost because of the high amount of steel and the large number of components, despite possibly being a fast solution. Therefore, solutions like exchanging a complete block-section of a ship is out of scope, just like comparable options with complete, large, pre-outfitted blocks. **The aim will be to reduce the number of components to be exchanged, making them well removable and having a ship suitable for multiple solutions from the start to avoid construction work.** How this is expected to be achieved will be explained in the upcoming sections.

[1]An increase in GT could lead to higher port fees and crew expenses

[2]This can be related, but they are not the same. The ship-yard-bill includes rent of the quay or dock, materials, and labour and only the rent of the quay or dock is determined by the length of the stay. If the ship-yard has very much work to prepare the refit in advance by constructing building blocks in advance so that a ship is moored only very shortly the ship-yard bill may be still very high, compared to a situation where all work is done whilst the ship is moored, but there is less work for the shipyard to be done because there is less installation- and construction work

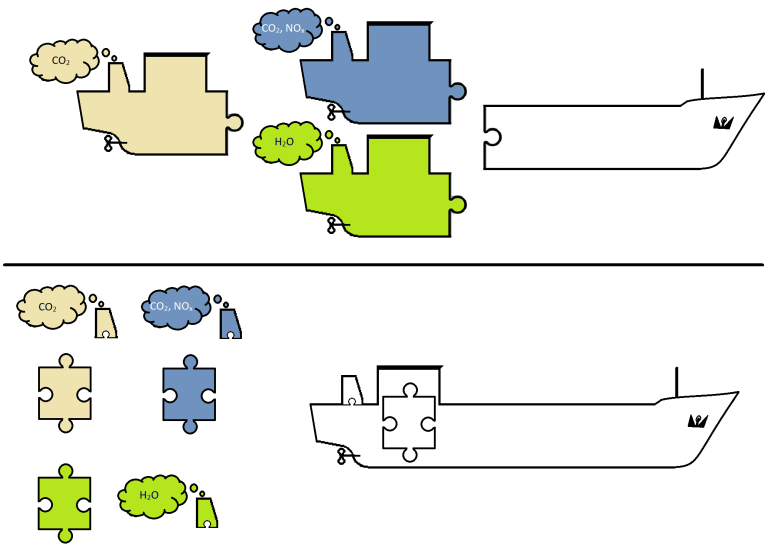

Figure 3.1: Graphical representation of different ways 'low-impact' could be defined: lower option is used for the definition in this research

3.1.3. Technology insertion for cargo ships

According to the previous text, there could be compelling reasons to refit the power supply system of a cargo ship and these reasons are also expected to motivate specifically a refit where a limited number of components is exchanged whilst the components that are not refitted are preferably left untouched. The question so far remains however, how can this be done? In commercial payload ships it seems that not a lot of work is put into how one could design a ship that can be upgraded throughout its life. In multiple naval texts this process of regular upgrade refits is mentioned. When a ship is designed to be refit with the aim of maintaining or upgrading functionality through installing the newest technological installations throughout its life, this is called technology insertion [30]. The information on technology insertion is used to find out how the design of a commercial ship could benefit from this knowledge in its ability to be refittable.

General refit enablers in a submarine Several thoughts on how a submarine could be prepared for a refit[31] could be helpful for this research. They are the increase of ship size, the use of installation routes, the use of service routes and the application of open system architectures. Especially the arrangement and outfitting aspects seem relevant for the confined space of a cargo ship's engine room as well. To improve moving or installing components in a confined space, the different solutions are explained below, all from the same paper.

The vessel's designed size could be increased, to have more space to move components around. Steel is not that expensive, so it would not be a very expensive solution in that sense, but in many cases, there was a reason that a ship-owner had a limited ship size in mind. This could for example be a threshold in GT, or a certain lock or port the ship should be able to enter. If there is not a specific limit on the size of the ship it might be convenient to make the ship slightly too large for the initial diesel installation, so that more space is available for the alternative installation. An increase in size will most probably also lead to a larger payload, bringing an extra advantage. In the scope of this research's cases it was determined that the hull should remain the same, so this is not applicable in this research, but it could be helpful in other designs.

A suggestion that can be applied is to have accurate and defined installation and removal routes for the equipment. For the submarine this is thought out mainly in extra openings that allow equipment to pass its hull, but in a cargo ship it will require thought on how to remove or install equipment as well. If part of the power supply system needs to be in the vicinity of the drive shaft, but also needs to be refittable, it is likely that it will not be at a convenient location to extract or install it. This means that a route should be planned that will not require excessive work on removing other components and ship structures to remove the refittable piece of equipment. If, for example, the main engine should be removable through the engine room bulkhead towards the hold, the path towards the cargo hold should be easily made free – or even permanently free if that is practicable – for the engine to be removed for an easy extraction. In this research the situation in which a path for a large component is blocked only by auxiliary systems that should be refit simultaneously with the large component is considered an ideal situation, because this allows an efficient use of the available space, without blocking refittable components.

Other suggestions are to use service routing or open system architectures. Service routing is about having dedicated spaces where cables and pipes pass through. To have more flexibility in the adaptation of technologies that were not known during the initial design, it is suggested to have dedicated service routing for cables and pipes. This way any new installation can be connected to the remaining ones and the service space is then available for the pipes and cables of the new installation. Open system architectures are mainly aimed at standardised system connections, physically and digitally. The open system architectures also provide a flexible basis, by providing a common interface and platform for electronic connections, that new installations could be designed to in the future.

Technology insertion at naval surface vessels Another document shows an investigation into adaptability in naval surface ships [30]. In this report, it is pointed out that flexibility and modularity could both help to achieve adaptability, but that they are not the same thing. Modularity allows for an exchange of technology within known boundaries, flexibility allows those boundaries to change. Modularity will receive more attention in the next section, the three mentioned solutions for flexibility will be explained further. Please note that apart from the upcoming paragraphs in this report – and many used sources – the clear distinction between flexibility and adaptability is not used: both principles are called flexibility in the rest of the report.

The first mentioned flexibility enabler is the use of spaces that can change in size or function, which is mainly applicable to ships without payload capabilities. In this way, spaces can be rearranged to have different functions. For example, a ship could be designed with an alternative installation significantly larger than the initial one. The excess space during the operational period of the first installation can have a different initial function and arrangements and function can be changed when the alternative installation is installed. This can be combined very well with the second mentioned means of increasing flexibility: to provide additional space in the ship or in the installation spaces.

Finally, additional services could be provided at a location where in the future different installations may be installed. These services could be for example additional capacity in power, cooling, or bandwidth. They could additionally be provided in terms of pipe and cabling ducts that allow for an installation with more connections to be installed in a certain location. This principle is comparable to the service routing from the submarine refit measures explained earlier.

What should be watched out for, apart from the enabling factors, are the possible disabling ones. When a refittable design is physically possible, it does not automatically mean that the design will be considered safe or that it will be acceptable in terms of parameters such as stability, payload or available cargo hold volume. When working with alternative fuels that are considered to have a low flashpoint, the safety regulations from class and flag can have a significant effect on the design of the systems containing such fuel. This is not something directly related to refitting, but it adds up to the differences between the systems.

Another aspect influencing the refittability of the design are design changes made during later stages of the design or during the operational time of the ship leading up to the refit. Small changes in details of the design can have a large impact on the ability to be refittable, when these small changes lead to big issues. This could be the case if the exit routing is blocked by inseparable items, such as long cables, or by large items or constructions that are moved during the design by a small distance into an area left free for the exit route of another large item. The latter could for example happen if a tank would be enlarged by one frame, whilst it had this specific size because otherwise the main engine could not pass it. Such design changes could also happen when repairs are executed without the proper knowledge by the crew on board about the exit routing.

Modularity to enable adaptability Finally, apart from flexibility, modularity is also mentioned as an enabler of adaptability when looking at naval surface vessels[30]. In the previous text it has been explained what could help to create flexibility, but the modularity has not yet received attention in any detail. There are more suggestions that modularity could help in technology insertion. It may not be specifically mentioned in the text about submarines [31], but when looking at some of the definitions used in section 3.2.1 it seems that in fact certain aspects of modularity are mentioned as a solution, like standardised interfaces and certain modular components. In the introduction of the report it was already stated that modularity could provide the ability to evolve, by allowing a system to be partly upgraded without having to alter the remaining part of the system [4]. When looking at a different approach to technology insertion [32] one of the two enablers of designing for insertion is again the adoption of open system architectures, which is mentioned as a ‘modular open systems approach’ or as a ‘modular open system design’. In these open system architectures, an important aspect is technology independence: ‘Technology independence depends on defining all interfaces such that the individual modules can be redesigned with substitute or upgraded components without impacting their functional interfaces with other modules’. Because modularity allows part of a system to be changed, whilst the rest of the system remains untouched, an important benefit can be reached in systems that have to undergo an update of their system throughout their operational life by exchanging parts of the system otherwise known as ’modules’. To know how to use this benefit in the advantage for designing a refittable ship, modularity needs to be examined closer.

3.2. Modularity for refitting a ship

Since it seems modularity can be used as an advantage in designing a ship so it can be refit with a low-impact, more information on this modularity is necessary. To realise this, a literature study into modularity is performed to show what modularity is, what methods for modular design look like and how these are applied in ship design. A general definition of modularity will be given first, in section 3.2.1. Secondly, some general ways to get to a modular system will be explained. This will be followed by some examples of how modularity is applied in shipbuilding. The chapter will conclude by outlining which theories can be useful for the search for a method for modular design of a cargo ship that allows a smooth refit of power supply components. These theories will form the basis for the development of the method for modular design for a ship in the next chapter.

3.2.1. Properties of modules

It is shown in literature that it is not easy to grasp modularity in one definition that finds full consensus. Multiple literature studies have been performed on modularity (e.g. [33], [34]) and at least in one of them [33] it was found that there is little consensus on modularity. It seems this lack of consensus is mainly found on how to come to modularity, however. Modularity sets rules for an architecture in organisation and product design, but the boundary conditions and precise definition differ. That modularity sets rules in both organisation and product design shows that modularity knows a very broad application. Even some of the claimed advantages and disadvantages vary significantly for different applications [35]. In this section a basis is given for understanding modularity, by finding the main properties of modules and then explaining them.

First, one of the older, well-cited definitions of modularity is given, that fits the properties later in this text [1]:

> “Modularity is a special form of design which intentionally creates a high degree of independence or ’loose coupling’ between modules by standardizing module interface specifications [3]

Several different properties are accounted to modules and modular architecture. The given definition already introduces the independence of modules and the standardised, loosely coupled, module interfaces as modularity properties. However, these are not the only properties accounted to modules, components in modules, and modularity. Six of these properties [4] are listed below.

1. A module is a sub-assembly or component of a larger system
2. A module is (relatively) independent from components outside the module
3. Modular architecture specifies well-defined, standardised, and decoupled interfaces
4. Modules can be recombined into multiple end products
5. There are degrees of modularity, as opposed to integration
6. Not in all circumstances will (more) modularity be more advantageous than (more) integrated design

[3] The original text was "Modularity is a special form of design which intentionally creates a high degree of independence or ’loose coupling’ between component designs by standardizing component interface specifications". Later in this report the word component is used differently and not meaning ’module’, so it was chosen to use the words as defined in this report in the quote from [1] also, to avoid any misunderstandings.

[4] These statements can be found in or backed up by: 1: [33], [36] a.o.; 2: [4], [36] a.o.; 3: [1], [37], [38], [39] a.o.; 4: [1], [36] a.o.; 5: [4], [33]; 6: [35], [37], [40].

Explanation of module properties The emphasis of the properties is different in different texts and when looking at how modularity should be achieved, there seems to be less consensus. There are differences in how a module should be independent, how strict this should be and there are some texts that include additional properties a module should have. Why modularity is not always more advantageous than integrated design will be explained below, after which some attention is given on the types of interfaces that are identified. The other properties of modules as given before will have their necessary share of attention throughout the research where this is applicable.

Despite the advantages of modular design, in some cases integrated design can perform better than modular design. The balance between modularity and integration is something that is expected to be similar in certain aspects for ships and for cars. In cars this is for example the case for the body when it comes to vibrations, where the subtle linkage between several car parts cannot be omitted [40]. For many designs of different kinds, modular and integrated design are combined [37]. This balance, between where integrated design or modular design is more appropriate, must be guarded. It is the aim to have modularity increase the ease of refit for the ship to be designed, but adding modularity to the design will only suit as a theoretical art piece if it would disproportionately decrease ship performance and ship owners would not benefit from it.

The interfaces of a module are the means to how the module relates to the rest of the system. The interfaces are supposed to be standardised or loosely coupled in a modular system. Both properties are aimed at decreasing the difference between how a system functions with alternative modules installed. The standardisation aims at a certain freedom of design within a fixed set of parameters: if the specifications of the interface are met by the module, it will not be important what is inside of the module. The loose coupling revolves around the idea that the rest of the system is not affected by any change of modules. Some claim the system should be decoupled, but in typical situations modules can be thought of that do in fact have effect on the rest of the system [37], so de-coupled is at best very loosely coupled. It can be argued whether it is the interface or the modules that are loosely coupled, as different sources use it differently, but in both cases, it is important the modules do not interfere with each other's functioning as otherwise they are not independent of each other.

Physical appearance of interfaces Interfaces can have different physical appearance. For example, Lego's interface is so standardised that almost any Lego piece can be placed virtually anywhere within the horizontal planes of a Lego environment, as this interface is very versatile. A car engine can typically only be installed in one place in a car, but multiple engines might be suitable for that exact spot and multiple cars might also have that same interface. This can be illustrated by the VAG platforms where Audi, Volkswagen, Seat and Skoda share multiple engines [41]. The interface is not as versatile, but very standardised. Different types of architectures have been named, which sets a standard for the interfaces and how the modules are connected to each other. This is illustrated in figure 3.2.

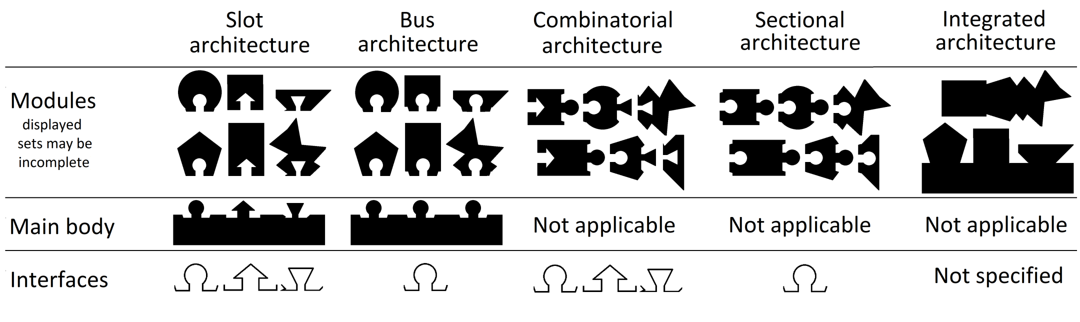

Figure 3.2: Representation of five different interfaces (own image)

These architectures have different names in different texts, according to [42], [43] and [37]. At least five types of architecture are identified, but combinations can occur, and even other versions of these interfaces are identified [43]. The displayed architectures are explained one by one:

- **A slot architecture**[5] is an architecture where a main body is present with different interfaces, so modules can only be replaced by modules with identical interfaces. Example: An interface on deck of a ship for different kinds of hydraulic equipment that can be swapped on that position.

[5] Sometimes referred to as "component swapping modularity"

- In a **bus architecture** a main body is present with several identical interfaces, in which modules can be placed in each of the positions with the identical interface. Example: Container racks
- The **combinatorial architecture** is the type of architecture where modules are only connected to other modules, and the interfaces are all different, but other modules with similar interfaces exist for a certain position that can replace the modules in that position. Example: car engines connected to other car systems
- A **sectional architecture** is an architecture with modules that are only connected to other modules, through identical interfaces. Example: piping systems with bolted flanges
- In an **integrated architecture** components are connected to each other with no standardised interface between them to disconnect and swap them. Depending on how the product is manufactured it may be possible to disassemble it, but it is not the aim to swap parts from it. E.g. a moulded power cord

Multiple kinds of interfaces and architectures can exist simultaneously in a large system. For example, the car engine may be connected to several other modules such as the car computer and the gearbox, but also to the 'main body', being the car itself. This means that the car engine is connected with combinatorial and slot interfaces. It is expected that different types of architectures will also be applied in the ship.

Continuing with modularity The aforementioned six properties of modules will be used in this research, and where it is relevant the different types of interfaces will also be applied. To explain the application of modularity better, some general other properties and modularisation techniques are explained in the next section. This will be followed by information on how modularity is used in ship design. The section afterwards will lay out what aspects of modularity could be useful for the remainder of this research.

3.2.2. General modularisation techniques

A method for modular design should give an idea on how to divide the system into modules, how to untangle the dependencies between subsystems and how to standardise or set up interfaces. So far it was not explained how this can be done, but it seems that there is not a single answer: many ways are explained of what properties or steps should be satisfied to come to a modular system. Three well-cited visions [34] are given below:

1. - Components within a module share similarities in life-cycle processes
   - Components within a module have little similarities to external components[33]
2. - Components within a module are interdependent (i.e. they must be dependent on each other)
   - Modular design requires a partition in design parameters to define which parameters will interact outside of their module, and how potential interactions across modules will be handled, so that modules can operate and be designed as black boxes[4]
3. Modular architecture includes a one-to-one mapping from functional elements in the function structure to the physical components (=modules in the context of this report) of the product [37]

Unfortunately, there is some disagreement between them. Baldwin and Clark [4] disagree with the statement of Ulrich [37], that one-to-one mapping from functional elements to modules is necessary. Gershenson, Prasad and Zhang [33] disagree with the interdependence of components within a module that Baldwin and Clark [4] demand from a module. Both [4] and [37] are among the most cited works in their field however, whilst [33] shows less significance [34], so it seems that none of the three works is undisputed nor definitely wrong. All three have aspects that could be applied in the design.

Firstly, the property that components within modules should share life-cycle processes [33] can be relevant for those components in the ship that are on the list to be refit at some point: they share the refit as a life-cycle process. This could give a lead as to how to separate systems.

To design modules as black boxes with standardised interactions [4] could also be suitable in the design of the power supply system. This would allow a new power supply system to be designed by a third party as a black box, whilst only handing over the information on the black box and its interfaces, so that less, but more clear information is available to the designing party. That neither provides a complete solution, however.

Finally, the one-to-one mapping from functional elements [37] is a more practical approach, where the aim is to have a collection of modules that all have one distinct function each, and all functions are served by single dedicated modules. This definition is strict, but the idea could help to define the combinations of components for modules.

Given that apparently there are multiple options to choose from – the list could be even longer – it may seem that a choice needs to be made in how to accomplish modularity and a modular architecture. Yet, there are no grounds to choose one over the other with the available information so far, and there is also the possibility that the different visions can be combined in a way, or even that the vision that suits best is not among those works. What can be learned from these approaches is that extra constraints within the design process are needed. In all three an extra property is given to the modules: they share similarities in life-cycle processes, their components are interdependent, or they have a one-to-one functional mapping. Such extra property is thought to be given with the purpose of the application of modularity to a specific situation. It should be found out what property should be given to the ship's system.

The pieces of a system as modules Modularity requires a way to separate a larger system into smaller, specified sections. More than 2000 years ago, Plato has written a dialogue in which a principle is explained, that can be applied to modularity as well:

> "The principle that dividing things by classes, should be at the joints, as nature directs, not breaking any limb in half as a bad carver might[6]."

It gives an accurate image of the delicacy of the problem, as the division between components in their modules is expected to make or break a situation. Finding the natural points of the division sounds like a good idea but challenging to acquire. The source where this quote was found initially is aimed very much at software modularity, – another example of the broad application of modularity – which makes it hard to reproduce the information in that specific text into a form suitable for designing the ship. And so, it is necessary to identify the extra properties of modules required in the situation of the refit of power supply components of a ship and how one can cut a system into logical portions. It is therefore chosen not to dig any deeper into modularity in general, but to see how modularity is applied in shipbuilding and afterwards to make an overview of theories that seem most suitable for the situation in this research.

3.2.3. Modularisation techniques applied in shipbuilding

Ships often are highly complex structures, engineered-to-order and of low standardisation. The ship-type, the market situation, margins, and available total capital all influence the capital available for a refit, the type of refit and the occurrence of refits throughout a ship's life. To apply modularity to refitting parts of the power plant of a general cargo vessel, it is checked how modularity is applied to shipbuilding in literature.

A cargo ship is not an offshore ship In the maritime field modularity has been used to achieve adaptability, mainly in non-payload vessels and some offshore ships, by exchanging operational modules. It was noted that a few important differences are present between such operational refit of a non-payload ship or a refit of parts that have auxiliary functions to the ship's operations of a cargo ship.

Firstly, the operational units are often located on deck, rather than low in the ship near the propeller shaft. This makes that operational units are often easily removed or installed because of vertical access.

Secondly, the economics of a work vessel is different. In the offshore market, there are project contracts for a few years and ships can have time in between such contracts to refit the ship to meet new contract's requirements. These contracts may even involve the availability of extra investments because either the new contract has specific requirements that necessitate a refit and the contractor pays for it, or the ship operates in a niche market where a ship can be refit for. For offshore ships this means that sometimes contracts pay well enough to allow a refit, especially if the ship was designed for a refit. This makes it logical that there is interest to design refittable offshore ships.

