# Alternative Energy Carriers in Naval Vessels

Design Options and Implications for RNLN Large Surface Vessels

J. E. Streng

**Report Nr.**
SDPO.21.010.m


TU Delft

# Alternative Energy Carriers in Naval Vessels

## Design Options and Implications for RNLN Large Surface Vessels

by

J. E. Streng

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday April 21st, 2021 at 11:00.

| | | |
|---|---|---|
| Student number: | 4294653 | |
| Project duration: | June 5, 2020 – April 21, 2021 | |
| Thesis committee: | Prof. ir. J.J. Hopman, | TU Delft, committee chairman |
| | Dr. A. A. Kana, | TU Delft, daily supervisor |
| | Dr. J. Jovanova, | TU Delft |
| | Dr. I. C. Dedoussi, | TU Delft |
| | Ir. I. P. Barendregt, | Defence Materiel Organisation |
| | Ir. J. H. Verbaan, | Defence Materiel Organisation |

An electronic version of this thesis is available at http://repository.tudelft.nl/.

# Abstract


Climate change and greenhouse gas emissions have been at the forefront of both public and academic debate for some years. Although the shipping industry has managed to remain relatively free of climate regulation this is changing with the IMO goals for 2050. The military sector has also escaped scrutiny on sustainability issues. But this is also changing as the Dutch Ministry of Defence expressed the ambition to reduce its carbon footprint, with the eventual goal to reduce the operational dependency on a scarce resource, and to comply with national and international regulation. The direct aim, therefore, is to reduce the fossil fuel consumption by 70%, and to comply with IMO regulations by 2050.

In this thesis the possibilities for reducing fossil fuel consumption and greenhouse gas emissions will be examined. This will be done for the seagoing large surface vessels of the Royal Netherlands Navy by using alternative fuels. The main research question which will be answered in this thesis is the following:

> *How are the design and the operational effectiveness of Royal Netherlands Navy vessels affected by the use of alternative energy carriers and energy conversion technologies that are needed to reduce the fossil fuel consumption of the Netherlands armed forces?*

This question is answered through the execution of two case studies of vessels with different mission profiles: the Zeven Provinciën class Air Defence and Command Frigate and the Landing Platform Dock Johan de Witt. For both vessels, a design process is carried out in which more detail is progressively added whilst down selecting the most suitable technologies.

The first step in the design process is an operational analysis. This operational analysis uses the perceived missions profiles and the RNLN maritime doctrine to make a prioritization in a set of technical properties or *measures of effectiveness*.

In the second design step, a systematic design variation is used to estimate the effect that different energy carriers have on the main dimensions of the vessel. The parametric design tool developed for this is an adapted version of the SPEC tool developed by Marin. The model estimates the required power and the weight of different weight groups of the vessel.

The final design step continues with a more detailed proposal for a power plant configuration for both case studies. With this detailed design a final assessment of the fuel consumption, exhaust gas emissions, and operational effectiveness is made.

Throughout the design phases it was established that the displacement of both vessels would increase significantly due to the lower energy density of the selected fuels. In the case of the Air Defence and Command Frigate, the high top speed and relatively high fuel and system weight lead to a larger increase in required fuel and installed power due to the increasing resistance when using anything but the most energy-dense fuels. For the Landing Platform Dock, which has a more modest power requirement and a relatively low system and fuel weight, the increase in displacement is smaller.

The use of fuel cells was also examined. For the Landing Platform Dock, there was an optimum load share of the fuel cell where the increase of system weight and the reduction of the fuel weight due to an increased efficiency were balanced. For the Air Defence and Command Frigate, no such optimum was found. The low power density of the fuel cells significantly increased the system weight, resistance, and thus the displacement.

In both case studies, the fossil fuel consumption and greenhouse gas emissions were reduced significantly. Due to the option to operate on only fuel cells, the vessels are also IMO tier III compliant.

The change in operational effectiveness was also dependent on the mission profile of the vessels. The operational effectiveness of the frigate improved due to a significant reduction in acoustic signatures. For the Landing Platform Dock, the design is mostly driven by the payload carrying capacity which is negatively affected by the choice of energy carrier and energy converter.

In conclusion, it can be said that the goals stipulated by the Ministry of Defence are attainable. The effect on the operational effectiveness varies between vessels but the overall fuel consumption, cost, and displacement are sure to increase significantly.

# Preface

The work that lies before you is the final piece in the puzzle of my seven-and-a-half-year study career in Delft. Give the current era in which climate change plays a prominent role in the public and academic debate it was always likely that my thesis would be related to sustainability. I had never imagined that I would apply the topic of sustainability in the area of naval vessel design. The combination proved to make for an interesting project in which I was challenged to translate abstract requirements into technical specifications. The project also gave me a better idea of how my two studies, an MA in International Relations and an MSC in Marine Technology, may sometimes meet.

As the final piece of this puzzle, the conception of this thesis has been a journey on its own. In this journey, I've received invaluable help and advice from a great number of people.

First and foremost from my daily supervisors Ir. Huibert-Jan Verbaan and Dr. Austin Kana. Huibert-Jan initially gave me the idea to graduate at the DMO and was always ready to explain how and when the particularities of naval vessels diverged from the conventional wisdom in ship design. Austin has been of equally great help and provided the guidance I needed to ensure the academic quality of my work. Together with the feedback and constructive criticism of Dr. Ir. Hans Hopman and Ir. Isaac Barendregt I could not have hoped for better supervision. I want to thank you all sincerely.

Besides my direct supervisor, I also want to thank my other colleagues at the Defence Materiel Organisation. Although there weren't countless coffee breaks, and I probably have not visited the DMO office more than two dozen times, the sincere interest from my colleagues at the Marine Engineering Office has helped steer my project in the early months. Dr. Bart van Oers, Dr. Rinze Geertsma and Dr. Etienne Duchateau have been of great help in trying to understand the questions which the DMO has on the subject and the greater system in which the Royal Netherlands Navy vessels operate.

I would also like to extend my gratitude to Alex Grasman, Martin van Hees, and Moritz Krijgsman from MARIN, for letting me use their design software and offering advice on my research method.

Without my friends, those from the TU Delft, Delft Challenge, Leiden University, and other places, I would likely not have made it this far. Although I consider myself to be an eager learner, I have also been eager to enjoy my friends' company and a beer or two after another summer resit.

Finally, I want to thank my parents and my brother, who have supported me through every step. Even though I might not always have been very clear about my study progress or the number of resits I've taken through the years, they've always supported me in my endeavours.

*J. E. Streng*
*Delft, April 2021*

# Contents

# List of Figures

# List of Tables

# Acronyms

**AMS** Maritime Systems Division (Afdeling Maritieme Systemen).
**AoA** analysis of alternative.
**AoO** area of operations.
**ATR** auto-thermal reforming.

**C2** command and control.
**CAPEX** capital expenses.
**CCCS** Capability Codes & Capability Statements.
**CER** cost estimating relationship.
**CFD** computational fluid dynamics.
**CODOG** combined diesel or gas.
**COFAICE** combined fuel cell and internal combustion engine.
**CoG** centre of gravity.
**ConOps** concept of operations.
**COTS** commercial of the shelf.
**CSS** combat support ship.

**DEOS** Defence Energy & Environment Strategy (Defensie Energie & Omgevings Strategie).
**DIR** direct internal reforming.
**DMO** Defence Materiel Organisation.
**DP** dynamic positioning.

**EEDI** Energy Efficiency Design Index.

**FAME** fatty acid methyl ester.
**FRISC** fast raiding interception and special forces craft.

**GHG** greenhouse gas.
**GMO** Fundamentals of Maritime Operations (Grondslagen van het Maritiem Optreden).

**HSC** high-end surface combatant.
**HVO** hydrogenated vegetable oil.

**ICE** internal combustion engine.
**IFEP** integrated fully electric propulsion.
**IMO** International Maritime Organisation.

**JSS** joint logistics support ship.

**KPI** key performance indicator.

**LCC** life cycle cost.
**LCF** air defence and command frigate (luchtverdedigings & commando fregat).
**LNG** liquefied natural gas.
**LPD** landing platform dock.

**MARIN** Maritime Research Institute Netherlands.
**MCV** mine countermeasure vessel.
**M-frigate** Multipurpose Frigate.
**MLU** mid-life update.
**MoD** Ministry of Defence.
**MoE** measure of effectiveness.

**MOTS** military of the shelf.

**NATO** North Atlantic Treaty Organisation.

**OEM** operational effectiveness model.
**OES** Operational Energy Strategy (Operationele Energie Strategie).
**OMoE** overall measure of effectiveness.
**OPEX** operational expenses.
**OPV** ocean-going patrol vessel.

**P2G** power to gas.
**PO** partial oxidation.

**RAS** replenishment at sea.
**RHIB** rigid hull inflatable boat.
**RNLN** Royal Netherlands Navy (Commando Zeestrijdkrachten).

**SCR** selective catalytic reduction.
**SEWACO** sensors, weapons and communication.
**SOFC** solid oxide fuel cell.
**SPEC** Ship Power & Energy Concept.
**SR** steam reforming.
**SRL** societal readiness level.
**STANAG** standardization agreement.
**SWBS** ship work breakdown structure.

**TRL** technology readiness level.
**TSSE** Total Ship System Engineering.

# Nomenclature

| | | |
|---|---|---|
| $\dot{m}_f$ | Fuel consumption | tonne/year |
| $U$ | Vessel utilisation | - |
| $sfc_{me,i}$ | Specific fuel consumption of main engine in operational point $i$ | g/kWh |
| $sfc_{aux,i}$ | Specific fuel consumption of main engine in operational point $i$ | g/kWh |
| $P_{me,i}$ | Brake power generated by main engine in operational point $i$ | kW |
| $P_{aux,i}$ | Brake power generated by auxiliary engine in operational point $i$ | kW |
| $T_i$ | Fraction of time spent in operational point $i$ | - |
| $E_1$ | Transport efficiency | - |
| $W_d$ | Deadweight | tonne |
| $V_s$ | Ship velocity | kts |
| $V_{max}$ | Maximum ship velocity | kts |
| $P$ | Power | kW |
| $P_{avg}$ | Average power over operational profile | kW |
| $P_{inst}$ | Installed power | kW |
| $P_{frac}$ | Fraction of installed power used | - |
| $P_{prop}$ | Propulsive power measured at the engine flange | kW |
| $P_{e-load}$ | Power needed for on board systems | kW |
| $W$ | Work performed | kWh |
| $f_j$ | Ship type correction factor in EEDI calculation | - |
| $f_i$ | Ship type correction factor in EEDI calculation | - |
| $c_{f,me}$ | Main engine specific carbon emission | g/kWh |
| $c_{f,aux}$ | Auxiliary engine specific carbon emission | g/kWh |
| $\Delta$ | Displacement | tonne |
| $W_{sys}$ | Weight of energy converters, transmission and propulsive equipment | tonne |
| $W_{fuel}$ | Fuel weight | tonne |
| $W_{struct}$ | Construction and outfitting weight | tonne |
| $PL$ | Payload | tonne |
| $SP_g$ | Gravimetric specific power | kg/kW |
| $SP_v$ | Volumetric specific power | kg/kW |
| $U_{g,cont}$ | Gravimetric contained energy density | MJ/kg |
| $U_{v,cont}$ | Volumetric contained energy density | MJ/l |
| $U_g$ | Gravimetric energy density | MJ/kg |
| $U_v$ | Volumetric energy density | MJ/l |
| $E_{req}$ | Required energy | kWh |
| $V_{hull}$ | Hull volume | $m^3$ |
| $L_{wl}$ | Waterline length | m |
| $B$ | Beam | m |
| $D$ | Depth | m |
| $FBD$ | Freeboard | m |
| $T$ | Draft | m |
| $C_b$ | Block coefficient | - |
| $C_{wp}$ | Waterplane coefficient | - |
| $C_f$ | Flare coefficient | - |
| $SWL$ | Lightship weight factor | $tonne/m^3$ |
| $\rho$ | Density | $kg/m^3$ |
| $C_{adm}$ | Admiralty constant, admiralty coefficient | - |
| $Aut$ | Vessel autonomy | days |
| $\eta_{sys,n}$ | System efficiency of system $n$ | - |

| | | |
|---|---|---|
| $\eta_{drive}$ | Distribution drive efficiency | - |
| $LoB$ | Length beam ratio | - |
| $BoT$ | Beam draft ratio | - |
| $FoT$ | Freeboard draft ratio | - |
| $Bias_{P,n}$ | Contribution to propulsive power by converter $n$ | - |
| $Bias_{W,n}$ | Contribution to total work over operational profile by converter $n$ | - |

# 1
# Introduction

The Dutch Ministry of Defence (MoD) has expressed the ambition to significantly reduce the consumption of fossil fuels by the armed forces of The Netherlands. In the OES [15] published in 2015 and subsequently the Defence Energy & Environment Strategy (Defensie Energie & Omgevings Strategie) (DEOS) [16] published in 2019 the MoD critically assesses the organisations footprint and operational energy demands. The operational energy demand - energy needed ”for flying, sailing, driving and compounds” [15] - is primarily met through the conversion of fossil fuels. Whilst the expectation is that the energy consumption for military equipment will increase, the accessibility and affordability of fossil fuels is expected to decline over the coming years [15]. The combination of these two factors could threaten the continued and secure operations of the Armed forces in the future. In order to safeguard the operational continuity, the MoD aims to reduce the fossil fuel consumption for operational use by 70% by 2050 (in comparison to 2010). This goal must be achieved whilst maintaining or increasing the armed forces' operational effectiveness and expeditionary deployability so that the forces can continue to execute their constitutional tasks [16]. In order to achieve these goals, the Maritime Systems Division (Afdeling Maritieme Systemen) (AMS) of the DMO is currently looking into the possibilities to reduce the fuel consumption of the RNLN surface vessels in various ways. Amongst the different possibilities to reduce the fossil fuel consumption is the use of alternative fuels or energy carriers and alternative energy conversion methods. The decision to use alternative energy carriers may be accompanied by yet unknown implications for the design and cost of these vessels and should therefore be carefully examined.

## 1.1. Current fuel consumption

Although the DEOS gives advice and points out specific projects where the overall environmental footprint of the defence forces may be reduced, these mostly pertain to the permanent real estate of the defence forces. This mostly comprises the non-operational part of the energy demand. Little guidance is provided as to how the fuel-saving of 70% will be achieved, apart from the statement that army compounds and the RNLN auxiliary vessels will become 100% self-sufficient [16]. In figure 1.1 the fuel consumption by fuel type is shown for various years. Replacing the diesel generators in compounds would decrease the diesel consumption significantly[1]. Yet it still appears that a reduction of 70% can only be achieved if the consumption of marine diesel and kerosene is also lowered significantly. Given that the different operational branches[2], the navy, air force and the army, possess and use different forms of equipment and therefore have different limitations and possibilities, striving for a 70% reduction in energy use for all branches equally may not be the optimal solution. The fuel consumption reduction for the army may be larger than 70% due to self-sufficient compounds, while it is highly likely that the fuel consumption of the air force will increase significantly with the replacement of the F-16 by the F-35 [74]. From both figure 1.1 and 1.2 it also appears that large variations in fuel consumption

[1] It is not known exactly what percentage of diesel consumption pertains to generators in compounds and what percentage to other equipment and vehicles.

[2] The fuel consumption of the different branches can be roughly associated with the division by fuel type in figure 1.1. Exceptions are the kerosene used for the RNLN helicopters, and the limited diesel consumption of the Marrechaussee

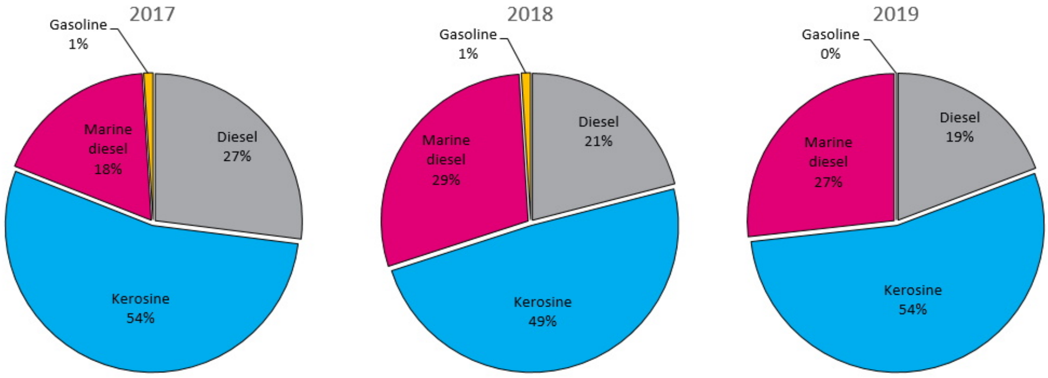


Figure 1.1: Operational consumption of the Netherlands armed forces by fuel type [8] [14]

between different years are possible. This can largely be attributed to the unpredictable nature of the international security situation in which a military operates and by extension the missions and exercises in which it engages. Other factors such as idle periods due to maintenance or other causes likewise contribute to the volatile and unpredictable nature of the fuel consumption. One recent example is the decision to station an ocean-going patrol vessel (OPV) in the Caribbean for an extended operational period of two years which will have a significant effect on the fuel consumption of the entire RNLN [94] [44]. From the large discrepancy of the values from different sources in figure 1.2, it is also apparent that for such a large organisation it is not necessarily an easy task to monitor the fuel consumption. Although these large variations could be the consequence of an operational difference it is also likely that different measurement methods have been used. To cope with this the MoD aims to measure and monitor the fuel consumption more closely so that more accurate data may be gathered [16].

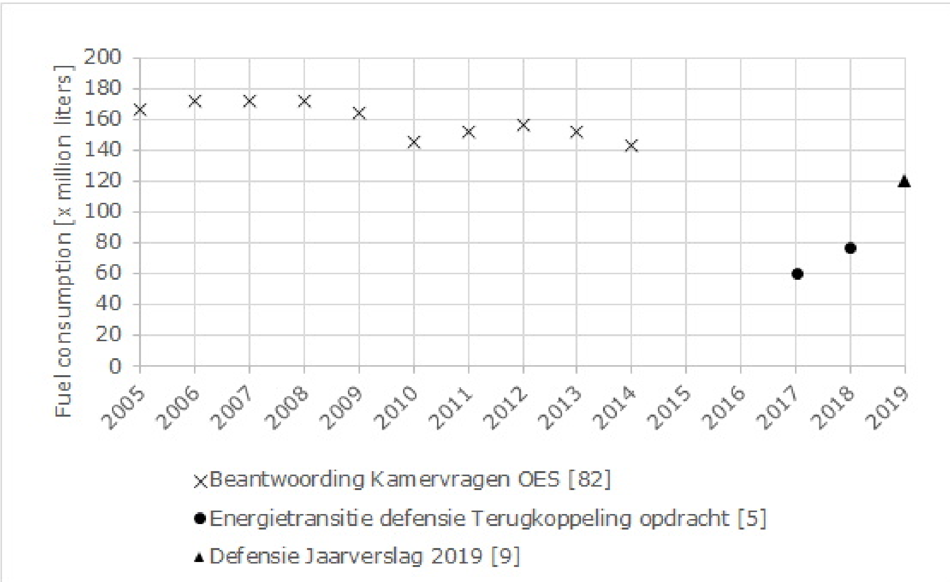


Figure 1.2: Fuel consumption from operational energy use [1] [8] [14]

## 1.2. Future fuel consumption

Although 2050 is still 30 years away the DEOS creates an urgent challenge for the DMO. Although it was concluded from figure 1.1 and 1.2 that it may be difficult to accurately predict the future fuel consumption of the defence forces some estimate must be made in order to know what measures are needed to achieve the goals. Without an estimate at the fleet level, it would also be impossible to set the required fuel savings for specific individual designs. Since the composition of the fleet until

2050 is largely known already an initial estimate can be made for the future fuel consumption using the vessels' operational profiles and utilisation rates. The fuel consumption is determined by evaluating the specific fuel consumption and power for all vessels at every point of their operational profile according to equation (1.1) [37].

$$\dot{m}_f = 24 \cdot 365 \cdot U \cdot \sum_{i=1}^{n} \left( sfc_{me,i} \cdot P_{me,i} + sfc_{ae,i} \cdot P_{ae,i} \right) \cdot T_i \tag{1.1}$$

Where:

$\dot{m}_f$ = Yearly fuel consumption for each vessel
$U$ = Vessel utilisation
$sfc_{me,i}$ = Specific fuel consumption of main engine in operational point i
$P_{me,i}$ = Brake power generated by main engine in operational point i
$sfc_{ae,i}$ = Specific fuel consumption of auxiliary generator in operational point i
$P_{ae,i}$ = Brake power generated by auxiliary generator in operational point i
$T_i$ = Time spent in operational point i as a percentage of total sailing time

In figure 1.3 the results of this analysis can be seen. This figure shows how the total fuel consumption changes as the old fleet is slowly phased out while new vessels are commissioned denoted by the blue and orange bars in the figure (the replacement schedule used can be consulted in Appendix A). It must be stressed that the fuel consumption found through this estimation method is not exactly the same as the fuel consumption documented in figure 1.2. It was already noted that the executed operations and exercises, as well as the planned and unplanned maintenance, are a cause of unpredictability. With such a problem as this however, such an estimation technique as used here is one of the few ways of making any prognosis of the future.

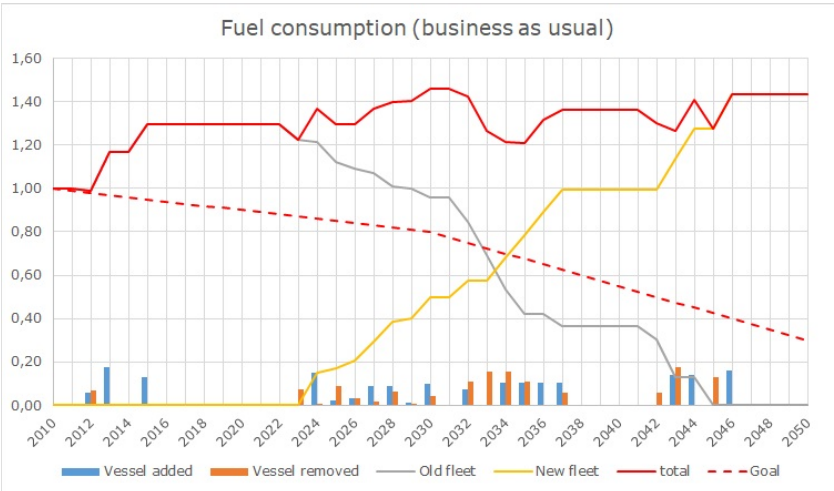


Figure 1.3: Yearly fuel consumption (normalised) until 2050 without major design changes

The red line shows the prognosis for the future fuel consumption based on the replacement of equipment as detailed in the *defensienota* [13] as well as the assumption that the joint logistics support ship (JSS) and OPVs will be replaced by similar vessels with a similar operational profile at the end of their lifetime. The dotted red line shows the goal in reduction of fuel consumption of 20% in 2030 and 70% in 2050, and it can be seen that the future fleet will not comply with those goals if no additional measures are taken. Since no drastic design decision can be taken anymore for vessels such as the the replacement for the Multipurpose Frigate (M-frigate), the combat support ship (CSS) and the mine countermeasure vessels, future vessels will have to be designed even more drastically to compensate for this. Notable points in the figure are the large dip in the blue line between 2031 en 2036 caused by the phased replacement of the air defence and command frigate (luchtverdedigings & commando fregat)s (LCFs) and the sharp spikes between 2042 and 2046 which are caused by the replacement of the OPVs and the JSS.

Since the design of all the vessels which will be delivered until 2030 is already well underway, making significant changes to the powerplant design would be very costly at this stage. Given the 30-year lifetime of the majority of the vessels, the composition of the fleet in 2050 is already determined to a large degree. Without making significant changes to the energy consumption and power generation concept of future vessels the fuel consumption would likely increase over the coming years as can be seen in figure 1.3.

In figure 1.4 different scenarios are shown. The first scenario in which future vessels will be designed or operated 20%[3] more fuel-efficient than older vessels. Another scenario in which the F-76 will be mixed with 20% bio-fuel. And one scenario where a combination of both is employed. It can be seen that when combining both measures the fuel consumption in 2050 would still be at roughly 90% of the level in 2010. Furthermore, simply mixing in 20% biofuel with the F-76 diesel is possible but will already have implications for the range of the vessels. To satisfy the 70% reduction and the other requirements, significant design changes will have to be implemented. Since the procurement process for the vessels which will be delivered between 2020 and 2030 is already in an advanced stage, the vessels delivered after 2030 will have to compensate if these former do not implement fuel-saving measures in their design. This creates an urgency for all future designs. When these design changes are postponed again, the vessels delivered after 2040 will have to compensate for the high fossil fuel consumption of the entire fleet possibly leading to infeasible designs.

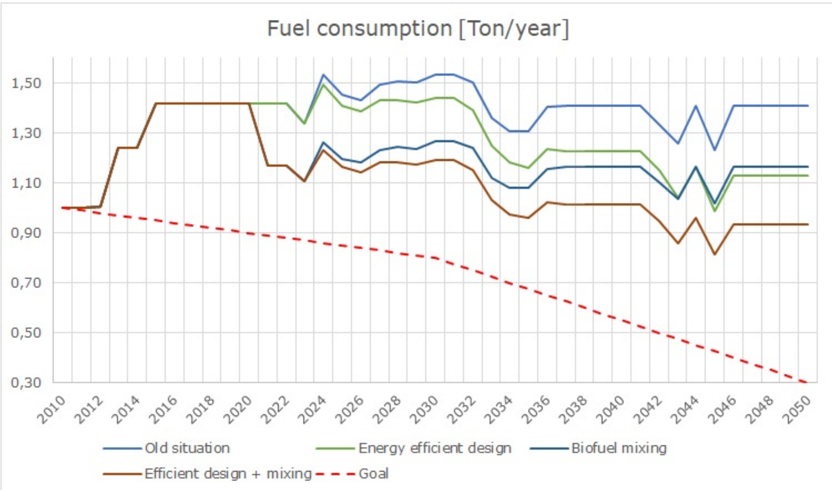


Figure 1.4: Projected fuel consumption (normalised) with different measures

## 1.3. Operational continuity

The motivation behind the OES and subsequently the DEOS is the potential risk associated with a reliance on fossil fuels poses to the continued and safe operations of the Netherlands armed forces. When considering this, it is not sufficient to examine only if and how a reduction of fossil fuel consumption can be achieved, but also whether this reduction contributes to increased continuity and safety during operations. When considering the degree to which the reduction of fuel use would actually reduce the dependency and thus the negative consequences for the operational effectiveness, it is not as straight forward that the RNLN should contribute to the same degree as the other branches. The dependency on fossil fuels is problematic particularly when it is difficult to supply this fuel to the theatre. For compounds of US forces in Afghanistan, the fully burdened cost of fuel - the total cost of getting the fuel to the end user - averaged around $400 per gallon (€105,- per litre) [87] [62]. This high price can be attributed to, in addition to the fuel price, the cost of tactical delivery assets such as trucks and sometimes planes, and the cost associated with the security of convoys in often hostile environments [25]. The MoD has also confirmed that the negative consequences of dependency primarily affect the security and continuity of compounds such as the one in Uruzgan, where supply lines are long and in-

[3] 20% is the estimated fuel consumption reduction achieved on the replacement of the M-frigate compared to a similarly sized older vessel [37].

secure [1]. The nature of the theatre aggravates this as grounds troops generally have a lower mobility and are more susceptible to asymmetric threats than naval formations as these have a higher mobility and are less constrained by their surroundings [54, p.170]. Naval vessels can often bunker their fuel in ports against commercial prices or use a sea supply line that is more resilient and less vulnerable and costly than supply lines overland [74]. This makes the urgency to replace fossil fuels with an alternative source lower for the RNLN than for the army. Additionally, any alternative energy carrier that might be selected and is not composed of fossil fuels will still have to be absorbed into the supply chain meaning no benefit is achieved with regards to operational dependency [37]. Some of these alternatives (which will be discussed in more detail in chapter 3) are also more difficult to transport, store and acquire or have a lower energy density thereby creating additional challenges in replacing fossil fuels. The DEOS itself thus does not seem to completely justify the need for the replacement of fossil fuels for the RNLN and while striving for the reduction of fossil fuel consumption, an eye should be kept on any organisational challenges.