A cargo ship typically does not work on project basis and since its function will be to move cargo in its hold regardless of how it is propelled and the type of contract, there is very few operational benefit from a refit of the power supply system. There is also not automatically as much funding available for cargo ships for a refit and a period between contracts will cost money as well.

Modularity as applied in shipbuilding Modularity is applied in shipbuilding, however, the focus in multiple literature pieces on modularity in shipbuilding mainly is on where and when to apply it, and not how to achieve modularity at design level. Several examples are mentioned on modularity in shipbuilding, in some only where to apply it, in others also how to apply it:

[6] This quote from Plato's Phaedrus, section 265e,was cited in [4] from the text of [44] and can be found in [45]

- In [6] modularity is used as a means to vary ship operational capabilities for an offshore support vessels, by exchanging task related (e.g. well intervention tower or crane) and ship (e.g. bow or engine room) modules, but it has not been explained exactly how the modules have to be designed. The definition of modules is indicated clearly to be based on functionalities and independence between modules.
- In [7], a modularisation technique from [46] is used in the modularisation of their virtual ship prototype, where a specific way of functional decomposition is used to come to a solution. This functional decomposition is unsuitable for the refit problem.
- In [41] a modularisation method is suggested also based on functional decomposition. In this method the procedure is find a function architecture first, in which all functions are shown, and then use that to set up a product architecture. Setting up this product architecture makes use of finding multifunctional components and modules, defining interfaces, and then establishing the size range for said modules. This modularisation method is aimed at ships specifically, but again the focus is more on operational equipment instead of auxiliary equipment (auxiliary to the function of the ship) and it is aimed especially at setting up a modular parts library rather than designing a single ship.
- For aircraft, axiomatic design is suggested as modularisation technique by [47], which shows great similarity to the application for a refit: the study aims to enable easy upgrades for a complex vehicle of relatively small series of which the body is expected to outlive some of its components. The used axiomatic design [48] is a mathematical approach to come from customer requirements, through functional requirements to design parameters and finally process variables to be able to produce what the customer wants. Again, the functional approach is leading, but it seems that the approach is aimed too much at the customers requirement to use at its full capacity in the refit problem.

None of the found methods can thus be used exactly on the refit problem, based on the aforementioned information, so the basic theories must be used to develop one. The functional decomposition or functional independence does come back in all four methods. It also seems that different applications make use of modularity for different advantages.

General benefits of modularity for ship-design Modularity is thought to be helpful to design a refittable ship because of the ability of a system to be changed partly without altering the rest of the system. In several other applications, both in shipbuilding and in other sectors, some other benefits can also be identified. It is used in ship-building and other sectors [41] to allow the design of individual system parts, so that a mix and match of modules can together form a specially customised system, which could save design efforts in comparison of designing every customised system individually. This is a way of standardising component families. Modularity is also used to set standards for modules' interfaces or to be able to use off-the-shelf products that have a standardised interface in a system. The standardised interfaces within a refittable ship could also be used to create a defined list of requirements for a supplier of an alternative installation for the ship. If it is possible that the interfaces can be designed in a desirable shape, the design of such alternative installation for the refittable ship could also be repeatable in another ship (not necessarily a refittable one). In that way, the modularity of the refittable ship could even lead to standardisation in other ships when supplier of the refittable ship's modules can put their modules in the market for other ship-owners. This could lead to ships that are designed for those modules instead of vice versa.

3.2.4. Application of the modularisation approaches for a refit

To apply modularity, the aim is to design a system that contains modules. These modules have several properties: they are subassemblies in the system, they are relatively functionally independent, they have standardised interfaces, and they can be recombined into different end-products. A ship would normally be integrated, but there needs to be a separation within the system to be able to exchange part of the system, and the separation needs to be found in a natural place. So far, no straight answer was found on how to apply modularity directly to design a refittable ship.

In ship-building modularity is used, but often it is used with an aim of exchanging operational modules or to bring standardisation in design options. Many applications view the functional independence of modules as an important factor. This does however not give exact guidance to where to separate the ship's power supply system and how to make it modular. There are some more applications of modularity that suit this functional independence that illustrate also how one could use modularity in the design process of physical parts.

One way of how one could design actual physical assemblies that suit modularity is described in a paper about a heuristic method for identifying modules in a product architecture [49]. This paper shows how modules can be identified in the design of several household appliances, by making use of identifying all functions that have to be satisfied in order to have the appliance function according to specifications, this can be seen in figure 3.3. Modules are then identified based on the dominant flows in the system. The level of detail is not suitable for the complete ship power supply system, but the graphical representation of a complete system with all its flows is at least one representation on how to apply modularity on functional level.

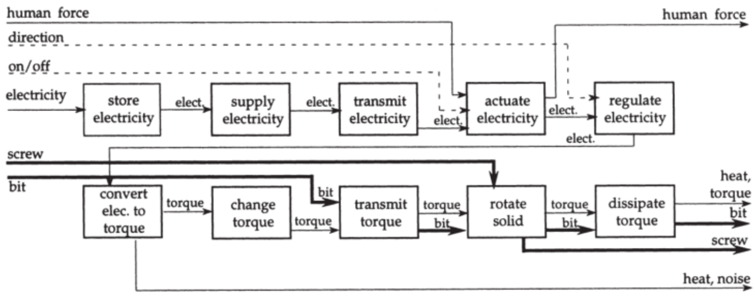

Figure 3.3: Capture from [49], to show how the flows of material, energy and signals could be charted

Overall, distinct information has now been found on modules and only few applications have been found that come very close to the refit issue at hand. As the case seems to be so specific, it will now first be seen how the available information can help in designing a ship's power supply system modularly, so that it can be refit.

4

The case ship

To ensure the theoretical steps are suitable and effective, they are verified by applying them to a case ship. The case ship used for the verification of the steps is based on a ship that has been built, which ships cargo throughout Europe, including dangerous cargo. The original design is to be altered in the next sections so it can be refitted from an installation like the original diesel propulsion to an installation that emits less GHG's. First the relevant properties of the original ship are given. The suitable power supply alternatives are to be determined in subsection 4.2. When the alternatives have been chosen the most important properties of the alternative installations are given.

It is assumed that the ship will be built soon and that it will be refitted in a timespan of around 15 years from now. It is also assumed that the ship will operate in a steady economic situation in which it has reliable opportunities for financially healthy operations. The ship is expected to maximally sail 8 days consecutively at nominal speed in normal operating conditions, and that round trips will typically not take more than 20 days, including a port visit, based on sailing data of the original ship.

As there is only limited time available and the design is made based on an existing design, only a limited amount of the ship could be changed. Also, the scope of the investigation does not allow modifications to the hull during the refit, it should keep its underwater-shape and length. Both constraints are not necessarily true for a different design and are not to become part of the method.

4.1. General parameters

The general parameters of the case ship are given in this section. From the operational profile of the short-sea cargo ship the minimum range is derived to perform its port-to-port operations and a comfortable minimum range, which allows to choose a port to bunker. The ship has a standard lay-out in the sense that its wheelhouse is at the aft of the ship and it has no special uncommon properties to take into consideration in this design assignment. A 3D model of the case ship is available as shown in figure 4.1. The main parameters of the ship can be found in table 4.1.

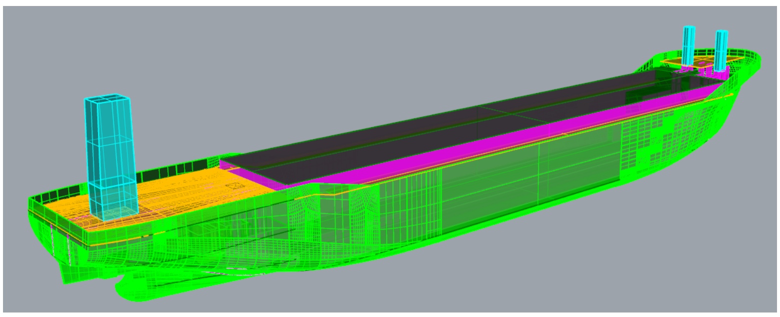

Figure 4.1: The model of the case ship

The original ship is built with one main engine and two auxiliary engines, all three running on MDO. It has an electrical bow thruster, which will not be in operation at the same time the ship delivers its maximal

Property	Value	
Length	98	m
DWT	4200	tonnes
Hold volume	6000	m^3
Nominal propulsion power	1100	kW
Maximal propulsion power	1600	kW
Minimal auxiliary power	75	kW
Nominal auxiliary power	150	kW
Maximal auxiliary power	300	kW
Total required power	1750	kW
Absolute minimal sailing range	10	days
Comfortable minimal sailing range	20	days
Original sailing range	36	days

Table 4.1: Relevant properties of the case ship (some numbers are approximations)

propulsion power. The required total power therefore comprises of the maximal propulsion power combined with the nominal auxiliary power. The main engine is connected to a gearbox with two outputs: one to the propeller shaft and one to a PTO. The large generator has the capacity to deliver maximal auxiliary power, the small generator to deliver just over nominal auxiliary power. The alternative configurations have not been determined yet.

4.2. Choosing suitable power supply systems

The ship is ought to be prepared for the installation of other - possibly large - components in the future, but it is not useful to prepare it for anything and everything on purpose. Some installations will never be amongst the most suitable solutions for a certain ship performing its operations. One of the properties of modules is that they should be exchangeable, so in theory the ship would be prepared for multiple options when it is modularly designed. However, even though modularity could make an installation more flexible, this cannot be used as a fact for a ship's power supply as a starting point and neither can the method be proven when nothing is known about the future installations. Therefore, for the development of the method and for demonstrating the possibilities for the case ship, a choice needs to be made for the alternative power supply system.

4.2.1. Criteria and approach for choosing power supply options

In chapter 2 a large range of alternative fuels was collected, and several alternative power supply units. The combinations of fuels and power supply units would lead to tens of configurations. Testing all these configurations would bring a broad overview of possibilities but would also require very much information. As the aim of this research is the development of a method rather than gathering alternative installations, a choice is made for a limited number of test cases.

To narrow down the options different configurations are evaluated in an objective and standardised approach. Multiple criteria are present that are not correlated in first sight, so a multi criteria analysis seems in place. The criteria are presented first, so it can be seen how these criteria can be applied. The complete analysis of the criteria can be found in appendix B. Only the criteria and the results are discussed in the main text, as the choice itself is not part of the main research.

For the criteria, a similar analysis of alternative fuels for inland ships [50] has been used as a basis. Some of their used criteria are merged so the comparison requires less information. It is thought that the merged criteria still provide coverage of all aspects, all be it in less detail. The analysis knows three steps: analysing the fuels, analysing the power supply units, and finally analysing the combinations of the most promising fuels and power supply units. The following criteria are therefore used, based on the criteria used in [50], for all three steps:

- **Emissions**
  The amount of emissions a fuel, power supply unit or combination produces. For the fuel, the GHG emissions are rated, for the power supply unit the NO_x emissions are rated and for the combinations both are used. Fuel efficiency is considered via the operational expenses, not via emissions. Indirect

emissions through the production, storage and logistics of a fuel are not considered, because techniques are still under development and these values are not fixed.

- **Technological readiness**
  This is a scale to see in how far this technology is expected to be ready in the upcoming years. Some techniques are already applied and are priced according to long-term marginal cost, others are only working in laboratory environments on small scale.
- **Investment**
  With this value it is rated how much investment is necessary to purchase the necessary equipment. This does not include expected refit cost, because the refit cost is dependent on the execution of the refit and the effect of the method.
- **Operational expenses**
  The operational expenses are assumed to be maintenance and fuel cost. In some contracts the fuel costs will be paid for by the charterer rather than the ship-owner, but it is assumed that high fuel prices will have negative impact on the ship-owner as well, for example by reduced interest from charterers in his more expensive services.
- **Size and weight of the installation**
  The size and weight of the installation will have their impact on the ability of the ship to bring revenue, as this will take up precious cargo space. The fuels will be compared to each other on energy density including storage facilities.
- **Impact on design**
  Changing the installation on board will always have some impact on design. Mainly the difference between the initial installation and the new installation is considered in this aspect.

The weight of an installation and its difference compared to the initial installation mainly affect the profitability of the ship if the design cannot compensate the negative effects in a way. The method might therefore affect how much influence these criteria have and therefore these criteria should not be taken to be as important as the criteria beyond the influence of the design. This means that not only there are different criteria that can be rated in different ways, but the criteria are not even equally important. This suits a multi criteria analysis (MCA) well [51], but the data necessary to quantify the performance of the different options is scattered and it is not the purpose of this research to collect and sort this data. Also, one important criterion has not been considered yet:

- **Suitability as a test case**
  An alternative installation from diesel ICE to any of the other possibilities should have some value as a suitable test case. In contrast to what is favourable in reality, the test configurations should have some significant differences with the diesel ICE configuration. If the only step in making the ship emit less GHG is switching fuel, it will not provide the necessary insight in how a method for modular design enabling a refit should look like.

The suitability as a test case is dependent on the scores of the other criteria, making it a dependent criterion. This adds up to the complexity of finding the independent ratings of the other criteria. Therefore it is chosen not to execute a complete MCA, but instead set up the performance matrix, rate all features qualitatively and analyse the performance of the different scores by rationale in order to come to a suitable test case.

4.2.2. Resulting choice

As said, it is not the purpose of this research to find the most suitable power supply for a short-sea general cargo ship. For this reason, the comparison can be found in appendix B. This comparison has resulted in a choice for the installations in table 4.2. The different configurations have also been labelled, the labels are acronyms made up of the first letter of the fuel, and either an M for the ICE (motor) or an E for electric propulsion with a fuel cell system. Their details will be discussed in more detail in the next section.

4.3. Technical information on the power supply units

Additional information is necessary to design the five different power supply systems. In this section, a general impression of the different power supply units is given. In section 4.3.4 information is given on the fuel treatment and storage.

Acronym	Fuel	Fuel treatment	Power supply unit	Torque delivery
DM	Diesel	Separator & day tanks	pressure ignition ICE	main engine
MM	Methanol	Pilot-fuel system	dual fuel or spark ignition ICE	main engine
ME	Methanol	Reformer	LT-PEM FC	Electric motor
HE	Hydrogen	none[1]	LT-PEM FC	Electric motor
LE	LOHC	Hydrogen extraction plant	LT-PEM FC	Electric motor

Table 4.2: Power supply configurations for the case ship

There are only two different power supply units to be designed in the case: the ICE, and the fuel cell (FC). Along with the units, some extra main components are necessary to deliver thrust to the propeller and electricity to the ship, as schematically shown in figure 4.2. The properties of the ICE configuration are discussed first, and secondly the FC configuration will be described.

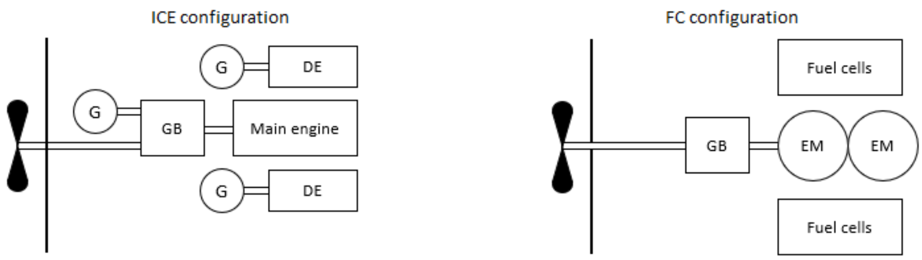

Figure 4.2: The two power supply configurations the ship will be designed for

4.3.1. Internal combustion engines

The internal combustion engines used in this investigation are three different diesel engines installed in one engine room, as in the original design of the verification ship. They are all three trunk piston engines, with 6 to 8 cylinders. The main engine of 1600 kW is used to propel the ship through the gearbox, the smaller engines of 300+ kW and 150+ kW are used to generate electricity. The gearbox is also fitted with a PTO, which allows the main engine to generate electricity at times the engine is not used at full power during transits. Diesel engines lose their waste heat in different ways: They radiate heat into the engine room, they lose heat through their exhaust gas and they heat up the liquids flowing through the engine; lubrication oil, cooling water and return fuel. To deal with these waste heat several measures are taken in an engine room.

To remove the heat of the engine in the engine room and to supply the engine with enough oxygen, the engine room is ventilated. The case ship's engine room can be ventilated with 40,000 m^3/h. The exhaust piping is insulated, so less heat is transferred from the exhaust gas to the inside of the ship. To actively cool the engine, water flows through the engine and through heat exchangers in a sea chest, so the sea water can cool the heated water from the engines. The smallest engine has one cooler, the other two have two each: one for HT cooling water of around 80-90 ^oC and one for LT cooling water of around 45-55 ^oC. The lubrication oil and return diesel of the main engine are cooled, this is executed through adding heat exchangers in the cooling circuits of the main engine. In case of running the engines on methanol, the return methanol is limited and is not cooled, but instead lead to a dilution tank where it is mixed with water to prevent flammability.

To start a piston engine, it needs to be rotated by an external force. For the main engine, this external force is delivered in the form of pressurised air, for the two generators electricity is used. For this reason, another source of electricity than the generators and a compressor with air vessels of adequate pressure are to be available on board. In the verification ship, the extra source of electricity is either the emergency generator (which has batteries as source of its own starting power) or the shore connection. Two large air vessels and two 30 bar compressors are also installed. To make it easier and less demanding to start the main engine the main engine is also installed with a pre-heater, which electrically heats the cooling water flowing through the cylinder heads to decrease the temperature differences across the engine parts and to expand metal parts that seal off any fluids or gases present in the cylinder heads.

The engines operate by internal combustion of the fuel. This can be ignited in several ways. In a diesel engine, running on diesel [2], the ignition of the fuel is caused by the temperature rise through the compression of the air-fuel mixture in the cylinder above the piston. Diesel is considered the standard to these types of engines, but different fuels can also be used, amongst which methanol.

The combustion process is more difficult when using methanol however, because methanol does not easily self-ignite. There are different methods of using methanol in a diesel-engine [53] and therefore a choice needs to be made to work with. The least complex way of ignition in terms of auxiliary components seems to be spark ignition. This does not require additional fuels to be installed on board and led to the engine, but it also does not increase efficiency, whilst an increase in efficiency is considered an important advantage. Spark ignition is therefore chosen only for the two generators. A more efficient method is to use an engine in which methanol is ignited by pilot diesel: a small amount of diesel (starting from 5% from the energy from the lower heating value (LHV) of the blended fuel) is added to the methanol. In an applied installation in a ferry [54] this is executed through exchanging the cylinder heads, injectors and fuel pump plungers, and adding a common rail system for the methanol injection, including a high pressure methanol pump. The injectors are capable of injecting both fuels with different nozzles into one cylinder. This part of the conversion is not expected to require change to the surroundings of the engine compared to the operation on diesel. Because of the technical readiness and available information, this type of installation is also applied in this research, but it is expected a realistic possibility that other techniques of fuelling a diesel engine on methanol may be more suitable in several years.

4.3.2. Fuel cell system

For the fuel cells[3] a previous design could not be used. Even though there are some ships that currently use fuel cells for their propulsion (see [29] for a list of examples), a fuel cell installation specifically suitable for the case ship is not among them. In section 4.2 it was already explained that for the case ship LT-PEM cells will be used. Based on the requirements as given in section 4.3.1, a total of 1750 kW of electricity is to be delivered to meet the ship's operational needs. In the case of the fuel cells, all delivered power is delivered in the form of electricity, so no separate generators are necessary. This situation is also illustrated in figure 4.2. The system is to be designed redundant enough that normal operation can be continued after any single failure in large part of the system [55] and therefore most of the components in the system have to be executed in pairs of two, each with at least half of the required capacity. It is expected that the ship can still sail at half of its power, although not at design speed.

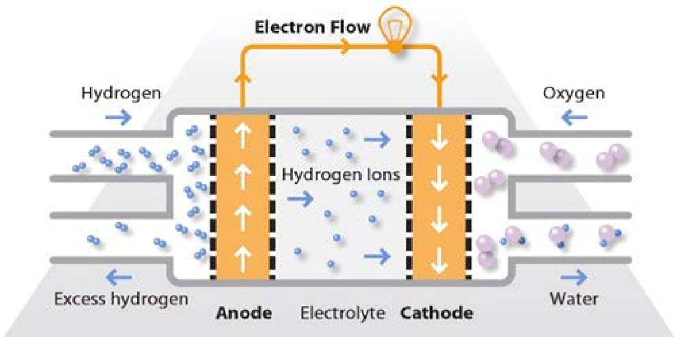

Figure 4.3: Schematics of a PEM fuel cell, taken from [29]

A fuel cell system revolves around the fuel cells. In the case of LT-PEM fuel cells, a fuel cell consists of membranes surrounding the cathode and anode, so that the electrons have to flow through the electrical system and the hydrogen ions can pass the membranes before being united with oxygen to form water. This principle is illustrated in figure 4.3. These membranes always must be humid and are sensitive to fuel impurities, especially in the form of carbon monoxide and sulphur [29], as this can obstruct the membranes. For this reason, LT-PEM cells require high quality water and fuel. The maximal theoretical voltage over one cell

[2]The term 'diesel engine' refers to an engine operating using the thermodynamic Diesel process which typically uses diesel as fuel, as opposed to an 'otto engine' which operates via the Otto process and typically uses petrol as fuel. This diesel process can also take place when a different fuel than diesel is used, so a diesel engine is not necessarily a diesel fuelled engine. More information on marine engines and these thermodynamic processes, please refer to [19].

[3]The technical details of this section were acquired by interviewing a fuel cell manufacturer

is 1.229 V [56], which drops when more power is delivered, so in general a stack of cells is used in order to raise the voltage to workable levels. The delivered voltage of a cell is linearly related to the efficiency. Since the latent heat in the vapour of the process is not used, the LHV may be used instead of the higher heating value. This also makes it possible to directly compare the efficiency with that of a combustion engine, but it should be noted that using the LHV for the efficiency does not acknowledge part of the process energy that can theoretically be used [57]. Using the LHV for the efficiency[56] leads to the formula:

$$\eta_{fc} = U_{fc}/1.254$$

Since the voltage decreases when higher power is demanded from the fuel cell, the fuel cell has the highest efficiency when it is delivering the lowest amount of electricity and the efficiency decreases gradually as more power is delivered. More fuel cells delivering a certain amount of power therefore means a higher efficiency. However, fuel cells cost money themselves, so some economic balance needs to be found by a ship owner between fuel cost or investment. According to [58], about 210 stacks would be recommendable for a 1750 kW installation. As 210 is not divisible in a double amount of practically numbered clusters, more stacks increase efficiency and the fuel processes also require some energy, it is chosen to install 240 stacks of fuel cells. The amount of energy the fuel processes cost will be explained in more detail in the next section. It is expected that the fuel cells will have an average efficiency of 51.5 % at the nominal power of 1250 kW over the lifetime of the ship, the calculations for the efficiency can be found in appendix C. All losses should be expected to be water cooled, at a temperature of 70 ^{o}C. This leads to a maximum required cooling capacity of 924 kW (100% - 47.2% of the maximum power of 1750 kW at end of life).

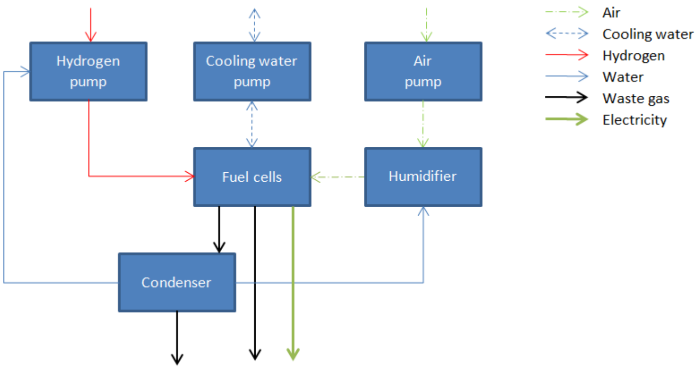

Figure 4.4: A schematic representation of the proposed fuel cell system

For each half of the 120 stacks a separate cooling pump, hydrogen pump, water circuit pump and air pump are to be fitted. One condenser will be used to recycle the pure water from the exhaust gases of the fuel cells. For each half of the fuel cell system a voltage regulator will have to be fitted, along with the necessary electric power components. This system is illustrated in figure 4.4.

Fuel cells need to be installed into a separate fuel cell space [55] with the right amount of ventilation and the right type of ceiling. It may therefore be necessary to build the structure of the ceiling upside down, so that the construction of the ceiling is under the floor of the cabins located above the engine room instead of at the underside of the ceiling. Components within the fuel cell space have to be approved with stricter certificates in regards to the explosion hazards of the used hydrogen, so the amount of components within the fuel cell space is to be kept limited to avoid the unnecessary expense of explosion proof equipment.

Finally, an electric motor is necessary. Just like the fuel cell system components the electric motors also need to be redundant. For this reason, it can be chosen to have a double input into one gearbox, have an electric motor that is double wound or two electric motors in series. It is possible to choose an electric motor that does not require a gearbox, but this does not seem to be the standard. In this design a gearbox will be used with a double wound engine that is operated at 1500 rpm.

4.4. Fuel storage and preparation systems

For the preparation of the fuels several installations are necessary. They will be explained here, as background information for designing the installation. All alternative fuels considered have a flashpoint lower than 60 ^{o}C (the LOHC is technically not a fuel, and its flashpoint is 200 ^{o}C [59], but the gaseous hydrogen produced from it is flammable). This means there are stricter rules the systems must comply to. This typically means that fuel pumps must be in separate spaces, with separate ventilation, of which the in- and outlets are considered hazardous.

4.4.1. The diesel system

The diesel system is the benchmark for installations and thought to be simple. However, several auxiliaries are typically used in a diesel system: a separator, and a settling tank and/or one or two day tanks. The separator is installed to remove any impurities from the fuel. First the fuel will be pumped into a settling tank, then through the separator into the day tank(s). This way, the engines can be fuelled through gravity or small pumps. A separator, two day tanks and a settling tank should therefore be included in the diesel-ICE configuration.

4.4.2. Methanol for the ICE

For the methanol ICE configuration, a high-pressure methanol pump and a pilot diesel fuel system are to be installed for the main engine, and a feed methanol pump is to be installed for the auxiliary engines. Methanol will be stored in the double bottom of the ship, according to regulations from Lloyd's register [60][4]. According to regulations the methanol pumps and valves must be in separate spaces, with airlocks or direct openings from deck. Tanks need to be surrounded by cofferdams, but they may be water filled.

4.4.3. Hydrogen for the FCs

The hydrogen FC configuration requires the storage of hydrogen, in cryogenic vessels. The vessels used as an example for this project [52] include the gasification unit built on, so no special installations are expected to be installed between the storage vessel and the hydrogen connection to the FCs. If the right grade of hydrogen in terms of purity is bunkered this can directly be fed into the fuel cell system. If the purity is not sufficient it may be necessary to install some filtering system for the hydrogen.

4.4.4. Methanol for the FCs

For the methanol FC configuration, the storage of the methanol is the same as in the methanol ICE configuration, but the LT-PEM cells require high grade hydrogen as fuel and not methanol. To overcome this issue a methanol reformer is installed, with a pressure swing absorption filtering system. The methanol reformer is also to be redundant and to be installed in the fuel cell space [55]. A readily available marine methanol reformer of the right size was not found, so instead a dummy installation with a size suitable for 1750 kW [13] was thought up, based on a land-based methanol reformer [62] and the feasibility of the concept on board of a submarine [63]. The used parameters for this installation can be found in figure 4.5. It is thought that the installation does require some extra components in terms of pumps, control cabinets and so on, but because of the highly conceptual form of the installation this is not applied in more detail. Based on the land-based reformer [62], the additional fuel usage of the reformer is around 17 %, or differently said the efficiency of the reformer is around 85%.

4.4.5. LOHC to hydrogen for the FCs

The final installation to be discussed is the LOHC configuration. The LOHC hydrogen release plant has been designed for land-based applications [64] and according to information of the manufacturer a marine unit's size would be in the order of 21 m^2 and 21 tonnes per MW of contained energy in the released hydrogen, and it should be around 3 meters in height. This means that for supplying the fuel cells about 110 m^3 of extra installation is necessary. Unfortunately, the release plant itself requires heat of around 300 ^oC and from an LT-PEM installation this heat cannot be produced by waste heat, since the installation produces heat of only 70 ^oC. Therefore, 59 % extra hydrogen from the LOHC is necessary, which could also be noted as an efficiency of 62.9/

4.5. The case ship used for validation

There will also be a second case ship to validate the method in chapter 6. The details of this second ship will be collected during the validation, so only the useful information is collected. The technical alternative set-

[4] During the project a newer set of regulations was discovered, for any application of regulations please refer to the interim guidelines for the safety of ships using methyl/ethyl alcohols as fuels as drawn up by one of the IMO committees[61]

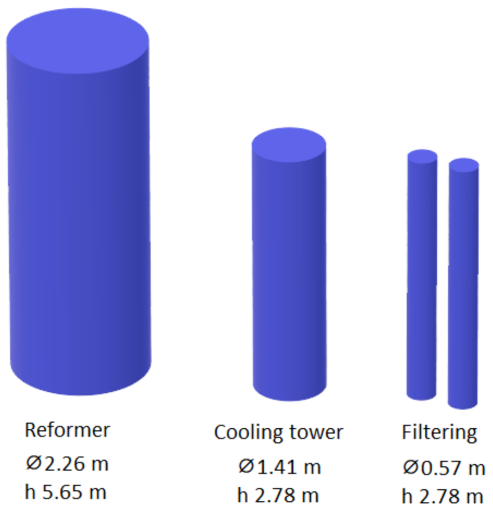

Figure 4.5: Parameters for the dummy methanol reformer used in the design of the methanol FC configuration.

ups of the first case ship will however also be the basis for the technical alternative set-ups of the second case ship. The assumptions made on the range, construction period and economics, as well as the determination of suitable alternative installations are also applied to the second case ship.

5
Developing the method

This research has the objective to develop and validate a method for the modular design of the power supply system of a short-sea cargo ship that allows a low-impact refit in order to reduce GHG emissions when the technology is ready. This chapter explains how the information of the previous chapters is used to develop this method, what the method brings as a result and what can be concluded based on the ship that was designed for verification of the steps.

The method is developed by analysing the available information from the prior text. In each step, theory is proposed and then it is verified if this theory is suitable by applying it to the case ship. If this shows the step is helpful, the design process continues towards designing the ship modularly. If the results seem unsuitable a different approach to the step is sought and verified.

The chapter will start with defining some of the used words, to avoid any misunderstanding. In developing the method, first the objective will be analysed, to have a solid basis for where the method should lead to.

The first part of the development of the method is analysing the previous information to find the suitable theories to apply in the method. To verify whether these theories are indeed suitable they will be applied to a case ship, which is set-up in section 4.3 and the theories will be tested consecutively in section 4.4. The results will be shown and analysed in the final two sections of this chapter.

5.1. Selection of relevant words

To avoid any misunderstandings because of the used words, the definition of several relevant words is given below. These words can also be found in the nomenclature at the beginning of the report.

Assembly	group of machine parts, especially one forming a self-contained, independently mounted unit [65]
Component	one of several parts of which something is made [66] (not necessarily meaning that a part does not have components itself)
Coupling	the degree of coupling between systems describes how much one system needs to be changed if another system is changed. [37]
Independent	not influenced by or connected with somebody/something [66]
Interface	(between A and B) - the point where two subjects, systems, etc. meet and affect each other [67]
Medium	the gas flows, fluid flows, signals, forces, and powers in a system
Modularity	modularity is a special form of design which intentionally creates a high degree of independence or 'loose coupling' between component designs by standardizing component interface specifications [1]
Module	subassembly (or occasionally a single component) with special features (See sec. 3.2.1)
Subassembly	a structural assembly, as of electronic or machine parts, forming part of a larger assembly [65]
Subsystem	a secondary or subordinate system [65]
System	a group of things or parts that work together [66]

5.2. Development of the method

The method is developed with the information from the previous chapter, as summarised in section 5.2.1. The approach to develop the method is an information based step-by-step approach, with the aim to get to the objective in a practical and organised manner. To develop each step, first the available theory and information are analysed, then a step is proposed, after which the step is verified or dismissed based on applying it to the case ship. To give a better idea of the steps taken, an illustration is given in figure 5.1. An analogy is used with designing the ship as a puzzle, to illustrate the method's most important steps.

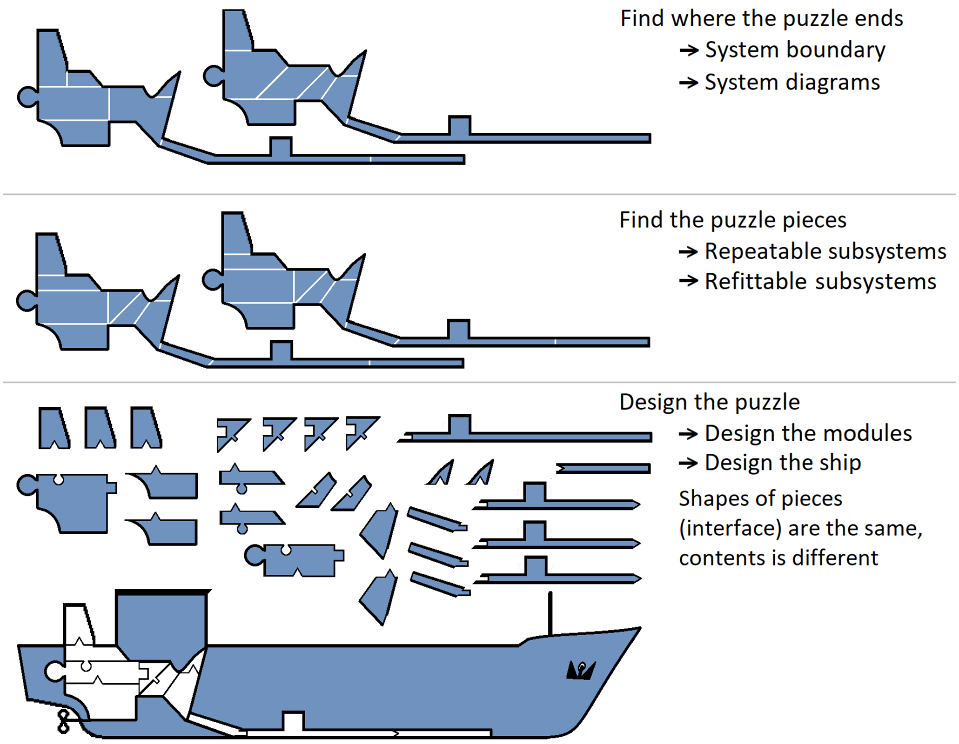

Figure 5.1: Illustration of the steps taken to design the modular ship

The developed method to design the ship with exists of three main phases:

1. Finding a demarcation between the refittable power supply systems and the rest of the ship, whilst providing basic system information
2. Finding the repeatable subsystems among the different power supply configurations
3. Finding the modules to design the ship with

In the upcoming sections it will be explained how these phases were developed, what they mean and why they were chosen. Each step will be developed with the information from the prior texts and with the information from the previous step(s). A step is proposed, and then it is verified by applying it to the case ship. If a step does not give satisfactory result a new step should be proposed. Using this approach, the method should be developed step by step.

In this section first the objective will be analysed to provide a basis for the first step. Several other steps will be proposed and verified, until a resulting design with the relevant aspects is delivered. This design will be presented in section 5.3. The steps will be summarised, after which the developed method and the resulting design are discussed.

5.2.1. Analysis of the objective

The objective of the research will be analysed in this section of the report. The objective is to **develop and validate a method** for the **modular design** of the **power supply system** of a **ship** that allows a **low-impact refit** in order to **reduce GHG emissions** when the **technology is ready**. Step by step the different aspects in this objective will be examined to see how this shapes the method.

Low-impact refit The low-impact refit affects the design. It was written in section 3.1.1 that in this research a low-impact refit is a refit in which only a limited amount of components is exchanged and in which it should be avoided to move components that are not to be exchanged; this means that this 'low-impact' refit poses three limits within the design. Firstly, there needs to be a demarcation between components that do and do not have to be refittable and secondly the components that do not have to be refittable should have a fixed position within the design. Thirdly, any component that should not be refit should not be significantly in the way of components that do, as otherwise the components that do not have to be refit would still have to be moved around.

Modular design The second aspect of the research objective is modular design. The different aspects of modularity and how to come to modularity were studied in section 3.2, and a method that can be directly applied to this design problem is not found. Functional independence did stand out as an important property of ship modules. This does not indicate where to start in designing the modules, so the general properties of a module are used and analysed for the application. These properties were given in section 3.2.1 as follows: a module is a subassembly within the system, it is relatively independent of components outside the module, it has well-defined interfaces with the rest of the system and it is exchangeable.

The functional independence seems to be the most important property, as that defines where the system can be split into modules. If it is defined where the modules end, it is known where the interfaces should be. When the interfaces are known it is known what properties a replacement module should have, so that also makes the module exchangeable. The split system automatically results in subassemblies, so if the location of the splits in the system can be found, based on the functional dependencies, all other properties should also be possible.

Functional independence is important, as the dependencies of parts of a system make it difficult to take a system apart. It is important to find a sensible system boundary, which makes it a logical step to pursue functional independence in the search for a method.

- A **demarcation between components** that do or do not have to be refittable
- A way to assign a **fixed position** in every design variant for those **components that do not have to be refit** between two consecutive alternatives
- A way to **assign space to move components** that are refittable **in or out of the ship** without the components that do not have to be refittable significantly in the way
- A way to **define which component should be in which module**
- A definition of modules that results in **modules that are functionally independent** from components outside these modules

This theoretical analysis gives meaning to only this small part of the objective: 'to develop a method for modular design that allows a low-impact refit'. For the functionality of the method this is expected to be the main part because the rest of the objective gives the context of the addressed problem and the components of interest. Ideally the method should also work for other cases than the situation sketched in the introduction of this report, since that allows more cases to benefit from the developed method, but it is the aim to develop a method that fits the context.

The context does therefore play an important role also. It gives direction to the design of the verification ship in terms of why, what parts of and when the ship will be refit: a refit of the power supply system in order to reduce GHG emissions when the technology is ready. From the scope in chapter 1 it is also known that the ship is a short-sea general cargo vessel, with little auxiliary power (<20% of installed power), with alternative installations technologically ready before 2050. This information will help in setting up the verification case.

The starting point It is necessary to determine what a logical starting point would be. The intuitive choice would be to start at the demarcation. It is not necessary to make the entire ship modular, as it is not expected that anything unrelated to the power supply refit is refitted when it is not broken or worn out. On the other hand, all components that are potentially refitted should be included in the investigation. It would add unnecessary complexity to the refit if parts of the ship will have to be refit whilst they were not designed for it. Setting up a first system boundary seems to be a good starting point, nevertheless. It allows to zoom in on the relevant components, instead of applying the method to the whole ship and later deciding that some components can be left out of the investigation. The application of the system boundary to the case ship should prove if this indeed is a workable first step.

How to continue from the system boundary does not seem obvious. Therefore, this is decided in a later stage, when it is known what information is present after finding the demarcation.

5.2.2. Establishing the system boundary

The system boundary is set up to establish the demarcation between what does and what does not have to be refittable. This should help in avoiding unnecessary work by making components refittable that will not be refit. It also is thought to help in assigning fixed positions to components that do not have to be refit. Since modules should be relatively functionally independent from components outside of them, this also means that the modules must be relatively functionally independent from the components that are not refittable. This means that this is extra information in finding out where the system boundary might be: it will eventually prove to be an important factor in where to place this boundary.

Since the verification ship is a ship that has been built with an ICE on MDO, this means that on one alternative an almost complete set of information is available. On the alternative configurations less information is available, but enough to produce a concept design in a suitable level of detail.

The essence of the system boundary is that the components that have no chance at being refit in this particular context should be on one side of it, and any component that has a chance of being affected in its ability to function should be on the other side of the boundary. Less theoretically: if the diesel engine is hauled out of the ship, which other ship components seize in their function or will have no function on board anymore? This criterion cannot be taken literally however, because anything on board is somewhat related to the diesel engine. A different criterion should be found.

Unhelpful criteria The initial criterion that was used for components being within the boundary was 'any component that is designed to operate with a specific power supply system should be within the boundary, as should any component of the power supply system itself', in which the power supply system was as defined in section 2.3. This criterion works, but it is still vague for some components and it does not provide any additional information for the later steps. Instead, it is tried to use the relatively functionally independence for clarification on the matter.

Modules should be relatively functionally independent. This is a broad term that can be interpreted in multiple ways, but in general an independence in functionality is sought (see section 3.2.1). As the modules should be relatively independent from the parts of the ship that are not refittable, this could bring an extra means to separate the system in a modular part and an integrated part. This relative functional independence can be charted in multiple ways, several of which have been tried:

- Capacity dependent: what components dictate the capacity of another component?
- Input dependent: what components are necessary to provide the input of a certain component?
- Output dependent: what components are dependent on the output of a certain component?
- Functionality dependent: what function does a component have within the system? (similar to the method found in [49])

Neither gave satisfactory results. The first three were not finished as they seemed to lack level of detail and did not show all necessary relationships, the fourth had a too high level of detail or a very much layered and interrelated structure. Combining them neither was successful. In all four of these attempts the 'mediums' had a significant role: the gas flows, fluid flows, signals, forces and powers. The mediums flowing through the system in certain amounts dictate the capacity of components, the necessity of components and how they are to be connected.

It was also found that an important simplification can be made before a new table is constructed. All components outside the system boundary can be put in one category: the 'non-modular ship systems' (NMSS). This can be done because for the modular system it is not relevant to know what is on the other side of this theoretical system boundary. Both halves of the system should be relatively independent from each other, and therefore only the relationships that possibly pass through the system boundary are of importance. This is in correspondence with the 'black box' theory from [4] in chapter 3. Another reason to want to simplify the rest of the ship, is because the rest of the ship has many components, with its own relationships. Therefore, the second attempt to find the dependencies is made by mapping the relationship between components of the modular power system (MPS) and the NMSS through the available mediums.