## 1.4. Environmental considerations

Apart from the safe continued operation, there are also environmental considerations that the MoD and DMO wish to take into account. Although most naval vessels and especially surface combatants are by law exempt from many civil regulations regarding quality, health, safety, and environment there are several reasons why the MoD may wish to comply with these rules regardless. Broader societal trends of environmental awareness and sustainability that led to the 2015 Paris accords are also apparent in the shipping sector with the International Maritime Organisation (IMO) 2050 strategy for greenhouse gas (GHG) emissions as the main set of goals within the industry [41]. The MoD has an important exemplary role as an official government body and wishes to accelerate innovation and technological change by acting as launching customer for different sustainable technologies [15]. Although the DEOS does not explicitly refer to GHG emissions the MoD cannot stay behind the commercial shipping sector in this area [94]. Regional or local regulation or safety and environmental standards could also hinder the RNLNs access to ports or regions where a low $NO_x$, $SO_x$, or particulate matter emission is required. This manifests itself for example in the (internal) requirement for all new RNLN vessels to be tier III compliant. The IMO strategy aims for a 50% (70% by tonnage) reduction of greenhouse gas emissions in 2050 (compared to 2008). In addition to the DEOS, the DMO also wants to make an effort to achieve these goals [74].

## 1.5. Challenges

Unifying the different goals stated in the DEOS on one hand and in the IMO strategy on the other brings along considerable challenges. The goals of reducing fossil fuel consumption on the one hand and reducing emissions, on the other hand, are often complementary but can be conflicting in some cases. Firstly, technological solutions aimed at reducing GHG emissions but not the consumption of fossil fuels, will have an effect on the feasibility of the IMO goals, but not on the feasibility of achieving the DEOS goals. Carbon capture is one technology that decreases GHG emissions, but not fuel consumption. Similarly, exhaust gas treatment may help in achieving a significant reduction of $NO_x$ emissions but may reduce the overall efficiency and thus increase fuel consumption. Conversely, the use of some bio- or synthetic fuels does decrease the dependency on fossil fuels, but depending on the method of production will not have a proportional effect on the reduction of GHG emissions and may increase or reduce other emissions depending on the fuel choice. Likewise, the different goals of the DEOS also do not seem to be complementary. The expeditionary deployability of a vessel currently depends to a large degree on the amount of fossil fuel it carries. Increasing the vessels endurance while decreasing the fuel capacity may thus prove contradictory.

Another challenge lies in the nature of naval vessel design and how it differs from commercial vessel design. Firstly, the motivation behind the fuel reduction for commercial vessels stems either from a cost perspective or from compliance with international emission regulation. In the case of the RNLN the motivation mainly stems from a need to continue operations when it is hard to maintain supply lines and thus concerns fuel consumption, not emissions [8]. Secondly, the operational requirements for a naval vessel are often much more varied, and the operational profile more complex than most commercial vessels.

Considering both the goals originating from the DEOS and the IMO strategy 5 unique goals that should be achieved by 2050 can be identified:

- A 70% reduction of fossil fuel consumption per ton-mile relative to 2010 levels must be achieved by 2050.
- A reduction of GHG emissions of 70% per ton-mile relative to 2008 levels must be achieved by 2050.
- $NO_x$, $SO_x$ and particulate matter emission must comply with international regulations
- The *operational effectiveness* should be maintained or increased
- The expeditionary deployability should be maintained or increased

Apart from the goals that have so far been described and examined in this chapter an important part of the acquisition process of any piece of equipment is the economical aspect. Here too different stakeholders represent different interests. The parliament has to agree on a defence budget with which the MoD has to ensure that both operational expenses (OPEX) and capital expenses (CAPEX) are covered. The goals presented so far may result in a more costly product and a higher investment but the way in which the operational cost develop are often uncertain. On the one hand, making a vessel more efficient will decrease the overall fuel consumption which is beneficial for the OPEX. On the other hand, the price developments of alternative fuels is still very uncertain and this may very well affect the OPEX negatively.

## 1.6. Design impact

Choices made with regards to the use of alternative (non-fossil) fuels may also have a significant impact on the design of naval vessels. Given the stringent requirements stemming from the important and difficult task of many naval vessels, the implications of these design decisions should therefore be thoroughly examined. The reduction of GHG- and other harmful emissions in commercial vessels have already been researched extensively [18] but this effort has not been replicated to the same degree in naval vessels. This knowledge gap may be filled by carefully examining how naval vessel design is different from commercial vessel design and what is deemed to be an effective design.

## 1.7. Research questions

In order to successfully uncover the relationship between the various technological solutions and the design implications they might convey onto the designs of various current or future naval vessels, the following research question must be answered:

> *How are the design and the operational effectiveness of RNLN vessels affected by the use of alternative energy carriers and energy conversion technologies that are needed to reduce the fossil fuel consumption of the Netherlands armed forces?*

The main research question has been divided into five sub-questions to capture the scope and depth of the problem more accurately:

1. How are the operational effectiveness of RNLN surface vessels defined and how is it influenced by changes in energy carrier & converter?
2. Which energy carriers and conversion methods exist for marine applications and what are their characteristics?
3. What design changes should be applied to which vessels in order to achieve the perceived goals?
4. What is the influence of these changes on the design and operational effectiveness?

## 1.8. Structure

This thesis is divided into two parts which have been performed and graded separately. The literature study comprises chapters 2 and 3.

In chapter 2 the existing literature on naval vessel design and effectiveness assessment is examined to gain a better understanding of how effectiveness is influenced in the early design stages. Technical factors of the design are the main considerations, although some attention is also given to strategical, economic, and operational factors.

Chapter 3 subsequently aims to provide a clear picture of the different technological solutions that are available. First, a broad overview of different categories of energy-saving practices is provided. Amongst those practices are the application of novel energy carriers and energy converters, which are then examined in more detail.

The final chapter in this first part is the explanation of the method that was developed for the remainder of the research. This is done in chapter 4. The second part comprises the execution of the selected case studies. This starts with chapter 5 in which the information from chapters 2 and 3 is brought together in an operational analysis of the two case study subjects. The technical characteristics and the design requirements of the different vessels will give some idea about the compatibility of the technologies with certain vessels.

This qualitative design is then continued into the next design phase in chapter 6 in which a parametric design variation is performed. In this systematic design variation, a simplified model of the two case study vessels is built. In this model, the operational profile and the energy carriers and energy converters can be varied. In this way, it is possible to obtain a first estimate of the influence of these changes on the main dimensions, power, and fuel requirements of these vessels.

Chapter 7 continues with the most feasible design from the parametric study and proposes a more detailed power plant configuration. This configuration is subsequently used to assess the effects on fuel consumption, exhaust gas emissions, and operational effectiveness.

After concluding the design study an additional chapter is dedicated to the broader complications which the proposed design may have. The applicability of the lessons learned in the case study will be applied to the entire fleet and the feasibility of the DEOS goals is once again examined. As the vessels operate within a system the evaluation of a design must not be limited to the assessment of the technical capabilities in an isolated system but in their real-world environment. Some more attention will thus be given to the factors that have not been discussed thus far.

In the penultimate chapter of this thesis, the overall conclusions will be presented and the research question answered. In chapter 9 the result will also be discussed, and recommendations for future research will be provided.

The thesis finishes with a more personal chapter in which the author reflects on the process of researching and writing the thesis. How the results have influenced the authors own predisposition towards the subject, and broader lessons that may have been learned.

# I

# Literature review

# 2

# Naval vessel design & effectiveness

The most important constraint mentioned in the DEOS is that the Netherlands Armed Forces must continue to be able to exercise their constitutional task. To achieve this the *operational effectiveness* and *expeditionary deployability* need to be maintained or if possible increased. In order to effectively judge whether or not this is the case, insight into the operational effectiveness as a concept and the expeditionary deployability must be gained first. This is the purpose of the first research question that was introduced: *How is the operational effectiveness of RNLN surface vessels defined and how is it influenced by changes in energy carrier & converter?*

Measuring the effectiveness of a naval vessel is not a straightforward procedure because a naval vessel often has a multitude of different missions it must perform at different times. Besides that, the different vessels of a fleet also have different operational requirements so the same procedure to measure the effectiveness may not be applicable for different vessels. Part of what makes effectiveness assessment such a difficult matter stems from the inherent difficulty in the design of naval vessels in general. Even the question of which requirements a naval vessel has to fulfil can be difficult on its own.

This chapter will take these difficulties regarding naval vessel design into account to sketch what the differences are with more conventional commercial vessel design practices. Before considering operational effectiveness in more detail, the cost-effectiveness trade-off will shortly be examined. After this, different methods of gaining insight into operational effectiveness and vessel requirements are considered. A beginning is made by looking into different key performance indicator (KPI)s that are used for commercial vessels, and why these may or may not be suitable for naval vessels. Some methods which are more often used in naval vessel effectiveness assessment are subsequently proposed, and a way of translating mission requirements to the performance of technical systems.

When looking at the effectiveness, this will be done on multiple levels. One of these aspects of the effectiveness of the fleet pertains to the technical capability of an individual vessel to meet the operational requirements. The effectiveness of a fleet however is more than the addition of the effectiveness of the individual vessels. More organisational traits that do not necessarily have to do with the vessels design directly can also be of importance. Aspects such as supply chain logistics and availability and readiness of the fleet at different points in time are not directly related to the design of the platform but may largely influence the capacity of the fleet as a whole to be effective.

## 2.1. Complexity of naval vessel design

In ship design there are largely two distinguishable types of vessels: transport vessels and service vessels [71] [93]. Whereas transport vessels are designed to perform the narrow task of transporting cargo from one point to another, service vessels often have a wider array of tasks that must be performed. Most naval vessels are in this sense service vessels with an often wide array of tasks that need to be or might need to be performed in sometimes remote locations. Furthermore, the composition of these tasks may change throughout the lifetime of a naval vessel as the context in which it operates is by definition ruled by politics and the security situation worldwide [71]. Missions may range from anti-submarine-, anti-air- or anti-surface warfare, humanitarian relief, sea patrol, and amphibious operations to simpler things such as cargo or personnel transport or support roles [71] [57]. The often hostile environment in which naval vessels sometimes operate that various classes of naval vessels are designed to operate at the high end of the spectrum of conflict (see figure 2.1) and as such should be designed to continue operation even after sustaining considerable damage, something that commercial vessels are not designed for. With these vessels, designers often go to great lengths in order to improve the survivability of the vessel. Another complicating factor that is true for all navies, but especially so for smaller (green water) navies such as the RNLN is the scale of production. Naval vessels are often tailored to the highly specific needs of the operator and are rarely commercial of the shelf (COTS) or military of the shelf (MOTS). The DMO accentuates in-house development more so than other countries' defence acquisition departments in order to get a similar product but with lower costs [39] [45]. This in house development means that series are often small, ranging from 1 vessel (the JSS) to 4 (the LCF) or at most 8 (the M-frigate[1]) for the larger vessels, and up to 10 for some smaller vessels. The small series but high production value mean that it is not feasible to develop prototypes that can give insight into the technical performance early on in the design process [5].

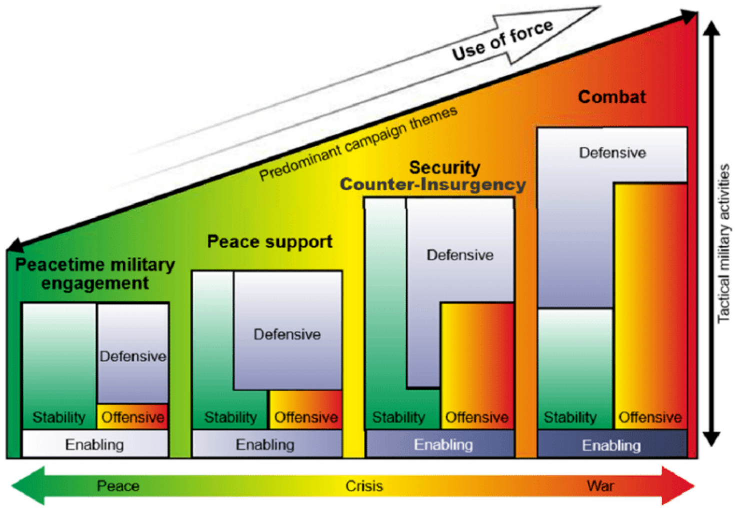


Figure 2.1: The spectrum of conflict indicates the level of force a unit may encounter [30]

In order to arrive at the optimal design, it may sometimes seem desirable to make a solution independent statement of the requirements. This would lead to a solution free of subjective biases of the customer and the procurement authority and thus avoid jumping to conclusions [5]. The problem with many naval vessels however is that their complexity makes the design problem ill-defined and unstructured [26]. With such "wicked problems", a term first coined in the public policy area, it is not possible to find a global optimum, and the design requirements and design choices instead must be based on the chosen solution direction [75]. For example, a submarine, a frigate, and an aircraft may all three be equally effective at engaging and destroying an enemy vessel, but despite these systems having the same mission, the requirements for all three could hardly be more different. In the case of a naval vessel, requirements also stem not just from the primary mission, but they need to sustain and house a large crew for extended periods of time as well [5]. As different solution concepts are explored, new requirements surface or old requirements become more specific. This process is referred to as requirement elucidation [95] [4]. This interdependence between problem definition, requirement identification, and solution direction also have a temporal aspect, meaning that the solution may change depending on the sequence in which decisions are taken may have a significant effect on the outcome [43].

## 2.2. Cost effectiveness trade-off

Continuous effectiveness assessment is important throughout the entire process of naval vessel design, but effectiveness is not the only consideration that needs to be taken into account. It is not difficult to imagine a feasible design that will have a high operational effectiveness and also complies with all the goals stated in the introduction. In the pursuit of these goals and the optimal design, the designer

[1] Of these only 2 are still in service with the RNLN

of any naval vessel is limited by the cost of the vessel. As the budget available for the procurement project is normally established in the early phases of the project simultaneously with the requirement statement. Besides a continuous effectiveness assessment, there are thus also various trade-offs that must be analysed constantly. One of these is the cost-effectiveness trade-off. There are many different sorts of costs associated with the construction and ownership of a vessel. In the commercial shipping sector, a distinction is often made between the acquisition cost and life cycle cost, and sometimes total ownership cost [76]. The conventional terms in shipping are OPEX and CAPEX, and life cycle cost (LCC) is a term often used as well. Under NATO ANEP-41 Ship Costing [64] LCC is divided into 6 categories: Sail-away Cost, Program Acquisition Cost, Program Life Cycle Cost, Total Life Cycle Cost, Total Ownership Cost and Whole Life Costs. May also be divided between the acquisition cost and in-service cost [64]. Cost estimation methods There are different ways of estimating the LCC of a program. Each of these has a different level of detail and can thus be associated and used in a different phase in the design process. The easiest manner of systematically estimating the LCC of a program is through comparison with previous similar projects. By comparing systems and subsystems an index that details the cost relative to the other project can be found. This is known as analogy ship costing [50]. Another way of doing this is through substitution cost indices [42]. In the analysis of alternatives phase, a similar situation can occur where few details are available so far but in this case, a comparison is not made to a previous vessel but amongst the different alternatives. Another benefit of using an index is that the cost-effectiveness ratios can be compared between different ships regardless of whether actual costs or substitution cost indices are used [42]. As the design progresses and more details are known, the next step is often parametric cost estimation [50] which is essentially a top-down estimation method [9]. A parametric cost estimation may be done for the entire ship. Displacement traditionally is one of the most widely used parameters in this case. But parametric cost estimation methods can become increasingly accurate when taking more individual cost estimating relationships (CERs) into consideration [83]. A CER is an estimation for one particular part of the cost of a vessel. Besides different parts of the ship work breakdown structure (SWBS) other factors also influence the cost. In the North Atlantic Treaty Organisation (NATO) framework 7 main categories are included in the SWBS. Some of these factors are shown in the list below [50]:

- shipyard work centre productivity
- stage of construction
- design complexity or design density
- economic inflation
- learning curve
- multi-ship material cost
- multi-ship engineering and planning cost
- material waste factor
- differences in procurement quantity and contract type

The most accurate method of estimating cost is the bottom-up approach [9]. of estimating the cost of each individual component, subsystem, or system. Naturally, more technical data is needed for such an Engineering Build Up Cost Estimating Model (Lee, 2005), or Direct Analysis method [76] Each of these methods has its advantages and disadvantages and a combination is used throughout the procurement process. At the DMO a combination of these techniques is also used based on ANEP-41.

## 2.3. Measuring effectiveness

In the design phase, it is important to systematically analyse the impact that design decisions have on a vessel in order to judge which solution is optimal. To judge the effectiveness of a naval vessel, a KPI may be developed. There are multiple ways of determining the effectiveness of any vessel. In this section, some effectiveness indicators and methods to determine these will be examined. This will be done for commercial vessels first, and later for naval vessels.

### 2.3.1. Commercial shipping sector

When looking at the total tonnage of all commercial vessels worldwide, the majority of the fleet is composed of different sorts of transport vessels. For transport vessels, it is relatively easy to find a KPI that tells something about the vessels effectiveness or efficiency. The difference between these two terms is also important however. With effectiveness ”The degree to which something is successful in producing a desired result or success” is meant, while efficiency is defined as ”achieving maximum productivity with minimum wasted effort or expense. ”The purpose of practically all transport vessels is to transport goods from one point to another. The effectiveness with which they do so depend on how many goods they can take, and how long it takes them; their capacity and speed. In reality however, constraints usually related to cost mean that it is not always feasible to design larger, faster ships. In the commercial shipping sector, the leading KPI is thus often based on efficiency, measuring the ratio of output to input. Having established that output can be measured in ton-miles (amongst others) the input subsequently needs to be defined. This is often the amount of fuel used or the work performed. A slightly different way of doing this is by expressing the transport efficiency as a ratio of the transported weight multiplied by the speed to the power needed as in the equation for $E_1$ [70]:

$$E_1 = \frac{W_d \cdot V_s}{P} \tag{2.1}$$

Where:
$E_1$ = transport efficiency
$W_d$ = deadweight
$V_s$ = ship velocity
$P$ = power
When integrating this equation over a certain time the performed work per ton mile will again be obtained.

$$\int E_1 dt = \frac{W_d \cdot s}{W} \tag{2.2}$$

where:
$s$ = distance sailed
$W$ = work performed
With some additional data this equation can relatively easily be transformed into various other indicators. If the specific fuel consumption is known the fuel consumption per ton-mile can be derived. If in addition to this the fuel price is known the fuel cost per ton-mile is also available.

Now that emissions from ships are becoming more and more important, a ratio of positive output to negative input can be constructed to obtain a sort of emission efficiency. This is what is done in the formula for the Energy Efficiency Design Index (EEDI) which is used by the IMO (see equation (2.3)). In this equation $P_{ME}$ and $P_{AE}$ represent the power of the main and auxiliary engine, $sfc_{ME}$ and $sfc_{AE}$ the specific fuel consumption of those engines, $c_{f,ME}$ and $c_{f,AE}$ are the specific carbon emissions of the fuel used. $CAP$ represents the vessel’s cargo capacity whereas $v_s$ is the ships design speed. The parameters $f_j$ and $f_i$ are correction factors for the ship type concerned. This is an example of a vessel with only a main engine and an auxiliary engine. When more complicated power plants are involved the equation can become larger, involving a power take-off, power take-in, other correction factors and parameters to include innovative power solutions [40].

$$\mathrm{EEDI} = \frac{\mathrm{f_j \cdot c_{f,ME} \cdot sfc_{ME} \cdot P_{ME} + c_{f,AE} \cdot sfc_{AE} \cdot P_{AE}}}{\mathrm{f_i \cdot CAP \cdot v_S}} \tag{2.3}$$

As the name already hints at, this index tells something about the efficiency of the design. The IMO uses reference lines which will become progressively lower over the coming years in order to ensure that both old and newer vessels will contribute to a reduction in GHG emissions.

### 2.3.2. Naval vessel effectiveness

The challenges which make designing a naval vessel an inherently complex process are also encountered when trying to capture the operational effectiveness.

Problems with the efficiency models that have been proposed in the previous section for commercial vessels are again associated with the multi-mission nature of many naval vessels. It must be noted however that some naval vessels such as the yet to be delivered CSS do fulfil the narrow mission of transporting supplies from A to B. For most naval vessels however, this is not the case. Attempts have also been made to apply the EEDI to naval vessels but many challenges have yet to be overcome. Michalchuk and Bucknall [56] have proposed an EEDI for warships but several problems with the application of such an index still exist as Stapersma points out [85]. In his piece on an EEDI for naval

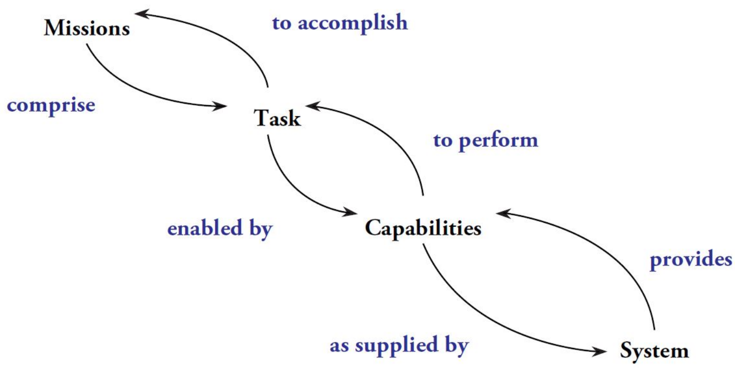


Figure 2.2: Mission Accomplishment Relations [21]

vessels, Stapersma considers the effective output of a naval vessel to be the capacity to transport military equipment across the sea. He also proposes to use the energy ultimately used by these military systems as a measure of their output. One could easily imagine a situation however in which a high top speed may be imperative to the success of the mission, where if the top speed would be 20% lower the mission would fail entirely, and not just be 20% less beneficial. An aircraft carrier for example is in terms of its mission relatively simple. If its operational effectiveness is expressed as the number of aircraft it can carry to the theatre, multiplied by the speed with which it does so, the optimal design may not be able to reach the high speeds necessary to launch said aircraft. Beyond the lack of an exhaustive description of the output of a vessel in the potential EEDI for warships, the current formulation only considers a single speed while the consideration of a more varied operational profile may yield more useful results. This is already performed in a preliminary study into the possible reduction of fuel consumption for the M-frigate replacement [37]. Although the use of a warship EEDI may thus be useful, the concerns raised by Stapersma lead to the conclusion that it is primarily effective when comparing alternative designs for the same vessel. When comparing different vessels the ship's capabilities have to be given a more prominent role than just its displacement and speed.

### 2.3.3. Operational Effectiveness Models

When viewing a naval vessel as a complex system, some things can be learned from a systems engineering approach. For complex systems, several modelling or simulation-based ways of deriving a system's efficiency can be proposed. By defining the systems performance requirements different alternative design can all be evaluated using system effectiveness simulations of the expected operation [48]. In *Application of Operational Effectiveness Models in Naval Ship Concept Exploration and Design* a design method for early-stage naval ship design is proposed [21]. In this method, the required capabilities and their associated operational characteristics are decided upon in an initial capabilities document. Then key performance parameters are established by which different designs can be judged. For this, the overall measure of effectiveness (OMoE) is employed. The OMoE for a design is traditionally established through pairwise comparison by an expert who gives his opinion on certain aspects of the design, but development of an operational effectiveness model (OEM) is meant to largely automate this. In such a model, the vessel is assigned certain *design reference missions* within a set of multiple operational situations. Model-Based System Engineering and Total Ship System Architecture are ”used to define and understand the relationships to operational effectiveness” [21]. Figure 2.2 shows how the effectiveness of the reference missions is ultimately affected by the technical solutions which are proposed.

By generating a large number of different operational situations in which different missions may need to be performed and subsequently assessing the effectiveness within each operational situation, an overall expected effectiveness of the system may be estimated. [21]. Although this method is still dependant on the input for the simulation it can be used to assess the effectiveness of different designs in different situations and thereby compare the designs.

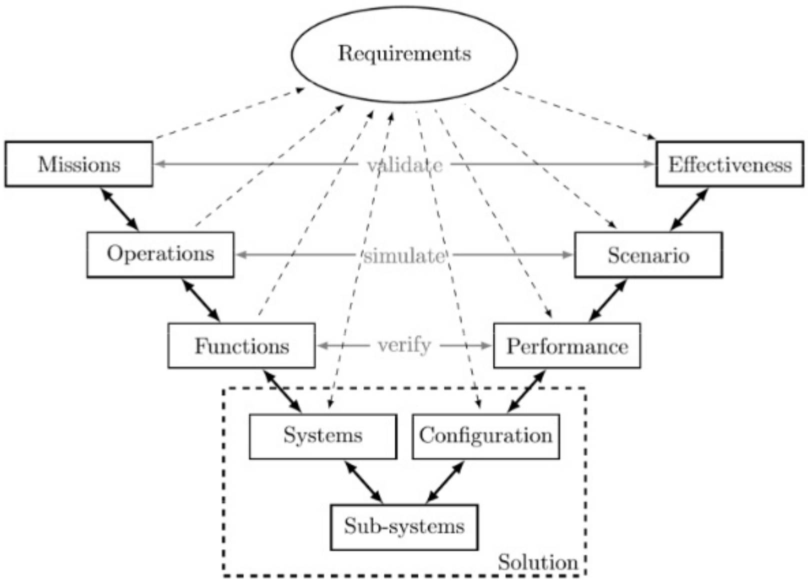


Figure 2.3: V-model of systems engineering[95]

### 2.3.4. Effectiveness assessment at DMO

Simulated effectiveness assessments are also used as a part of the design process at the DMO [95]. It is almost impossible to gain insight into what the actual design requirements are without first looking at potential solutions, which in term influence the requirements. DMO uses a design method similar to the systems engineering approach. The V-model of system engineering is seen in figure 2.3 and the similarities with figure 2.2 are readily apparent. Here too there is a hierarchy that encompasses the mission, operation, function, and system. The Total Ship System Engineering (TSSE) developed by NATO is an adapted form of systems engineering and forms the basis for the concept design stage at DMO [95]. For now, the focus will be limited to the effectiveness assessment. This assessment is performed by defining a measure of effectiveness (MoE) for every task that needs to be performed [66]. A standardised approach to such an effectiveness assessment has been developed in the NATO capability codes and capability statements and the Fundamentals of Maritime Operations (Grondslagen van het Maritiem Optreden) (GMO).