Standardisation of in- and outputs To set up the table with mediums, in which the NMSS is seen as one system, means the system boundary must be estimated before the analysis. This is corrected in an iterative process as will show in further steps, so it is not essential to get it right the first time and multiple starting points could be used. In the application the criterion was 'might it have to be refittable?'. The result for the case ship based on the second approach can be found in figure 5.2.

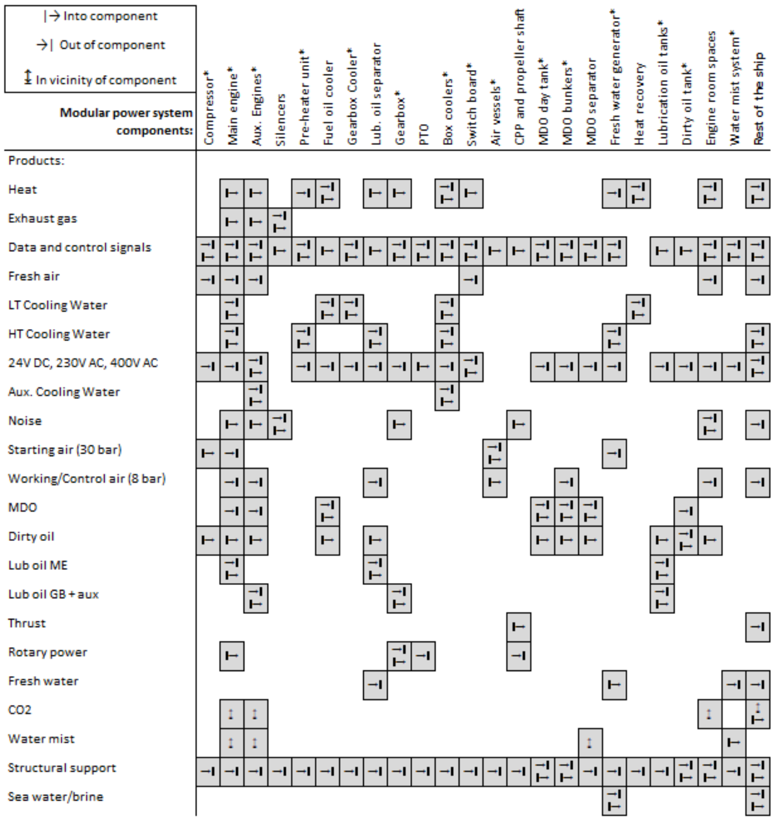

Figure 5.2: Table with the main mediums to be found in the diesel-engine system

The results from this analysis are satisfactory. Even though it still has a low level of detail, it clearly shows the mediums that might pass the system boundary, because of their presence in both systems. For each of these mediums that pass the boundary, two possibilities can be identified, to untangle the MPS and NMSS:

- **Standardisation**: The medium flow should be (or stay) standardised, meaning the MPS should be able to deliver to or receive the medium from the rest of the ship regardless of what is installed in the MPS. Examples: 230 V AC, thrust, work & control air, fresh water,
- **Separation**: The subsystems the medium is present in should be (or stay) split, so that there are two separate subsystems operating with the medium, so the medium does no longer cross the system boundary. Examples: High temperature cooling water (MPS subsystem for engine cooling, rest of the ship subsystem for AC), sea water (MPS subsystem for making fresh water, rest of the ship deck wash/ballast system), structural support (Structural support is entirely entitled to the rest of the ship, so it is separated. It should nevertheless be standardised to the extent that the ship structure is suitable to carry any of the proposed installations, as it is not possible to have not interaction over the system boundary)

This thought of creating either separation or standardisation mainly comes from the black box approach[4] that was mentioned in section 3.2.2. In this theory the modules are approached as black boxes, so only how to handle the interaction across modules needs to be defined. If the whole ship is seen as two modules with one standardised interface, this approach allows to define exactly the interaction between the MPS and the rest of the ship. If the method stopped here however, it would not give information on how to design the ship, nor would it help in deciding how to refit only half of the MPS, so the method is not finished yet.

Setting up system diagrams To provide information on the systems within the MPS in the different configurations, each MPS was mapped in a system diagram, in terms of single-line medium connections of components and subsystems. This simultaneously serves as a check on whether the identified dependencies indeed lead to a constant NMSS and to provide better information for any upcoming steps.

Common mediums were immediately left out of the diagram: the mediums that virtually all components within the system require. In the case ship this means that standard electricity connections and data and control signals were left out of the diagrams. First it will be explained why these mediums were left out, after that it will be explained what the setup is of the system diagrams.

- The standard electricity connections (24 V DC, 230 V AC and 400 V AC) are left out because they have a standardised interface, are relatively small and do not require particularly special treatment in any way. They do need a connection across the system boundary.
- Data and control systems are left out because they are a network with very many sensors and actuators, that are relatively small. Data networks could cause problems in a refit, due to software changes, but it is not within the scope of this investigation to investigate the digital side of a refit.
- Structural support is left out of the diagram, but also of the entire MPS. The structural support comes from the hull of the ship, which is a system of structural members and hull plating that has a very high dependency amongst its parts. For cars it is found that subtle linkage in structural parts in terms of vibration and strength make an integrated design more suitable for the structural assembly compared to a modular architecture[40]. The dependency of structural components is thought to be comparable in the dynamic environment of the sea to the dependency of the structural members of cars. If the hull had to be cut into sections that are part of the modules, it would also become more difficult to model and design the hull and therefore the hull is seen as one single component, with a clear function for many of the ship's components. This does not mean that the hull cannot be altered throughout the further design.

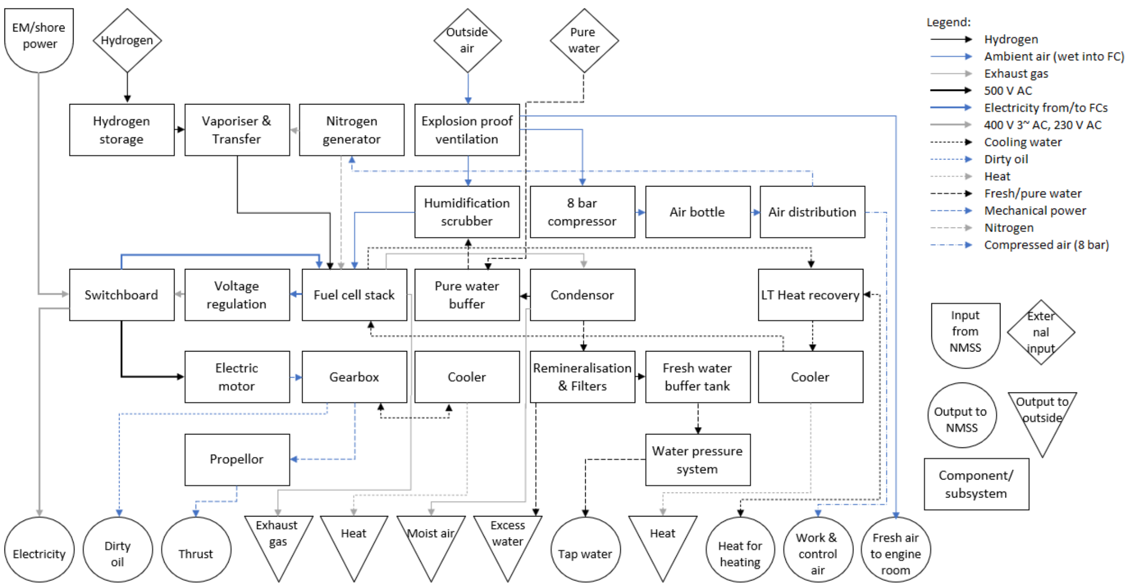

Figure 5.3: System diagram of the hydrogen fuel cell system

The system diagrams include information on how components are connected within the MPS and how the MPS is connected to the NMSS through their connections by the mediums. Several component-blocks are subsystems: a simplification of a group of components to a subsystem, treated as component. This is done based on technical intuition, but mind that these components are subsystems with multiple components and the grouping may be wrong for using it in a modular system.

The connections are strictly functional, as it is the aim to show the functional dependencies between components and not the physical properties of the systems. An example of a system diagram can be found in figure 5.3, the complete collection of system diagrams can be found in appendix C. These system diagrams provide very valuable information, and they give a clear answer to where the theoretical boundary between the MPS and the NMSS is.

The system boundary between the MPS and the NMSS can be found in the system diagrams by excluding any component from the system diagrams that is used in the same configuration and capacity in each of the alternatives, so that it can definitely stay. If there is any doubt about in- or excluding a component it seems wise to keep it within the MPS. It is expected that it will be less work to exclude components from the MPS than to find out something was wrongfully excluded during an actual refit.

5.2.3. Dividing the systems into logical parts

The table of the in- and outputs of the MPS into or from the NMSS formed the basis for the system boundary. The system diagrams provided the information the different MPS configurations. The system diagrams also provided a final check to the system boundary, so now the system boundary is established, and information is available on the MPS configurations for the upcoming steps.

The MPS is not quite modular yet: It may have a standardised interface with the NMSS, but it comes in five different unique systems, without a clear approach on how to divide it into exchangeable pieces. The system should be divided in a logical and natural way according to section 3.2.2. One of the constraints of the 'low-impact' refit was translated into the property that modules should have a fixed position within the system, regardless of the chosen definite alternative. This is thought to be the next logical lead in the process.

In this step the system is split into small pieces, and these pieces are refined in several ways, to accommodate the refit.

Repeatable subsystems The differences and similarities between the different configurations are expected to play an important role to define those fixed positions. The overlap between systems defines which components could be packaged together, and therefore the overlap between the different components is investigated. This investigation has led to about 40 unique combinations of subsystems that can form the five MPS configurations. In figure 5.4 the found subsystems are indicated for the hydrogen – fuel cell configuration of the test case.

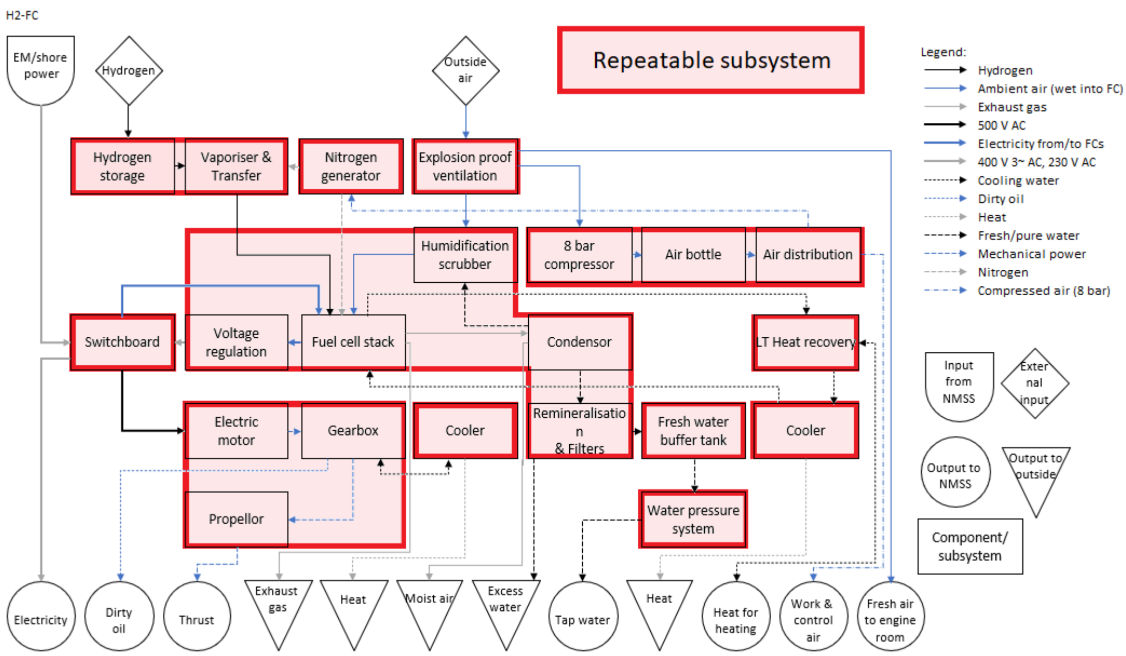

Figure 5.4: System diagram of the hydrogen fuel cell system, with indications of the overlap between this and the other MPS configurations

The pieces are the smaller or larger groups of components that are always together. They are either the combinations of components that are identical in several configurations, or the combinations of components that are unique for a configuration. It is chosen to name these combinations the 'repeatable subsystems' (RSs). The combinations are smaller, unique subsystems within the MPS, and it are those subsystems that can be repeated in multiple configurations or are unique. The physically largest RS is the NMSS. The NMSS has been added, because otherwise it is not possible to close all flows within a configuration with the RSs alone.

The RSs are no modules, as the information on the RSs does not include a physical description and are therefore incomplete, but they give an overview of which components belong together. They need extra refinement, however.

Splitting component blocks In finding the RSs it turns out that some of the component-blocks from the diagram are not suitable as one subsystem, looking at whether such subsystem can be repeated in an identical way in all the systems the subsystem's components are used in. For example, the pressure air systems of the ICE and FC configurations are given in figure 5.5. The systems as shown in the system diagrams are both different, and therefore would be two subsystems with no repeatable parts between the ICE and FC configurations. The air distribution panel would however be potentially the same, and therefore in the 30-bar configuration for the ICE the distribution system is split in a reduction panel and a distribution panel. This distribution panel seems to be similar so far. It would need to be checked for capacity, but it is estimated that the difference in capacity of pressurised air must be considerable before this leads to problems.

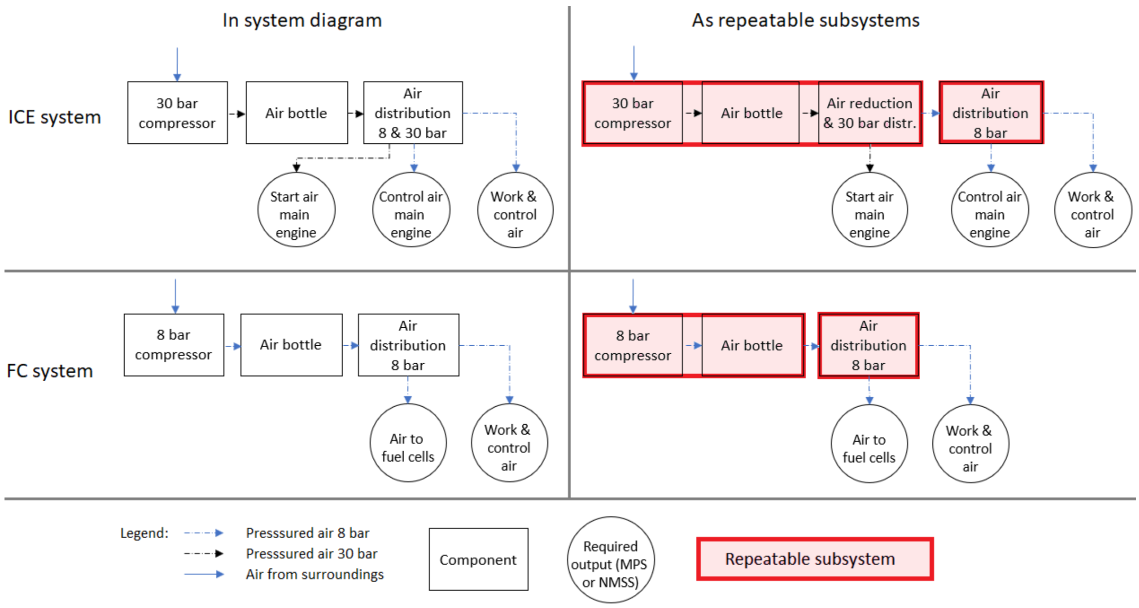

Figure 5.5: Example of repeatable subsystems in the pressurised air system, with comparison representation of the system in the system diagrams

Enabling design choices So far only the information from the five optimised MPS configuration was used to find the RSs. Some design choices might be made prior to developing the system diagrams, but this does not mean these choices will turn out the most suitable ones for the refittable design too. The set of RSs could be further expanded by adding additional RSs with a function present in the MPS with different connections, requirements, or outputs. This is thought to especially be helpful if the RSs are used for different designs in the future as well, or if different versions of the design might be built.

An example is the supply of freshwater. Fresh water is originally supplied by a freshwater maker in the ICE configurations and from the produced water by the FCs[1] in the FC configurations. This allows waste outputs to be used for water generation in both types of configuration: heat from the high temperature cooling water (± 90^{o}C) of the main engine, and the moist air of the fuel cells. Other ways of water production do exist however, including systems that can be used for both types of MPS configuration. Examples include:

- Freshwater generator suitable for 70 ^{o}C cooling water
- Reverse osmosis

[1] No source has been found that claims this would be a suitable way of producing potable water, but it is added in the design to show the potential possibility of producing water from a waste output of FCs as well. In a future scenario where this way of water production would be developed it is thought to be a realistic solution.

- Not producing it on board, but having it supplied into potable water tanks

Adding this kind of design options where applicable, allows the set of RSs to become a portfolio of possible solutions for a design. This allows the designer to know where to choose from, and to know available alternative functional subsystems. This is beneficial, because if one appliance was chosen over another in the optimised situation because of minor differences and another option would function better in a situation where it would have to combine with a different power supply unit, this information is readily available. The collection of alternative RSs allows a quick overview of the connections of certain subsystems, which make it more convenient to identify where to choose from. More information is not yet included because it is not necessary yet to have detailed information on each RS in this stage, especially if designers have some knowledge about the components in the RSs of prior experience.

Organising the RSs The collection of RSs contains a structured view on how components can be combined. The aim was however to find out how modules can be designed and therefore the RSs need further fine-tuning.

Subsystem:	Modular power system: DM	MM	HE	LE	ME	Subsystem description:
Water3			x	x	x	remineralisation
Water6			x	x	x	8 bar hydrophore
MeOH2		x				Dilution and discharge
MeOH3		x				Pilot diesel system and storage
MeOH4		x				Methanol injection and spark plugs
Bunker2		x			x	Methanol bunker system
MeOH1		x		x	x	Methanol bunkers double bottom
Elec4-2		x	x	x	x	Internal distribution switchboard

Figure 5.6: Example list of how it is determined which repeatable subsystem belongs in which modular power system

How to group or place components in the ship as modules, and the capacity and physical properties of the RSs are not known yet. The system diagrams combined with the RSs do give the information which RS is installed in which MPS configuration. It seems optimising the RSs further is not straightforward as it is not directly visible where to optimise them. It is chosen to information about MPS configurations in combination with the RSs and thus to sort the RSs to the MPS configurations they are used for.

This gives five lists of RSs to be used. In figure 5.6 an extract from the list of RSs is given for the case ship. In the list it can be seen the RSs have been given some ID (e.g. Water3, MeOH3, etc) and the acronyms as defined in table 4.2 are used again for the MPS configurations. In appendix C the detailed lists are shown.

Splitting RSs and finding refittable subsystems The objective of the method was not to design a modular ship, but to design a refittable ship using modularity. This means that certain de-optimisation in the performance of the ship could be justifiable when this fits the assumption of the low-impact refit better. In other words: design changes that lead to less components that need to be exchanged are allowed if the negative impact on performance is limited. This is not part of the modularisation, but it is of the complete research objective.

On several occasions this optimisation could be executed for the installations in the case ship as well. To demonstrate what happens with the RSs two different steps are indicated. In practice, it is a more continuous process. First, several RSs are split into different parts, secondly the changes in the MPS configurations are presented that optimise more towards a refit instead of stand-alone performance. Throughout this process of optimisation towards a refit the RSs will have to be checked on their capacity or flow to see if their re-use will be physically possible.

Subsystem:	Modular power system: DM	MM	HE	LE	ME	Subsystem description:		Subsystem:	Modular power system: DM	MM	HE	LE	ME	Subsystem description:
Thrust1			x	x	x	Electric motor, GB, shaft, FPP	→	Elec5			x	x	x	Electric motor
								Thrust1			x	x	x	Single input GB, shaft, FPP
Thrust4	x	x				GB, PTO, shaft, CPP	→	PTO	x	x				PTO
								Thrust4	x	x				double output GB, shaft, CPP

Figure 5.7: The split repeatable subsystems of the case ship

Two RSs on the list have been split, as shown in figure 5.7. Both have the function to deliver thrust from the main power generation output: for the FC systems this is the RS with the electric motor , single-output gearbox (GB) and fixed pitch propeller (FPP) and for the ICE systems this is the RS with the dual-output GB, PTO and controllable pitch propeller (CPP). For both, the electric component (the electric motor or PTO respectively) has been taken as one RS and the gearbox and propeller as the other repeatable system, introducing two extra RSs. This allows, if the capacities match, to share the gearbox and propeller between the different options. This could save significant investments incurred by not having to refit the GB, and it was understood that it leads to an acceptably small loss in performance.

After the split, several changes to the installed RSs were made. One change is keeping the GB, but several others were also applied. The full set of changes is displayed in figure 5.8.

	Modular power system:					
Subsystem:	DM	MM	HE	LE	ME	Subsystem description:
CH1	x	x				HT heat recovery, elec heater, boiler
CH3			x	x	x	LT heat recovery
Comp1	x	x				30 bar compressor
Comp2			x	x	x	8 bar compressor
Elec4-1	x					Init. distribution switchboard
Elec4-2		x	x	x	x	2nd distribution switchboard
Fuel1	x			x		Side bunkers
MeOH1		x		x	x	Methanol bunkers double bottom
Thrust1			x	x	x	1-output-GB, FPP, EM
Thrust4	x	x				2-output-GB, CPP, PTO
Water1	x	x				Fresh water generator
Water3			x	x	x	Pure water remineralisation
Water6			x	x	x	8 bar hydrophore
Water7	x	x				30 bar hydrophore

	Modular power system:					
Subsystem:	DM	MM	HE	LE	ME	Subsystem description:
CH1	x	x	x	x	x	HT heat recovery, elec heater, boiler
CH3						LT heat recovery
Comp1	x	x	x	x	x	30 bar compressor
Comp2						8 bar compressor
Elec4						Main distribution switchboard
Elec2	x	x	x	x	x	External distribution switchboard
Elec3-1	x					Initial internal distribution switchboard
Elec3-2		x	x	x	x	Second internal distribution switchboard
Fuel1				x		Extra bunkers in side and bottom
MeOH1	x	x		x	x	Methanol bunkers double bottom
Thrust1						1-output-GB, FPP
Elec5			x	x	x	EM
Thrust4	x	x	x	x	x	2-output-GB, CPP
PTO	x	x				PTO
Water1	x	x	x	x	x	Fresh water generator
Water3			x	x	x	Pure water remineralisation
Water6						8 bar hydrophore
Water7	x	x	x	x	x	30 bar hydrophore

Figure 5.8: List of changes in subsystems

In most of these changes the capacities have been checked, this will receive more attention in the next section. The justification for the changes is listed below. This includes the check in capacity for the changed systems, and for the box coolers that are expected to be shared between all MPS configurations.

- The original heating system is to stay in all configurations. It could possibly lead to a more frequent usage of the electric heater and boiler in the FC systems because of the lower cooling water temperature (70 ^{o}C instead of 90 ^{o}C), but it is expected that this effect will be limited as 70 ^{o}C will probably still lead to a central heating temperature of higher than room temperature.
- The compressor is not exchanged, as the initial compressor has a capacity determined by the ICE, which is higher than what is required in the FC configuration. The air bottles can be placed in hard to reach locations so different air bottles will not save space and the limited size difference in compressor is thought not to justify the acquisition of a new compressor.
- It is thought that electric components are costly, and they have many connections, therefore it is chosen to make the switchboard modular. One half should remain in the ship at all times to serve the NMSS, the other half should serve the MPS and should be replaced in the refit, and the interface between them should be standardised in capacity and type of connection. The location for the MPS half should be dimensioned so switchboard for any reasonable configuration should fit there.
- In regards of fuel capacity, the ship will require about twice the required diesel volume in methanol, and about eleven times the diesel volume in LOHC. It seems acceptable to have a range of double the minimum, but eleven times seems unacceptable as this would decrease ballast possibilities. Therefore, diesel and methanol will use the same fuel storage, but the LOHC will be stored in additional tanks as well. Methanol storage has higher regulatory requirements because of its low flashpoint compared to LOHC and diesel. For that reason, the diesel storage is prepared so it can be brought up to methanol standards during a refit without additional construction work. For the LOHC several ballast tanks will have to be prepared for a conversion to carry LOHC without additional construction work. Pure hydrogen cannot use this type of fuel storage and will have its own storage.
- It is thought the GB can be re-used when switching from an ICE to an FC system. In a typical optimised system for an ICE, a dual output gearbox with PTO is connected to a CPP. In a typical optimised electrical system, a single output gearbox is connected to a FPP from an electric motor. It is not a technical

issue however, to connect the electric motor to a dual output gearbox with a CPP at the range of the ICE, if the electric motor has the right frequency range. Some disadvantages of this situation are that this requires a slightly heavier gearbox, with a more expensive and slightly less efficient propeller, and that it reduces the amount of suitable electric motors. The advantage in the case of a refit is that this saves the expense of a new propeller, propeller shaft and gearbox, and it may also make the refit more straightforward. For this reason, the design will made around an electric motor for a generator set of the same family as the original main engine, and the gearbox with CPP will be maintained.
- From the information about a freshwater maker using cooling water [68], such fresh water make should still perform using water of 70 ^{o}C, but with lower capacity. It may be necessary to install a freshwater maker with a higher capacity in the initial installation, or the pure water generated from the FCs could be used as an additional fresh water supply.
- With the 30-bar compressor remaining in the installation the hydrophore also does not need to be changed.
- Finally, the box coolers capacities were checked. The cooling system of the ship consists of 5 coolers in the original configuration: two for the main engine, two for the largest auxiliary engine and one for the small auxiliary engine, of which in total 3 HT coolers and two LT coolers. To the cooling systems several auxiliary systems are connected of which some require heat and others deliver heat. The water temperature of an LT-PEM fuel cell system is about 70 ^{o}C and about 2400 kW needs to be water cooled (see appendix C. The ICEs deliver around 650 kW between 75 and 90 ^{o}C in their HT coolers and around 850 kW around 55 ^{o}C in their LT coolers. The temperature difference causes the coolers for the HT cooling water to reduce slightly in performance, but to increase the LT cooler in performance. No detailed calculations have been performed, but it is assumed that a cooling system can be designed that would function in both systems, but that would not be excessively larger, because of the high temperature difference with the sea water. Such system should include a small LT cooler for the auxiliary systems that have a low operational temperature compared to the fuel cells, such as the gearbox, CPP and possibly the electric motor.

These changes lead to the last version of the list with RSs. The complete list can be found in appendix C with the other lists. This final list consists of 37 used RSs, of which 9 are used in all MPS configurations. The systems are built up of 9-13 different exchangeable subsystems.

For any subsystem that is installed in different configurations it should be checked that it is able to perform its function in all these configurations. As far as enough data were available on the systems this was checked. More calculations should be performed with the manufacturers data to provide certainty.

The systems built with this final set of RSs consist of subsystems that have been adapted for the refit as far as acceptable or practical. As the RSs still include a limited amount of physical information and the available information has been used for a large part, the next step would be to investigate the physical appearance of the system.

5.2.4. The design process of designing modules and ship

The goal of this research is to find a method for designing a ship with a refittable power supply system by using modularity. The final phase of the method should provide a way of designing the ship, including its MPS, in a form that would allow to continue the design of the ship past the concept design, preferably based on the previously found RSs. This phase turns out to have three steps: grouping components functionally, designing the ship and the modules, and then re-designing it. The last step was not intended. The three steps will be explained in this section.

Grouping components according to functionality The RSs are relatively independent, functional subsystems, and in the list with these subsystems it can be identified which subsystems will be on board simultaneously. It is known that modules need to be functional, exchangeable units, with a standardised interface and relatively independent from other modules. Therefore, it is proposed to use the RSs to identify how subsystems can be used as a basis for modules. First an approach for identifying possible modules is proposed, after that the approach is verified by applying it to the case ship.

In chapter 3, it was explained that functionality of systems is an important factor in determining how modules should be formed in ships and refittable systems. So far, mainly the interactions of components with each other were used to identify how they relate. This is also true for the RSs; only their interactions have been used to analyse and define them. The interactions of components largely define the interface for them because the interactions define the necessary connections.

In the ship, a subsystem often meets and affects more than one other subsystem. The interfaces are expected to be more similar in functionally similar subsystems, as mutual functions often require mutual connections. Apart from the connections for the mediums flowing through the subsystems, the space available for a certain subsystem also needs to fit the replacement subsystem. This makes the available space part of the interface. The interfaces of the modules are therefore to be relatively standardised in terms of available space and connection possibilities. The available space should follow from designing the ship with the modules and in the design the connection possibilities should be prepared.

Modules should also be exchangeable. The system that is studied is not expected to have many identical interfaces. This means that modules can be installed in one place only. This also means that different modules with a certain interface should be in the same position, but not at the same time. To avoid empty spaces and to avoid that modules would have to have different locations in different configurations, it is important to identify how subsystems that share interfaces replace each other, in order to see if these subsystems are suitable to be designed as modules.

To identify subsystems that could form modules it is proposed to use the function of subsystems within their MPS to group components into groups of subsystems with similar functions in different MPSs. If no similar functions can be found, the secondary way of grouping them is analysing the possibility of a shared location by not being on board simultaneously.

To verify this approach, it is applied to the RSs of the case ship. The found different groups of RSs are illustrated by figure 5.9, the complete list is added to appendix C.

The process was relatively straightforward to perform for the case ship. First the RSs with a clear function were grouped. They replace each other in different MPS configurations; sometimes completely, and sometimes partially. Secondly the RSs that are shared between the systems were listed. If the capacities are sufficient, they will not be refitted and do not have to be modular, apart from a standardised interface where connected to modules. Finally, some RSs were left that did not have similar functions: these subsystems and their function are unique to certain MPS configurations. They are called additional subsystems. The additional subsystems could impose an extra challenge in standardising the interface of them, because of their differences and the fact they do not specifically replace each other.

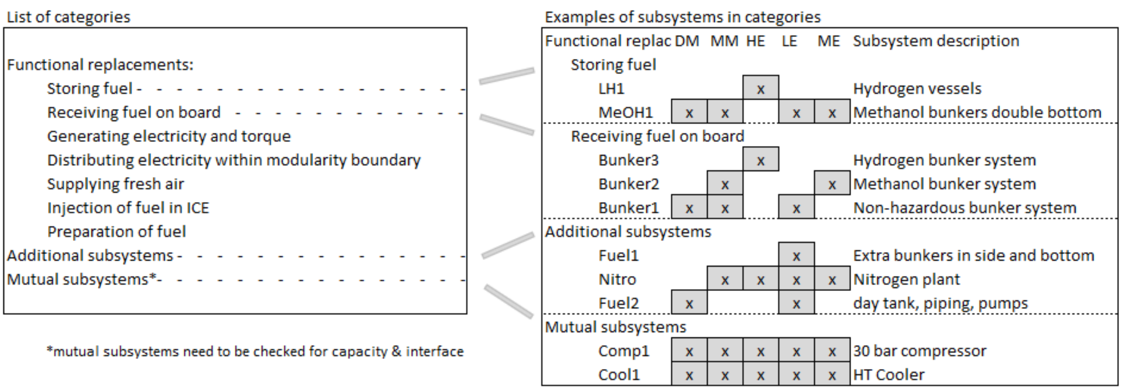

Figure 5.9: Functional categories in which modules can be identified, that can possibly share location and other interface properties

The RSs could be grouped, and a limited number of component groups was found. These groups contain components that do replace each other and have similar functions, apart from the additional subsystems. The step is deemed possible, but from analysing the list of groups it cannot be concluded if the step is helpful. This step could therefore not be verified on its function, only on its possibility. It is thought that only designing the ship could verify the suitability of the groups.

Initial 3D design The components of the MPS have now been grouped as subsystems that have a common functionality and that can replace each other. The subsystems still are not modules as they have not been designed and therefore it cannot be known if they are suitable to replace each other and if the ship can thus be refitted by using them.

The objective of this research is to come to a ship design in which as few components as practically possible are moved in a refit. This design should incorporate the physical properties and relations of components, has enough de tail and is complete enough to take further than the concept design. As most functional properties of the subsystems are known, but the physical properties are still not integrated in the design, it seems these properties are now to be included to come to the design of the modules.

The physical properties of the modules are thought to have little meaning, if they are not included in the system, they are to be installed in. Not only the modules within the MPS, but also the NMSS components define the interfaces of the modules.

Considering the knowledge on a technology insertion and the assumption on the low-impact refit, interfaces are thought to be prepared in terms of connection possibilities instead of pre-outfitted connections. Based on the theory about refitting naval ships this preparation could be cable ducting, pipe ducting and possibly extra branches in existing infrastructure. It does not seem worthwhile to prefabricate all possible connections for all possible modules for a location because it is too uncertain to justify this, and it is not expected that a refit will take place more than once. This would render connections for the installations that are not chosen as alternative completely useless.

To design the ship several constraints should be respected, that follow from modularity or the low-impact refit:

- Components should be in the same location in each configuration that they are used for.
- It is not preferable that module locations are empty in any of the MPS configurations, especially not large, dedicated, locations.
- Components should be removable or installable without moving components around that are not refitted simultaneously
- Construction work should be avoided where possible
- Interfaces should contain preparation for the connection of modules

As both the MPS and the NMSS have a role in defining interfaces, and the physical properties of the components seem necessary in continuing with the design, it is proposed that the next step should be to model the components and the ship, and to design them in 3D. The existing 3D model of the ship should be altered so the design becomes suitable for all the considered MPS configurations. It is expected that the previously found functional groups will help in determining which components should be at the same location, so that they can share an interface.

With the available technical details on the original design, the ship was designed. A fixed basis was designed that is the same for each configuration, and the exchangeable components of the MPS replace each other. Several considerations made during this initial design can be found in appendix C

Many of the original components were repositioned to make a clearer distinction between replaceable MPS subsystems, and the NMSS and shared MPS subsystems. This means the proposed order gives a system in which the systems can be exchanged without moving components around unnecessarily. The method is still not completely verified however, because it has not been checked if the ship would be able to comply to all regulations.

Complying to low flashpoint fuel regulations After an initial design with the groups, the design is checked on compliance with regulations to see if the design is realistic. Normally, the engine room is one compartment, with one ventilation system, containing multiple ICEs on diesel. This is not tolerated for ships using a low flashpoint fuel, such as methanol or a gas. The design was clearly flawed in this point.

The methanol storage requires cofferdams, a ventilated pumproom, a pressure relief valve and a safe location for bunkering [60], the methanol pump for the injection of fuel into the ICE requires a separate ventilated space with an access from deck or an airlock [60] and the fuel cell space requires a flat ceiling, ventilation, closed walls and also an access from deck or by an airlock [55]. The dedicated ventilation requires separate intakes and outlets which are classified to be surrounded by hazardous zones, varying from 4.5 to 10 meter in diameter, which could often not overlap. Part of these safety measures were known already, so a fuel cell space was for example incorporated in the initial design, as were cofferdams around the methanol tanks, but the design also had to be changed in multiple ways.

To understand the impact of the regulations on the refittability of the ship the design was altered to incorporate most of the regulations. In this process the constraints of the low-impact refit were respected, even though several subsystems did get a dedicated location on board instead of a shared location. These dedicated locations on board could be found in cofferdams and a separate space in the engine room. The design was altered to comply to the rules for a methanol ICE and most of the fuel cell rules, a hazardous zone plan for the methanol ICE configuration can be found in appendix C, several examples of changes are:

- The bunker connections for methanol and diesel were designed in two different locations instead of one
- The engine room got an extra entrance directly from deck through a trunk, for which about 1 m^2 was sacrificed from an officer's cabin
- The methanol feed pumps, and several valves were located in a cofferdam between methanol tanks instead of in the engine room
- Air intake and outlet pipes were designed in several places: along the wheelhouse to above the bridge, through the keel duct to the mast on the bow and through the funnel.

It is the intention to locate all subsystems of a functional subsystem group in the same location if technically possible, so they can be exchanged with components from the same group in a refit. To follow the regulations, several subsystems of some groups need to be designed in different places and certain subsystems should be placed or designed in a less convenient way. Because this leads to a less convenient design, in not all cases it is justifiable to design the initial installation according to the stricter rules as well. This leads to a physical separation between the subsystems of functional groups. In this design it was possible however to maintain an exchangeable set-up by using locations that would normally be left empty, such as cofferdams. The constraint to preferably not leave locations empty in different MPS configurations has been bended in that sense.

At the first glance, it seems this design complies to the standards of the low-impact refit, the most influential regulations and of a system with modules. In the upcoming sections it will be analysed if this verifies the method, and it will be summarised what steps were taken.

5.3. Resulting case ship design

The resulting design of the method for modular design applied to the case ship is presented in this section, with the aim of verifying the method. The method is supposed to use modularity to design a ship able to undergo a low-impact refit to change its power supply system. The design should therefore be modular, and it should enable a low-impact refit.

In this section first part of the original design is given to give a sense of comparison. Secondly, the general and engine room arrangement are given to show where components are located. This will be followed by an explanation of how components can be removed or installed. Finally, some information is given on the safety measures taken.

5.3.1. Recognizing the original design is not modular

The case ship is based on an existing ship, for which an arrangement and 3D model were available. Using an existing design as a basis gives two possible directions to the design: staying close to the original design in order to respect as many of the original design decisions as possible, or rearranging components without knowing if this is realistic. The first direction does not give as much freedom, but the second direction might result in an unrealistic design. To avoid any unrealistic designs, it was chosen to rearrange only the necessary components. This would also give insight in how little (or much) effort is necessary to design the ship with modules.

In figure 5.10 the original engine room arrangement is given, in which it is indicated which components belong to the MPS and which to the NMSS. This arrangement shows how mixed the components were in terms of the two system halves as identified in the method. A more detailed engine room arrangement can be found in appendix C.

For the case ship the most convenient way of removing the engines would be horizontally through the engine room bulkhead into the hold. This too would demand several components to be removed that are part of the NMSS.

This means the case ship's original design was not suitable for an easy refit for two reasons. Firstly, the components that were not to be refit had to be reinstalled to make space for a new installation. Secondly there were components in the way of removing or installing new components. This realisation is one of the reasons a special investigation was considered.

A final remark about the relationship with the new and the original design is made. All the components shown in the original engine room arrangement are included or replaced in the new design. It is important

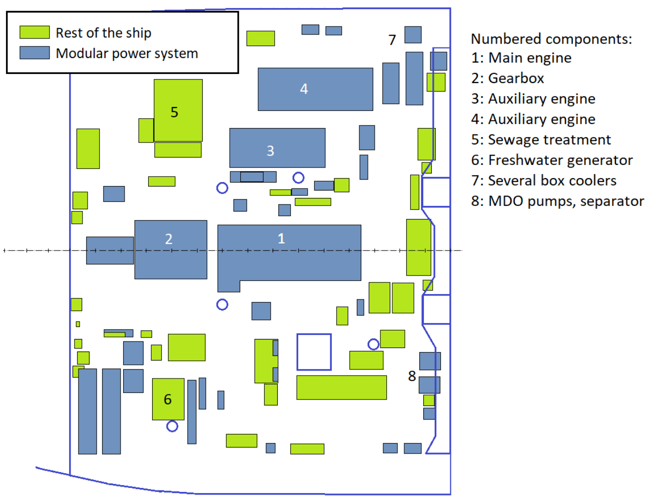

Figure 5.10: Indication of the modular power system in the original engine room arrangement

to guard this, because the modular design should preferably not reduce the functionalities of the ship or be incomplete. In some cases, certain components are replaced by different components because of their part or dependence on the power supply system, but the functionalities of the system should not change.

5.3.2. Resulting design

The aim of the design was that any component that is not to be refitted is not to be replaced or removed during the refit and that it can stay installed in the same place during the entire lifetime of the ship. To realise this situation, locations were assigned to refittable and to non-refittable components. These locations are given in figure 5.11. In a 3D model the mentioned components were designed in those locations, to see if it would fit in practice, these resulting designs are given in appendix C.

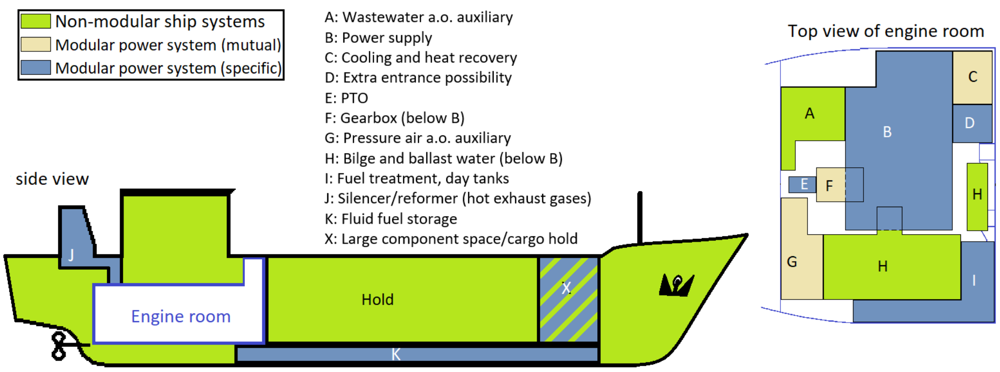

Figure 5.11: The modular design of the case ship – a simplified arrangement

In figure 5.11 several locations are shown in the ship in which components are installed. The locations have been labelled in three categories, for locations containing:

- NMSS components
- components that are mutual/shared between configurations
- specific MPS components that are not the same for all configurations

Only components from the specific MPS locations are exchanged and therefore only the locations of specific MPS locations need to be specially considered for modularity or other preparations that should aid a refit. In table 5.1 it is indicated which specific MPS components are installed in which location. The following aspects are considered in aiding the refit:

- If the engines are removed, it is thought this should happen horizontally through the engine room

Area	DM	MM	HE	ME	LE
B	ICE + ICE aux		FC + FC aux	FC + FC aux + reformer parts	FC + FC aux
D	Empty	Pump room entrance, methanol pump, valves	FC entrance	FC entrance + reformer parts	FC entrance
E	PTO		Empty		
I	Day tanks, separator, transfer pump	Nitrogen generator	Nitrogen generator, FC converter cabinet		
J	Silencers and exhaust		Ventilation outlet	Ventilation outlet + reformer parts	Ventilation outlet
K	Diesel storage, ballast	Methanol storage + pumps, ballast	Ballast	Methanol storage + pumps, ballast	LOHC storage
X	Hold		Cryogenic storage	Hold	Hydrogen release plant

Table 5.1: Description of largest components in certain locations, as shown in figure 5.11

bulkhead into the hold. There is one NMSS component in the way for this operation, in location H. This component is easily removed.