### 2.3.5. Translating missions to technical requirements

When combining the approaches that have been examined in the previous sections it becomes possible to determine which vessels must possess a certain capability by making the capability breakdown as in figure 2.4. When additionally assigning weights to specific branches it also becomes visible which capabilities should be prioritised in the design process. A vessel for instance may be expected to perform mission A 10% of the time, while it performs mission B 20% of the time. Similarly, capability A may contribute more to the effective performance of a task than capability B. Finally, it must be noted that tasks and capabilities are not necessarily unique to certain missions; A certain capability may be needed for two different tasks.

When it is known which vessels are expected to perform certain missions, this method can be used to get insight into the capabilities that are required for the vessel. Such specifications have been made before, for example by Knegt [46] visible in table 2.1. In this table, the mission which the vessels of the RNLN are expected to perform are seen. A weight could be assigned to each mission in the case of multiple missions. Various mission scenarios can also be performed, as did Knegt, to obtain a mission profile for the vessels.

The model that Knegt developed can be expanded upon greatly by more different mission types. There are several descriptions for the different mission types that naval vessels may have to perform. Operations may be placed somewhere on the spectrum of conflict indicating the intensity of the use of force which may be encountered as in figure 2.1, or they may be placed somewhere in the trian-

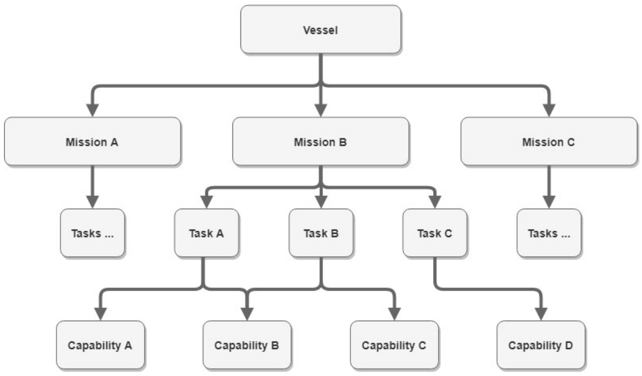


Figure 2.4: Mapping necessary capabilities to a vessels missions

Table 2.1: Vessel type mission matrix

| | Landing | AAW | ASuW | ASW | Supply |
|---|---|---|---|---|---|
| Submarine | | | X | | |
| LPD | X | | | | |
| LCF | | X | | | |
| M-Frigate | | X | X | X | |
| Patrol | | | X | | |
| JSS | X | | | | X |
| CSS | | | | | X |

gle of maritime operations as presented in the RNLN maritime doctrine (figure 2.5). NATO has also constructed a similar, more expansive list with the requirements for vessels [63].

## 2.4. Vessel requirements

The simplified method of translating technical requirements from a mission profile is not completely straightforward in all cases. The design problem very much remains a wicked problem and one may still expect significant differences between the design of a submarine and that of a surface vessel, even when both are designed for the same missions. After obtaining the methodology which can be used to assess a vessels effectiveness, the input for this method needs to be determined.

### 2.4.1. Operational profile

The operational profile of a vessel is an important design driver. The fraction of time spent at certain velocities dictates for which speeds certain aspect of the design need to be optimised. Especially the configuration of the power plant will change depending on the operational profile, this will largely be covered in the next chapter.

### 2.4.2. Operational requirements

From the analysis of the missions, tasks, and capabilities which the vessels must fulfil a list of systems that provide in those capabilities can be made. The generation of many alternative lists of systems is essentially a part of what happens in the concept exploration phase. Each of these systems will influence the effectiveness in a myriad of ways. To gain insight into these interactions they may be divided into different categories. Each change of the design will affect one or more of these categories, and that these categories collectively make up the total effectiveness of the vessel. One such a list of categories could be based on efforts made by Brown and Andrews [22]:

- Speed
- Stability
- Strength
- Seakeeping
- Style
    - Stealth

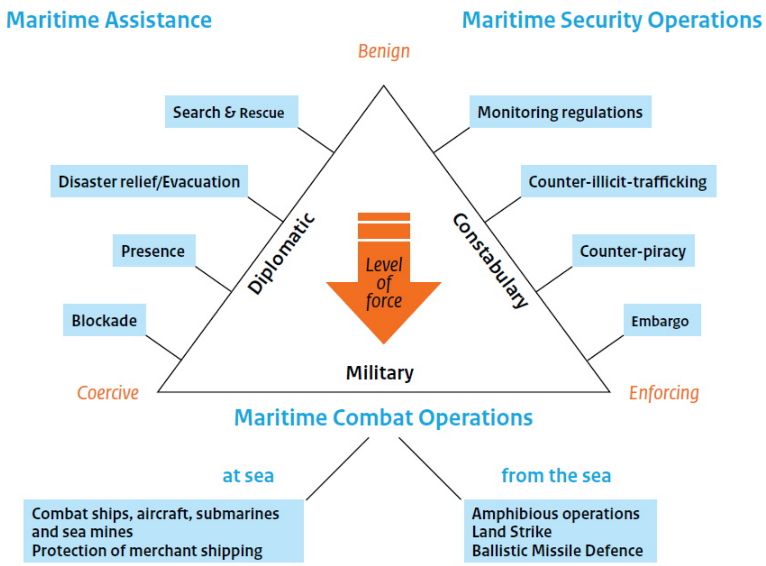


Figure 2.5: Fundamentals of Maritime Operations [57]

- Protection
- Human factors
- Sustainability
- Margins
- Design Issues

This list is primarily used to explain how naval vessel design differs from the design of commercial vessels and is also relatively old (1980). From some of the items in the list, it is not directly clear how they influence the operational effectiveness of a vessel.

A more extensive attempt at listing all factors which influence the effectiveness of a vessel is made at the national level in the GMO[57] and on the international level in the NATO Capability Codes & Capability Statements [63]. In both these documents, an extensive list of missions and an exhaustive overview of the necessary capabilities for each possible mission is given. The complete list of capabilities is very detailed. When considering the capabilities that apply to the platform, however, these can be simplified and categorised in a similar manner to Brown's and Andrews' list. The list of technical characteristics that are constructed from the capability statements is shown in the list below.

- Offensive capabilities
- Survivability
  - Susceptibility
  - Vulnerability
  - Recoverability
- Mobility
  - Top speed
  - Acceleration and deceleration
  - Mobility
- Range
- Endurance/autonomy

Besides the NATO Capability Codes and the GMO this list is based mainly on conversations with DMO colleagues [96]. This list is not necessarily mutually exclusive with the list proposed by Andrews. In fact, most of the items that are part of the Brown and Andrews' list can also be categorised according to these specifications. Speed falls under the denominator of mobility, stealth and protection are included in survivability. Seakeeping is a requirement for mobility in heavier weather or at higher speeds.

Sustainability is almost a synonym for endurance in this context. Only stability has been given a less prominent role, as this is a requirement for any vessel, and not unique to naval vessels. It is more readily apparent how these categories influence the success in missions.

### 2.4.3. Offensive capabilities

On the battleships of the early 20th century, the main weapons were prominent features of the vessel, with batteries of large guns arranged all over the deck. Developments in weapon technology have drastically changed the look of most modern warships. Vessels designed to operate at the high end of the spectrum of conflict now feature extensive sensor technology with which it can direct a host of weapon systems such as anti-ship, anti-air, anti-ground missiles or torpedoes. sensors, weapons and communication (SEWACO) systems can be integrated into overall command and control (C2) systems so that information may be shared with other vessels, helicopters or maritime patrol aircraft. A range of smaller self-defence weapon systems also features on ships designed for less intense combat situations. The highly sophisticated SEWACO systems nowadays require more power than their predecessors. Ever stronger radars, increased automation, and adoption of direct energy weapons are expected to increase the power demand for onboard systems even further in the future [37]. In this thesis, the term 'offensive capabilities' refers to everything regarding the SEWACO systems themselves and will not be considered in detail. The trend of increasing energy consumption however should be ignored when contemplating power plant configurations of future naval vessels.

### 2.4.4. Survivability

The survivability plays a large role on the vessels that may be subjected to situations that are in the high end of the spectrum of operations which can be seen in figure 2.1. Examples of operations along the spectrum are the assistance in disaster relief or humanitarian aid at the lower end, peacekeeping missions or anti-piracy somewhere in the middle, and wartime operations at the high end. For vessels operating at the high end of the spectrum, it is important to maintain the ability to accomplish the mission by avoiding or withstanding weapons effects [38] As can be seen in figure 2.6 the survivability of a naval vessel is composed of several distinct areas which are influenced by both the design and the operation of the vessel. These aspects can be roughly divided into three categories: susceptibility, vulnerability and recoverability [72] [38]. Although all three aspects are part of the survivability of a vessel their influence on the survivability of a vessel will depend on the necessary capabilities of a vessel. For some vessels, one aspect is more important than the other [20]. A submarine relies more on its ability to remain undetected, while a frigate relies more heavily on its defensive capabilities in order to survive.

Susceptibility

The susceptibility of a naval vessel has to do with the ease with which it can prevent being engaged or hit [72]. This includes the prevention of detection and the use of countermeasures such as jamming equipment or chaff. When considering the platform and not the own weapons and sensor the most important aspect from figure 2.6 in this category is the prevention of detection. This can be achieved mainly by reducing the signatures of the vessel. The signature of a vessel exists of several components:

- Infrared (IR) signature
- Acoustic signature
- Pressure signature
- Electromagnetic signature
- Visual signature

The powerplant affects most of these signatures, but in different degrees depending on the selected system. The sound and vibrations generated by a diesel engine and gearbox affect the acoustic signature, and the hot exhaust gasses of an internal combustion engine can easily be detected by infrared sensor systems. High currents in electric propulsion and other systems, in turn, generate electromagnetic fields which may also be detected. Finally, the visual signature may be influenced by the powerplant primarily through the emission of smoke in the exhaust gas. Mitigating measures exist for some of these effects, but these do often incur cost in the way of efficiency, occupied volume, or cost.

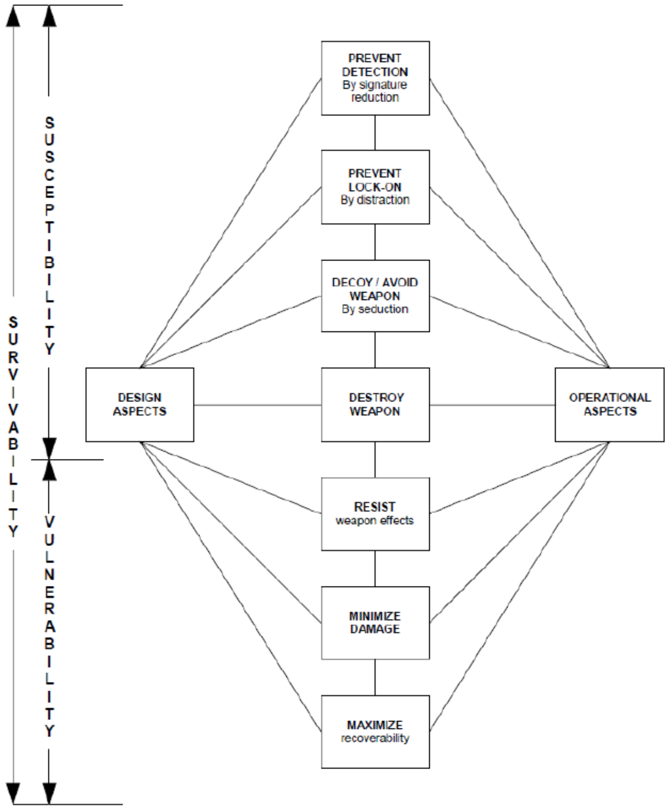


Figure 2.6: Survivability [72]

Vulnerability
The vulnerability of a vessel concerns the damage that will be done by an impact or the sensitivity to impact. This damage comes in two forms often referred to as primary and secondary damage [20] [38] [72]. The first is the sensitivity of the system to primary damage. If a system is very sensitive to damage, a weapon's impact may easily disrupt the operation, leaving the vessel dead in the water and possibly without weapon, sensor, communication systems and propulsion. The second aspect is the possible propagation of damage if sensitive fuel systems are compromised. Fuels with high flammability and especially gasses may be prone to explosion when compromised and will exacerbate any damage already done. Flooding is also a form of secondary damage that can cause dangerous situations in a maritime context.

Recoverability
The recoverability of a vessel refers to the degree to which, and the time within which any lost capabilities can be recovered [72]. This may be done by switching to backup systems in the case of redundant engine rooms for example. Recoverability analysis is still a difficult field as it is hard to correctly model damage propagation and human response to this damage [72].

### 2.4.5. Mobility

Mobility is a category that is related to some of the other categories on this list but also has some merits of its own. A high mobility can help to avoid being hit by projectiles or torpedoes by outmanoeuvring the projectile or by moving beyond weapon range. It becomes easier to remain close to a group or fleet and potential dynamic positioning (DP) operations can also be regarded as an aspect of mobility. The mobility of a vessel is mostly affected by the available power at any given moment. A higher available brake power means the vessel will be easier to accelerate and decelerate giving it more options to outmanoeuvre attacks. As such mobility could be argued to be a factor of survivability. There is some criticism however regarding the value of mobility in outmanoeuvring attacks. The ability to come to a dead stop within two ship lengths is a requirement that helped naval vessels in the second world war to avoid torpedoes. Now, with increasingly smarter weapon technologies it is less certain that a high mobility has any influence on the ability of the vessel to avoid weapon impact. Apart from the impact the mobility has on the survivability of the vessel, some factors of mobility can also be important in other ways. When acting as part of a fleet or an escort, the vessels must be able to comfortably sail at the same speed as the rest of the group and when patrolling or intercepting, speed and mobility can also influence the success of the mission. Mobility can also be important on patrol- or anti-piracy missions as it may help to intercept targets (although this task can be performed by a rigid hull inflatable boat (RHIB), fast raiding interception and special forces crafts (FRISCs) and helicopters as well). Another aspect of mobility is manoeuvrability. For the ability to remain in the same position it may be beneficial to have DP capability. This can be important for vessels that conduct amphibian operations or for vessels otherwise delivering support from a stationary location. During operations in littoral waters, mobility can also be an issue. Smaller vessels can be a solution here.

### 2.4.6. Range & endurance

Range and endurance also influence the effectiveness of a vessel, albeit through a somewhat different mechanism than the other factors that have so far been considered. All other factors influence how well a vessel can fulfil its mission, while range and endurance influence how long a vessel can do so. When a vessel has a greater endurance it can simply stay at a area of operations (AoO) for longer. If a vessel is not present at the AoO it can simply not fulfil the mission [94]. The range a vessel has similar influences how far away an AoO can be for it to be within the reach of the vessel (without refuelling stops). Range and endurance are often hard requirements that have to be fulfilled entirely for a concept to be considered feasible and as such are not entirely the same as the other factors considered earlier [95].

Range

The range of a vessel depends on two main factors, namely the cruising speed and the fuel capacity and is normally expressed in nautical miles. The range of a vessel is a requirement that does not directly stem from the missions a vessel is expected to execute but from the expected AoO and the AoO vicinity to the home port or allied bases. The required range and transit speed of a vessel subsequently influence the fuel capacity or the amount of energy that otherwise needs to be stored. Simply making sure the vessel can either reach the analysis of alternative (AoA) faster or remain longer directly increases the effectiveness of the vessel from 0 to 100%, for the period the vessel otherwise would not be present. A larger fuel capacity, or lower fuel consumption (due to a lower hotel load or reduced resistance) thus reduces either the transit time or the need for refuelling stops.

Endurance

The endurance (sometimes also referred to as autonomy [36]) of a vessel is a measure for the time a vessel can spend at the AoO independently. The endurance of a vessel relies on all the different consumables that are needed for operations. This ranges from ammunition to food, and from spare parts to water. All these products need to be stored for which volume and displacement are needed. The endurance and thus the storage capacity needed is also heavily influenced by the mission profile and the size of the crew, with more crew obviously necessitating larger stores. Not all systems will be a reliable as others. The reliability, mean time to failure and the ease of repairs or maintenance at sea may be a vital factor in determining the endurance of a vessel. Although the main machinery is in principle designed to last at least as long as the time between major maintenance periods, not all systems are equal in this regard. This is something that should be taken into consideration especially with systems that are relatively new or unused in similar applications. For example, an internal combustion engine is in principle subject to more wear and tear due to its mechanical nature than a fuel cell but ICE technology is much more mature than a fuel cell which also influences the reliability. The requirement for a specific endurance ultimately stems from the needed operational days. although this is influenced by the vessels endurance, this is also influenced at the fleet level. The size of a class also influences the number of days that the vessels of that class can operate year-round [95].

## 2.5. Constraining factors

Apart from the requirements listed above that are specific for different types of naval vessels there are also constraining factors. The two most important constraints that are considered here are displacement and volume, and organisational constraints.

### 2.5.1. Displacement, volume & area

Depending on the type of vessel the displacement, volume, or deck area is often a limiting factor [36]. SEWACO systems, accommodation, auxiliary systems and storage of food, spares, ammunition, fuel and other consumables all compete for the capacity of the vessel. A large part of the available displacement and volume is also directly related to the operational profile and the autonomy of a vessel, as this is dictated by the amount of fuel the vessel can carry. To complicate matters further the location where a system or component is placed inside a ship can strongly influence the ease of operation and effectiveness [77] [49] [93]. Requirements for speed and resistance can further limit the hull to very slender designs which will also affect the centre of gravity (CoG) location and the stability of the vessel [5]. A slender hull furthermore puts constraints on the shape which an engine room can have making the arrangement a complex puzzle. An increased displacement in turn leads to an increased resistance which could necessitate a more powerful propulsion arrangement which again consumes more fuel.

## 2.6. Other factors contributing to an effective navy

Of course, the technical capabilities of individual vessels is not the only factor that comprises the effectiveness of a countries Navy as a whole. Other factors can severely enhance or restrict these capabilities and it is important to treat some of them in some more detail.

### 2.6.1. Doctrine

Also, an important part of the GMO[57] a military's doctrine is hugely influential on its effectiveness. Ranging from small scale tactics to large scale strategy, the manner in which personnel and materiel are used can often be the difference between being successful or unsuccessful. Although the technical sophistication can hugely influence the tactics that are used during operations, technical superiority is by no standard superior to good doctrine [54]. Although technical developments sometimes create opportunities for new tactics, the reverse is also true with new tactics being developed to counter technical developments [54]. In this thesis doctrine as a whole will play a minor role. Military doctrine is simply an entirely distinct subject from ship design. In this project, an attempt is made to acknowledge the role doctrine plays in the effectiveness of naval vessels but the reader should be well aware that the author is no authority on this subject.

### 2.6.2. Logistics

Apart from the effectiveness and the capabilities of individual vessels, the choice for different energy carriers or converters might have more profound consequences for the organisation as a whole. The parallel use of different concepts within the same organisation can introduce friction on several levels. The consumption of multiple fuel types or mixtures such as F76, biofuels, synthetic fuels, hydrogen, and others will further strain supply chain logistics (add reference). The availability of alternative fuels is expected to increase over the coming years, especially on large shipping routes but these may not coincide with the AoA of the RNLN fleet. The capacity of the RNLN fleet, but also the logistics framework of important allies such as NATO must be considered to assess the ultimate feasibility of alternative fuels. Furthermore, the use of different systems will require more knowledge of these systems and education, training, and placement of qualified personnel may become costly and even more troublesome than it already is [58].

### 2.6.3. Maintainability

Although it does not directly influence the effectiveness with which a functioning vessel executes a mission, maintainability can be an important aspect of a ships effectiveness over its lifetime. Maintainability can also be gathered under the header of 'sustainability' when again considering Brown and Andrews' list. As almost every RNLN vessel gets a midlife update, an extensive renewal programme to renew its viability, it can be important to foresee in this update. Placing engines and other machinery in such a way that they may be removed with minimal destructive alterations of the vessel's hull or superstructure will make the mid-life update (MLU) significantly easier, less costly, and faster. This in turn will lead to a higher readiness of the fleet. Apart from the MLU the regular planned and unplanned maintenance is also important. The size of a class is often based on both costs and the desired deployment. When vessels need more maintenance than foreseen, it can happen that no vessels of a class are available for deployment at a given moment.

## 2.7. Conclusion

In this chapter, it was seen that a naval vessel is often a complex system that has far-reaching consequences for the manner in which the design comes together. Simply defining the requirements for a naval vessel is already a complex task since these requirements are subject to global security situation and political decision-making process that both change over time. This makes it difficult to set up requirements for the vessel, to begin with. Naval vessel design is often referred to as a 'wicked problem' as well, which means that it is difficult to begin thinking of what the requirements are without knowledge of the solution direction. Throughout the design process, it is important to keep an eye on the effectiveness of the vessel and continually validate that the vessel will comply with the requirements. Effectiveness assessment for a single task or mission can be performed through simulation of the task or mission in various situations and the stochastic combination of all missions expected to be performed over a certain time period can then shed more light on the effectiveness of the vessel as a whole. From the GMO and the CCCS, a simplified list of technical properties can be constructed which influences the effectiveness of a vessel depending on the missions the vessel has to perform.

- Survivability
  - Susceptibility
  - Vulnerability
  - Recoverability
- Mobility
  - Top speed
  - Acceleration and deceleration
  - Manoeuvrability
- Range
- Endurance/autonomy

In the early phases of the design process, it is not always possible to simulate the effectiveness of vessels entirely. In such cases, as in this thesis, the effectiveness can be judged qualitatively on the basis of this list. The effectiveness simulations do not add to the fundamental understanding of the relations between technical systems and effectiveness except in very specific conditions.

Besides the effectiveness cost are also an important part of the equation of any procurement project. Different methods of estimating the life cycle cost of a new vessel have been examined in this chapter. in most early design phases either relative cost indicators or parametric cost estimation can be used.

Cost and effectiveness are perhaps two of the most important drivers behind the design of naval vessels and although it was not the purpose of this chapter, almost no mention of emission reduction or otherwise environmentally sustainable practices is found in the vast literature on naval vessel design.

# 3
# Technological solutions

To achieve the goals set out by the DEOS and the IMO different technological solutions are available or may become available in the future. This chapter will examine these technologies[1] and attempt to answer the following research question: *Which energy carriers and conversion methods exist for marine applications and what are their characteristics?* In the first section in this chapter a broader categorisation of different means of reducing the energy consumption and engine emissions is made. This can help place the subject of alternative fuels into the wider context of energy saving measures. From these categories the subjects of power converters and energy carriers are subsequently examined into more depth in the following sections. In the second through the fourth section energy pathways - different combinations of energy sources, carriers, and converters [32] - are discussed starting with energy sources, moving on to energy carriers and finishing with on board energy converters. The properties of different sources, carriers and converters will be examined to present a clearer idea of emission reduction potential, fossil fuel reduction potential, and consequences it might have on the vessel design. In the fifth section a selection of promising energy carriers and conversion methods will be further scrutinised and the influence that their properties have on the effectiveness as was discussed in the previous chapter is analysed more closely. In the conclusion of the chapter it will be summarised which technologies are most promising for the application on naval vessels.

## 3.1. Possibilities for energy & emission reduction

There is a multitude of ways in which the fossil fuel consumption and emissions of vessels can be reduced and different methods to categorise these have been developed. One method used in a recent systematic review study uses the following 6 categories: *hull design, economy of scale, power and propulsion, speed, fuel and alternative energy sources, weather routing and scheduling* [18]. In this section some more detailed explanation will be given for each of these categories and their applicability for the RNLN will be shortly considered. The review study mentioned above mostly considered measures to reduce $CO_2$ emissions but not other emissions while it was seen that these are still of significant importance for the DMO. The process of after treatment will thus also be added as a category.

Hull design

Hull design can reduce fuel consumption by decreasing the vessels resistance and improving the seakeeping behaviour through hydrodynamical optimisation. The optimisation of hull design in order to achieve this is not a new phenomenon, although various methods have become more accessible. The resources needed for good hull form optimisation have long been a barrier as both computational modelling and testing with physical models is resource intensive. With computational resources becoming more widely available and the development of new estimation methods and computational fluid dynamics (CFD) tools, hull optimisation is increasingly popular and accessible as a method of reducing energy consumption. Depending on the reference design, an optimised hull can achieve a reduction in resistance anywhere between 2% and 30% [18]. Both physical and computational methods are increasingly

[1] In the context of this thesis ”technologies” refers to the combination of on board energy storage and on board energy converters that together power the vessels propulsion and other systems.

integrated in various stages of the design process at DMO [27]. Not all optimisation strategies for hull design can be used to their full potential for all naval vessels however. Vessels which have a varied operational profile cannot be optimised for one specific operating speed [23]. This diminishes the potential that for example a bulbous bow may normally have on cargo vessels [23]. The optimisation thus becomes more complex and the results are sensitive to the correct estimation of the operational modes.

Economy of scale
Economy of scale refers to the concept that it is usually more fuel efficient to use one larger vessel, than two smaller vessels with the same amount of cargo. When doubling the deadweight of a vessel, the increase in power is typically in the order of two thirds [18]. At the DMO the size and number of vessels is typically determined by the requirements set by the RNLN and the MoD and in terms of operational effectiveness fewer, larger vessels are not necessarily superior to more smaller vessels. Economy of scale is thus not an area in which the DMO aims to achieve an advantage. Economy of scale in the reduction of GHG emissions should not be confused with economy of scale that is used for the purpose of lowering developing cost. Although producing at a larger scale may bring down development cost and thereby make more costly but sustainable alternatives feasible, this is more of a project management aspect, and not necessarily a design or operational aspect.

Power and propulsion
Power and propulsion should be understood as the optimisation of the efficiency of power conversion and the reduction of power consumption on board. An optimal efficiency in the power conversion can be achieved by considering different power plant configurations for different vessels. Vessels that primarily operate at a single operating point may be optimised for this condition with a diesel engine directly powering the propeller shaft with a fixed pitch propeller without a gearbox to minimise losses. A vessel with a highly varying operational profile may achieve a higher efficiency when opting for a fully integrated electric powerplant with multiple generators, electric motors and a controllable pitch propeller [86, p.103]. Savings may range from 1% to 40% [18]. This category also includes various power saving devices both for the onboard power consumption as for the propulsive power. Such devices may include LED lighting, waste heat recovery, variable frequency drives, twisted rudders and others. Finally the energy consumption is also influenced by operational aspects. Optimising operations and sailing at lower speeds has a large potential to reduce energy consumption. These are all options which DMO is actively pursuing. The CSS for example will have LED lighting and twisted rudders installed [73]. Especially the example of LED lighting is a quick win, as this also reduced the need for on board cooling [94]. Previous research into the reduction of energy consumption by optimising operations has been performed by Jelle Bos [17]. In this thesis attention will be given to the variety of power plant configurations that are available since this is closely connected with the potential of different alternative fuels.

Fuels and alternative energy sources
Fuels and alternative energy sources pertain to the use of non-fossil fuels to reduce $CO_2$ emissions. This can be through the use of energy sources that contain no carbon altogether such as ammonia or hydrogen, or through the use of fuels which have a lower emission throughout all the stages in their lifetime (production, transportation, combustion). The concept of well-to-wake (or well-to-wheel in the automotive industry) takes the total footprint of the fuel into consideration and thus includes the production and transportation [55][18]. It appears that a $CO_2$ emission reduction between 25% and 85% is achievable depending on the method of production and transportation [18]. Other alternative energy sources such as wind and solar power may reduce the fuel consumption by 1-50% and 2-12% respectively [18]. By using fuel cells instead of combustion engines, another 2-20% reduction could be achieved, and solar power may cut down fuel use by anything from 2-12% while wind power may decrease the GHG emissions by anything between 1 and 50% depending on the route and conditions [18]. The DMO has already started studies on the mixing of marine diesel with bio-fuel [19], and the subject of alternative fuels and conversion methods is also the prime focus of this project.