- The PTO is only removed when the engine is removed. It is expected it will not be an issue to remove the PTO whilst area B is practically empty
- It is expected that the components in area I are small enough to be removed or installed without major issues.
- Area D is suitable to accommodate an extra entrance from deck, by making an airtight duct through the accommodation into the engine room. It is expected that any low flash point fuel using installation requires such extra entrance because of regulations, so a second entrance is to be prepared in any design.
- Location X contains either the cryogenic hydrogen storage or the hydrogen release plant, because they are too large to be fitted anywhere else in this design. This location would otherwise be used as hold, so the zero-emission installations cost hold volume in the case ship. It costs about 3% of the hold volume for the hydrogen release plant, or about 7% of the hold volume for the hydrogen vessels. The range of the ship in case of using cryogenic hydrogen is also smaller, because it was not possible to make the tanks large enough to sail 20 days without interfering with the sight lines from the wheelhouse. The range instead is 14 days.
- The double bottom of the ship and the sides of the ship, indicated as location K, will mainly be used for ballast water. Four tanks in the double bottom are designed for methanol storage. The LOHC requires more than four tanks, so in an LOHC configuration most ballast tanks should serve as fuel tanks instead. The LOHC is not a flashpoint fuel, and it can be used to trim the ship with because the LOHC remains on board after taking the usable hydrogen out of it, so this is not expected to be a major issue that the LOHC replaces ballast water if the piping of the ballast system is prepared.
- Above the keel of the ship the cable ducting is split in two parts. One half will serve the NMSS, the other half should comply to the regulations for low flashpoint fuels, so the fuel piping can be run through it. This ducting should run from the engine room to the bow, so the hydrogen piping can also be contained in it and the pressure relief piping of the methanol storage can be led to the mast on the bow.
- To accommodate the regulations about hazardous zones the funnel is prepared to contain ventilation outlets, as are two corners of the wheelhouse. On the bow of the ship the mast is used to guide the pressure relief valve of the fuel storage upwards to a save height.

At the level of detail of the design in the 3D model, the design seems possible according to several experts, although the methanol reformer in the funnel is tight. The design contains all necessary components that were in the original design of the NMSS and of the different designed MPS configurations [2].

So far, the possibility of designing a ship with the RSs that were previously developed seems possible but grouping the components to function was difficult to preserve because of safety regulations. Only a limited

[2] It was later realised that a buffer is recommendable in the ME and LE configurations, because of fuel production reasons. A buffer could be realised for example be batteries or hydrogen storage.

number of configurations has been tested, so it is also checked whether alternative configurations would be possible.

5.3.3. Alternative configurations of the design

Only a limited number of power supply systems was considered, but the aim was that the ship should be prepared for multiple options, including ones that are not considered in the initial design. The design is not tested on how it would function with other installations, but there are multiple configurations that share similarities with the ones considered.

In table 5.2 eight energy carriers and three power supply units are considered, and it is indicated which of those could also be possible based on the current design. Four of the combinations were considered in the design. Of the remaining twenty options, thirteen seem possible, depending on their availability and technological readiness at the time of the refit.

	Biodiesel	Hydrogen (liquefied)	Methanol	LNG	Methane (liquefied)	Ammonia (liquefied)	LOHC	$NaBH_4$
ICE	y	y	d	y	y	y	y	m
Gas turbine	y	y	y	y	y	y	y	m
LT-PEM FC	m	d	d	m	m	m	d	m

Legend:
- y: No red flags, but possibly some technical advancement necessary
- m: Unclear if technically possible in current arrangement
- d: Considered in the design

Table 5.2: Thoughts on possible other installations

The reason for thinking certain options are possible are as follows:

- A gas turbine is smaller than an ICE, so this should fit in location B. A gas turbine does require higher amounts of air, but the air ducts and funnel do currently have some margins. This should be checked.
- The liquefied fuels have the same or a higher energy density then liquid hydrogen, so the cryogenic storage of the hydrogen is also suitable to contain the other liquefied fuels [52].
- It is not known how sodium borohydride powder is to be taken on board and it is technologically not ready yet. This makes any application of it uncertain.
- It is dependent on the size of the reformer used if other reformers can be in the place of the methanol reformer. In all reformers, including the methanol reformer, more technological advancement seems necessary before they can be applied in ships (source: personal contact with reformer companies)

Other installations that are not similar have neither been checked, such as other fuel cell types. These are typically larger [13] but are less sensitive to fuel impurities. They do require a buffer to overcome load fluctuations. It is hypothesised that the buffer and fuel preparation could be installed in location B and the fuel cells in location X. This would require cooling in the bow of the ship, which is not prepared, but the fuel and ventilation infrastructure seem suitable for such set-up.

5.3.4. General remarks of designing in this fashion

In designing the ship for the low-impact refit to reduce GHG emissions, several aspects were encountered that are relevant for meeting the objective for this research but are to a designer. Some recommendations and considerations are listed here:

- Entrance to hazardous spaces directly from open deck imposes a hazard for the crew, especially in bad weather. An airlock is also allowed as an entrance from a non-hazardous to a hazardous space, but in a small ship this is more difficult to realise. In bigger ships it is advised to consider an airlock for crew safety
- Regulations are currently still being developed. It seems recommendable to work together with the class societies so that the design of a ship with low carbon emissions can be a learning project for both.
- It can also be recommendable to have the design approved for the alternative designs during the initial designs, so if regulations change prior to the refit the ship would still be able to be classified after the refit.

5.4. Summary of the steps taken

The process of designing the ship consists of several steps, in which three phases were identified. The method starts from an initial conceptual design or at least design requirements. The method ends at providing information at concept design level, to continue the design from there. It is expected that the principles used to develop the method should be respected throughout the entire design process, but the continuation of the design has yet to be performed.

Phase 1: Demarcation
1. Identify the flows in the MPS
2. Make a system diagram of each MPS configuration
3. Determine the interactions between MPS and NMSS
4. Standardise or eliminate the interactions

Phase 2: Finding suitable repeatable systems
1. Determine which combinations of components are identical in multiple MPS configuration, and which combinations are unique. These combinations are the RSs
2. Add additional RSs that contain relevant different design options
3. Find overlap between RSs that can be eliminated by changing prior grouping of components

Phase 3: Designing modules
1. Make a table indicating which RSs are necessary for which MPS
2. Check that RSs that are installed in multiple MPS configurations match in capacity
3. Reconsider which RSs are in which MPS to better facilitate a refit
4. Group the RSs according to function
5. Design modules and the ship's arrangement, based on the RS groups and the physical properties of the components

These different steps resulted in several pieces of information that will be analysed in the following sections. The following information was created during the steps:

- A matrix with the in- and outputs of the MPS
- A system diagram for each of the MPSs, with the standardised connections
- A collection of RSs, including some design options that were not in the original designs
- Several of the iterations of the RSs required for the MPSs
- A 3D model of the ship, including the considered MPS configurations

5.5. Analysis of the development and verification results

In this section it will be analysed if the development of the method has led to a satisfactory result. First it will be explained how the resulting design is modular, secondly it will be explained if the method fits the objective of this research and finally an adjustment is made to the method as presented in the previous section.

5.5.1. Modularity of the design

The ship seems suitable to allow an exchange of the power supply system or components of its power supply system, and the method to come to this point was based on modularity. It is not yet determined if the ship actually consists of modules, or if the design is modular. The definition of modularity quoted in section 3.2.1 [1] was:

> Modularity is a special form of design which intentionally creates a high degree of independence or 'loose coupling' between modules by standardizing module interface specifications.

Also, modules were described in section 3.2.1 to be relatively independent subassemblies with a standardised interface that can be recombined into multiple end products. When looking at the design in section 5.3 the used definitions of modularity and modules seems to be respected. The subsystems are not interacting with other systems, apart from the interactions with other subsystems that are standardised. The ship can be refitted to a different power supply system, so multiple end products can be obtained. Modules for the ship are not prefabricated, but subsystems are typically located together and assembled onto each other, making them a subassembly.

5.5.2. Verification of the method

In a number of steps, a case ship has been designed to fit the objective of this research;

> to develop and validate a method for the modular design of the power supply system of a ship that allows a low-impact refit, in order to reduce GHG emissions when the technology is ready.

A design resulted in which four different installations are designed that have lower GHG emissions then the original diesel installation, that can be refitted respecting the assumptions on a low-impact refit. Several other similar installations are expected also to be suitable for this design, providing they are technological ready at the time of the refit. The design was thought to be modular as well, so this leads to the conclusion that the method has led to a satisfactory result.

5.5.3. Adjustment of the method

The method has given a result that seems to fit the objective of this research. In that sense the method is deemed successful. However, the method as presented in the previous summary proved to give one issue in the process of designing the case ship: the initial 3D design had to be altered to accommodate safety regulations, even though these regulations were not dependent on the design and could therefore have been included earlier in the design.

To come to a satisfactory result sooner, one adjustment to the method is proposed: the safety requirements for the components that have a high impact on the design (e.g. ventilation, air intakes, air outlets, pressure relief valves, explosion proof spaces) should be labelled in the RSs. It is thought this should help in sorting the RSs into groups that can replace each other, as the safety requirements have a strong impact on the interface of the systems. This adaptation should be verified during the validation.

6
Validation of the method for modular design

To validate the method for modular design a second case ship is designed with the method, to be suitable for a refit of its power supply components. The method will be validated by applying the adjusted method to the second case ship, and then analysing if this is possible and gives satisfactory results.

First, the adjusted method will be presented. Secondly, the method will be applied to a second case ship. This will include some information on how the steps are applied and helpful. The results of the applications will be given at the end of section 6.2.4. Finally, the application of the method and the result will be analysed.

6.1. Overview of the steps to be taken

In the previous chapter, the steps of the method were summarised and adapted to the analysis of the results. In the validation these steps are taken as well, except of one adjustment: Halfway the investigation into RSs, the most significant safety measures are to be included in the information on the RSs.

Phase 1: Demarcation
Phase 2: Finding suitable repeatable systems
1. Determine which combinations of components are identical in multiple MPS configuration, and which combinations are unique. These combinations are the RSs. **Include information on most significant required safety measures**
2. Add additional RSs that contain relevant different design options
3. Find overlap between RSs that can be eliminated by changing prior grouping of components

Phase 3: Designing modules

As the second case ship is different attention should be given on if the method is suitable to apply to the second case ship as well. Also, the resulting design should fit the objective of the research.

6.2. Taking the method's steps

The method is validated, by taking all the method's steps again, but for a different ship. It cannot be published which ship this is exactly, the details of the ship are presented in the confidential appendix D. Only those results necessary for the validation of the method are presented in this report, the design will not be presented in detail.

6.2.1. The starting point for the method

The method starts at the level of a conceptual design or a set of design requirements. In case of the validation case a concept design is available. It is again a short-sea cargo vessel, but this time it is always propelled by an electric motor. The set-ups as presented in table 6.1 are used.

It is assumed that the ICE requires a selective catalytic reduction (SCR) in all ICE configurations, to reduce NO_x emissions. It is also assumed that a thermal oil heater in the exhaust of the ICE is used to generate 75% of the required heat for the LOHC power plant for the ICE-LOHC configurations, to reduce the losses of the

	MGO	Methanol	Liquid H_2	LOHC
ICE	DM	MM	x	LM
FC	x	ME	HE	LE

Table 6.1: Overview of chosen alternatives in the case-ship, with their used acronyms.
It is chosen to use acronyms that are consistent with the previously used acronyms, even though all six configurations are in fact electric. The M on the second position stands for the motor in the ICE configuration, the E on the second position now specifically means a fuel cell configuration, rather than an electric configuration

LOHC hydrogen release plant. A buffer for the fuel treatment plants is also necessary, it is assumed this buffer should be able to perform one hour of nominal sailing.

In this first step the expected bunker capacities and expected size of the main installations have been determined. If diesel is the benchmark, the following relative sizes of the installations have been found:

Configuration	Fuel storage type	Relative volume	Fuel treatment	Relative volume	Power supply
DM	Integrated tanks	100 %	Separator, settling & day tank	100%	ICE
MM	Integrated tanks	230 %	Separate pump room, pilot fuel	±100%	ICE
LM	Integrated tanks	695 %	Hydrogen release plant, heater	1450%	ICE
ME	Integrated tanks	245 %	Methanol reformer	250%	LT-PEM FC
HE	Cryogenic tank	800 %	Gasification, built in tank	0 %	LT-PEM FC
LE	Integrated tanks	740 %	Hydrogen release plant	1350 %	LT-PEM FC
LM, ME, LE			1h capacity Li-ion batteries	10 %	
			1h capacity 350 bar H_2 vessel	35 %	
			1h capacity Lead acid batteries	85 %	

Table 6.2: Relative volumes of the main installation, only one buffer necessary per configuration. Relative volume of buffers also relative to fuel treatment of DM

The volume for the fuel cells and ICE are not compared, as it is not straightforward to determine which components and part of the volume of a space should be included. Both are expected to fit in an equal amount of TEUs for the power required. Also, the size of the integrated tanks is not relevant, as these integrated tanks are placed in parts of the ship that can only be used for liquid storage of non-cargo fluids. The cryogenic tank or tanks are not expected to fit in the double bottom or double side of the ship, so they will take up useful space.

The arrangement of the ship is not published, as this is not necessary for the method. The steps of the method are aimed at functional relationships and do not consider the rest of the ship.

6.2.2. Finding the system boundary

A matrix with the in- and outputs present in the expected MPS should be constructed to find the system boundary, according to the steps taken for the design of the first case ship. Such matrix is constructed for the diesel-ICE configuration. As it is not known exactly how the different alternative installations relate to the in- and outputs of the rest of the ship, this step cannot be finished without the information from the system diagrams. The construction of the matrix is informative to execute, but it seems that it is not essential. Instead, the standardisation and separation of the mediums is executed when drawing the system diagrams.

The system diagrams of the different MPS configurations could easily be constructed with the information of the prior case. The different configurations should be presented by a combination of components that is optimised for that configuration, without a refit in mind. Because of the lack of information for ending the in- and output matrix, the connections between the MPS and the rest of the ship were not yet standardised or separated in the first version of the system diagrams. The system diagrams are used instead, to determine which connections can be standardised, and which can be separated. To explain how this is done, a small section of the system diagram of one of the ICE configurations is given in figure 6.1.

Four important components of the electricity system of the ship are shown. In the second case ship the electric motor is included in all configurations, so it can be included in the rest of the ship rather than the MPS. The voltage converter had to be included, as the output voltage of a genset is not expected to be the same as the output voltage of the fuel cells. The battery charger and batteries must be included because they are only necessary for the ICE and not for the fuel cells. The local distribution may have the same connec-

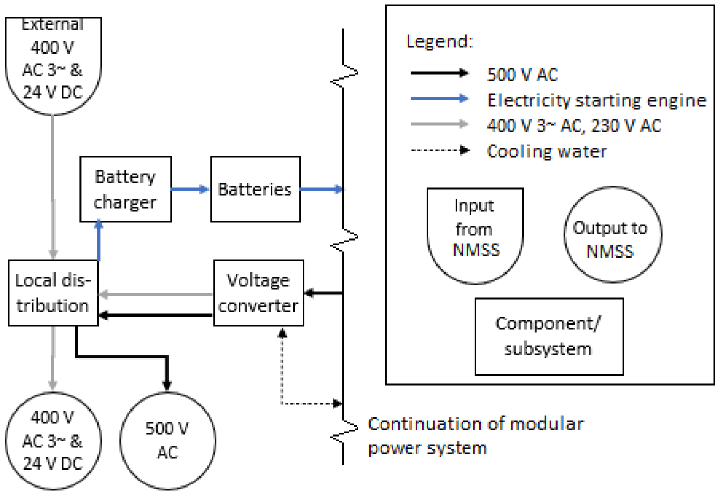

Figure 6.1: Section of the electric components in the system diagram of an ICE configuration

tions in the system diagrams, but because the network of 230 V AC and 400 V AC is not drawn in the system diagram, this is misleading. The network is expected to be different in each configuration, so the local distribution components are expected to be different as well. The external power, originating from the emergency generator and the power-to-shore connection, is necessary to be able to start the system up in both ICE and FC configurations. If not all of them required this connection it still had to be included as a standardised input, but the connection would not be used in in all the configurations.

For all components it has been determined whether they are not necessary in each configuration, and if they are necessary in each configuration whether their in- or output could be standardised or that a separate system could be thought up. For example, the coolers cannot be standardised, so even though all system configurations require coolers the coolers have to be within the MPS. The cooling water necessary for some auxiliary systems that are not related to the power supply can be standardised, and therefore a standardised cooling water connection between the MPS and the rest of the ship is also established. These standardised in- and output mark the end of the MPS and therefore the system boundary is now found.

6.2.3. Identifying repeatable subsystems

The RSs are found by finding the similarities between the different system diagrams. All components that are grouped together in each configuration they are installed in, should be drawn as a RS. The MPS of the second case ship seems to be less complicated compared to the first case ship, as now only 19 RSs are found, they can be found in appendix D.

For each of the MPSs it is determined which of those RSs should be present. This gives a list of the 18 RSs and the rest of the ship, in which is indicated which subsystem is present in which configuration. This list is shown in figure 6.2. The four components (3, 4, 12 and 14) that are highlighted will receive further attention in the next section. The buffer for fuel production lag has not been chosen yet; this can be executed in different ways (two battery types and 350 bar hydrogen are considered). The buffer will be chosen during the design, when it is known where a location for the buffer can be realised and which buffer will fit there better.

Refittable subsystems The listed RSs could be used as a basis for modules as they are, but that would lead to unnecessary removal or installation of similar systems. Instead, several components are recombined so that they are more similar and more exchangeable. In figure 6.2 the four subsystems that are recombined this way are highlighted. They are the fuel storage and transfer of the liquid fuels and the extra tanks necessary for the methanol ICE and diesel ICE configurations. Even though a couple of components within those subsystems are the same, they are not combined with components identical to the other subsystems. Small design changes could make them identical however, so that less components will have to be designed and refit.

First, the subsystems are split, as can be seen in figure 6.3. This extra work is necessary, as the combinations of components taken directly from the diagrams are not as practical as desired. After splitting the subsystems, they are recombined again, where some of the components will have to be designed for the user with the highest requirements. E.g. the small tanks will have to suit the day and settling tank amount for the

ID	DM	MM	LM	HE	ME	LE	
1	x						Ventilation
2	x						Crank case ventilation (standard)
3		x					DF injection, dilution tank
4	x	x					MGO transfer, bunker, day tank, injection
5			x				Thermal fluid heater
6			x				H2 injection
7		x	x				Crank case ventilation (hazardous)
8	x	x	x				Gensets, battery charger, SCR, voltage converter, internal distribution
9	x	x	x				Silencer
10				x			H2 cryo tanks
11					x		MeOH reformer
12		x			x		Meoh bunker and transfer
13						x	h2 burner
14			x			x	H2 release plant, LOHC bunkers
B			x		x	x	Buffer for fuel production lag
15				x	x	x	Fuel cells, local distribution, pure water tank, humidifier, condenser
16		x	x	x	x	x	Explosion proof ventilation, nitrogen generator
17	x	x	x	x	x	x	Cooler
18	x	x	x	x	x	x	Non-modular ship systems

Figure 6.2: List of repeatable subsystems present in the different configurations of the MPS

ID	Power configuration: DM	MM	LM	HE	ME	LE	Repeatable subsystem:		ID	Power configuration: DM	MM	LM	HE	ME	LE	Repeatable subsystem:
4	x	x					MGO transfer, bunker, day tank, injection	⇨	a	x						MGO transfer, bunker
									b	x						Day tank
									c	x						Separator
									d	x						MGO injection
									e		x					Pilot fuel bunker, transfer
14			x			x	H2 release plant, LOHC bunkers	⇨	f			x			x	H2 release plant
									g			x			x	LOHC transfer, bunker
12		x			x		Meoh bunker and transfer	⇨	h		x			x		MeOH transfer, bunker
3		x					DF injection, dilution tank	⇨	i		x					MeOH dilution tank
									j		x					MeOH/MGO injection
15				x	x	x	Fuel cells, etc	⇨	k				x	x	x	Fuel cells, local distribution, humidifier, condensor
									l				x	x	x	Pure water tank

Figure 6.3: Splitting the found repeatable subsystems into some of their components

diesel system, but also meet the requirements for the dilution and pilot fuel tanks. These new combinations can be found in figure 6.4. In this recombination the first physical property of the systems is used from table 6.2. It is assumed that the 245% capacity necessary for the methanol-FC configuration is acceptable as a standard bunker capacity also for diesel, but that for the additional 555 % capacity necessary to meet the LOHC-FC configuration extra bunkers will need to be installed or adapted from void or ballast spaces.

ID	Power configuration: DM	MM	LM	HE	ME	LE	Repeatable subsystem:		ID	Power configuration: DM	MM	LM	HE	ME	LE	Repeatable subsystem:
a	x						MGO transfer, bunker	⇨	19	x	x	x		x	x	Fluid bunker & transfer
g		x			x		MeOH transfer, bunker									
f			x			x	LOHC transfer, bunker									
f (again)			x			x	LOHC transfer, bunker	⇨	20			x			x	Extra bunkers
b	x						Day tank	⇨	21	x	x		x	x	x	Small tanks (2+ compartments)
h		x					MeOH dilution tank									
j		x					Pilot fuel bunker, transfer									
k				x	x	x	Pure water tank									
c	x	x					Separator	⇨	22	x	x					Separator
d	x						MGO injection	⇨	23	x						MGO injection
e			x			x	H2 release plant	⇨	24			x			x	H2 release plant
i		x					MeOH/MGO injection	⇨	25		x					Dual fuel (MeOH/MGO) injection

Figure 6.4: Rearranging the split subsystems into new, better exchangeable, subsystems

Another simplification to the design is to prepare the ship with crank-shaft ventilation suitable for using hazardous fuels, also in the diesel-ICE configuration. The crank-shaft ventilation suitable for the use with hazardous fuels has the same function, but higher requirements. It is chosen to prepare the crank-shaft ventilation so that no structural work is necessary to bring it up to the standards of different fuels in case the ship would be refit to the MM or LM configuration. This decision could also have been made during the design of the modules and the ship, but in reducing the number of different components to install, it seems more helpful in this step. The resulting list can be seen in figure 6.5

When comparing the first list from figure 6.2 and this list it can be seen that the number of subsystems has increased. This is due to taking the small components that make RSs different out of those RSs and making them independent, so that the rest of those RSs can be identical. This was illustrated in figure 6.3 and 6.4. So even though a larger number of different RSs is listed, a lower number of components is expected to be changed.

	DM	MM	LM	HE	ME	LE	
2							Crank case ventilation (standard)
1	x						Ventilation
23	x						MGO injection
25		x					MeOH/MGO injection
21	x	x					Small tanks (2+ compartments)
22	x	x					Separator
5			x				Thermal fluid heater
6			x				H2 injection
7	x	x	x				Crank case ventilation (like hazardous)
8	x	x	x				Gensets, battery charger, SCR, voltage converter, internal distribution
9	x	x	x				Silencer
10				x			H2 cryo tanks
11					x		MeOH reformer
13						x	H2 burner
24			x			x	H2 release plant
20			x			x	Extra bunkers
B			x		x	x	Buffer for fuel production lag
19	x	x	x		x	x	Fluid bunker & transfer
15				x	x	x	Fuel cells, local distribution, pure water tank, humidifier, condenser
16		x	x	x	x	x	Explosion proof ventilation, nitrogen generator
17	x	x	x	x	x	x	Cooler
18	x	x	x	x	x	x	Non-modular ship systems

Figure 6.5: Renewed list of the repeatable subsystems per configuration

6.2.4. Designing modules and the ship

In figure 6.5 a list is shown with the necessary subsystems for the different MPS configurations. The final step before designing modules is identifying them. In identifying the modules, the functional similarities are found between modules that replace each other. Thus, the list is changed again, this time it is sorted to function. This list can be found in figure 6.6, on the right-hand side. The left-hand side in the figure, with the indicated locations, will be explained later.

Location:		Configuration:							
		Functi	DM	MM	LM	HE	ME	LE	
A	Except:	Power supply							
		7	x	x	x				Crank case ventilation hazardous(-prepared)
		8	x	x	x				Gensets, battery charger, SCR, voltage converter, internal distribution
		9	x	x	x				Silencer
	also b	15				x	x	x	FCs, local distribution, pure water tank, humidifier, condenser, FC space
A		Safety additions for mutual systems							
		1	x						Ventilation
	also m	16		x	x	x	x	x	Explosion proof ventilation, nitrogen generator
B		Injecting fuel in ICE + fuel pumps							
		23	x						MGO injection (fuel pump built on engine)
		25		x					MeOH/MGO injection + high pressure methanol pump
		6			x				H2 injection + gas valve
C		Extra energy storage							
		21	x	x					Small tanks (2+ compartments)
	s	20			x			x	Extra bunkers
		B			x		x	x	Buffer for fuel production lag
D		Added systems							
	b	22	x	x					Separator
		5			x				Thermal fluid heater
	E	24			x			x	H2 release plant
		13						x	H2 burner
	(e)	11					x		MeOH reformer
S		Main energy storage							
	c, d(, e)	10				x			H2 cryo tanks
		19	x	x	x		x	x	Fluid bunker & transfer
M		Mutual systems							
		17	x	x	x	x	x	x	Cooler
		18	x	x	x	x	x	x	Non-modular ship systems

Figure 6.6: List of the repeatable subsystems per configuration, with an indication of how they could share locations

The functionally similar subsystems are thought to have similar connections, or at least routing of their components, which makes up a large share of their interfaces. The modularity requires them to have interfaces that can be standardised to some extend and that includes the routing of the connections. Also, there is an overlap between regulations for some of the functionally similar subsystems, which is also convenient. There is another reason why the similar subsystems need to be sorted: there needs to be physical replacement between some of the subsystems, so they need the same location. This can also be identified from the list, except that for this step it needs to be known approximately how large the components in the subsystems will be. Until this step still no physical properties have been used to determine how to sort the subsystems.

For several components, the volume ratios are known from table 6.2. The other systems are less significant, calculations have been performed and are shown in appendix D. In general, the functional groups are to be in the same location, because of their -generally- similar connections and size. Some exceptions are necessary however, because this is only true generally, whilst the system must work completely. This is shown in the right column of the table in figure 6.6. In the first column the general location of the functional group is indicated. A-E are locations that require a dedicated space on board that can be exchanged, M is mutual and could be installed in a space that has components of the rest of the ship in it and/or is hard to reach, and S is located in the sides and bottom of the ship and will also not be exchanged, but possibly rearranged in connections.

The exceptions require more explanation. They are found because of three principles:

1. Locations should be re-used by as many systems as possible, so not in all configurations some location(s) is (/are) left empty

2. If a large system cannot be placed in a shared location because of its size, it might be wiser to appoint it a dedicated location that makes the ship less practical when this large installation is installed, than reserving this large space in all configurations

3. The system may be designed for 6 configurations, but if it is possible to design it with other configurations in mind, this is advisable, since it would make the ship more versatile

There are six exceptions in location, also shown in the left part of figure 6.6. These are the reasons for those exceptions:

- **Cryogenic hydrogen tanks**[1] are large cylindric tanks, the available space of which could also be filled with other large cylindric tanks for cryogenic or pressurised storage, for e.g. methane or ammonia. The hydrogen-FC configuration requires very few auxiliary systems, meaning that the location of auxiliary systems such as B, C and D can be used for this configuration. For C and D this seems to be the case, but using location B for hydrogen storage would make the system less modular, as that would make it harder to combine an ICE with hydrogen or a different fuel that requires a large cylindric tank. For that reason, only location C and D are replaced by the cryogenic tank. If locations C and D are too small, location E could also be considered.
- **The fuel cells** are installed in location A, but considering location B is dedicated for the injection of fuel in an ICE, location B can also be used for fuel cells.
- **The nitrogen generator** is part of the explosion proof ventilation subsystem. This is installed in all considered configurations that do not use diesel, and it is expected that a nitrogen generator will also be necessary for alternative fuels that have not yet been considered. For this reason, it is chosen that the nitrogen generator can be in a location where it is not to be exchanged by any different component, like the components of the rest of the ship.
- **The extra bunkers for LOHC** are also to be in the sides and bottom of the ship because this is the most practical location for such fluid. It is not an issue that this leaves very little room to ballast the ship, as the LOHC is not consumed during the operation of the ship and is comparably heavy as water.
- **The MGO separator** is placed in location B, as it is expected to be small enough to fit with the other components and it shares some connections and fire hazards with the other components.
- **The H_2 release plant** expected to be too large to be installed in location D with the rest of the systems. Therefore, a location E is suggested for this subsystem. It is practical to locate D and E together however, as location D provides the heat for the release plant and it may have some ventilation with possibly hazardous exhaust gas. This may also be convenient for the **methanol reformer**, which also is larger than the hydrogen burner and thermal fluid installation.

Designing the ship The subsystems are distributed over different locations as shown in figure 6.6. The subsystems on those locations determine the modules. It would be possible to design modules that replace everything on that location. This would be the most modular solution that is expected to be the easiest to exchange. In several locations this would mean that a small number of components is exchanged by comparable components (e.g. the separator in location B). It would also be possible to design them on component level where each identical component is looked at as a module. This would require more modules, but less components to be exchanged. That is a design decision the design initiator should make. In the verification design the general arrangement prevented complete modules to be installed so it made more sense to look at

[1] This may also be one tank, that has not yet been determined

components as modules when that prevented unnecessary component swapping. In this design this limit for prefabricated module size is not that strong because there is still room for change in the general arrangement.

The design has not been elaborated into detail as with the previous ship, a suggested engine room arrangement is given in figure 6.7. Components that will not fit in area D, such as the methanol reformer, could be placed on top of D. Area D is located near the exhaust of the power supply unit, which is convenient if heat is required or extra exhaust possibilities are necessary for them. There are two engine room entrances, one for the space that is to be explosion proof and one for the space that is not. Depending on what the majority of the components are, the entrance to area A could be enclosed by bulkheads instead of the entrance to area B, so that there is a separation between components that need to be explosion proof and components that do not.

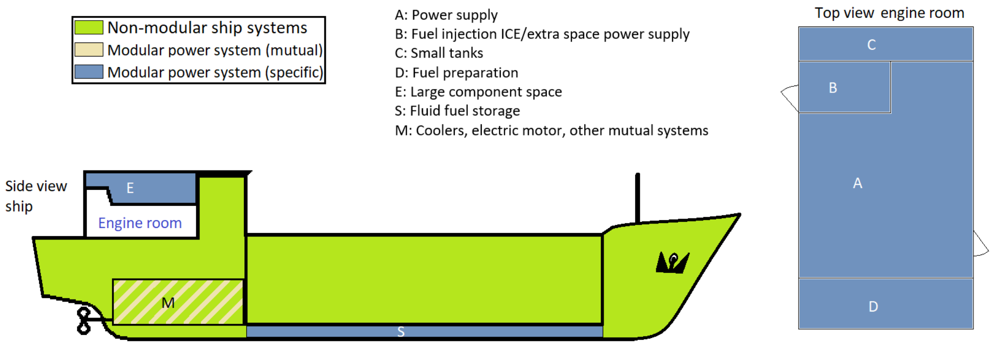

Figure 6.7: The engine room and general arrangement for the second ship, according to the previously identified locations

Designing the ship into more detail and designing the rest of the ship is not expected to be a problem in this design, so this is not further elaborated. Again, it will remain important that the interface remains up to standard, so that all proposed systems will fit into the design in later design phases.

6.2.5. Analysis of the design

Before any conclusions can be drawn about the method or the design, it should be determined if the design is modular, if the components can be refit and how the installations affect the design.

Refittability of the components The location of the engine room allows vertical access, so it is expected that only vertical obstructions should be avoided to allow a refit. This means that routing of cabling and piping should receive extra attention, as was also emphasised in the literature concerning technology insertion.

The locations of the components have been chosen so, that the components will not have to be moved to locate other components in their destined positions. Only specific systems are located in the engine room, which means that any shared or non-modular ship system is not at risk of being in the way of a refit.

The initial design of this ship has advantages in comparison to the first case ship. The vertical access makes it easier to maintain accessibility to components for removal or installation, and the electric propulsion allows to have a physical separation between the propellor shaft and the power supply system. The latter leads to the possibility of putting the engine room anywhere deemed suitable, including a location that has vertical access, so these advantages are related. If the method is applied to a ship concept that only has requirements as baseline, it may be helpful to understand this advantage of the electric propulsion.

Effect of the installations on the design Like with the first case ship, the hydrogen options seem to be too large to place in any convenient location, so either the hydrogen storage or the LOHC hydrogen release plant have to be placed in an inconvenient locations such as on top of the engine room or in the hold. This is not something the method can prevent as the method cannot change the size of the components. It is something that the ship can be prepared for, for instance by making the top of the engine room or another location of the ship suitable for expanding it with the oversized installations.

Modularity of the design The subsystems in the list in figure 6.6 can be considered modules. They are relatively independent subsystems, that have a standardised interface, because of which they can be exchanged by other subsystems. The standardised interface between the modules is limited in its standardisation of connections, because of the difference between the modules. Their interfaces in terms of size and safety requirements are more standardised, however.

As with the first case ship, it is expected that this second case ship too can be refitted to the considered and other similar installations, such as using LNG, methane, ammonia, or biodiesel. If it would be possible to use the area on top of the engine room for expanding the installation it may also be possible to use different kinds of fuel cells, but this should be determined with reliable data.

6.3. Analysis of the application of the method

The second case ship is used to validate the method, but in doing so the method is also verified again. This also leads to the final version of the method within this research.

The findings of the second verification are given first, followed by the findings regarding the validation. The analysis is finished with some general conclusions about the used technical installations.

6.3.1. Verification

With the method the second case ship is designed to the point where the first items are modelled (see appendix D) to check if they fit according to the locations in the figure 6.7. This concludes the method, as the method should only bring a concept design. The design should be continued in the conventional manner but respecting the constraints of the modularity and refittability of the design.

The adjustment of the method, to include the safety requirements in the RSs, has proven to be practicable. It also helped in identifying how to group components. However, the second case ship has a less complicated installation compared to the first, so this could be tested more reliably with a more complicated case.

Based on the second design process, a second adjustment to the method is proposed: the table with in- and outputs of the MPS can be skipped. The system diagrams provide the same data in a more organized way. It is not expected that this is case dependent, because in retrospect this is also true for the first case.

Again, the system is modular and satisfies the low-impact refit assumptions. The method proves to demarcate which components can be put together of different power supply installations and doing so, different options can be installed. So, the constraints as set in the objective and scope have been met, and the second applications verifies the method again, including the small adjustment.

6.3.2. Validation

The effect of applying the method was satisfactory, as it resulted again in a modular power supply system for a ship. Not many alterations had to be made to the method, and it is expected that the alterations are completely independent from the case it was applied to.

The method was developed in the context of uncertainty of ship-owners about which installation to choose as power supply to reduce the GHG emissions of their ship at some point. It was chosen to seek an answer to this problem by developing a method that allows a short-sea cargo ship to be designed with an initial installation that is technically ready and later be refitted with an alternative power supply installation that emits less GHGs. The method results in two case ship designs that fit this profile. Both have been developed with an alternative design in which a diesel ICE configuration can be refitted with a few considered installations and likely also several other installations that are similar but not specifically considered.

It cannot be concluded based on the two case ships if the method has made the MPS so independent that it is suitable to be replaced by an installation that is not similar to the considered installations. So far, only designs have been made for considered installations.

In general it is concluded that the method is effective in reducing the uncertainty of ship-owners, because a ship can be designed so that it can use a diesel ICE as initial installation, whilst it can be refit to another installation within the low-impact refit assumptions of this research.

7
Conclusion and recommendations

In this research a method for the modular design of a power supply system of a short-sea cargo ship was developed. Instead of using an existing modularity method, the method was developed for this purpose, because in literature, modularity in shipping is used mainly for large section-block modules and operational modules. For this research, a modularity method was required that looks at a ship in a higher level of detail and recognises all the small interactions between the components. This was found by applying the general modularity principles and the assumptions on a low-impact refit to one of the case ships and verifying if the proposed steps led to a final modular design.

Before drawing any conclusions, the method will be presented in its final form, after having been applied to two case ships in the prior chapters. The method gives satisfactory results, as will be explained in the third section, but it also requires further attention on several aspects. These recommendations for further research are given in section 7.3.

7.1. Final presentation of the method

In the previous chapters the steps of the method were performed on two different short-sea general cargo ships, for configurations using a fuel cell system or an internal combustion engine system, and diesel, methanol, or hydrogen. Hydrogen was stored either in a cryogenic vessel, or in a liquid organic hydrogen carrier (LOHC). Not all combinations were investigated, but all investigated combinations could be realised with the use of the method.

Verifying the steps to those two case ships have led to this form of the method, which allows to design a ship in which a switch from one configuration to another is possible with minimal construction work and without moving components around that are not supposed to be removed or installed during the refit.

The method is applied after an idea is formed about the requirements, and after executing the final step the designer is left with a concept design. The general arrangement is partially developed or altered during the final phase of the method, to allow access for removal or installation of the modules, but the method is focussed on the design of the power supply system.

Phase 1: Demarcation

1. Make a system diagram of each power supply configuration
2. Determine the interactions between modular power system and non-modular ship system
3. Standardise or eliminate the interactions

Phase 2: Finding suitable repeatable systems

1. Determine which combinations of components are identical in multiple modular power system configuration, and which combinations are unique. These combinations are the repeatable subsystems. Include information on most significant required safety measures
2. Add additional repeatable subsystems that contain relevant different design options
3. Find overlap between repeatable subsystems that can be eliminated by changing prior grouping of components

Phase 3: Designing modules

1. Make a table indicating which repeatable subsystems are necessary for which modular power system

2. Check that repeatable subsystems that are installed in multiple modular power system configurations match in capacity
3. Reconsider which repeatable subsystems are in which modular power system to better facilitate a refit
4. Group the repeatable subsystems according to interface requirements, like safety requirements, function, and size
5. Design modules and the ship's arrangement, based on the repeatable subsystem groups and the physical properties of the components

7.2. Conclusions on the method

A method for modular design of a short-sea cargo ship is developed that helps in refitting a power supply that emits less greenhouse gas emissions. The application of the method to the two case ships indicates that the method gives a satisfactory result, because of three reasons.

First, the assumption on a low-impact refit prescribes that a low amount of structural work is necessary, that no components should be moved that are not to be refit and that the number of components to be refit should be kept low. The method leads to a design in which all components have a fixed position regardless of which of the considered power supply configurations is installed, and there is a removal and installation route that makes that no components have to be moved unnecessarily, so a low-impact refit seems possible.

Secondly, the modularity principles have led to a clear demarcation between the part of the ship that needs to be modular and the part that can remain unaltered. This means that only a small part of the ship receives the special treatment of modularisation, which saves work, but the standardisation of the interactions between the modular systems and the non-modular systems also means that this interface is well specified. A well-specified interface is expected to make it easier to design an installation for that was not considered among the test case installations.

For neither of the two case studies the available space had to be enlarged if an installation was small enough to fit in the original installation space. Of course, the method cannot change physical properties of installations, but it was managed to prevent that any significant space would have to remain unused in a certain configuration. This means that no space had to be reserved for the method.

The final reason for deeming the result satisfactory is that the modularity principles have resulted in a structured separation between the subsystems, that allow to identify how the system can be divided into smaller pieces. The subassemblies of the modular power system as designed with the method are relatively independent and have a largely standardised interface, which allows them to be exchanged during the refit without redoing the whole technical installation of the ship. This makes those subassemblies modules and the power supply system modular, whilst it helps in exchanging the power supply system.

Application of the method therefore seems to aid in designing a refittable short-sea general cargo ship. Only a very limited amount of information was ship specific, so it is expected that the method could even be applied to other ship types, or even other systems. However, first some remarks should be made on the method.

7.3. Recommendations for further research

Because the objective of the research was to develop a method, and the method had to be developed from the basis, the development of the method received most attention in the process. Therefore, several aspects of the method and the way it was verified and validated should receive further attention.

Firstly, the method leans heavily on the assumption that a low-impact refit means low construction work, few parts exchanged and no unnecessary movement of parts. To fully know if the method is making a refit less costly, this should be researched. Also, the effect the small changes to the systems that were deemed justifiable during the second phase of the method should be quantified to know if they were in fact justifiable.

Secondly, without building and refitting an actual ship the method cannot be fully verified and validated. It is not recommended to build a ship solely to confirm the suitability of the method, but any positive effect of the method cannot be proven as long as no ship has been built and refitted that has been designed by the method.

Only a limited number of configurations was designed in the test cases. Therefore, it is not yet proven if the method enables the refit of any other system that was not considered. It is hypothesised that the standardisation of the interface between the modular power system and non-modular ship system helps in designing a different installation, but this remains yet unproven.

Finally, modularity was used as a basis for the method. Modularity prescribes in principle that any considered configuration should be exchangeable with any other considered configuration, but in the context of this investigation that is not necessary. The system would also be suitable for the low-impact refit to reduce greenhouse gas emissions if the method would be developed only to serve the refit from a diesel engine on diesel to a different configuration. It might be interesting to know how this would change the design, but as the method did not require any space to be reserved in the case ships, this extra investigation might not be strictly necessary.

All in all, there are several aspects of the method that could receive further attention, but there is not evidence that the method would not function in another case, whilst it worked for two cases so far. The method did not have a negative effect on their designs and does enable the relevant factors of a low-impact refit. Therefore, even though the method could be validated more strongly, it is expected that the method can enable a ship-owner to make its ship more climate-friendly halfway the ship's lifetime, instead of scrapping it or remaining to emit more greenhouse gases.

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A
Overview fuel properties

This appendix contains the relevant chemical properties of fuels used in this report.