There exists a vast number of different fuels, all with different applications, different properties and different sources. Therefore, it is not always easy to come up with a straightforward list of 'alternative energy carriers' and their properties. When aiming for a reduction in fossil fuel consumption one alternative fuel may be promising, while another can be more beneficial when trying to reduce GHG emissions. Table 3.1 attempts to present a simplified view of various fuels with their associated source and converter. In reality there are often different fuel pathways for one fuel [32]. In order to consider the effects a certain fuel will have on $CO_2$ emissions or cost a life cycle assessment needs to be performed. A life cycle assessment of energy carriers is often referred to as the "Well-to-Wheel Analysis" which assesses all the energy used and emission generated during the various production, transportation, and conversion steps throughout its lifetime [3]. The equivalent term for vessels would be the "Well-to-Wake" [55] [32] or "Well-to-Propeller" analysis [24]. A further division may be made between the Well-to-Tank and the Tank-to-Wake portion of the assessment. The former refers to all emissions and efficiencies pertaining to the production and transportation, while the latter refers mainly to the fuel economy of the vehicle itself [3]. For one specific fuel, the Well-to-Tank emissions may differ greatly depending on the pathway. Hydrogen for example may be synthesised from water through electrolysis using renewable energy making the resulting fuel almost completely carbon free, but hydrogen can also be obtained by reforming fossil fuels with a variety of different processes , or even through biological transformation[2] of bio-mass [2]. All these processes require different feedstocks and sometimes additional energy for the conversion ultimately leading to varying Well-to-Tank emissions and efficiencies.

Weather routing and scheduling

The last category of measures which reduce the energy consumption and GHG emissions is that of weather routing and scheduling and pertains to the reduction of fuel consumption through smart voyage planning taking into consideration the wind, sea-state and current directions. This is implemented in the RNLN when vessels are on transit to save on fuel cost and reduce transit times. When performing missions it is not always possible to avoid certain areas or weather systems because of constraints on the operational area [74].

After treatment

In order to reduce fuel related emissions (emissions resulting from complete combustion) and cylinder process related emissions (emissions resulting from incomplete combustion) a variety of strategies can be used [84].The three main strategies are those of fuel pre-treatment, engine modifications and exhaust gas treatment [84], or: before-, during- and after combustion techniques [59]. The selection of an alternative fuel leading to a lower emission has already been considered, and engine modifications fall largely outside the scope of this project which leaves exhaust gas treatment. Exhaust gas treatment systems, commonly referred to as scrubbers [59], can be used to reduce levels of $NO_x$, $SO_x$, particulate matters, and sometimes $CO$ and unburnt hydrocarbons depending on the type. The most popular are wet scrubbers using water and selective catalytic reduction systems using urea or $NH3$ [84]. Since the RNLN uses a low sulphur fuel, selective catalytic reduction (SCR) aimed at $NO_x$ emission reduction is the only after treatment system used on board RNLN vessels.

### 3.1.1. Current efforts at DMO

Apart from the above conceptualization that was made in the literature, DMO has also identified components that are necessary in order to achieve the goals set by the OES [37]. In figure 3.1 the three wider categories as identified by the DMO are shown. These are applicable not just to ships but to organisations and their equipment in more general terms. The present project mainly pertains to the physical component when considering these three categories.

For this project, solutions pertaining to the categories of *Power and propulsion* and *fuel and alternative energy sources* will be considered. For the first of these two categories, the emphasis will be on the configuration of the powerplant, and not so much on the application of energy saving devices for the hotel and systems load. Although this is certainly a subject in which the DMO is interested it falls outside the scope of this project. The use of alternative fuels and energy carriers is of course closely related to the layout of the power plant since different energy carriers often utilize different systems for the energy conversion [31].

[2]Transformation of bio-mass into hydrogen by bacteria.

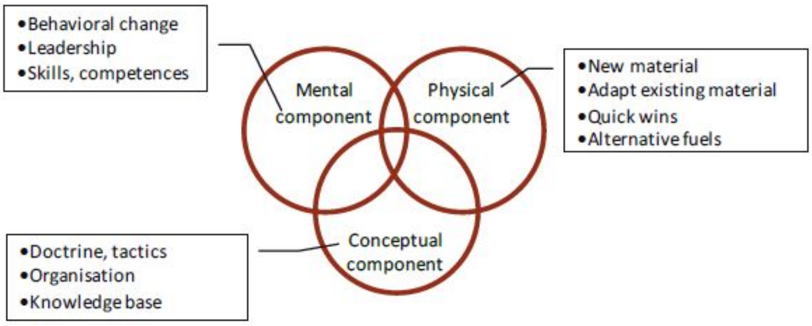


Figure 3.1: Different components of the implementation of the OES [37]

## 3.2. Energy sources & fuel production methods

The fuels or energy carriers that are used today mostly originate either from a fossil or a renewable source. Although fuels derived from biomass can also be considered as a renewable resource these are considered separately here. The term renewable energy is often used to refer to energy generated as electricity.

Table 3.1: Different sources and carriers of energy

| Source | Carrier | Type | Converter |
|---|---|---|---|
| Fossil | HFO<br>MDO<br>LPG<br>LNG | | Internal combustion engine |
| Biomass | Advanced biofuels<br>Bio alcohols | | Internal combustion engine |
| Renewable | Hydrogen<br><br><br><br>Ammonia<br>Syngas<br>Synthetic alcohols<br>Batteries | Liquid<br>Compressed<br>Cryo-compressed<br>Material based<br><br>(other synthetics)<br><br>Lithium ion<br>Lead acid | Internal combustion engine<br>Fuel cell<br><br>Electrical machine |
| Nuclear | Uranium | | Reactor + steam turbine |

### 3.2.1. Fossil fuels

Fossil fuels are all the hydrocarbon fuels found within the earth's crust that have been formed from dead organic matter over millions of years [47]. This organic matter captured and subsequently stored $CO_2$ millions of years ago, effectively taking it out of the atmosphere. By using these fuels, this $CO_2$ is reintroduced into the atmosphere leading to climate change [47]. Since the primary goal of this thesis is the reduction of fossil fuel consumption, these fuels will not be considered in great detail. Both for the RNLN and the wider commercial shipping sector however it is not possible to change to other fuels on a short term and the role of fossil fuels during this transition therefore has to be acknowledged.

### 3.2.2. Biomass

Biomass is increasingly used as a resource for the production of biofuels which can be used on their own or mixed with conventional gasoline or diesel [10] [3]. Since atmospheric $CO_2$ is captured in the biomass during its production the Well-to-Wake $CO_2$ emissions can be up to 80% [18] lower than they would be for a comparable fuel that absorbs no atmospheric $CO_2$. Various biofuels do have combustion properties similar to existent liquid fossil fuels and can therefore often be used in the same engine with minimal alteration. This is called a drop-in fuel or drop-in solution. In many cases, biofuels are mixed with regular diesel to achieve a reduction in GHG emissions while maintaining the necessary fuel characteristics for operation such as combustion characteristics, density, and specific energy. Of the different products on the rightmost column of the figure HVO and fatty acid methyl ester (FAME) are the most likely candidates for biofuel at the moment and will be further considered. In general a distinction is made between first, second and third generation biofuels. First generation biofuels are produced from edible food sources and therefore compete for land with food meant for human or animal consumption. Given the rising pressure on productive land this is not seen as a sustainable solution over the long term as it may drive up food prices and lead to other problems and challenges associated with large scale monoculture agricultural practices such as deforestation, soil degradation, and a reduction in biodiversity. Second generation biofuels are produced from food waste and therefore more sustainable [10]. Currently, the availability of non-edible vegetable oils is not sufficient yet for the production of all biofuel, but the production capacity has been rising [10]. Third generation biofuels will be produced from algae or alternative sources such as. These processes are currently in development and have not yet reached an industrial production capacity [24]. It must be noted that the processes of reforming feedstock into fuel can often be energy intensive, and it goes without saying that the energy source used for this purpose has an enormous influence on the well to tank emission of the fuel.

### 3.2.3. Renewable energy

Renewable energy refers to all energy sources that do not directly depend upon a scarce resource which is consumed in the process [79]. Important sources of renewable energy are solar, wind, thermal and hydro (biomass is often also considered to be renewable). One of the disadvantages of renewable energy in general, and wind and solar energy specifically is the irregularity of production [2]. Since the energy production is dependent on weather conditions it does not always match with the demand [79]. It is expected that power to gas (P2G) will play an important role in the storage of renewable energy. Although primarily intended to store energy for the electricity network on shore, P2G also makes it possible to use renewable energy on marine applications. The production of the fuel used does have implications for degree to which the fuel is sustainable. Reforming of liquefied natural gas (LNG) still releases fossil carbon into the atmosphere and is thus not a ’clean’ hydrogen solution.

## 3.3. Energy carriers

A selection of technologies which might partially replace F-76, the NATO designation for the low sulphur marine diesel oil used, must be determined.

### 3.3.1. F-76

The marine diesel oil used by the RNLN and other NATO partners has to comply with the NATO standardisation agreement (STANAG) 1385 which dictates limits for the various characteristics of the fuel. These limits, and the actual determined values of a laboratory analysis performed on a sample of F-76 fuel obtained from the Royal Naval College (KIM) in Den Helder are shown in table 3.2 [65] & [19].

| Description | STANAG | | Measured | Unit |
|---|---|---|---|---|
| | Min. | Max. | | |
| Content synthetic components | - | 50 | 0 | $\% \, v/v$ |
| Density (15 C) | 800.0 | 880.0 | 847.4 | $kg/m^3$ |
| Sulphur content | 0 | 1 | 0.05 | $\% \, m/m$ |
| Viscosity, kinematic (40 C) | 1700 | 4300 | 2784 | $mm^2/s$ |
| Flashpoint closed cup | 60 | - | - | $°C$ |
| Cetane number | 40 | - | 45.1 | - |
| Cetane index | 43 | - | | - |
| Gravimetric specific energy | - | - | 42,580 | $MJ/kg$ |
| Volumetric specific energy | - | - | 36,082E3 | $MJ/m^3$ |

Table 3.2: F-76 standard- and measured characteristics

### 3.3.2. HFO

As mentioned earlier in the section on fossil fuels their application is of limited use for this project. Furthermore, although HFO is used widely in the commercial shipping sector the RNLN does not use HFO in its vessels as it does not comply with the standards of standardization agreement (STANAG) 1385 [65]. HFO will thus not be considered further.

### 3.3.3. LNG

LNG is perhaps the greenest fossil fuel and can as such be a good choice to adhere to national and international regulations. LNG consists mainly of methane which has a relatively low carbon content compared to other fossil fuels, and thus has a low specific $CO_2$ emission [32]. Storage of LNG however remains difficult as its boiling point at atmospheric pressure lies at -163 °C making storage onboard more difficult. For this reason, the majority of LNG powered vessels are LNG carriers on which the necessary systems and safety precautions are already present. Given that methane itself is a potent greenhouse gas the GHG emissions vary depending on the system design. Incomplete combustion may lead to uncombusted LNG being expelled together with the exhaust gas. This is referred to as methane slip and can lead to a contribution of GHG emissions for LNG powered vessels. The total GHG emissions for LNG powered vessels could be roughly 15% lower than that of a reference diesel engine, but bad design could lead to higher GHG emissions [97]. A large benefit of LNG powered vessels is the potential to decrease other emissions. $NO_x$ emissions are generally 75% lower, particulate matter emissions can decrease by a factor 10, and $SO_x$ emissions can be a 100 times lower than the limit for emissions control areas [97]. It is however, still a fossil fuel and as such cannot help achieve a significant reduction of fossil fuel consumption which is the goal stated in the DEOS. Its $CO_2$ reduction potential is also limited for the same reason [24]. Because of this limited potential to achieve both the GHG and the DEOS goals that were set, LNG will not be taken into further consideration in this thesis.

### 3.3.4. Hydrogen

Hydrogen can be synthesised from water using the process of electrolysis or by several different reactions involving hydrocarbons (these are further explained in section 3.4.5). It can be stored as super cooled liquid at -253 °C, or as a pressurised gas. In both forms the spherical or cylindrical tanks combined with the cooling or pressurising system greatly lower the actual specific energy of the system as can be seen in figure 3.6. The low volumetric energy density of liquid and compressed hydrogen make it unsuitable as a logistic fuel [2]. Efforts into storage of hydrogen in an intermediate form are also being pursued to deal with these issues Most of these intermediate forms do need reforming before being able to use them as a fuel. As discussed earlier some high temperature fuel cells can perform this reforming internally. Generally however, the reforming steps will add to the complexity of the system necessitating extra equipment lowering the energy density of the system and the efficiency [2].

### 3.3.5. Ammonia

There has been some interest into the use of ammonia as a marine fuel in recent years. Ammonia can be used directly as a fuel for combustion engines, but can also be considered for application in fuel cells with when reforming steps are taken [28]. The storage of ammonia is either pressurized at 10 atmospheres at a temperature below 25°, or at one atmosphere and cooled below a temperature of -34°. The storage conditions add considerable barriers to the applications of ammonia as a fuel on any vessels that do not have the installations for storage yet. As such, the application of ammonia as a fuel has so far been limited to ammonia carriers [28]. One of the advantages of ammonia is that there is a considerable production capacity worldwide, although only a small part of this ammonia is derived from renewable sources [32].

Table 3.3: Characteristics of liquid ammonia

| | Density | Kinematic viscosity | Volumetric specific energy | Gravimetric specific energy | Sulphur content | Auto-ignition temperature | Cetane number |
|---|---|---|---|---|---|---|---|
| | kg/m3 | mm2/s | GJ/m3 | MJ/kg | ppm | C | - |
| (de Vries, 2019) | 682.8 | - | 12.7 | 18.6 | 0 | 651 | - |

### 3.3.6. Hydrotreated vegetable oil

HVO is a biofuel which is produced by a chemical reaction between lipoids and hydrogen which removes the oxygen from the fuel producing a biofuel which is stable in the long term [32]. The properties of HVO are similar to that of normal diesel, although the density is somewhat lower. Combined with the lower gravimetric specific energy this leads to a somewhat lower volumetric specific energy than F-76, but still comparable or slightly higher than that of FAME. HVO also has more beneficial flow properties and is again, much more stable than FAME [82]. The greatest disadvantage of HVO is its relatively poor lubrication properties compared to the measured value of F-76, although it does still fall within the ranges specified by STANAG-1385. HVO is a liquid at atmospheric pressure at a temperature of 20 °C and can thus be suitably stored and pumped by existing infrastructure on board and on land without additional measures.

Table 3.4: Characteristics of HVO diesel

| | Density | Kinematic viscosity | Volumetric specific energy | Gravimetric specific energy | Sulphur content | Flashpoint | Cetane number |
|---|---|---|---|---|---|---|---|
| | kg/m3 | mm2/s | GJ/m3 | MJ/kg | ppm | C | |
| EN15940 | 765-800 | 2-4.5 | | | <5 | >55 | >70 |
| (Labeckas, 2019) | 780 | 2.92 | 34.2 | 43.8 | <1 | 79.5 | 78.9 |
| (Boumeester, 2017) | 781 | 2.905 | 34.2 | 43.8 | 1 | 78.5 | 73.9 |

### 3.3.7. Fatty acid methyl ester

Biodiesel is a popular term for a fuel composed of FAME. It is produced by the transesterification of fatty acids which can be won from feedstocks or animal fats by reacting them with methyl or ethyl alcohol [10]. Many of the characteristics of FAME biodiesel are similar to petrodiesel and as such it can be blended with diesel without major engine modifications. The lubrication properties of biodiesel are slightly better than those of normal diesel, resulting in a somewhat higher efficiency. Other characteristics such as flashpoint, density, specific energy and cetane number are generally comparable to those of normal diesel. With regards to emissions, biodiesel slightly outperforms diesel in almost every aspect. The absence of sulphur in the fuel reduces $SO_x$ emissions and the more complete combustion also reduces particulate matter and $CO$ emissions. Only $NO_x$ emissions are slightly higher than in normal fuels [3]. One of the major challenges with FAME is its storage stability which is relatively poor. Even in normal diesel with a small percentage of FAME mixed in the quality may deteriorate in a matter of months, although this process can be significantly slowed by the use of additions [11].

Table 3.5: Characteristics of FAME biodiesel [67]

| | Density | Kinematic viscosity | Volumetric specific energy | Gravimetric specific energy | Sulphur content | Flashpoint | Cetane number | Oxidation stability at 110 C |
|---|---|---|---|---|---|---|---|---|
| | kg/m3 | mm2/s | GJ/m3 | MJ/kg | ppm | C | | |
| EN14214 | 860-900 | 3.5-5 | 30-31.5 | 35 | - | >120 | >51 | 6 min |
| (Ong, 2013) | 838-879 | 3.91-6 | 33.9-35 | 40 | 8-14 | 160-191 | 47-58 | 3.5-9 min |

### 3.3.8. Alcohol fuels

Ethanol and methanol have long been recognised as viable energy carriers for various applications [3]. Of these two alcohols, methanol chemically has the shortest chain and therefore the highest H/C ratio leading to relatively low $CO_2$ emissions. When methanol is produced from renewable sources, the well to wake emission becomes almost negligible. Methanol can be produced by a reaction between $CO_2$ and hydrogen. Methanol is a liquid under normal circumstances and as such is relatively easy to store and transport using existing infrastructure. Methanol does have some significant disadvantages though. It is very toxic and needs additional safety measures to mitigate the associated risks. Methanol is also a very low flashpoint fuel which can have consequences for the survivability of the vessel. The low flashpoint means that the fuel must be carefully isolated from any ignition sources which will be very costly on some vessels. Furthermore, the energy density of methanol is much lower than that of F-76 or different other alternatives. Both ethanol and methanol have properties similar to diesel and are sometimes used as an additive to improve the cetane number [3]. Both fuels however have a negligible sulphur content, an almost non-existent particulate matter emission and a much lower $NO_x$ emission than F-76 [24].

When considering the longer alcohol chains butanol is the most likely candidate to be used as a fuel. In table 3.6 the difference in energy densities between the different alcohols can easily be seen. Although not quite the same as F-76 or some other biofuels, butanol has a relatively high energy density for an alcohol fuel. Some of the disadvantages of the shorter chains are also overcome: Butanol does not mix with water which overcomes corrosion problems and storage stability [88]. Butanol however is currently not as economically competitive as ethanol or methanol [88].

Alcohol fuels are not only used as fuels in themselves, but can also be used for the purpose of esterification [10]. This reaction is used to convert vegetable oils into the FAME bio fuel that was discussed earlier which results again in a higher energy content.

Table 3.6: Characteristics of different alcohol fuels [51] [3] [32] [10] [88]

| | Density kg/m3 | Kinematic viscosity mm2/s | Volumetric specific energy GJ/m3 | Gravimetric specific energy MJ/kg | Sulphur content ppm | Flashpoint C | Octane number - | Boiling point C |
|---|---|---|---|---|---|---|---|---|
| Ethanol | 785 | 1.2-1.5 | 21.09 | 26.9 | 0 | 11 | 109 | 78 |
| Methanol | 792 | 0.6-0.75 | 15.8 | 20.0 | 0 | 12-20 | 108.7 | 64 |
| Butanol | 810 | 3.6 | 26.9 | 33.2 | 0 | 35 | 98 | 117.25 |

### 3.3.9. Batteries and capacitors

The potential of batteries has been steadily growing over the past decades. As of yet, batteries are still very costly and their specific energy is often still very low when compared to other energy carriers. Batteries as primary energy carriers are not yet viable on vessels that have a larger required range or an endurance of more than one or two days [37] [32]. Batteries can be important in a role of temporary energy storage on board however. Battery based energy storage can help dampen fluctuations in either energy demand when the load response of the primary power converters is not quick enough as may be the case in various fuel cells and some diesel engines depending on the configuration. Batteries can also facilitate periods of silent operation without diesel generators operating as is already shown by many diesel electric submarines. (Super)Capacitors are also starting to play an increasingly important role in on board energy storage. The high specific power and the low charge and discharge time make the capacitor a suitable storage medium for applications where a high power output is required for very short durations. Typical examples in naval vessels are direct energy weapons which primarily the US navy is testing. Directed energy lasers and rail guns require high currents for often a short duration of time (often in the range of seconds). Figure 3.3 illustrates the relation between energy density and power density. The diagonal lines indicate how long a system can operate at its rated power [52]. The load response of certain power supplies is also very different. The load response (the speed with which a system can react to a change in the load) of some fuel cells can be in the order of hours or minutes. Generators or combustion engines which are not shown here have a load response in the order of minutes to seconds. Batteries can generally react within seconds and the quickest load response is achieved with super conductors.

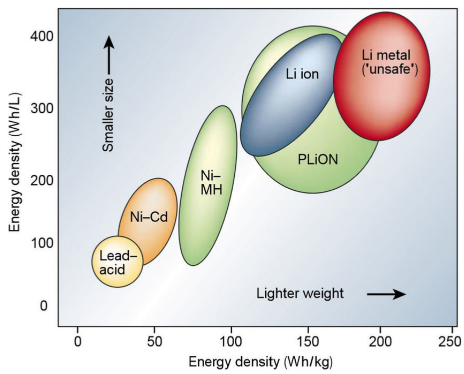


Figure 3.2: Energy density of batteries [29]

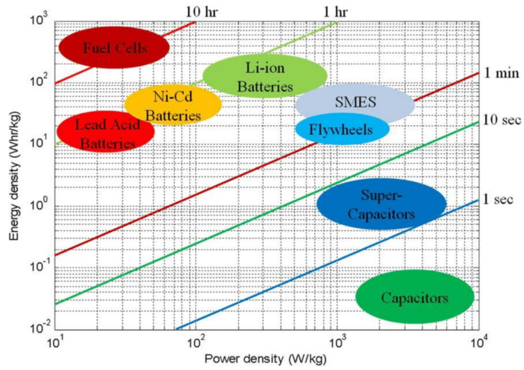


Figure 3.3: Energy and power density of storage systems [29]

### 3.3.10. Wind and solar power

Renewable energy can be stored via some of the energy carriers that have been discussed above, but solar and wind power can also be used more directly onboard vessels. In the commercial shipping sector there are various examples of wind assisted propulsion using rigid sails, kites or flettner rotors. Some ships also use solar power to provide part of the electricity needed on board. These options do have their limits however and are not always viable for naval vessels. Wind assisted propulsion can reduce the fuel consumption up to 50%, but the benefit can also be as low as 1% [18]. Of course this depends on the weather encountered and the route taken. When sailing across the ocean it is often possible to plan the voyage in such a way that wind assisted propulsion is effective, but when such freedom isn't available it becomes a liability. The equipment for wind assisted propulsion also has a significant footprint and can take up valuable deck space and increase the vessels radar cross section. Solar power also takes up a lot of deck space. These constraints, and the unreliable characteristic mean that both wind and solar power pose a risk to the operational continuity on naval vessels wont be considered further.

### 3.3.11. Nuclear

The application of nuclear power has a very high potential for both the reduction of GHG emissions and the reduction of fossil fuel use. The MoD however has chosen not to pursue this option in the near future for several reasons. The cost associated with the acquisition and maintenance of nuclear systems is very high. A 2011 estimation for the US navy calculated that a nuclear powered fleet would only be more cost effective at an oil price of US$120 per barrel [34]. Furthermore, the technical skills and knowledge to maintain and repair, and possibly modernise nuclear powered vessels are not present within the DMO or RNLN. This means that the MoD has to relinquish a large degree of its independence on this matter. The benefits of nuclear power also become more apparent the larger a vessel becomes, and the size and displacement of RNLN vessels is relatively small in comparison to vessels of larger (nuclear) blue water navies. In addition to the technical and economic barriers to the adoption of nuclear powered naval vessels, the societal and political views also make nuclear power an unlikely candidate. Particularly the incident in Fukushima in 2011 has further reduced the support that nuclear energy has amongst the general population [24]. The combination of these factors is enough reason for the Ministry of defence not to pursue the acquisition of nuclear powered vessels. Therefore this option will not further be considered in this review.

## 3.4. Energy converters

The diesel engine has for a long time been the workhorse of the maritime sector. Besides the reciprocating engine the gas turbine has also proven itself in many applications and is especially popular for its high power density. Besides these two combustion engines the fuel cell seems to be one of the most promising energy converters for the future. These converters are all used to convert chemical energy into either mechanical or electrical energy. When considering powerplant configurations, the electric motor should also be included as this is the primary way to convert electrical into mechanical energy. This section will shortly examine the different technologies available and review their viability for naval applications. Some attention will also be given to various options for hybrid configurations.

### 3.4.1. Diesel engine

When mentioning a diesel engine we normally refer to the reciprocal or piston internal combustion engine. The technology behind the diesel engine is highly developed and there is a large variety in models for various points of operation and a large range of powers (500-80.000 kW), shaft speeds (80-3.500 rpm) and efficiencies (35-60%). The diesel engine is a relatively simple engine and as such is easy to maintain and has a high reliability. This also allows it to be relatively insensitive to fuel quality. Another main advantage is that it can have a high fuel efficiency for a combustion engine. The largest disadvantages of the diesel engine are the low power density and the high specific emissions [86]. The typical torque speed characteristic of a diesel engine can be seen in figure 3.4. One of the disadvantages of a diesel engine is that operation outside of the design point often severely inhibits its performance. At low engine speeds the engine has a low torque which restricts quick acceleration or deceleration. This can be a problem especially when using diesel direct drive propulsion. The application of a gearbox or controllable pitch propeller solves this problem to a great extent while improving overall efficiency at the cost of a lower peak efficiency in the design point and increased complexity. Typical power densities for medium speed 4 stroke diesel engines range from 0.05 $MW/m^3$ for engines with and rpm of 400 to 0.15-0.2 $MW/m^3$ for engines with and rpm up to 1200 [86]. Typical power densities for modern diesel engines range from 45 to 71 W/kg and from 32 to 55 W/L [52].