Information on two hydrogen carriers is given in figure A.1, where the properties are given for the hydrogenated and dehydrogenated constitution for both. In both cases the dehydrogenated fuel needs to be taken back to shore, so in calculating the necessary weight and volume for the fuel the least advantageous properties need to be taken into account. The molar quantity of the fuel stays the same when the hydrogen is extracted, so it are the weight per mole and the volume per mole that need to be compared. It can be concluded that for the LOHC the hydrogenated and for the H2Fuel the dehydrogenated volume and mass properties should be referred to for a fair comparison.

In figure A.2 the energy densities are given for a number of fuels. The densities for hydrogen and natural gas are given for different conditions. Two hydrogen carriers are considered: a liquid organic hydrogen carrier (LOHC) and sodiumborohydride, which is referred to with the brand name H2Fuel.

Figure A.3 values the estimated energy densities of fuels including their storage.

Name		LOHC [25]		Metal hydride: 'H2Fuel' [26]	
Chemical reaction		$C_{21}H_{38} \rightarrow C_{21}H_{20} + 9\ H_2$		$NaBH_4 + 2\ H_2O \rightarrow NaBO_2 + 4\ H_2$ + 40 MJ per kg of H_2	
Chemical constitution		$C_{21}H_{38}$	$C_{21}H_{20}$	$NaBH_4$	$NaBO_2$
Gravimetric density	kg/m^3	913 [69]	1,044 [69]	1,070 [59]	1,779 [59]
Molar mass [70]	g/mol	290.51	272.37	37.83	65.80
Molar volume	m^3/mol	3.18E-04	2.61E-04	3.54E-05	3.70E-05
Relative weight H_2 [70]		6.25%	6.66%	21.32%	12.26%

Table A.1: Properties of two hydrogen carriers in hydrogenated and dehydrogenated condition.

Fuel:	Diesel	LNG	LPG	DME	NH_3	PPO	FAME	Ethanol	MeOH
Energy density (MJ/L)	36.6	20.8	24.4	19.2	12.7[15]	34.8	33.3	21.1	15.8
Specific energy (MJ/kg)	42.8	48.6	45.5	28.9	18.6[15]	37.8	37.5	26.7	19.9
Specific mass (kg/m^3)	855	428	537	665	682[59]	920	888	789	791
Flash point (^{o}C)	60 [14]			-42.2			173	12	9
LFL (vol%)	1%	5.3 %	2.2 %	3%	14%			3%	6%
UFL (vol%)	7%	15 %	9.5 %	24%	33%			28%	50%

Fuel:	CNG	LOHC	H2fuel	Pure H_2				
Storage conditions:								
pressure (bar)	250	p_0	p_0	p_0	350	500	700	p_0
temperature (^{o}C)	0	20	20	0	0	0	0	-253
Flash point (^{o}C)		200						
LFL (vol%)				4%				
UFL (vol%)				77%				
Energy density (MJ/L)	9.32	6.84	13.1	0.0108	3.73	5.33	7.46	8.49
Specific energy (MJ/kg)	48.6	7.49	7.35	120	120	120	120	120
Specific mass (kg/m^3)	192	913[69]	1779 [59]	0.090	31.1	44.4	62.1	70.8 [59]

Table A.2: Properties of selection of fuels, based on lower heating values. Remarks: Energy density, specific energy and specific mass from [71], unless otherwise specified. Flash point, lower flammability level (LFL) and upper flammability level (UFL) from [59], unless otherwise specified. Flammability limits for methane for LNG and propane for LPG from [72], limits may differ based on gas mixture. The values for pure hydrogen are calculated as ideal gas with properties from [70].

	Diesel	PPO	FAME	Ethanol	MeOH	LNG	LPG	DME	NH3	CNG	LH2	LOHC	H2-700bar	H2-500bar	H2-350bar	H2fuel
MJ/dm³																
[52]	-					13.2					5.82					
[73]	32.3	-	-	-	14.4	16.3	-	-	10.4	-	6.30	4.10	-	-	-	-
[24]	23.6	-	-	-	-	-	-	-	-	-	4.07	3.95	1.36	1.40	1.17	5.46
[18]	-								8.51							
[74]	-	-	-	-	-	-	-	-	-	-	-	-	-	1.69	1.32	-
[13]	29.5	-	-	-	12.6	11.9	-	13.3	8.28	-	4.32	-	-	-	-	-
[75]	-	-	-	-	-	19.7	-	-	-	-	5.40	-	-	-	1.39	-
Average	28.5				13.5	15.3		13.3	9.07		5.18	4.03	1.36	1.54	1.29	5.46
Without container	36.6	34.8	33.3	21.1	15.8	20.8	24.4	19.2	12.7	9.32	8.49	6.84	7.46	5.33	3.73	26.2
MJ/kg																
[13]	29.9	-	-	-	14.0	26.6	-	19.8	13.0	-	9.00	-	-	-	-	-
[52]	-	-	-	-	-	25.4	-	-	-	-	19.8	-	-	-	-	-
[24]	35.9	-	-	-	-	-	-	-	-	-	16.8	5.08	4.25	4.21	5.36	18.2
[74]	-	-	-	-	-	-	-	-	-	-	-	-	-	4.20	3.27	-
[76]	-	-	-	-	-	-	-	-	-	-	-	-	-	4.50	-	-
[75]	-	-	-	-	-	25.2	-	-	-	-	15.2	-	-	-	1.93	-
[77]	36.2	31.8	31.6	22.8	-	24.2	21.1	13.5	-	15.0	7.24	-	-	-	7.53	-
Average	33.0	31.8	31.6	22.9	14.0	25.6	21.1	17.7	13.0	15.0	12.8	5.08	4.25	4.31	4.52	18.2
Without container	42.8	37.8	37.5	26.7	19.9	48.6	45.5	28.9	18.6	48.6	120	7.49	120	120	120	14.7

Table A.3: Energy density and specific energy of fuels including their storage facilities. Values for fuels without container are given as presented in table A.2

B

Choosing a suitable case propulsion configuration

In this appendix it is determined what suitable power supply systems would be for the case ships. In section 4.2.1 of the report criteria for choosing a suitable power supply system for the test case are developed. The criteria were:

- Emissions
- Technological readiness
- Investment
- Operational expenses
- Size and weight of the installation
- Impact on design
- Suitability as a test case

In this appendix it is explained how these criteria are used to find a suitable system for the verification and validation cases. Both case ships will be a short-sea general cargo ship of comparable size, and the power supply systems should be ready for a refit in approximately 15 years from now. For this reason, the analysis is executed once, for both ships at the same time.

As explained in section 4.2.1 the approach of finding suitable subsystems is based on analysing the performance matrices of the options. Three performance matrices will be set up and analysed. First the fuels are analysed, secondly the power supply units are analysed and finally a choice is made between a selection of combinations of fuels and power supply units.

B.1. Energy carrier choice

The first performance matrix will be set up with energy carriers. The energy carriers listed in table 2.2 are used as a basis. In this table already batteries were excluded, so there are only fuels and hydrogen carriers to be rated.

All the energy carriers from table 2.2 are rated, except hydrogen stored under pressure. Hydrogen in any stored condition is amongst the fuels with the lowest densities. The difference in stored energy density between storing hydrogen pressurised or cryogenically is also significant. It is not expected that the pressurised hydrogen can be justified when it is used as a primary fuel, given that even storing hydrogen in different ways does not lead to high energy densities.

Ammonia is also included as energy carrier. Ammonia can be stored in insulated tanks at a storage temperature of -34 ^{o}C or under a pressure of about 10 bar at room temperature [15]. Both types of storage would typically be in a cylindric vessel. In a ship design box-shaped tanks would generally be more convenient because boxed shapes can more easily be fitted in the double bottom under the hold floor or in other places that do not carry cargo, in comparison to cylindrical storage. Theoretically, boxed shaped ammonia storage would be possible with insulated tanks. Because there is still room for advancement for the test case systems, the situation that ammonia is stored in box-shaped insulated tanks at -34 ^{o}C is considered, but if this is considered a suitable option the technical viability of this concept should be checked.

The following ratings have been used for the different criteria:

- The fuels are rated on a relative scale of most negative effect(-), medium effect(±) or most positive/least negative effect(+).
- For rating the emissions, the fuels have been rated (+) for no local emissions, (±) for no net emissions and (-) for adding fossil carbon to the global carbon cycle.
- The readiness and availability criterion has been rated according to current and expected future availability according to [3] and [8].
- The investment is based on the expected complexity of the storage system, based on the temperature and pressure of the system as found in table 2.2.
- The fuel prices have been based mostly on expected future prices from, again, [3] and [8], in which it should be noted that for some of these fuels the price is based on demand rather than marginal costs and therefore is sensitive to market changes. For methanol (MeOH) and ethanol the current price per MJ has been compared based on [78] and [79].
- The energy density is compared to MGO in which (+) means that it needs the same or less volume on board, (±) means more than 1 time the volume necessary, (-) means more than 2 times the volume necessary.
- The impact on design is based on the type of fuel container and the treatment of the fuel before feeding it to the power supply unit, relative to the initial MDO situation, in which (+) means positive impact (small/no extra components) and (-) means negative impact (large components).

		Bio/synth diesel	LPG	LNG/ methane	bio/ synth gas	Ethanol	Methanol	Ammonia	NaBH4	LOHC	Liquid H2
Individual fuels	Emissions	±	-	- ±	±	±	±	±	+	+	+
	Readiness & availability	±	+	+	±	-	±	-	-	±	±
	Investment	+	±	-	±	+	+	+	±	-	-
	Fuel price	-	+	+	-	±	±	-	-	-	-
	Energy density (stored)	+	±	±	±	±	±	-	-	-	-
	Impact on design	+	-	-	-	±	±	±	±	±	-

Figure B.1: Ratings of the different fuels found suitable

There are no clear winners or losers, but that all options have their advantages and disadvantages. In reducing the options to work with in further stages it seems that some choice needs to be made. This will be discussed below.

Looking at the ease of switching fuels bio- or synthetic diesel is the least invasive option. Even though it has a slightly lower energetic density than MDO, the overall impact on the design and range is very limited and would therefore be an interesting option for a low-impact fuel switch. Downside is the high fuel price.

The next 6 fuels that will be analysed, can be divided in two categories: gases (LPG, LNG and other gases) and liquids (ethanol, methanol and liquid ammonia). These are the fuels that are neither diesel nor hydrogen. First the gases are analysed.

From the gases LNG and LPG are fossil and do therefore not contribute on closing the carbon cycle, even though they reduce emissions. The bio gases do have a closed carbon cycle, the synthetic gases could have a closed carbon cycle if the carbon used is from captured CO_2 or renewable carbon sources. LNG and LPG have similar or better ratings on all other aspects except the investment of LNG. However, LNG could be replaced by liquid methane that can be produced in a biological or synthetic process, leading to lower net emissions in the future. Looking at the ratings LPG seems to have a better rating than LNG, but that is solely due to the fact that the rating only has three steps. The investment for an LNG installation out-prices that of an LPG (or similar) installation because of the cryogenic conditions, but LNG is cheaper than LPG and it has better availability [3]. As there are several synthetic or bio gases in development and butane or propane do not seem to be very high up the list, it makes most sense to look into LNG as this can also be phased out to be replaced by non-fossil methane. LNG and methane will therefore be added to the comparison in later stages.

Of the remaining fluids ethanol, methanol and ammonia, only methanol was reported to be used in commercial ships [20], even though ethanol has higher energy density. Ammonia appears to be even less mature. Ethanol has a higher current price compared to methanol and the differences between them in other aspects are small [80], so typically methanol is seen to be the more attractive option. As methanol is also the only one of the three fluids that has already been applied, it is chosen to only further investigate methanol.

Finally, from an emission point of view hydrogen seems to be the best solution, but this furthermore seems to be less advantageous. Comparing the three hydrogen options, the LOHC seems to be the most mature yet somewhat practical solution. The downsides to the LOHC are that it needs to stay on board after taking the hydrogen out and that the extraction plant takes up valuable space as well ([64] and personal communication with a representative of the company Hydrogenious LOHC Technologies GmbH). Neither of the three solutions is commercially applied in ships yet, but the LOHC has several prototype installations on shore [81] and MAN even has concept hydrogen storage vessels based on their LNG storage tanks that are approved in principal [52]. $NaBH_4$ may have a higher energy density than the LOHC and liquefied hydrogen, but lacks a current practical application which makes it questionable to be mature enough to be applied on board in the upcoming 30 years. LOHC does have practical applications and is relatively easy to store, reducing problems with regulations and handling equipment. It can also be expected that if the process of hydrogenation is efficient, the prices and environmental impact of LOHC may be lower than liquid hydrogen, by the absence of the energy consuming liquefaction process. Therefore even though the LOHC lacks a current distribution network and is not very energy dense, the LOHC is seems to have enough advantages to take it further into consideration given the fact that it is very convenient to store on board, but does not produce harmful emissions. For the previous two categories (the gases and liquids) the technological differences were small, so it was easy to choose the one that seemed most suitable. However, between the hydrogen that is difficult to store yet easy to extract and the LOHC that is easy to store, but difficult to extract, the differences are so large that it cannot be estimated which of the two would fit better in the design without designing it first. Therefore, the hydrogen and LOHC are both taken into account in the final step of choosing the power supply system.

This means that five fuels will be checked for their compliance with energy supply units in the last step of this analysis: bio/synthetic diesel, methane, methanol, liquid hydrogen and the LOHC.

B.2. Power supply unit choice

The five energy converters have been compared in the same manner as the fuels. The results can be found in figure B.2 and are based on the information from table 2.3 [13] and [18]. For the converters the criteria as listed in the beginning of this section have been used.

For a small ship, operating in the short-sea business typically the size of the installation is more limited than on large ocean-crossing ships, because these large ships have the advantage of economy of scale and a larger range. This means that for large ships the fuel consumption is more important because they need to carry more days of fuel, and the installation can be of a larger type, because the installation will not linearly grow along with the required power, but instead the installation will benefit from economy of scale. That said, still for a small ship this applies to a certain extent also. As fuel consumption is a large part of the operational expenses of a ship, the efficiency of an installation is still very important for smaller ships, but certain installations that may be more efficient are just too large to justify in a ship of limited size.

		Fuel cells	ICE	Gas turbine	Steam turbine	COGES
Individual power supply units	Emissions	+	-	±	±	±
	Readiness	±	+	+	+	+
	Investment	-	+	-	-	-
	Opex	+	+	-	-	±
	Size & Weight	-	±	+	-	-
	Impact on design	-	+	±	-	-

Figure B.2: Ratings of the different energy conversion options

Looking at the ratings, the ICE seems to be the most financially attractive option, followed by the LT-PEM FCs, of which some are expected to have a competitive price per kW by 2022 in comparison to ICEs [3]. There are as said other types of fuel cells, that may be more efficient, but also more expensive, larger and slower.

The three turbine options are more expensive than the ICE and FC, but in certain case studies they might prove the most suitable solution. In terms of operating a small ship however, the gas turbine has the largest advantages of the three turbine options, because it is the smallest installation. The smaller installation may be less efficient, but the economy of scale on the steam turbine or the combined installation will not be in place, so that it is expected to cost too much valuable space to gain a better efficiency. Therefore the gas turbine is taken further in the comparison, together with the more financially attractive solutions of the ICE and LT-PEM FC. The solution producing most emissions is the ICE, but this could be reduced by taking extra measures such as catalytic reduction or special engine features.

B.3. Choice in power supply system

In the foregoing sections, 10 fuels and 5 energy conversion options have been selected and rated. As this would lead to a total of 50 combinations, this was reduced to 5 fuels and 3 energy conversion units, leading to 15 combinations. It turns out that all 15 options will be possible now or in the future[1], but not all options are completely developed yet. The different options have been compared on the six aspects that have been determined previously. First, each of the ratings of the individual converters and fuels were added leading also to (- -) and (+ +) ratings. Secondly, it was estimated whether the combination would amplify a positive or negative effect and their readiness was checked as far as practicable. It should be noted that the rating of the emission of methane is dependent on whether LNG or a synthetic/bio source is used and that it is unclear what the price for circularly produced methane will be in the future.

	Individual fuels				
	Bio/synth diesel	LNG/ Methane	Methanol	LOHC	LH2
Emissions	±	- ±	±	+	+
Readiness & availability	±	+	±	-	±
Investment	+	-	+	-	-
Fuel price	-	+	±	-	-
Energy density (stored)	+	±	±	-	-
Impact on design	+	-	±	±	-

Individual power supply units			Combinations				
Fuel cells	Emissions	+	+	± +	+	++	++
	Readiness	±	-	±	±	-	+
	Investment	-	±	--	-	--	--
	Opex	+	±	++	+	±	±
	Size & Weight	-	±	-	-	--	--
	Impact on design	-	±	--	-	-	--
ICE	Emissions	-	-	-- -	-	+	+
	Readiness	+	+	++	+	±	+
	Investment	+	++	±	++	±	±
	Opex	+	±	++	+	±	±
	Size & Weight	±	+	±	±	-	-
	Impact on design	+	++	±	+	+	±
Gas turbine	Emissions	±	±	- ±	±	+	+
	Readiness	+	+	++	+	-	±
	Investment	-	±	--	±	--	--
	Opex	-	--	±	-	--	--
	Size & Weight	+	++	+	+	±	±
	Impact on design	±	+	-	±	±	-

Figure B.3: Options of choice with their ratings

It can be seen that there is no perfect solution. All solutions have positive and negative properties and therefore any of the solutions could be suitable in a specific situation.

Even though the solutions should be suitable for the ship, the objective of this research is not to find the best solution for the ship. Instead, choosing some suitable options is merely necessary to validate the method, as has also been stated in the beginning of this section containing the criteria. That said, the results of the validation will be more valuable if they are determined from a realistic point of view. Therefore, for choosing the alternatives the ability to be used as a realistic, but useful, test-case is very important as well, and the alternatives will be chosen based on different arguments and the ratings.

From the three best performing solutions (Bio-diesel-ICE, LNG-ICE and methonol-ICE) only methanol-

[1] This can be found in the following sources: FC options: [13]; ICE and gas turbine on methanol: [82]; ICE and gas turbine on LNG or hydrogen: [3]

ICE makes sense to use as a test-case. There is not much to refit going from a diesel-ICE set-up to a bio-diesel-ICE set-up, so this does not involve a refit. The LNG-ICE option seems to be the most mature option based on the matrix, but also based on the fact that there already are ships sailing with a LNG installation with a dual fuel ICE engine for decades [83]. This might mean that it is very possible to retrofit LNG, but this also requires to design a ship to be able to switch from MGO to LNG. If a ship is expected to sail on LNG or methane in the future, it makes more sense to design it with LNG from the start and not to put MGO in as initial installation and refit it to LNG. Therefore, from these three best-rated options this leaves methanol-ICE as the first suitable test-case.

From all options, three of them only have one plus in their ratings, so they are left out solely on their poor performance in the rating. These excluded options are: Bio/synth diesel + FC, LOHC + gas turbine, and LH2 + gas turbine.

It is known that for the test case and also the validation case, the ship will have an ICE in the initial installation, powered on diesel. So far, no arguments have been found to justify a gas turbine replacing an ICE. In the ratings the ICE outperforms the gas turbine combinations also. Therefore, even though the gas turbine might be a suitable solution for a ship with a new design, it does not seem sensible to replace an ICE with it. It will still produce small amounts of nitrogen, will be less efficient and have higher repair cost, which will make it even more difficult to earn the investment of the second installation back. Only the maintenance cost and vibration are expected to be slightly reduced. Therefore, the other fuels in a gas turbine are also excluded.

This is also the case for designing a fuel cell installation on LNG, as that would also require a reformer installation or a different kind of fuel cell. This research is partly centred around the uncertainty of which fuels might prove to be most obtainable in the upcoming decades, so it cannot be completely ruled out that methane will be a suitable fuel in the future. It is however just not expected that methane will come into the market at a price justifying a refit to cryogenic tanks, whilst still having local GHG emissions when putting hydrogen into those tanks would prevent the expense of buying a methane-reformer and all local emissions, so the LNG-FC is ruled out as well.

The hydrogen solutions so far have had little criticism, but they have strong negative ratings on most of their aspects. The only rational reason to use hydrogen, either liquid or from an LOHC, is to have zero (local) emissions. For that reason, it makes most sense to feed it into a fuel cell rather than an ICE, because an ICE will still produce nitrogen emissions. Also, it is expected that an FC will have a higher efficiency ([84], appendix C), so it will require less of the costly and spacious fuel. Earlier it was already concluded that it is difficult to say which of the two hydrogen solution will have a lower impact on the design without designing it, so that still gives no reason to choose one over the other. It was also concluded that it is expected that refitting a ship to storing methane in cryogenic tanks will probably not be justifiable any time soon, but working with liquid hydrogen will still provide some insight in this type of storage. As it is convenient to have two different types of installation to have a broader range in the test-cases, it is chosen to use both as a test-case. This leaves the initial installation and four alternative options based on the combination of three fuels and two conversion units:

	Methanol	LOHC	Hydrogen (liquefied)
Fuel cells	✓	✓	✓
ICE	✓	X	X

Table B.1: Chosen test case configurations

C
Details on the verification case - CONFIDENTIAL

This appendix is confidential and therefore intentionally left empty.

D
Details on the validation case - CONFIDENTIAL

This appendix is confidential and therefore intentionally left empty.