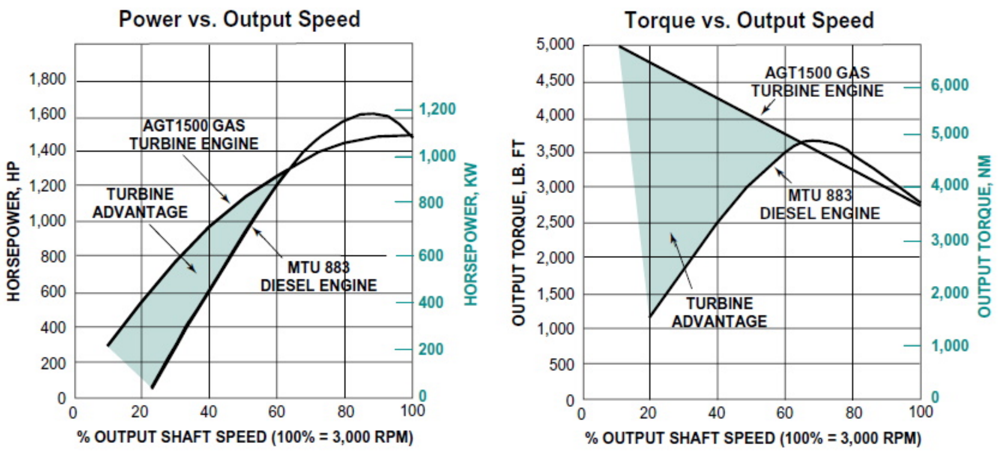


Figure 3.4: Torque-speed and power-speed characteristics of a diesel engine and a gas turbine compared (add reference)

### 3.4.2. Gas turbine

The gas turbine is a rotating internal combustion engine which is often used in situations where a high power output is needed but only limited space is available. The gas turbines high power density makes it well suited to these circumstances. Disadvantages of the gas turbine are the lower fuel efficiency when compared to the diesel engine and the requirement for a higher quality fuel. Gas turbines have been extensively used in naval applications. The limited space in frigates has often lead to the installation of diesel engines for transit and gas turbines for sprint speed applications. Typically the power for a gas turbines ranges from 6.000 to 26.000 kW. Another big advantage of the gas turbine in relation to the diesel engine is the low $NO_x$ emission due to a different combustion process [86]. As can be seen in figure 3.4 the gas turbine also offers great potential for quick acceleration as it has a high torque output at low shaft speeds. Typical power densities for gas turbines range from 100 to 1200 W/kg and from 45 to 450 W/L [52] . The large discrepancy between the values can be partially attributed to the construction differences between simple and complex cycle gas turbines, where in naval applications the simple cycle turbines are often used for their higher power density, at the cost of lower fuel economy [86].

### 3.4.3. Fuel cells

Compared to internal combustion engines fuel cells are a relatively novel technology that has been making large steps in maturity over the past years. Still much progress can be made and in some cases must be made before the technology can successfully be applied at a large scale and in marine applications. Contrary to internal combustion engines fuel cells convert the chemical energy stored in fuel into electrical energy instead of mechanical energy. The primary advantages of fuel cells are their high theoretical efficiency, much higher than that of an internal combustion engine, and the lack of mechanical parts. The lack of mechanical parts means that there is little wear and reliability and maintenance should become less difficult and less costly over the longer term. Some of the disadvantages of the fuel cell can be attributed to their relatively low technology readiness level (TRL). Some of the problems with the adoption of fuel cell technology currently have to do with the relatively slow dynamic behaviour and the limited experience in on board applications [24]. The working principle of a fuel cell can easily be described with the figure[3] below (figure 3.5). Fuel and oxygen are channelled through the cathode and anode that are separated by an electrolyte. These fuel and the oxygen then react and ions are exchanged over the electrolyte. This induces a voltage difference between the cathode and anode across which a load can be connected. Although the basic principle is similar for all types of fuel cells many different types can be distinguished. The main differences lie in the electrolyte which is used. Different electrolytes also lead to other operating characteristics such as operating temperature and the fuel types that can be used. An overview of different fuel cell types that seems promising for marine applications is given in table 3.7.

[3]Depending on the type of fuel cell the flow fuel, by-products, and charged particles can be different.

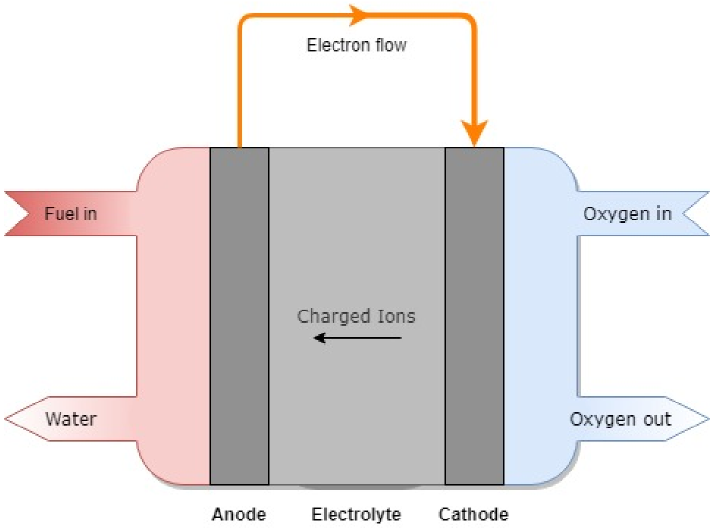


Figure 3.5: Functioning of a fuel cell

Table 3.7: Characteristics of several types of promising fuel cells [31] [52]

| Type | Fuel | Poisonous substances | Operating temperature | Internal reforming | Efficiency | Power density estimated W/kg | W/L |
|---|---|---|---|---|---|---|---|
| HT PEMFC | H2 | S, CO (>10ppm) | 65-85 | No | 35-60 | 250-1000 | 300-1550 |
| LT PEMFC | H2 | S, CO (>3%) | 140-200 | No | 35-60 | | |
| PAFC | H2 | S, CO (>3%) | 140-200 | No | 35-45 | - | - |
| MCFC | H2, CO | S | 650-700 | Yes | 40-55 | 7.75-25 | 1.75-20 |
| SOFC | H2, CO | S | 500-1000 | Yes | 45-60 | 8-80 | 4-32 |

The fuel that is used by the fuel cells is pure hydrogen in the majority of the cases and reforming of the fuel is necessary before the fuel can be used in the fuel cell. Internal reforming of the fuel at the anode can take place in the fuel cells with a higher operating temperature such as the solid oxide fuel cell [52]. Internal reforming can pose problems to the fuel cell however, leading to a lower reliability. For this reason it is common to apply on board reforming of fuels such as ammonia, diesel, bio-diesel, LNG and methanol [52].

### 3.4.4. Electrical machines

When using a partially or completely electric propulsion solution electric machines are often an integral part of the power plant. Electrical machines play a role both in the generation of electric power in the form of generators and as converters of electrical power to mechanical power when used as a motor. Depending on the type of electrical machine different torque speed characteristics can be obtained and with modern power electric circuits it is possible to obtain both an efficient operation at the design point, and a high torque at start up [80]. Due to this flexibility it is possible to operate a system efficiently in many different off-design or part-load operating points [86].

### 3.4.5. Fuel (pre-)reforming

Most of the fuel cells that are considered to be viable options for marine applications run on hydrogen gas. Depending on the type of fuel cell this fuel supply needs to be of a high purity as was discussed in section 3.4.3. A steady supply of high purity hydrogen can be achieved by using liquefied hydrogen as the storage medium, but its low energy density has considerable disadvantages. Another option to achieve said supply of hydrogen is to reform other hydrogen carriers through one of several reforming processes that can occur in a separate system (pre-reforming) or inside the fuel cell stack direct internal reforming (DIR). The most common of these processes are auto-thermal reforming (ATR), partial oxidation (PO) and steam reforming (SR) of which the latter is the most efficient [60]. In the steam reforming process the fuel is introduced to a reaction vat together with steam, heat and a catalyst to produce hydrogen and carbon monoxide [12]. Depending on the feedstock used there are slight differences in the process. The ideal temperature, pressure, steam/fuel ratio and catalysts are all differ per feedstock. It appears that the alcohol fuels (i.e. ethanol, methanol, butanol) have some advantages such as lower carbon depostition and reaction temperatures compared to other hydrocarbons [60]. Especially methanol is noted to be an easily convertible feedstock that can be reformed at much lower temperatures than other feedstocks (300°C as opposed to >500°C)[69] and thus result in a higher thermodynamic efficiency. Besides the different reaction temperatures different feedstocks also have different optimal pressures, steam/fuel ratios and other catalysts. Although the basic chemical reaction is the same, the conditions under which it performs optimally are quite different. Different system configurations are also possible depending on the origin of the heat and steam provided [90]. DIR has the added benefit of using the heat and steam generated in the fuel cell itself, with external reforming this heat and steam may partially be sourced from the fuel cell but may also be provided externally. As an effect the system efficiency of a fuel cell without external pre-reforming is higher. A fuel cell without pre-reforming however is more prone to degradation due to internal stress from thermal gradients, carbon depositions, and uneven current distributions [52]. The requirement for a pre-reformer may negate the perceived benefit of using certain types of fuel cells as the system efficiency may drop to 40% which is similar to internal combustion engines (ICEs) [52].

### 3.4.6. Configurations

The varied operational profile of most naval vessels has often lead to the application of hybrid configurations. Since turbines and diesel engines can perform poorly under part load [86] such a hybrid configuration can offer more flexibility. When comparing an optimised hybrid configuration to a conventional diesel direct drive, fuel savings of up to 40% can be achieved [18]. Oftentimes one or more diesel engines are chosen for cruising operation and one or more gas turbines are fitted for higher speed operation. With the addition of fuel cells and improving battery technology more different hybrid configurations can be considered. When applying these hybrid configurations, the less advantageous properties of one system may be balanced by a different system in another operation point. Besides the power generation, the power transfer to the vessels propeller also has different possible configurations ranging from a direct drive to fully electric propulsion, or again a combination of both. Conventional layouts rely on combinations of diesel engines, diesel generators, gas turbines and electrical machines. Alternative configurations with steam turbines also exist, but are not common since the heating of steam boilers is usually inefficient or done with nuclear power. Due to the low efficiency a conventional steam boiler will not be considered and a more in depth analysis of the potential of nuclear energy is given in section 3.3.11. Configurations with fuel cells are relatively novel but can be implemented in different ways. The fuel cell can be used as the primary power generator or in a hybrid solution. Depending on the energy converters and energy carriers selected it may be necessary to include an exhaust gas treatment system in the configuration.

## 3.5. Design influence

Now that a host of different technologies have been considered it has to be analysed how these technologies may influence the operational effectiveness as was considered in the previous chapter. This will be done through a relatively simple trade off analysis that can be seen in table 3.8. As some of these technologies have not been adapted to naval vessels before it is possible that not all effects are considered in this analysis. When new knowledge surfaces the method can remain the same however. This systematic approach makes alterations fairly easy. Since the input for this table is subjective a short justification for some of the choices that are seen in the table will now be given.

### 3.5.1. Energy carriers

The survivability of energy carriers is mainly related to the storage conditions. Fuels that are stored in a pressurised or cooled condition generally pose a larger threat to the vessel itself. These systems are also presumed more difficult to recover. The difference between the different alcohol fuels is based on their hydrofilic characteristics. When in contact with water, ethanol and methanol will become less suitable as a fuel, while this problem is less pronounced with butanol. The manoeuvrability is generally not influenced by the energy storage, but more by the conversion method and the configuration. Volume and displacement of the fuels are dependent on the gravimetric and volumetric energy densities of the system. Logistics points to the ease with which the fuel can be absorbed into existent logistical

Table 3.8: An initial estimate of how different energy technologies influence technical capabilities

| | Carriers | | | | | | | | | | Converters | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F-76 | LNG | Hydrogen | Ammonia | HVO | FAME | Ethanol | Methanol | Butanol | Batteries | Diesel | Turbine | Fuel cell | Electic motor |
| Survivability | | | | | | | | | | | - | - | + | + |
| Susceptibility | Depends on converter | | | | | | | | | | - | - | + | + |
| Acoustic | | | | | | | | | | | – | - | ++ | + |
| IR | | | | | | | | | | | - | - | - | + |
| Vulnerability | ++ | - - | - - | - - | ++ | ++ | - | - - | + | - | + | - | - | + |
| Recoverability | ++ | - - | - - | - - | ++ | +- | - | - - | + | - - | - | - | ++ | +- |
| Mobility | Depends on converter | | | | | | | | | | + | ++ | - | + |
| Top speed | | | | | | | | | | | + | ++ | - | + |
| Acceleration | | | | | | | | | | | + | ++ | - | ++ |
| Manoeuvrability | | | | | | | | | | | Depends on configuration | | | |
| Volume | ++ | - - | - - | - - | + | + | - | - | +- | - | + | ++ | +- | + |
| Displacement | ++ | - - | - - | - - | + | + | - | - | +- | - | + | ++ | +- | + |
| Logistics | ++ | - - | - - | - - | ++ | + | + | +- | ++ | | Depends on fuel | | | |
| Maintenance | ++ | - - | - - | - - | + | + | - | - | + | +- | + | - | ++ | + |
| Cost | Not in scope | | | | | | | | | | ++ | - | - | + |

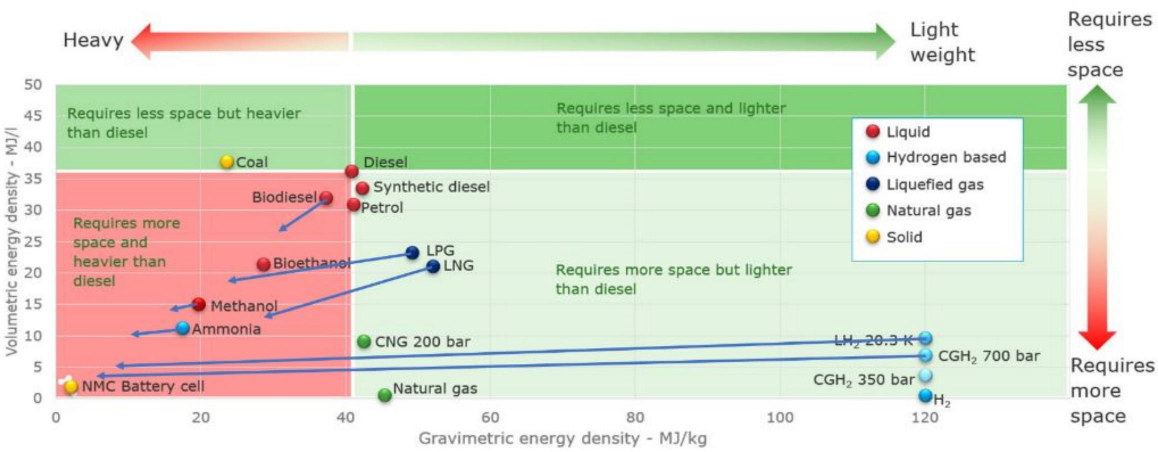


Figure 3.6: Gravimetric and volumetric energy densities of different marine fuels [32]

infrastructure. The influence on ease of maintenance of fuels is mainly dependant on the need for auxiliary systems but also on their lubricity. Likely one of the largest influences the energy carrier has is related to its energy density. Figure 3.6 clearly illustrates how energy densities of different fuels vary. In the figure the fuel itself, but also the fuel including its storage system is included as some energy carriers require more elaborate storage systems which utilise more space. This for example is the reason that the gaseous fuels, which can also be observed in figure 3.6 to have a low energy density, have received a negative rating in both volume and displacement which affects the potential range for a vessel. This would not be a problem for a vessel which remains in the harbour or only goes on short voyages, but becomes more problematic when a higher endurance is required.

### 3.5.2. Energy conversion

The survivability of energy converters firstly is influenced by their signatures. The pressure/hydrodynamic signature should not be influenced by the chosen energy conversion as in this stage it is assumed that the hull shape or the vessel velocity does not change. The radar cross section also does not change so the most important signatures are the acoustic signature and the infrared signature. The acoustic signature of the diesel engine with its reciprocating parts is of course the worst, followed by the gas turbine. The fuel cell has hardly any acoustic signature, apart from that created by the fuel pumps and the electric motor is also relatively silent. The IR signature of diesel engines, turbines, and fuel cells is expected to be in the same order of magnitude. Diesel engines and gas turbines both produce hot exhaust gas, but this can be cooled. For the fuel cell a lot of heat is generated for the reforming process. The consequence that a chosen converter has for the manoeuvrability is dependent on the maximum power and the load response, there are no surprises here. The maintenance on a fuel cell should become much easier as the technology is adapted, while that for a diesel engine, electric motor, and turbine remains the same. The cost of turbines is still relatively high given that they are not used very much. Fuel cells are still costly because they have not been adapted on a large commercial scale in maritime applications yet.

## 3.6. Conclusion

This chapter started with the examination of the available literature on methods aimed at the reduction of GHG emissions. Although relevant for this study as the IMO goals are also listed, this approach is not entirely the same as the approach favoured for the MoD which is aimed at the reduction of fossil fuel consumption. Furthermore, some of the methods for GHG emission reductin used in the commercial shipping sector are not always applicable to naval operations such as weather routing and wind assisted propulsion. The literature regarding the technical feasibility of the application of different fuel types in different engines is however quite complete and is also relevant for naval applications. Various energy carriers and energy converters were considered and their benefits and drawbacks were subsequently applied to the operational effectiveness framework that resulted from the previous chapter. Given the results from the preliminary analysis of the different available technologies a selection can be made with which technologies to continue. Of the energy carriers it seems logical that any fuel which has difficult storage conditions, all the gasses, are no longer considered. Their application on naval vessels would be unpractical and it would not be possible to absorb these into the supply chain. With regards to the energy converters it is quite clear that each converter that is considered so far has its own distinct advantages and disadvantages. These will all be considered further.

# 4 Method & Case Study Selection

In the literature study, it was examined which aspects can be important in the operational effectiveness of a naval vessel and how these aspects may be influenced by different alternative power and energy concepts. As was seen in section 2.1 it is often difficult to draft the complete set of requirements for a complex system without first knowing more about the solution direction. This property of wicked problems and requirement elucidation also means that the general table of properties at the end of the previous chapter is not a satisfactory answer to the main research question. This chapter will examine the way in which the third research question can be answered: *What design changes should be applied to which vessels in order to achieve the perceived goals?* The results from the case studies will also help to answer the fourth sub-question: *What is the influence of these changes?* A method will be presented in which the knowledge from chapter 2 and chapter 3 will be combined to arrive at an actual design that will satisfy the DEOS goals. In order for the solution to be most helpful for the specific problem which the DMO currently encounters it may be helpful to consider two case studies of potential new vessel designs which the DMO will encounter within the timeframe set by the DEOS. As was shortly explained in the introductory chapter in section 1.2 there are essentially two problems in one, and in order to achieve the goals set out by the DEOS two different approaches are needed. The first approach pertains to the alteration of operations and installations of the vessels which are already commissioned, and those which will be commissioned shortly. For the vessels scheduled to be delivered further into the future the possibility to make more radical design changes arises. This chapter will focus on the second approach by setting up an analysis of alternatives for two replacement vessels that may have to be designed in the near future. In the introduction, an estimate for the future fuel consumption of the RNLN fleet was already made. Now that more specifics about the available technologies are known, an estimate of the impact of the application of different fuels can be made. A translation must now be made from the requirements of the fuel consumption of the total RNLN fleet to a requirement for the individual vessels which will be considered in the proposed case studies. In figure 4.1 a prognosis of the fuel consumption of the fleet is given again. The red line in this figure denotes the total fossil fuel consumption under the assumption that vessels commissioned after 2020 will use 20% less fuel than vessels of the same displacement and with the same operational profile from before 2020, and under the assumption that the F-76 diesel will be diluted with 20% HVO. Since it will be difficult and costly to make large design changes to the vessels being delivered up to 2030, these are shown separately as 'new vessels' in the figure. It can subsequently be seen that these vessels alone already reach the allowance of fossil fuel consumption under these assumptions. This means that all vessels that are either updated or delivered after 2030 must have a net 0 fossil fuel consumption.

For the remainder of the case studies, this will be the primary goal. The secondary goals of complying with IMO regulation regarding non-GHG emissions will also be respected. When the design is then finished, it will be analysed whether the goal of reduced $CO_2$ emissions is also satisfied.

## 4.1. Case study subjects

In order to validate the hypothesis that different power & energy concepts will have distinctive design implications for various vessel types two case studies will be performed. This section will aim to explain

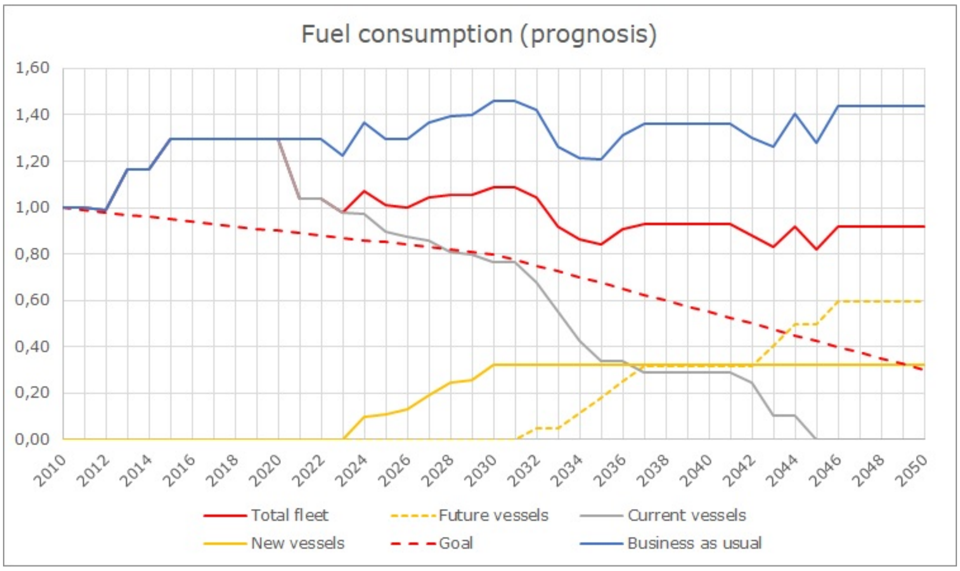


Figure 4.1: Prognosis for RNLN fuel consumption

the method behind these case studies and the reason the studies are performed in this way. Attention is then given to the selection of the cases and the tools that will be used. Finally, an overview of all the necessary information and data for the case studies is presented.

## 4.2. Case selection

In chapter 2 a shortlist of important properties and characteristics of naval vessels designed to perform different missions was created. In selecting vessels for the case study two different aspects should be carefully considered. First, it should be considered which cases will provide the best insight into the design relations which are sought to uncover. If two vessels that largely execute the same missions are selected for a case study it may be difficult to see how the relations vary with different vessel types. It is important therefore to choose two vessels that each have a different mission profile. Secondly, it may be helpful to select the cases based on the utility for DMO in the process of developing a roadmap towards achieving the DEOS goals. This would mean that it is most helpful to select one of the vessels for which the design process is not progressed to a point where alterations would become very costly, but that is nonetheless delivered and commissioned before 2050.

Table 4.1: Replacement schedule RNLN surface vessels

| Project | Planned date |
|---|---|
| Combat Support Ship | 2024-2030 |
| Mine Countermeasure Vessels | 2024-2030 |
| Replacement M-frigates | 2027-2028 |
| Replacement auxiliary vessels | 2025-2034 |
| Replacement Landing Platform Docks | 2030-2032 |
| Replacement Air defence & Command Frigate | 2034-2038 |
| Replacement Joint Support Ship | 2046 |
| Replacement Ocean-Going Patrol Vessels | 2043-2044 |

Table 4.1 shows a list of replacement projects for the coming decades. Apart from the JSS and the OPVs all these projects feature in the 2018 *Defensie Nota* [13]. Since development on the CSS[1], M-frigate and the mine countermeasure vessels (MCVs)[2] is already well underway alterations to the design would be too costly and lead to considerable delays. The replacement of the auxiliary vessels is already being studied but the design direction makes these somewhat less suitable for this study as

[1]The design for the CSS is already finished and the contract for its construction has been signed.
[2]In addition to being in an advanced design stage the procurement process for the MCV was performed by the Belgian MoD and the Netherlands had limited influence on this design.

a host of different vessels will be unified in the same design family [27]. This modularity adds its own difficulty to the design process which makes it an unlikely case for this case study. For the remaining four classes only some preliminary work regarding the requirements specification has been performed but the designs are not yet specific which means that alternative power & energy concepts can still be considered. Since it is not certain that the JSS and OPV will be replaced by a similar concept these are not selected for the case study either. When looking at the first requirement it seems that the remaining two vessels satisfy this requirement very well. In the following subsections, the design requirements and mission profile for these two vessels will be further examined.

### 4.2.1. Landing Platform Dock

Add description from *systeemplan*.In table 4.2 in chapter 2 the only designated mission for the vessel is landing. In reality, this is somewhat more nuanced though. The landing platform docks (LPDs) are amphibious assault/transport ships designed to support marines and helicopters in their operations close to shore. The LPDs therefore need to have a large transport capacity for landing craft, personnel, helicopters and other equipment. The vessel is designed to operate in medium intensity conflict under the protection of frigates or other warships but also has self-defence capabilities. The vessel is also well suited for lower intensity conflict, humanitarian relief operations and command roles.

### 4.2.2. Air defence and Command Frigate

The LCFs primary role is air defence of not just itself but also the fleet in which it is sailing. As such it is not only important that the frigate has the required equipment for this job, but also that it can keep up with the fleet it is deployed with. Together with its other missions, this makes the frigate a vessel that is constrained by its displacement and volume.

## 4.3. Design steps

The analysis will take place in three distinct steps. As the designs progress through the steps the designs will become increasingly detailed. Meanwhile, the number of alternatives studied decreases. This partially overlaps with the design practice at DMO (as can be seen in figure 4.2) where a set-based design approach is used within the TSSE method [95]. Set-based design is a design method with which many alternative designs are created and explored in parallel. Contrary to point-based design, like the design spiral used for ship design, multiple solution directions are examined simultaneously [81]. Although point-based design may lead to a feasible design, set-based design is more likely to lead to a global optimum. This process is illustrated in figure 4.3. It must be noted however that point-based and set-based design are not mutually exclusive. In the early design phases, a set-based design is often beneficial but when the AoA leads to a single preferred design a point-based design will be required to continue.

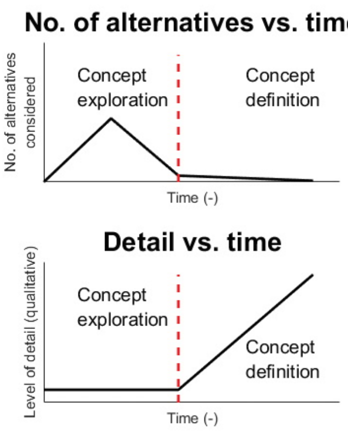


Figure 4.2: Concept exploration at DMO [95]

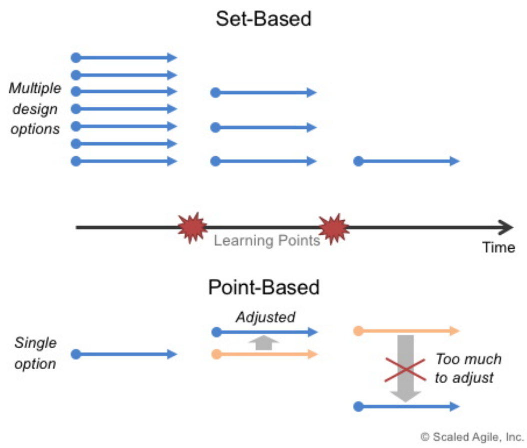


Figure 4.3: Set based design [78]

The set-based design that takes place at DMO in the preliminary design phase is largely automated by the so-called packing approach [33]. To be able to use this approach for the present design problem the correct inputs for the software need to be generated as the packing approach currently does not consider alternative energy carriers and power plant configurations. Without an automated approach, however, the generation of many alternative designs for multiple ship types would not be feasible within the time and resource constraints applicable for this project. Additionally, identifying the interesting alternatives places a considerable burden on the naval architect. ”This can be notoriously difficult if one designs a vessel with an unfamiliar configuration or with unfamiliar systems” [93]. The use of the packing approach for this project may not be feasible as this is a complex piece of software, and much time would be spent simply getting to understand the software and not producing designs. For this reason, an exhaustive automated set-based design method will not be considered further in this project. The data gathered in this thesis could be used to improve the input so that alternative energy carriers and converters may be included in this set-based approach in the future though.

Instead of the comprehensive but time and resource-consuming process, a simplified design approach is chosen. The AoA will take place in three distinct steps in which the level of detail increases progressively. The first step will consider the different options only at a qualitative level without making a physical model. In the second step, a parametric ship design is generated in order to get a better understanding of the various design considerations. In the last step, a more detailed design of the most promising option will be made in order to validate the earlier hypothesis and come to the final conclusion. These three steps are explained in more detail below.

### 4.3.1. Qualitative design & operaitional analysis

In the first design step, a qualitative assessment will be made. The different options presented in chapter 3 will be considered for the case study subjects. Using the method presented in chapter 2, figure 2.4, the mission profile and operational profile can be translated to technical requirements for the vessel. This can in turn be used to prioritize between different MoEs. A first estimation for the solution direction may then be made. This step in the design process has the that a large progression in the AoA can be made with relatively little effort. The drawback is that this step is heavily influenced by the quantity and the quality of the information that is available. Without a proper understanding of how both the technical (sub-)systems and the overarching system (the naval vessel or even the fleet) function it is impossible to make a justified decision. If this is the case the design progress will advance to a stage in which more detail is necessary, without reducing the number of possible designs thus increasing the work which will be needed. In the operational analysis, two assessments must first be made. For the first, it will be analyzed what the mission profiles of different vessels are. The mission profiles will be expressed as a relative measure of importance which each mission has for a certain vessel. An example for such a profile which was made in another study can be found in table 4.2 [46].

Table 4.2: Vessel type mission matrix

| | Landing | AAW | ASuW | ASW | Supply |
|---|---|---|---|---|---|
| Submarine | | | 1 | | |
| LPD | 1 | | | | |
| LCF | | 1 | | | |
| M-Frigate | | 1/3 | 1/3 | 1/3 | |
| Patrol | | | 1 | | |
| JSS | 1/2 | | | | 1/2 |
| CSS | | | | | 1 |

The second analysis that will take place is an analysis of the required technical capabilities for each mission type. These assessments may be based on an effectiveness assessment for a single mission - be it through a simulation or expert knowledge, pairwise comparison, or any other method. When combining these two assessments a first indication about the required technical capabilities and design priorities for certain vessel types is provided in a systematic manner. One of the primary focuses of the qualitative design will be validation of the input in these tables through conversations with experts on these topics at DMO. A similar validation will then be performed for the outcomes.

### 4.3.2. Parametric design

In this step, a parametric design for the vessels will be made to see how the main dimensions might change when a different energy carrier or power plant configuration is selected. This approach is similar to the studies that have so far been performed at the DMO both into the replacement for the m-frigates and into the auxiliary vessels [6]. A parametric design study is a powerful method for quickly generating many different designs while also getting a better insight into the quantitative consequences different concepts will have on the design. The drawback of a parametric design is that the result is reliant on the various assumptions that are used to build the parametric model. Relations are often linearised while this may not be true in reality. As long as the validity of these assumptions are taken into account when analysing the results the parametric design may still a valuable tool that can quickly add detail and reduce the number of alternatives without being too resource-intensive.

### 4.3.3. Detail design

In the detailed design, one configuration with the most promising alternative fuel is considered for each case. This step will simultaneously validate some of the assumptions on which the parametric design was based, and give more accuracy to how much certain aspects of the design may change. It is important to specify to which level of detail the 'detail design' will be made. A complete finished design of a naval vessel takes many man-hours of work and is not feasible within this project. Instead, a design will be proposed with varying levels of detail. Especially the weights and volume which the power plant and the fuel storage occupy will be determined more accurately. For other (sub-)systems the parameters from a reference vessel will be used and assumed largely constant between the different designs. This will also ensure that the energy carrier and conversion method is the only variable that changes throughout the design process. The exact level of detail of the different components of the design is not known yet as this will also depend on the outcomes of the previous design steps. Especially the areas in which large changes are seen, or where unexpected results surface will need additional attention in this step.

# II

# Design study

# 5 Qualitative Design

The first design step in the chosen approach consists of a qualitative design. In this step the concept of operations of the case study subjects and the technical characteristics will be judged in a qualitative way without quantifying vessel or system dimensions. In this step no representation of the physical shape and form of the vessels will yet be made, but an operational analysis is executed. This chapter will propose a method in which this can be systematically performed as to gain insight into the current design challenges, but also to yield a method which may be easily adapted to various design variations. This method may than be adapted to fit other vessels, missions types, and future technologies in research yet to come.

In the first section the maritime doctrine of the RNLN will be examined. An array of missions is considered and for both case study subjects it is determined where the emphasis of their operations lies. For the different missions it is subsequently determined which design aspects generally contribute to the operational effectiveness of these missions using the measures of effectiveness established in the literature study.

In the following section the missions breakdown and capability breakdown are combined. This will result in a ranking of design aspects which should be prioritised for different ship types. This result will be examined and validated closely for both the case study subjects. A comparison is made to the other large surface vessels of the RNLN to place them into the context of the fleet-system, as opposed to just the ship-system.

Finally the design priorities will be compared against the assessment of technical properties which has been made for all the different energy carriers and energy converters. This will result in a first assessment of which technologies are suitable for certain vessels.

## 5.1. Mission Profiles

The applicability of certain technologies to different vessels is highly dependent on the requirements of those vessels. Those requirements in term stem from the expected missions which these vessels will need to execute. In table 5.1 a simple mission designation is seen [46]. The use of this table in the relevant study was different than it will be in this project however. In 'Winning at Sea' this table models the capabilities the vessel supplies for the purpose of simulating different scenarios. In this project such

Table 5.1: Mission designation for the RNLN large surface fleet

| | Landing | AAW | ASuW | ASW | Supply |
|---|---|---|---|---|---|
| Submarine | | | x | | |
| LPD | x | | | | |
| LCF | | x | | | |
| M-Frigate | | x | x | x | |
| Patrol | | | x | | |
| JSS | x | | | | x |
| CSS | | | | | x |

a view may not be sufficient. Instead of viewing the ship-system as the supplier of a capability which is needed in the (simplified) political or security situation, the ship-system demands these capabilities from the technical system on board. The table can be improved upon in two clear ways. The first improvement lies in the specificity of the data. It is not enough to know that a vessel must execute a mission at some point, but a weight distribution between different missions should be added. This can be based on the amount of time the vessels will be spending on each missions or a measure of relative importance of every mission. The latter is the preferred option for naval vessels. This is due to the fact that they are designed for a task which they will only rarely engage in in peace-time. Using time to weigh the importance of different missions would introduce a bias towards peace-time missions instead of conflict-time missions. The second way in which this table can be improved upon is by adding more different missions. A larger variety of missions can be found in the GMO or the NATO Capability Codes & Capability Statements (CCCS) together with a description of the mission and a statement of different level requirement necessary to execute these missions. In the GMO the missions have been divided into three different categories as illustrated in figure 5.1. In the following subsections a short assessment of the applicability of each of these missions will be made for the two case-study subjects and a small selection of other vessels. In the literature review it was seen that the requirements also stem in part from the solution direction which is chosen for the design. The larger the difference between two solutions, the larger the difference in the requirements. Although it is still necessary to keep this in mind, the present research focusses on large surface vessels. This means that all platforms have a large similarity between them which partially mitigates this problem. In the next section various cases where this problem is still apparent will be shortly considered. The vessel-mission designation which is presented in matrix 5.2 has been populated with more vessels than just the two case studies. This serves in part to help validate the method and to sketch a clearer picture of the differences in design between more different vessels. The requirements for the ship-system can never truly be separated from the requirements for the fleet-system so it may be helpful to see the case study subjects in the context of the larger fleet.


Figure 5.1: Three types of operations according to the Fundamentals of Marine Operations [57].

### 5.1.1. Maritime assistance operations

**Missions** Maritime assistance operations are operations using military capacity in support of diplomatic efforts or civil authorities [57]. Maritime assistance to diplomacy can be done by 'showing the flag'. This can be done simply to underscore friendly relations between nations or sometimes to backup diplomatic claims, for example by entering disputed waters, this is referred to as naval diplomacy. Maritime capacity building focuses on supporting, advising and training local law enforcement agencies such as the coastguard, navy, or police [57]. Maritime capacity building almost always refers to support of civil or military agencies of other states. When supporting other civil authorities of the own state this is referred to as 'maritime support to civil authorities'. This can be in the context of search and rescue, fishery inspection, law enforcement, maritime monitoring or 'support of services with specific military capability' [57] such as explosive ordinance disposal, diving, or logistic operations. Disaster evacuation and humanitarian relief operations are also part of maritime assistance operations. A recurring characteristic of these missions is that they take place in a low conflict environment and as such do not often require vessels with significant armaments and special capabilities. Depending on the mission some specialist equipment may be required - explosive ordinance disposal, diving operations - or logistic and transport capability in the case of humanitarian relief operations. Some maritime assistance operations can be performed by almost any naval vessel. For operations such as military diplomacy the mere presence of a naval vessel is enough. however, the strength of the message that is sent is directly proportional to the importance of the naval asset which undertakes such a mission. When considering the large surface vessels of the RNLN only the LPDs and JSS regularly engage in missions such as disaster relief. The OPVs are also unique in the large surface fleet in that they regularly engage in assistance to civil authorities with several coast guard duties.

### 5.1.2. Maritime security operations

Maritime security operations are often categorized as low level conflict operations against civil actors breaching (international) law. The missions types within the maritime security operation domain that are most worthwhile to discuss are the maritime interdiction operations, counter-terrorism operations and the monitoring of international regulations such as UN regulations and security council resolutions [57]. For maritime security operations the AoO is of large influence on the authority responsible for the operations. Operations such as 'countering of illicit trafficking and prevention of the violation of blockades' can largely be performed by the coast guard or customs authorities in coastal waters. When these operations take place in less friendly environments they are often missions executed by the RNLN. Mission where more resistance can be expected such as counter-piracy or counter-terrorism are also the terrain of the RNLN as these rely on the direct offensive or defensive action with military force [57]. At the lower end of the level of force used in these missions it is mainly civil authorities performing these missions. When more force is necessary the OPV is the vessel of choice, when a high level of force is required other vessels can also be committed. Although vessels such as the OPV, JSS or LPD are not designed to engage in combat themselves, they can be equipped with maritime helicopters, FRISCs, and marines in order to execute these tasks.

### 5.1.3. Maritime combat operations

Maritime Combat Operations are the most essential part of the navies tasks [57]. A distinction can be made between maritime combat operations at sea and maritime combat operations launched from the sea.

#### Maritime combat operations at sea

The four main categories of maritime warfare are those of anti-submarine warfare, anti-surface warfare, anti-air warfare and naval mine warfare. The first three forms of warfare are almost entirely reserved for the surface combatants such as frigates, cruisers and destroyers (although the RNLN only possesses frigates, and submarines. Destroyers or cruisers are often designed to perform all these forms of naval warfare whereas frigates are constricted by their size and are often optimized for one aspect. The Dutch LCFs or the M-frigate for example are designed for anti-air, and anti-submarine warfare specifically. Naval mine warfare can be split into offensive and defensive mine warfare and the RNLN only actively participates in the latter by maintaining a fleet of mine countermeasure vessels (check claim and find reference). Within the RNLN the frigates are specifically designed for these types of combat operations.

#### Maritime combat operations launched from the sea

Besides maritime combat operations conducted at sea, maritime combat operations launched from sea are also a part of the maritime striking power of a navy. Such operations comprise amphibious operations in which a force is either introduced to-, or extracted from hostile territory ashore. Maritime strike operations pertain to often offensive action directed at hostile territory initiated from the sea. This can be with aircraft from carriers, with (cruise) missiles launched from vessels or with naval guns. This is a capability which is mostly used offensively and as such is not a focus of the RNLN. Maritime special operations are often small scale and are performed clandestine [57]. The RNLN large surface vessels do not execute these operations themselves but can often assist in the deployment of the assets that are to perform these operations. The submarines for example are highly suitable for this purpose. With other vessels the delivery of these assets will be more likely to be performed by smaller air- or watercraft such as helicopters, FRISCS, or RHIBS. This is something which can be done by both the OPVs or the LPDs. The Riverine operations are not under consideration here since this is not a type of operation that is conducted by the large surface vessels.

### 5.1.4. Maritime sustainability and maritime manoeuvre

There is another type of operation which is not directly related to the tasks of the RNLN but nonetheless is essential in support of these operations. For some forms of maritime manoeuvre away from friendly ports it may be necessary to support a vessel, a task-group, or sometimes a ground force with logistical and organisational capabilities. These operations are necessary to sustain the force in the AoO. The most important missions which help to sustain these operations are the following:

- Replenishment at sea
- Strategic transport
- Sea basing
- Command & control

These missions support either a maritime force in the execution of its mission or in the case of strategic transport (and sometimes sea basing) the maritime logistic capabilities fulfil in the needs of a ground force. Both from the characteristics as from the system plans of the RNLN vessels it is clear which vessels in the fleet fulfil these roles. Currently the only vessel with replenishment at sea (RAS) capability is the JSS although the yet to be delivered CSS also has this as one of its primary roles. Both the JSS and the LPDs can execute the tasks necessary for the remaining missions of sea-basing, strategic transport and command & control. Additionally, the LCF also has command facilities on board.

### 5.1.5. Mission-vessel matrix

Having considered the most important missions which the RNLN vessels have to fulfil it is possible to use the information to populate a mission-vessel matrix which relates the priority which different vessels will give to different missions. This matrix is shown in the table below. It should be noted that besides the case study subjects, other RNLN large surface vessels have also been included. This is to give a better image of the tasks of the case study subjects in relation of the whole navy. It is also apparent that not all missions that were discussed are included in the table. Operations such as maritime assistance to diplomacy are not reserved for any specific vessel making it difficult to weigh this mission. Similar argumetns are valid for the operations ’presence’, ’blockade’ and ’embargo’ where it depends on the severity and the situations place on the escalation ladder. Yet other operations such as ’riverine operations’, ’maritime strike operations’ and ’naval mine warfare’ are not included as the vessels presented have no significant role in the execution of these tasks.

It must be noted that this table does not represent a profile of the missions in which a vessel will engage throughout its lifetime. Depending on the demand and availability of vessels it may occur that a frigate will engage in a maritime assistance operation if no OPV or other designated vessel is able to do so. When a new class of vessels is commissioned, or when additional vessels are acquired the mission profiles may change. The different vessels are in the end only an instrument to supply a part of the total capabilities needed by the RNLN. Adittionally, this profile may look different in war time as opposed to peace time operations. It is once again seen that it is very complex to get an accurate estimation of the activities of naval vessels. As the emphasis of this chapter is on decision support it is important that this data is accurate enough to support design decisions. These decision will not be based solely on the results of this exercise. Some further consideration into the sensitivity of this data is given in section 5.3.1.

Table 5.2: Mission profiles for the different RNLN vessels

| | Maritime Assist. | | Maritime Security | | | Maritime Combat | | | | Maritime Sustainability | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Assist. to Civil Author. | Disaster relief/ evacuation | Monitoring Regulations | Maritime interdiction operation | Counter-terrorism | ASW | ASUW | AAW | Amphibious | Replenishment at sea | Strategic transport | Sea Basing | Command |
| LCF | 0 | 0 | 0 | 0 | 0 | 0.15 | 0.15 | 0.5 | 0 | 0 | 0 | 0 | 0.2 |
| MFF | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.2 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| LPD | 0 | 0.1 | 0 | 0.05 | 0.05 | 0 | 0 | 0 | 0.3 | 0 | 0.15 | 0.15 | 0.2 |
| OPV | 0.2 | 0.1 | 0.1 | 0.2 | 0.2 | 0 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| JSS | 0 | 0.15 | 0 | 0.05 | 0.05 | 0 | 0 | 0 | 0.15 | 0.4 | 0 | 0.1 | 0.1 |
| CSS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.3 | 0 | 0 |

## 5.2. Mission requirements

This section will further examine which capabilities are necessary for a certain mission. The list of technical capabilities and design drivers of which the importance will be evaluated is the same that has been established in the literature study in chapter 2. This list is shown again here:

- Offensive capabilities
- Survivability
  - Susceptibility
  - Vulnerability
  - Recoverability
- Mobility
  - Top speed
  - Acceleration and deceleration
  - Manoeverability
- Range
- Endurance/autonomy
- Payload volume
- Payload weight

In the literature study it was established that the points of this list are the main contributors to the operational effectiveness of many types of naval vessels. As designs get more detailed other properties also affect the operational effectiveness, in this stadium of the design however such a level of detail is not yet reached and the list of properties is this assumed to be sufficient.

In order to fill the mission-capability matrix an assessment of the contribution of each capability to each mission has to be made. This assessment will be performed by ranking the importance for each capability between 0 and 9. Survivability and mobility itself will not be considered since they are compound measures consisting of other measures of effectiveness that can be assessed more directly[1]. Similarly to other subjective ranking systems such as the analytical hierarchy process and the quality function definition it appears that this scale is best suited to subjective prioritization (add

[1] Mobility for example is the average of manoeuvrability, acceleration, and top speed.

reference). This also means that the total total contribution of different capabilities to a mission will be higher than one or 100%, and that the total capability contribution may differ between missions. Although this may seem counter intuitive at first this means that the difference in the absolute level of requirements between missions will also be illustrated in this method. To put this in different terms: the cumulative requirements of different missions are simply much higher for the various maritime combat operations than for maritime assistance operations. The following subsections will contain an explanation for the ratings of the relevant missions that have been covered in the previous section.

### 5.2.1. Maritime assistance operations

For missions that entail assistance to civil authorities the capability requirements are relatively modest. Although basic navigation and communication systems are always required there is no need for advanced sensors or weapon systems. What distinguishes the needs for a vessel designed for such a mission from the most basic seaworthy vessels is the need to maintain operability and manoeuvrability in very heavy weather which puts requirements on the vulnerability and the propulsion system. For disaster relief and evacuation operations the main concern is the transport capability. Both high reserve displacement and volume are needed for the payload which may consist of relief supplies or evacuees.

### 5.2.2. Maritime security operations

For the different missions in the maritime security domain it is observed that a higher survivability is required. This manifests itself mainly in vulnerability and recoverability. Susceptibility is not necessarily a large problem yet as armed insurgents, pirates, and illegal traffickers often possess only small arms. Both tracking and intercepting do put higher requirements on sensor systems and vessel mobility. Especially in anti-piracy and maritime interdiction operations however a dual strategy may be chosen. A vessel with a high top speed may be utilised for interception, or a slower vessel equipped with FRISCs or helicopters may be used. It is difficult to capture a rating for such a broad level capability requirement when it is not yet decided which specific strategy will be taken.

### 5.2.3. Maritime combat operations

The requirements for the different maritime combat operations at sea are the highest. For these missions high-tech SEWACO systems are absolutely necessary. Differences between these missions can be seen primarily at the level of survivability. Chances to evade a submarine are higher than the chances another surface vessel may be evaded which influences the balance between susceptibility, vulnerability and recoverability. This distinction is also seen with the requirements for mobility. A frigate with a high mobility may have an edge over an enemy submarine or surface vessel but outrunning a jet is improbable for even the fastest vessels. In this case the mobility partially influences the ease with which an enemy is engaged or intercepted but there are also links to the susceptibility, this is yet another interdependence between the measures of effectiveness. It must be noted that in opposition to the portrayal in popular culture, the chances of outrunning or outmanoeuvring a modern torpedo by any large surface vessel are slim to none (find reference).

### 5.2.4. Maritime manoeuvre/maritime sustainability

The mission requirements for the supporting missions often stem from the need to transport goods and materiel. The largest difference between the four mission types that are presented are where the emphasis lies. This in turn depends on the goods transported. In strategic transport missions it is often equipment which is transported and although heavy, this equipment mostly requires very large volumes to transport. For the replenishment of fuel however, the emphasis lies on displacement as fuel has a far higher density than equipment.

### 5.2.5. Mission-capability matrix

When all of the above considerations are taken into account the missions-capability matrix may look something like the example that can be seen in table 5.3. The choice to rank every technical capability on a scale between 1 and 9 indeed results in different total scores for each mission. As it was hypothesized the result of this is that it is readily apparent that some missions demand a higher level of overall capability than others. It is almost trivial that the requirements for a vessel executing a mission in assistance of civil authorities are lower than the requirements for a surface vessel designed to engage in anti-submarine warfare. It must also be noted that although a value is given for range and endurance in this overview, these are normally not mission dependent. Requirements for the range and endurance of a vessel are often considered as a separate 'hard' requirement which must be met independent of the role of the vessel. The endurance for practically all the RNLN large surface vessels for instance is 30 days.

Table 5.3: Contribution of important properties to the effectiveness to particular missions

| | Mar. Assistance | | Mar. Security | | | Mar. Combat | | | | Mar. Sustainability | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mar. Assist. to Civil Authorities | Disaster relief/ evacuation | Monitoring Regulations | Maritime interdiction operation | Counter-terrorism | ASW | ASUW | AAW | Amphibious | Replenishment at sea | Strategic transport | Sea Basing | Command |
| SEWACO | 1 | 1 | 1 | 3 | 3 | 9 | 9 | 9 | 3 | 1 | 1 | 3 | 7 |
| Susceptibility | 1 | 1 | 1 | 1 | 1 | 9 | 5 | 3 | 1 | 3 | 3 | 3 | 3 |
| Vulnerability | 3 | 1 | 3 | 3 | 3 | 3 | 7 | 9 | 7 | 3 | 3 | 3 | 3 |
| Recoverability | 1 | 1 | 1 | 3 | 3 | 7 | 7 | 7 | 5 | 3 | 3 | 3 | 3 |
| Range | 3 | 5 | 3 | 3 | 3 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Endurance | 3 | 5 | 3 | 3 | 3 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Top speed | 3 | 3 | 3 | 5 | 5 | 7 | 9 | 5 | 5 | 5 | 3 | 3 | 5 |
| Acceleration | 3 | 1 | 3 | 3 | 3 | 7 | 3 | 3 | 3 | 1 | 1 | 1 | 1 |
| Manoeverability | 3 | 3 | 3 | 1 | 1 | 7 | 3 | 3 | 7 | 3 | 1 | 3 | 3 |
| Payload volume | 1 | 7 | 1 | 3 | 3 | 1 | 1 | 1 | 7 | 5 | 7 | 7 | 5 |
| Payload weight | 1 | 7 | 1 | 3 | 3 | 1 | 1 | 1 | 7 | 9 | 5 | 7 | 3 |
| Total | 23 | 35 | 23 | 31 | 31 | 61 | 55 | 51 | 55 | 43 | 37 | 43 | 43 |

## 5.3. Vessel requirements

The former two matrices can be combined to obtain the importance of any capability or technical characteristic for all the different vessels that have so far been taken into consideration. Using the weight -the priority of the mission- and the importance of a certain capability for that mission the importance of a certain capability may be calculated branch by branch.

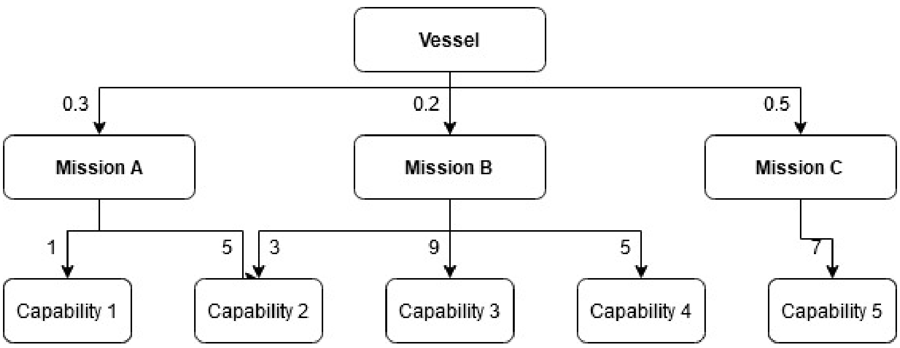


Figure 5.2: Mission breakdown

The multiplication process through all these different branches for all different vessels is essentially the same as multiplying the two matrices that have been filled in the previous sections. The result of this process is found in the table below. In order to illustrate and more easily distinguish between the priorities for different capabilities a color scale has been added. Dark green are considered the most important capabilities while dark red are the least important. Some explanation is necessary however. Especially 'volume' and 'displacement' deserve extra attention. In this method both volume and displacement are defined as the necessary volume and displacement to facilitate a payload. This is not the same as the total volume or displacement as the vessel itself, which is not necessarily unrelated from the other capabilities presented here. The example of the LCF will be examined more closely. At first sight it appears that volume and displacement are not important design drivers for this class since these have a rating of 2.2 and 1.4. The necessity of a high top speed is estimated at 5.4 however and a high top speed is negatively impacted by both a large volume and displacement. The correlation matrix below shows how each measure of effectiveness is influenced by another.

Table 5.4: Correlations between different measures of effectiveness

| | Susceptibility | Vulnerability | Recoverability | Range | Endurance | Top speed | Acceleration | Manoeverability | Volume | Displacement |
|---|---|---|---|---|---|---|---|---|---|---|
| Susceptibility | x | | | | | - | - | - | + | + |
| Vulnerability | | x | | | | | | | - | |
| Recoverability | | - | x | | | | | | | |
| Range | | | | x | | | | | | - |
| Endurance | | | | | x | | | | | |
| Top speed | - | | | | | x | | | - | - - |
| Acceleration | - | | | | | | x | | | - - |
| Manoeverability | - | | | | | | | x | - | - |
| Volume | + | - | | | | - | | - | x | ++ |
| Displacement | + | - | | - | | - - | - - | - | ++ | x |

Although this correlation matrix reveals no surprises it is important to be aware of these correlations. Especially when considering the frigates it is seen in table 5.5 that these have no stringent requirements for volume or displacement. However, the strong negative correlation between displacement and top speed mean that regardless of the low requirements stemming from table 5.5, a lot of effort must go into ensuring that the displacement is limited. It appears however that displacement - top speed, and displacement - acceleration are the most limiting couplings to be aware of during the design process. The other correlations that are seen are between recoverability and vulnerability -when the initial damage due to an impact is greater, it becomes more difficult to recover lost capabilities afterwards-, susceptibility and top speed, acceleration and manoeuvrability -although it is difficult to outrun modern weapon systems a high mobility may help to stay out of range of threats-, a high volume and displacement similarly make a vessel more prone to detection and thus have a positive correlation with susceptibility. What remains are the correlations between a high displacement and all the factors contributing to mobility. These same correlations exist to a large degree for volume, since volume itself has a strong positive correlation to displacement.

### 5.3.1. Sensitivity analysis

As was already noted in the associated sections, it is difficult to establish exact values for the positions in table 5.2 and 5.3. The rate of success in different operations depends on more than just the technical capabilities of the vessel and the concept of operations and expected missions for a vessel can change over time due to political or other circumstances. It is therefore not hard to imagine that the values in the given tables may differ depending the source. There are multiple ways of dealing with this issue.

Table 5.5: Importance of different technical characteristics to RNLN surface vessels (red= high priority, green = low priority)

| | SEWACO | Susceptibility | Vulnerability | Recoverability | Range | Endurance | Top speed | Acceleration | Manoeverability | Paylaod (Volume) | Payload (weight) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LCF | 8.6 | 4.2 | 6.6 | 6.2 | 5 | 5 | 5.9 | 3.2 | 3.6 | 1.8 | 1.4 |
| M-Frigate | 9 | 7 | 5 | 7 | 5 | 5 | 7 | 5.4 | 5.4 | 1 | 1 |
| LPD | 3.3 | 2 | 4 | 3.4 | 4.8 | 4.8 | 4.2 | 1.8 | 3.7 | 6.2 | 5.5 |
| OPV | 3.4 | 1.8 | 3.6 | 3 | 3.6 | 3.6 | 5 | 2.8 | 2.2 | 2.4 | 2.4 |
| JSS | 2.3 | 2.2 | 3.3 | 3 | 4.8 | 4.8 | 4.5 | 1.5 | 3.4 | 5.6 | 7 |
| CSS | 1 | 3 | 3 | 3 | 5 | 5 | 4.4 | 1 | 2.4 | 5.6 | 7.8 |

Three options are considered here. The first would be to request input regarding these values from many different sources, Designers, sailors, commanders, the general staff, political personnel, and to take the average of their opinions. This process however will evoke further questions regarding the selection and weighing of the different voices. Another option would be to estimate within what range certain values may fall and perform a probabilistic analysis or a simulation (monte carlo) in order to reach a more acurate conclusion. In this case a more simple approach is taken first. A small selection of the values which may be deemed controversial will be systematically varied within both matrices. The subsequent result of this variation on table 5.5 will then be observed. Depending on the magnitude of the change of the results, and of the subsequent conclusion with regards t the design solutions, another manner may then be used if necessary.

**Mission profile variation**

The first two variations are variations of the mission profiles for both the LCF and the LPD (original in table 5.2). The changes to the profile are seen in table 5.6. It could be argued that the LCF is a frigate which is more capable of anti-surface and anti-submarine warfare than it is made out to be in table 5.2. Another argument which could be made is that the mission of the LPD is more focussed on amphibious assault. When the input data is changed to reflect these statements the result in the final vessel capability matrix can be seen in table 5.7.

The changes which are seen in table 5.7 are expressed as absolute changes from table 5.5. The changes are relatively small in this case and when ranking the design priorities the only difference is that vulnerability and recoverability are now valued the same, whereas there used to be a minor difference between these.

**Importance of speed**

Following are two scenarios where the mission-capability matrix has been altered that are both concerned with the importance of the top speed for certain operations. In the first analysis the importance of the top speed for maritime interdiction, counter-terrorism, ASUW, ASW, AAW, and RAS operations has been reduced. In the second analysis the value attached to top speed has been increased for maritime interdiction, counter-terrorism, ASW and AAW [2] has been increased. The results can be seen in table 5.8. It appears that an increase in the speed has a less pronounced effect on the design priorities than a reduction of the importance of the speed. Such a reduction does seem to be rather influential, especially for the faster vessels i.e. the frigates. This must be taken into account later.

## 5.3.2. Air Defence and Command Frigate

For the LCF it is clear that there is a strong emphasis on the SEWACO suite. Although the different subsystem and their functioning within the sewaco suite are not a focal point of this study it is important to maintain the necessary reserve displacement and volume, plus a future design margin for these systems in a new redesign. The high priority of the SEWACO systems most likely signals a low flexibility.

[2] ASuW already has the highest speed requirement

Table 5.6: Sensitivity analysis variation 1 input (red = negative change in input, green = positive change in input, yellow = input constant)

| | Maritime Assist. | | Maritime Security | | | Maritime Combat | | | | Maritime Sustainability | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Assist. to Civil Author. | Disaster relief/ evacuation | Monitoring Regulations | Maritime interdiction operation | Counter-terrorism | ASW | ASUW | AAW | Amphibious | Replenishment at sea | Strategic transport | Sea Basing | Command |
| LCF | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | -0.1 | 0 | 0 | 0 | 0 | 0 |
| MFF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LPD | 0 | 0 | 0 | -0.05 | -0.05 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 |
| OPV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| JSS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CSS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 5.7: Sensitivity analysis variation 1 result (red = negative change in MoE importance, green = positive change in MoE importance, yellow = contant MoE importance)

| | SEWACO | Susceptibility | Vulnerability | Recoverability | Range | Endurance | Top speed | Acceleration | Manoeverability | Volume | Displacement |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LCF | 0 | 0.4 | -0.4 | 0 | 0 | 0 | 0.3 | 0.2 | 0.2 | 0 | 0 |
| M-Frigate | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LPD | 0 | 0 | 0.4 | 0.2 | 0.2 | 0.2 | 0 | 0 | 0.6 | 0.4 | 0.4 |
| OPV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| JSS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CSS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 5.8: Effect of the reduction and increase of the rating for top speed for maritime security operations

| | Top speed | |
|---|---|---|
| Vessel | Reduction | Increase |
| LCF | -2 | 1.3 |
| M-Frigate | -2 | 1.6 |
| LPD | -0.6 | 0.2 |
| OPV | -1.2 | 0.8 |
| JSS | -1.2 | 0.2 |
| CSS | -1.4 | 0 |

This means that when confronted with a decision between the propulsion plant and a radar system, the radar system will receive priority. Furthermore it can be seen that vulnerability and recoverability are of high importance as well. Especially recoverability is highly influenced by the operations, training and crew procedures, but also the redundancy and reliability of systems play an important role. The attainable top speed is of relatively high importance as well. The remainder of the measures of effectiveness are not of significant importance in themselves. However, when also applying the correlations between the different measures the restrictions in weight and volume again appear.

### 5.3.3. Landing Platform Dock

The main considerations for the landing platform dock are both the volume and the displacement. Added restrictions on the placement of the volume surface from the capability requirements of helicopter operations and amphibious operations. No additional limitations arise when comparing the high and low rankings of the capability requirements with the correlations in the correlation matrix.The overall requirements of the platform are moderate in most categories which leaves a lot of design freedoms.

## 5.4. Technology trade-off & results

During the literature study a trade-off matrix with the qualities and characteristics of different energy carriers and energy conversion methods was constructed. With larger matrices it may be valuable to automate the analysis but in the case of the vessels which are considered here it is possible to do so by hand. When comparing the various design alternative which are presented in table 5.9 the prioritization can be performed according to the result from the analysis of the vessel capability matrix and the correlation matrix. In this section a selection of feasible technologies will made on the basis of the vessel capability matrix presented before.

### 5.4.1. Air Defence and Command Frigate

From the vessel-capability matrix and the correlation matrix appeared that the vulnerability and recoverability are both important design aspects for the LCF. The vulnerability and recoverability are influenced by both the energy carrier and the energy converter that is chosen. The other high priority lies in the mobility, and mainly in the top speed at that. From the correlation matrix it appears that volume and displacement need to be limited since these have a high negative correlation with the attainable top speed, and from technology trade off matrix it appears that the energy converter also influences this via the power density of the converter. Following the high priority that is given to both vulnerability and recoverability it appears trivial to discard gaseous fuels such as LNG, hydrogen and ammonia from the comparison. Their requirements for storage and the associated risk regarding damage propagation make these fuels unsuitable for surface combatants. Methanol has considerable drawbacks in this situation such as the relatively low flashpoint, toxicity, and solubility in water making it an unlikely candidate. Ethanol and butanol both fare better in this regard. When looking at the energy density which is important due to the volume and displacement restrictions, it appears that besides the already disqualified fuels, batteries are also disqualified. This leaves HVO, FAME, Ethanol and Butanol. The same approach can be used for the selection of the energy converter. The requirement for a low vulnerability and a high mobility (and thus a limited displacement) are again leading. With proper use the diesel engine and the gas turbine have a very low vulnerability. Both concepts have been in use for a long time and are well adapted for marine applications. Theoretically they are prone to wear and tear due to their mechanical movement, especially the diesel engine with its reciprocal movement, but this influences the lifetime and maintenance more than it influences the direct reliability and vulnerability in the short term. Their high power density also makes both the diesel engine and the gas turbine an excellent choice for use on board frigates. The low susceptibility and high potential for redundancy make the fuel cell an excellent choice regarding vulnerability, but their low power could lead to a large increase in weight. On the basis of the results of the sensitivity analysis it was argued that speed may not be such an important factor. If this would be true, both the required power and the limit to displacement would weigh less heavily and there is a potential for machinery with a lower power density as well.

### 5.4.2. LPD

From the first results of the requirement analysis of the LPD it appeared that there is a relatively large degree of freedom in the design. The two most important requirements, an adequate volume and displacement, ensure that a large platform without strict limitations is available to work with. The consensus at the DMO is that this indeed gives some flexibility with regards to the design solutions. In terms of the available design solutions from table 5.9 the results differ slightly from the solutions available for the LCF. Since the LPD can be seen more or less as a volume driven design, volume is the most important driver. The ideal energy carrier therefore would be one with a high volumetric energy density. The gravimetric energy density is somewhat less important here. The biodiesels are generally already quite close to F-76 in their characteristics but FAME especially has a beneficial ratio between the volumetric en gravimetric energy density. Here again the various alcohol fuels would also be contenders. When examining the potential of different energy converters there is again some more freedom. The requirements for a top speed and acceleration are quite low and it the vessel would thus lend itself quite well for the application of fuel cells.

Table 5.9: Properties of the various energy carriers and energy converters

| | Energy carriers | | | | | | | | | | Energy converters | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F-76 | LNG | LH2 | NH3 | HVO | FAME | Ethan. | Methan. | Butan. | Batt. | Diesel | Turbine | Fuel cell | Electic motor |
| **Survivability** | | | | | | | | | | | | | | + |
| Susceptibility | | | | | | | | | | | - | - | + | + |
| Acoustic | | | | | Depends on converter | | | | | | - - | - | + + | + |
| IR | | | | | | | | | | | - | - | - | + |
| Vulnerability | + + | - - | - - | - - | + + | + + | - | - - | + | - | + | - | - | + |
| Recoverability | + + | - - | - - | - - | + + | +- | - | - - | + | - - | - | - | + + | +- |
| **Mobility** | | | | | | | | | | | + | + + | - | + |
| Top speed | | | | | | | | | | | + | + + | - | + |
| Acceleration | | | | | Depends on converter | | | | | | + | + + | - | ++ |
| Steering | | | | | | | | | | | Depends on configuration | | | |
| **Volume** | 1 | 0.62 | 0.24 | 0.35 | 0.95 | 0.92 | 0.58 | 0.44 | 0.75 | 0.03 | + - | + + | - - | - - |
| **Displacement** | 1 | 1.26 | 2.82 | 0.44 | 1.03 | 0.88 | 0.63 | 0.47 | 0.78 | 0.01 | + - | + + | - - | - - |
| **Logistics** | + + | - - | - - | - - | + + | + | + | +- | + + | | | | | |
| **Maintenance** | + + | - - | - - | - - | + | + | - | - | + | +- | + | - | + + | + |
| **Cost** | | | | | Not in scope | | | | | | + + | - | - | + |

Table 5.10: Selected technologies

| LCF | | LPD | |
|---|---|---|---|
| Energy Carrier | Energy Converter | Energy Carrier | Energy Converter |
| HVO | Diesel engine | HVO | Fuel cell |
| FAME | Gas Turbine | FAME | Electric motor |
| Butanol | Hybrid (combustion) | Butanol | Diesel engine |
| Methanol | | Methanol | Hybrid (fuel cell) |
| Ethanol | | Ethanol | |

## 5.5. Conclusion

In this chapter the concept of operations (ConOps) of the different vessels or the RNLN were examined. For all RNLN large surface vessels estimates were made with regards to their mission profile to identify which mission or operations are most influential on their design. Using the MoEs from the literature study (chapter 2) it was also estimated what technical characteristics were important contributors to the succes of these operations. Together these two matrices resulted in in a rating of the different MoEs (table 5.5). This rating is supports the naval architect in the decision making process during the early design stages. The results from this operational analysis were compared to the potential technological solutions. From this comparison it was established that from the two case study subjects, the LPD potentially has the most design freedom. The requirements for survivability limit the use of gaseous fuels for both vessel types, and the requirements for a high mobility (top speed and acceleration) limit the application of fuel cells on board the LCF due to their low power density and slower load response. In terms of energy carriers it was found that besides F-76, there was potential in the different alcohol fuels and the biomass based HVO and FAME. The outcome of this process is also summarised in table 5.10. Since the inputs to the different matrices were subjective a sensitivity analysis has been performed into the values which were perceived to be most uncertain. It was found that especially the requirement for a high speed and acceleration on various missions had a large influence on the final design, and that by reducing the required speed more design flexibility is gained.

# 6
# Parametric Design

In this chapter a parametric design variation will be performed on the case study subjects. For both vessels a selection of designs is procedurally generated with different power plant configurations and different energy carriers. The design variation in this chapter is performed using a design algorithm which is based on the SPEC tool developed by Maritime Research Institute Netherlands (MARIN) with some important changes that allow a greater degree of freedom. In the first section of the chapter some consideration will be given to the manner in which the parametric design will be executed. In the second section the selected design tool is examined into more detail. This will help to find the strengths and weaknesses of the design tool specifically for the application to large naval surface vessels. The third section is dedicated to the explanation and selection of the correct design variables and associated use-cases as they are called within the design tool used. The results of the parametric design will then be presented followed by a conclusion and extensive discussion.

## 6.1. Parametric design

In the early design stages or the concept exploration phase it is often the goal to assess many different ship design concepts. There are multiple ways to generate these designs amongst which procedurally generated ship designs. These procedures can vary from more complex to more simple computer algorithms. One specific example of such an algorithm is the packing tool used at DMO. For this procedure a high quantity of specific knowledge already has to be available. Parametric design is a more simple procedural design exploration method. Parametric design is the systematic variation of specific design parameters in order to generate multiple different ship designs. The starting point of a parametric design algorithm can be a reference design or empirical relations and coefficients based on many reference designs. The power of such a design method lies in the ability to create many different designs in a short timespan which will allow the designer to judge what the influence of some of the basic design parameters is. There are also disadvantages to the use of parametric design approach however. The process of procedural variation of different design parameters is often indiscriminate towards the nuances and details of ship design. Some of the generated design may not be viable for a host of reasons. When varying for example the length and width of a vessel one will eventually run into problems regarding the layout, stability and strength of a vessel. Some of these factors could be accounted for in the parametric design stage, but this will inevitably add to the complexity of this step of the design stage which in turn limits the overall applicability and makes it harder to verify the results. As long as the level of detail needed corresponds with the complexity of the model the experienced naval architect is often able to judge the limits of this method of analysis. The consequence of this is however, that a naval architect must oversee the process and critically assess the results before moving on but this is no different from any of the other steps in the design process.

### 6.1.1. Setup of the parametric design

The parametric design is most helpful with determining the design parameters that can be expressed in physical dimensions. This means that some of the factors influencing the operational effectiveness of a naval vessel cannot be easily be assessed in this step. The parameters which can be assessed are those regarding the main dimensions, fuel consumption, and power requirements of the vessel. The main parameter which will be varied is the choice of energy carrier and converter which has direct consequences for the weight and volume of the stored energy and the weight and volume of the energy converter. This will then have consequences for the displacement of the vessel. When quickly considering the consequences which a lower energy density fuel will have it must be noted that the increase in displacement is not limited to the extra fuel which must be taken on board. Figure 6.1 illustrates how the increased fuel capacity also occupies more volume and therefore increases the construction weight of the vessel and the displacement. Subsequently the resistance increases which has consequences for the required engine power and fuel consumption, once again arriving at an increased fuel weight. It is clear that this process may take several iterations before converging on the new dimensions of the vessel.

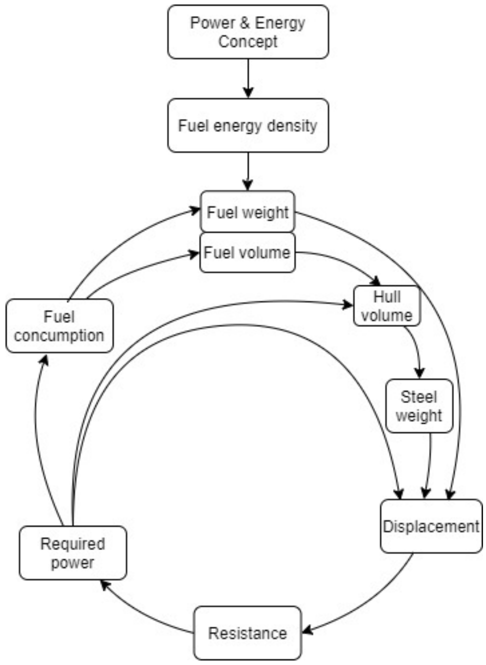


Figure 6.1: A decrease in energy density leads to an larger increase in the ships displacement

## 6.2. Marins Ship Power & Energy Concept (SPEC) tool

MARIN is currently developing a parametric design tool specifically for assessing the influence which different power and energy concepts have on the ship design. This tool, which is called Ship Power & Energy concept (SPEC) within the Quaestor design tool. Quaestor in turn is a knowledge base which brings together different models, methods and information for the designer to work with [91]. In this section SPEC is examined more closely. SPEC has two main functionalities. The first functionality is the 'ranking'. In this function the main particulars of a vessel can be entered as well as the 'top goals' that the ship owner has. This will then generate a ranking of different alternative energy carriers and their converters which can be included in a design. This ranking is based on multiple factors such as cost of ownership, $CO_2$ emissions, TRL and societal readiness level (SRL) that each have a weight assigned to them. The second function of SPEC can help a designer to quickly make different design variations and analyse the influence of these variations on different aspects of the design and operation of the vessel. SPEC enables the user to quickly generate multiple alternative designs by using its built-in information database and by creating a simplified vessel. As in any modelling exercise it is important to be aware of any simplification and its validity in the case which is being examined. The speed and ease with which SPEC generates these different designs is achieved by making use of several simplifications which bring the vessel back to a basic model existing of simplified weight and volume groups. In figures 6.2 and 6.3, two designs of the same vessel are seen which show some of the simplifications that are made. Some of the most notable simplifications in these figures are the following:

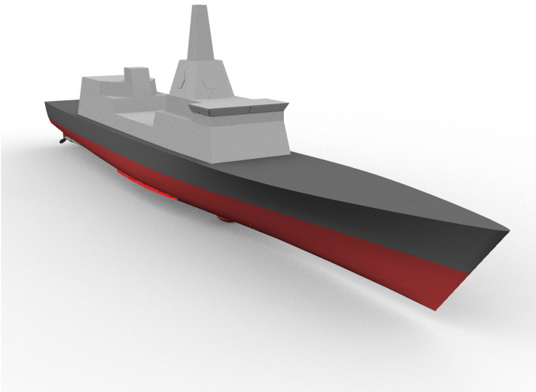

Figure 6.2: A generic frigate design without further simplifications

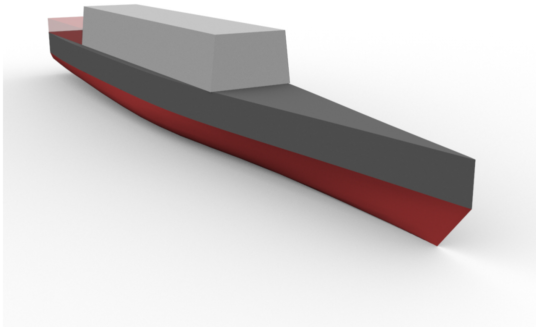

Figure 6.3: The same design with the basic SPEC simplifications

- The superstructure is reduced to a block with a height, width, length and a block form factor.
- The cross section of the hull in the xy above the waterline is constant and equal to the water plane cross section.
- The design has a constant freeboard height.

Other simplification cannot be directly observed from these two figures. In the following two subsections an extensive overview of the relations and assumptions in the design tool are presented as equations. In figure 6.4 the dependencies of the different calculation steps are shown. There are three forms of data represented in this diagram and used by SPEC. The first data type is technical data of the different energy carriers and energy converters. This data is saved in the Quaestor knowledge base and stems from Marins sustainable power project in which knowledge of proprietary research and expert input from the *European Forum for Sustainable Shipping: Sustainable Alternative Power for Shipping* is combined [61]. This data is imported into questor and subsequently retrieved by SPEC when a particular concept is selected for a design. The second data type is the user defined constant. These are parameters such as the block coefficient, length-to-beam ratio or the operational profile. These parameters remain constant throughout all different implementations of the SPEC tool. In this manner SPEC ensures that the analysis is performed with a constant hull form. The last data type is the variable parameter. This parameter varies between different designs and different iterations made by the built in solver. For the systematic generation of multiple alternative designs different combinations of the parameters can be kept constant or varied. SPEC uses a Newton-Rhapson solver to find a solution for which all the equations become consistent. In the example of figure 6.4 the process has been shown in such a way that many of the other main dimensions depend on the vessels beam $B$. This means that the function for $\Delta$, or any other parameter in which the designer is interested for that matter, can be expressed in terms of various constants and the beam as the only variable. In this manner the solver can be used to find at which beam the problem converges after which all parameters for this specific design are known.

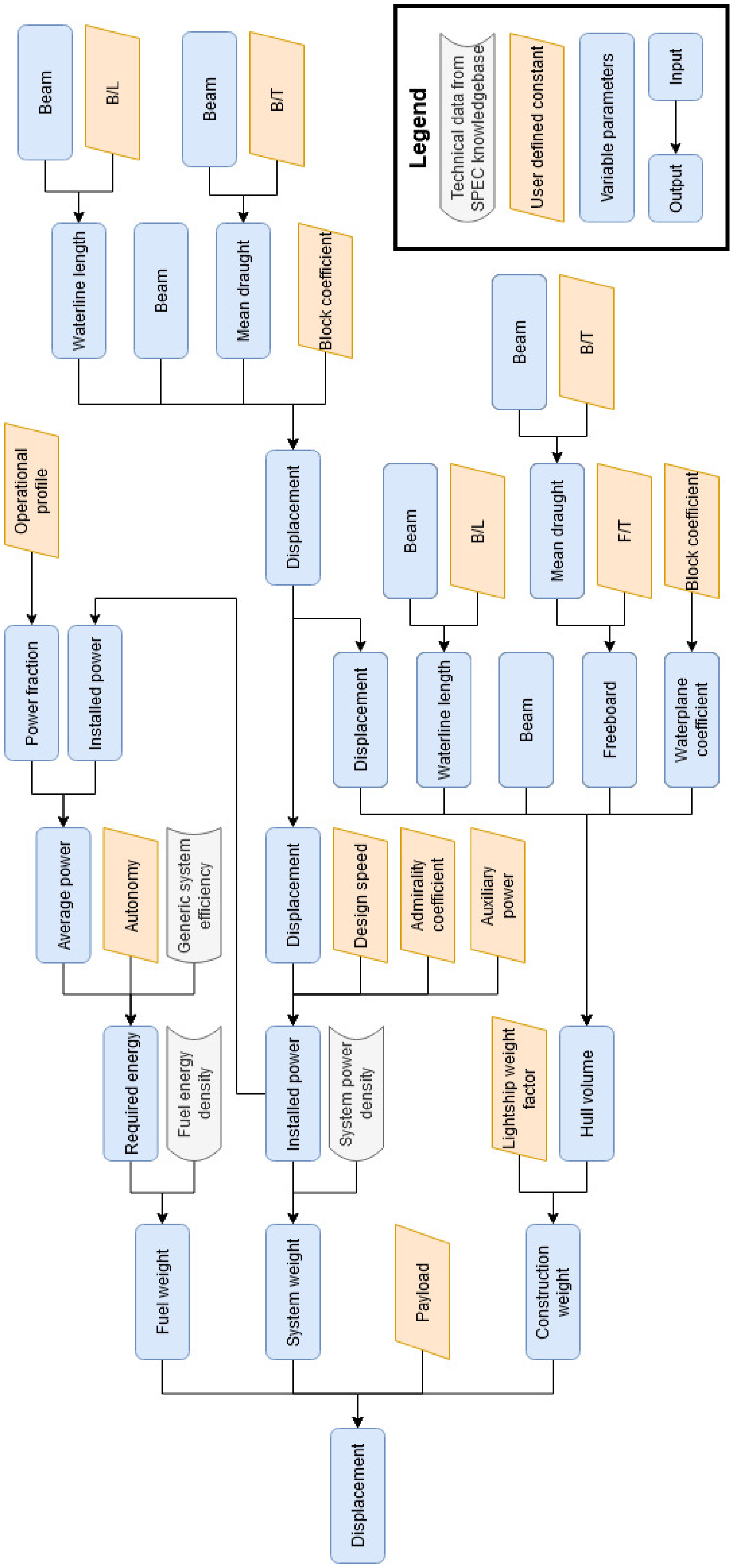


Figure 6.4: A graphical illustration of the various dependencies within the SPEC algorithm

### 6.2.1. Mass & volumes

The SPEC algorithm simplifies the vessels displacement by dividing it into three main categories:

- System & fuel weight
- Structural weight
- Payload

Together these categories make up the total displacement of the vessel:

$$\Delta = W_{system,fuel} + W_{struct} + Payload \tag{6.1}$$

These three weight groups have been chosen in such a way that each group is either an independent variable or will remain constant throughout the design variations.

$$W_{system,fuel} = W_{system} + W_{fuel} \tag{6.2}$$

The weight of the system and the fuel as described in equation (6.2) is the main dependent variable. (In figure 6.4 this weight group has already been split into its two contributors.) Depending on which power storage and generation concept is chosen for the design the weight for the total system including the fuel will vary according to the contained energy density of the fuel and the power density of the power generator. It is important to consider the contained energy density since the systems surrounding the storage of the fuel can heavily influence the storage density as was seen in chapter 3. For fuels that can be stored under atmospheric conditions is not as large, but especially compressed or criogenically cooled fuels have a much lower contained energy density. Apart from the energy density and power density of the energy carrier and converter, the operaticonal profile, efficiency and displacement also influence the total system weight. The weight of the system is further explained with the help of equation (6.3) and (6.14), while equations (6.4) and (6.11) are used to calculate the fuel weight.

$$W_{system} = SP_g \cdot P_{inst} \tag{6.3}$$

Where: $SP_g =$ the specific power of the energy converter and the auxiliary systems in kg/kWh.

$$W_{fuel} = \frac{E_{req}}{U_g} \tag{6.4}$$

$U_g =$ the contained gravimetric energy density of the selected energy carrier.

$$W_{struct} = V_{hull} \cdot WF_{lightship} \tag{6.5}$$

The hull volume is estimated by separating the underwater and the above water volume of the hull. The underwater volume of the hull is calculated by dividing the displacement by the seawater density, while the above water portion is calculated under the assumption of a constant freeboard and a constant cross section which is equal to the waterplane area. This formula is seen in equation (6.6) Within SPEC, the waterplane coefficient is estimated as a function of the block coefficient which can be seen in equation (6.7)

$$V_{hull} = \frac{\Delta}{\rho_{sea}} \cdot L_{wl} \cdot B \cdot C_{wp} \cdot (D - T) \tag{6.6}$$

$$C_{wp} = C_b \cdot (1.607 - 0.661 \cdot C_b) \tag{6.7}$$

It will need to be examined what the consequence of this relation in equation 6.7 are and whether or not this approximation holds for the vessels in this case study. As can be seen in figures 6.2 and 6.3, the assumptions of a constant free-board and a constant cross section already have some influence on the hull volume. Also using a different waterplane coefficient would exacerbate these inconsistencies.

It must also be noted that for the lightship weight factor that is used for the calculation in the structural weight in equation 6.5, only the hull itself is accounted for. For a large cargo ship this is not a large problem as the superstructure is small relative to the hull, and even smaller relative to the ship including its payload. For some specialist service vessels however, this assumption may not hold. The landing platform dock for example has a superstructure which amounts to roughly one third of the total enclosed volume. The implications of this will later be addressed in the section 6.3.

The remaining weight group is the payload. This group consists of the weight which do not belong in the other groups and thus are not part of either the construction and outfitting, or systems related the energy storage and conversion. This weight group thus includes a very broad collection of different systems. As such, it is not the same as the traditional definition of payload which includes cargo, weapons, and personnel. It is possible to be so indiscriminate of the difference between these weight groups since it does not matter for the ships power & energy concept whether the payload is mainly composed of trucks that have to be transported, weapon systems or a large superstructure housing command facilities or crew accommodation. It must be noted that this is not the conventional definition of payload.

### 6.2.2. Power & energy

The required installed power of the vessel comprises of the required propulsive power and the auxiliary power. The required propulsive power is calculated using equation (6.8) for the design displacement and the design speed while auxiliary power is a user defined constant. When the vessel scales up or down the hull shape is assumed to be constant. In order to estimate the required power at different displacement and velocities an approximation using a constant admirality coefficient is used:

$$C_{adm} = \frac{\Delta^{2/3} \cdot V_{max,prop}^3}{P_{prop}} = constant. \tag{6.8}$$

In reality the admirality coefficient is not always equal for a constant hull shape. This assumption only holds true if the resistance curve of a vessel is quadratic and a large degree of similarity between the two compared vessels is maintained. The first criterion is often true at froude numbers (6.9) up to 0.25-0.3 []. At higher froude numbers the resistance and thus the required power increases with a rate higher than $v^3$. This is thus important for fast vessels, but also for the comparison between vessels that differ greatly in displacement. As displacement and thus the length of the vessel increases or decreases throughout the design variations the froude number will also change because the required maximum velocity $V_{max}$ remains constant.

$$Fr = \frac{v}{\sqrt[2]{gl}} \tag{6.9}$$

Despite these limitations, the admiralty coefficient is an often used tool during the preliminary design phase due to its simplicity. Using the admirality coefficient the required propulsive power[1] for different vessel velocities at different displacement can then be calculated by rewriting equation (6.8) to equation (6.10).

$$P = \frac{\Delta^{2/3} \cdot V^3}{C_{adm}} \tag{6.10}$$

Using the maximum velocity as an input in equation (6.10) this will result in the maximum propulsive power needed which can be subsequently used in equation (6.3) to find the weight of the energy conversion system.

Apart from the maximum power requirement it is also important to look at the overall operational profile and other factors which influence the quantity of energy required to be carried. As was presented earlier, the required energy $E_{req}$ is a important input for the contained fuel weight which is calculated using equation 6.4. In SPEC the required energy is calculated using equation 6.11.

$$E_{req} = P_{avg} \cdot 24 \cdot Autonomy \cdot \eta_g \tag{6.11}$$

where:

$autonomy$ = the required number of days of autonomous operation
$\eta_g$ = generic efficiency of the selected energy carrier & converter

[1] Propulsive power here refers to the break power dedicated to propulsion and not to the propeller power. The difference between these two is the transmission efficiency which is accounted for in the generic efficiency $\eta_g$.

The efficiency used here is a generic efficiency which is composed by the efficiency of the drivetrain which is either direct or electric and the efficiency of the converter and a potential reformer that might be installed. The efficiency and thus the specific fuel consumption that is used in the algorithm is taken to be constant over the entire operational profile. In reality the efficiency of an energy converter is influenced by its working point. For the average power required the operational profile of the vessel is used. In this operational profile it is possible to enter many different operating points with the required power in that operating point and the time spent at that operating point. The power required in operating point $i$ is calculated with equation (6.12). Using equation (6.13) the tool then calculates what fraction of the maximum power the average power consumption is.

$$P_i = \frac{\Delta_i^{2/3} \cdot V_i^3}{C_{adm}} + P_{aux} \tag{6.12}$$

$$P_{fraction} = \frac{\sum_{i=1}^{n} P_i \cdot t_i}{P_{inst}} and P_{avg} = P_{fraction} \cdot P_{inst} \tag{6.13}$$

where:
$t_i$ = the relative fraction of time spent at point $i$ in the operational profile

### 6.2.3. Powerplant configuration

Another simplification which is used in the SPEC design tool pertains the power plant configuration. SPEC only allows the selection of one single power & energy concept for a design. The weight and volume requirements of the energy converter of this design are subsequently modelled using the total installed power which is calculated with equation (6.14). The occupied volume and displacement is then calculated with equation (6.3).

$$P_{installed} = P_{propulsive,max} + P_{auxiliary} \tag{6.14}$$

This has two major consequences for this particular project. It is currently not possible to use the SPEC tool to look at hybrid configurations with two or more different energy converters. One promising concept is the combination of a fuel cell and a combustion engine. Another combination which has become a much used solution in naval vessels is the combination of a reciprocating diesel engine and a gas turbine. The second consequence is that the weight and volume scale linearly with the total installed power from equation (6.14). The power calculated in this equation is the maximum power which is expected to be needed at any given moment in time. Vessels may have a much higher installed power however. This can be due to the application of two different types of power conversion such as the combination of a diesel engine and a gas turbine as was mentioned earlier. This problem is further exacerbated by the requirements for a high redundancy which is found in many naval vessels. The air defence and command frigate has a total installed power of over 52,000 kW. This is divided over 2 gas turbines, 2 diesel engines and 4 diesel generators and it cannot all be used at the same instance[2]. Even though the maximum total power consumption will never surpass 40,000 kW in practice, all these engines and generators do occupy space on the vessel. Furthermore, equation (6.3) uses a continuous linear scale for the sizing of the energy converter. For converters like reciprocating engines this function not be continuous but increase step-wise with every added cylinder. It can also be expected that four smaller diesel generators occupy more space than two larger diesel generators with equal total power. For the sake of redundancy it may however prove beneficial to install more smaller generators.

### 6.2.4. Economic factors

Apart from the physical attributes of different system configurations and designs, SPEC also gives an estimate of the lifetime ownership cost based on the investment cost of the power and energy concept and the projected lifetime operational cost. Although this is an interesting and necessary perspective from which the problem of alternative fuels must also be approached, it is not the main concern of this project. It is especially difficult make predictions about the availability and price of various alternative energy carriers in 30 years from now without too much uncertainty. These developments are heavily influenced by the decisions of different polities and private actors. Although these decisions may have

[2]Depending on the configuration it is possible to use all the power at the same time. This mostly depends on the type/number of gearboxes.

a basis in the general physics concerning the energy carriers many other factors that are not within the scope of this thesis are also in play.

### 6.2.5. Summary of simplifications applied in SPEC

After having carefully reviewed the functioning of the selected design tool a number of assumptions and simplifications have been discovered which may influence the rest of this design step. These simplifications will have to be reconsidered during the design, and when analysing the results. They may also serve as a good starting points for future updates and improvements to the design software[3]. The most important simplifications are the following:

- All different weight groups are brought together in only 4 different categories
- constant hull cross section in the xy plane above the waterline
- simplified function for the waterplane coefficient depending on the block coefficient
- constant admirality coefficient
- constant freeboard height
- All structural weight is in the hull
- Engine power density is a continuous linear function
- All efficiencies are taken as constant values

Some of these simplifications and restrictions of the SPEC tool make it difficult to conduct a more extensive design analysis with the software. Especially the absence of the possibility to create design that employ more than one energy converter or energy carrier is very limiting when looking at naval vessels. The simplification that is made with regards to the waterplane coefficient and the hull volume also adds a large margin of error which makes it difficult to judge the validity of the design variations and thus the conclusions regarding these design variations.

## 6.3. Input & validation

The original plan to verify the results of the design tool by making a reference design, a design which mirrors the actual design made by the DMO but in SPEC, may not be feasible for the LCF since it uses both a gas turbine and a diesel engine. For the LPD the reference design will likely result in a much lower displacement due to the simplifications made in the waterplane coefficient and the hull shape. This section will examine how large these differences are. The first design that is generated with SPEC is made by supplying the tool with all the needed parameters as they exist on the actual vessel as designed by DMO. The resulting design will be called the SPEC reference design.

### 6.3.1. Air Defence and Command Frigate

For the Air Defence and Command Frigate the largest struggle in generating a representative model lies in the representation of the engine room layout. As mentioned before it is not yet possible in SPEC to account for either the large redundancy, or the combination of different energy converters which is present in the LCF. When considering the extra redundancy is could be expected that the actual weight is higher than the weight suggested by SPEC. On the other hand the peak power is generated by gas turbines which have a significantly lower power density than diesel engines. In equation (6.15) an estimate is done for the actual machinery weight of the LCF, while two different estimates are made in equations (6.16) and (6.17).

$$\begin{aligned} W_{sys,actual} &= P_{inst,diesel} \cdot SP_{g,diesel} + P_{inst,turbine} \cdot SP_{g,turbine} \\ &= (6000 + 11000) \cdot 17.5 + 39000 \cdot 1.5 \\ &= 342\,ton \end{aligned} \tag{6.15}$$

$$\begin{aligned} W_{sys,1} &= P_{inst,diesel} \cdot SP_{g,diesel} \\ &= 55200 \cdot 17.5 \\ &= 966\,ton \end{aligned} \tag{6.16}$$

[3]MARIN and several partners are working on a joint industry project which has similarities to the present project and the results may therefore be useful.

$$
\begin{aligned}
W_{sys,2} &= P_{inst,diesel} \cdot SP_{g,diesel} \\
&= 42000 \cdot 17.5 \\
&= 735\, ton
\end{aligned}
\tag{6.17}
$$

It is obvious that these two estimates are too high. Simply adjusting the installed power to obtain the correct weight is not an option since this will have an influence on the admiralty coefficient and the fuel consumption. Another consequence of the simplifications can be found in the hull volume and construction weight. To acquire the hull volume of the DMO design the FIDES model is consulted. In this 3D model the volumes and weights of different parts of the design can be found. It appears that the hull volume according to the fides model is roughly 20-25% larger than the hull volume calculated in SPEC which has obvious effects on the steel weight.

In order to check whether the reference design is close to the actual design a number of data sources for the design of LCF has been used. The FIDES models, weight calculations, stability booklets and system plans have all yielded the necessary data. The different loading conditions are known, as well as the different SWBS weight groups. The construction and outfitting weight of the hull and the superstructure can be found seperately in the weight reports. The construction weight which scales with the design is only the part of the hull. The outfitting and construction weight of the superstructure are included in the payload as these will remain constant. The payload additionally consists of all other weights that do not fall into the group of either the fuel or the energy converter system. The payload thus consists of several different weight groups that belong both to the lightweight and deadweight such as SEWACO systems, food stores, ammunition, crew facilities and others. The result of the reference model can be found in table 6.1 along with a comparison to the original DMO design. It can be seen that the reference model created in SPEC is not close in the weight to the DMO design. Furthermore, instead of showing a higher system weight than the DMO design the system weight is actually lower. This was found to be due to an error with the import of the technical database in SPEC.

### 6.3.2. Landing platform Dock

For the reference design of the LPD the same approach is taken as with the LCF. The reference design which was obtained can is given in table 6.1. The values in this table require some more explanation than those of the design of the LCF. It can be seen that some of the main dimensions are in principle quite close to the actual design. It can be seen however that there are rather large discrepancies for the construction weight and the system weight.

Table 6.1: Dimensions of the SPEC reference models compared to the DMO model

| | LPD | | LCF | |
|---|---|---|---|---|
| | DMO design | SPEC | DMO design | SPEC |
| Structural weight | 1 | 0.71 | 1 | 0.95 |
| System weight | 1 | 0.17 | 1 | 0.35 |
| Fuel weight contained | 1 | 0.88 | 1 | 1.15 |
| Fuel weight uncontained | 1 | 0.88 | 1 | 1.08 |
| Payload | 1 | 1 | 1 | 1 |
| Displacement | 1 | 0.843 | 1 | 1.129 |

### 6.3.3. SPEC validity

Having made the two reference designs using SPEC and comparing them to the actual DMO designs it is clear that there is quite a large difference. SPEC may still be used to compare different power and energy concepts with the reference models but this does present some problems. The first is the error in the import of the technical database. This error means that a large number of the different concepts simply outputs wrong data. Even if the data would be correct there is no way of translating the effect on the reference design to a potential effect on the real RNLN naval vessels since the reference design does not correspond with the actual design. The structural weight also presents a problem, as well as the system weight for vessels using a hybrid power plant. Together these factors make the results deviate to far from the teal design. It must thus be concluded that the SPEC designtool is currently not suitable for this project.

## 6.4. Improved design algorithm

It is clear that a simplified parametric design approach can lead to substantial challenges. In order to overcome the challenges and limits of the SPEC design algorithm an adapted design algorithm will be developed. The development of a custom design variation algorithm is time intensive but also very useful. The higher degree of customizability allows for the implementation of more variables. The largest challenge in the development is not to overcomplicate the algorithm. Although the goal is to make the method more suitable for large naval vessels, the goal is not to make it suitable only for the two case study vessels. This new algorithm is largely based on the ideas behind SPEC. It is still based on the same idea of expressing all dimensions in one parameter, the vessels beam in this instance, and solving all subsequent equations to find a converging solution. The algorithm will however be expanded somewhat so that the limits found in the previous section can be overcome. The first subsection will focus on the implementation of hybrid configurations into the design tool. The second part will further examine the hull volume and construction weight while the third part looks into the customizability of the technical design data. A short subsection on other minor changes is also added in subsection 6.4.4. There are also some aspects of SPEC that are not included in the adapted design algorithm, these will be quickly considered in section 6.4.5. Since most of the equations behind the SPEC algorithm have not changed these will not be discussed into detail here. In appendix B a complete mathematical description of the design algorithm has been included.

### 6.4.1. Hybrid configurations

The most significant improvement over the previously used tool is the implementation of a hybrid configuration feature. The new approach offers the possibility to select two converters, two energy carriers, and two fuel pre-reformers in any possible combination. This greater freedom does come with added complexity since the code also allows for combinations which may not be possible in reality. The user should thus be cautious when formulating the different experiments. It is important that a converter, carrier and pre-reformer are compatible (e.g. a combination of F-76, a solid oxide fuel cell (SOFC) and an ammonia cracker is not a viable combination, but can be selected in the code). The greater flexibility of the design algorithm also requires more preprocessing of the operational profile. An example of this process is given in table 6.2 below. This example works with a vessel in which two converters are installed as part of a fully integrated electric propulsion system: a 10.000 kW diesel generator and a 2000 kW fuel cell. The fuel cell mainly provides the electric hotel load and propulsion at low speeds. The ICE provides further power needed for propulsion.

Table 6.2: Example of operational profile pre-processing

| Operational point | $P_{prop}$ | E-load | $P_{tot}$ | T | $P_{fc}$ | $P_{ice}$ |
|---|---|---|---|---|---|---|
| 1 | 0 | 1000 | 1000 | 0.25 | 1000 | 0 |
| 2 | 1000 | 1000 | 2000 | 0.2 | 2000 | 0 |
| 3 | 4000 | 1000 | 5000 | 0.15 | 2000 | 3000 |
| 4 | 7500 | 1000 | 8500 | 0.35 | 2000 | 6500 |
| 5 | 10000 | 1000 | 11000 | 0.05 | 2000 | 9000 0 |
| Weighted average | 3925 | 1000 | 4925 | 0.25 | 750 | 3175 |

In this example the average power $P_{avg}$ is 4925 kW and the power ratio of the two converters are

$$r_{P,1} = \frac{2000}{2000 + 10000} = 0.167 \tag{6.18}$$

and

$$r_{P,2} = \frac{10000}{2000 + 10000} = 0.833. \tag{6.19}$$

$$P_{inst} = P_1 + P_2 = P_{prop} + P_{aux} \tag{6.20}$$

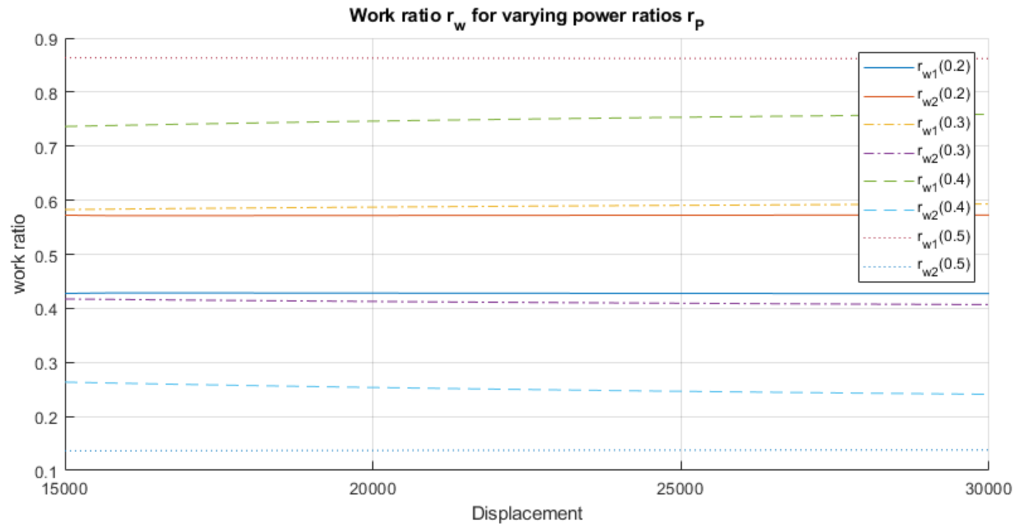


Figure 6.5: The work ratio for the LPD over varying power ratios

The installed power of both machines can be used to determine the machinery weight using equations (B.18) and (B.19). In order to also determine the weight of fuel needed it is necessary to evaluate not the installed power, but the average power which is delivered by each converter. This does require the user to specify a procedure for the application of the power generated by the different converters. In the example in table 6.2 as well as in all the other operational profiles in this experiment the procedure is such that the primary converters uses all its power first before the secondary converter is called upon. This procedure ensures maximum efficiency (if the primary converter is a more efficient fuel cell such as in the example). An example of an alternative procedure would be to supply 90% of the required power with the primary converter and the remaining 10% with an ICE so that rapid changes in the load are more easily accounted for by the ICE which has a quicker load response. For the fuel consumption per converter the average supplied power over the operational profile of the vessel needs to be evaluated. By evaluating the weighted average power per converter as supplied in the table

$$r_{W,i} = \frac{P_{avg,i}}{\sum_{n=1}^{3} P_{avg,n}}. \tag{6.21}$$

the contribution of the different converters is found. This ratio $r_{w,i}$ can then be used in the calculation of the required energy and thus the fuel weight according to equations (B.14) and (B.17). One additional problem surfaces when using this approach. The parameters $r_{P,1}$ and $r_{P,2}$ are set at the beginning of an experiment and remain constant throughout the design algorithm. From equation (6.4.1) however it can be derived that part of the installed power is constant, namely the auxiliary power, while the power needed for the propulsion increases with the vessels displacement:

$$P_{prop} \propto \Delta^{2/3}. \tag{6.22}$$

As the displacement changes this also means that the ratios $r_{W,1}$ and $r_{W,2}$ change. This presents a potential problem since these ratios are manually calculated on a spreadsheet and not in the Matlab script[4]. To judge the magnitude of this effect a comparable operational profile is used and the work ratio of the two converters is plotted over a large range of displacement. In figure 6.5 it is clearly visible that the displacement effect on the changing work ratio is very small for the chosen power ratios. The largest variation that is seen amounts to two percentage point over a twofold increase of the displacement. Given the total accuracy of the design tool at such a large displacement variation the assumption of a constant work ratio $r_W$ between the two converters is possible.

[4]Due to the inability to run Matlab on a company computer and the restriction on using the actual operational profile on a private computer.

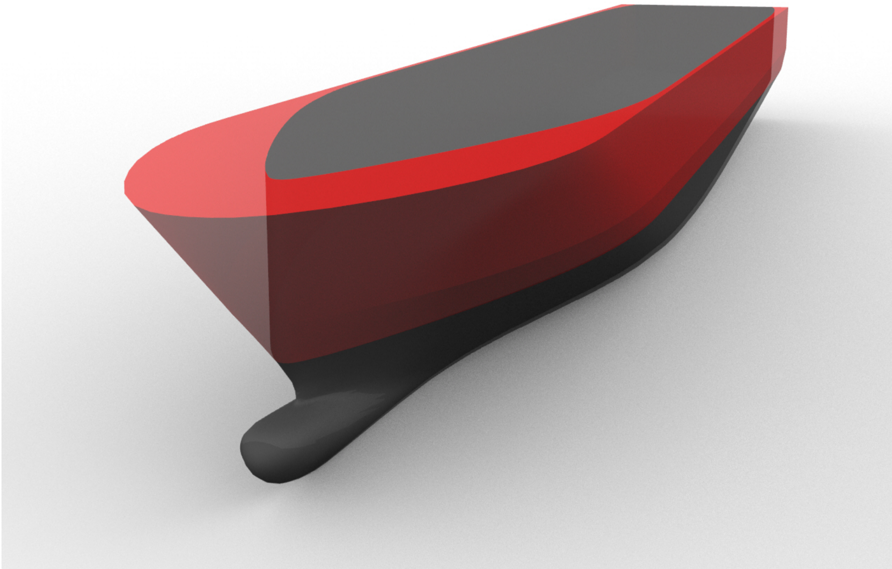

Figure 6.6: A visualization of the flare coefficient on the LPD

### 6.4.2. Construction weight

In section of the previous chapter it was also found that the SPEC tool severely underestimates the hull volume and thus the construction weight of the design. This resulted in an error of as much as 25% of the construction and outfitting weight which corresponds to an error in the range of 10% on the displacement. Since a decrease in displacement has significant consequences for the resistance the fuel and system weight decrease to some degree as well. In the end it is difficult to estimate exactly how large the influence of the smaller hull volume is on the final solution and it was therefore difficult to control for this. In the adapted version of the model this has been solved in two different ways. The first and most significant is the use of a more accurate estimate of the waterplane coefficient. For both case study subjects the waterplane coefficient is known and can thus be used in the design variation. The second measure has been the implementation of the flare coefficient $C_f$. Both can be recognized in the original equation (6.6) which is also shown below.

$$V_{hull} = \frac{\Delta_1}{\rho} + L_{wl} \cdot B \cdot FBD \cdot C_{wp} \tag{6.23}$$

by including a factor $C_f$ this equation is transformed into equation (6.24). The effect of this is to include the hull volume which falls outside the constant cross section. This is visualised for the LPD in figure 6.6.

The flare coefficient itself depends on the hull form and is the ratio of the constant cross section hull volume over the actual hull volume.

$$V_{hull} = \frac{\Delta_1}{\rho} + L_{wl} \cdot B \cdot FBD \cdot C_{wp} \cdot C_f \tag{6.24}$$

The flare coefficient can be visualized in figure 6.6. The flare coefficient for a bulk carrier will be close to one, while the flare coefficient of a faster container vessel is higher than one. For the two case studies the values of the flare coefficient are around 1.05 for the LPD and 1.10-1.15 for the hull of the LCF.

### 6.4.3. Technical data alteration

As the script is now built in matlab the tool also allows for quick alteration of all input variables including the technical parameters associated with the different energy converters, energy carriers, distribution drives and potential pre-formers. This also allows for the inclusion of technologies which were not included in the previously used design tool for whichever reason. A small degree of forecasting how the design implications will change over time as technologies further improve is also possible in this manner. For some technologies it is not unimaginable that they will continue to improve in the coming decades. The power density of certain fuel cell types for instance is expected to improve. The adjustment of these values must have a strong and justified basis however. It is for instance not within the common line of expectations that the energy density of F-76 will increase.

### 6.4.4. Other alterations in the adapted algorithm

Some other minor alterations have been introduced into the adapted design tool. Whereas SPEC used three main weight categories: system weight, structural weight, and payload, the weight groups have been expanded somewhat. The system and fuel weight are separated in the adapted design tool, and the 'payload' weight group is renamed. This is done to avoid confusion, as this weight group is larger than would be expected for just the payload. The categorization used for the weights can be seen in table 6.3.

Table 6.3: Weight groups use in the adapted design tool

| Weight group | Content |
|---|---|
| System weight | Energy converter and auxiliary systems required for energy conversion |
| Fuel weight | Weight of the energy carrier and the containers (i.e. fuel tanks) |
| Structural weight | Construction and outfitting weight of the hull |
| Rest weight | All remaining weight including: operational facilities (including SEWACO), consumables (exluding fuel), personell, accomodations, cargo, superstructure construction; assumed to be constant |

### 6.4.5. SPEC benefits

Although the adapted design algorithm shows considerable promise there are some aspects on which the SPEC tool remains superior. The user friendliness of the Marin developed tool is simply superior and not prone to user error de to its simple layout and straightforward interface. Since the adapted design tool is built in Matlab and uses excel files for the input of technical data and the experiments it is much more prone to user error. Because thee the economic consequences of the design alteration are not the main focal point of this thesis the different economic calculations performed in SPEC are not included or improved upon in the adapted design tool either. Although the economic analysis is very much an important aspect of the problem is a topic deserving a graduation project of its own. The designers of the SPEC tool have already drawn some conclusions with regards to the potential areas of improvement as well, which is also why these will not be examined into more detail. These two points are the most important aspects in which SPEC remains superior. The likeness of the two algorithms also means that the features of the adapted design algorithm may be easily implemented in SPEC in the future. In this sense, the two tools complement each other.

## 6.5. Validation & verification

The adapted design tool will first be verified in a manner similar to that in the previous chapter. The first test of the new model was to approximate the weight groups of the actual design of the LCF and LPD as made by the DMO. In table 6.4 the dimensions of the reference model are given for both the SPEC tool and for the adapted model. The values in the table are normalised in relation to the dimensions of the DMO design.

These results show a significant improvement in accuracy over the SPEC tool. Given the simple data which is used as input the adapted reference models are within an acceptable margin of the DMO designs. This means that the conclusions which are drawn from the following experiments on the reference design will likely be indicative of the consequences of design changes to the real world design as well.

Table 6.4: Verification of reference designs with SPEC and the new adapted design tool

| | Air defence and command frigate | | | landing platform dock | | |
|---|---|---|---|---|---|---|
| | DMO design | SPEC | Adapted | DMO design | SPEC | Adapted |
| Structural weight | 1 | 0.91 | 1.01 | 1 | 0.71 | 0.90 |
| System weight | 1 | 0.35 | 0.98 | 1 | 0.17 | 1.01 |
| Fuel weight contained | 1 | 1.15 | 1.00 | 1 | 0.88 | 1.08 |
| Fuel weight | 1 | 1.08 | 1.00 | 1 | 0.88 | 1.08 |
| Rest weight | 1 | 1 | 1 | 1 | 1 | 1 |
| Displacement | 1 | 1.129 | 1.031 | 1 | 0.843 | 0.981 |

## 6.6. Experiment selection

The different experiments which will be conducted with the adapted design algorithm will be shortly presented here. In total 8 different experiments are conducted. 4 for each case study subject. In chapter 5 it was already established which energy carriers looked most promising. These will now be applied to see what the effects of the overall dimensions on the vessels will be while maintaining the original power plant configuration. This will be the first set of experiments. In addition to the most promising alternatives a selection of the less promising alternatives will also be included in this experiment. In some cases these energy carriers were excluded from the selection based on a perceived negative influence on the vessel effectiveness not directly related to the vessels main dimensions. In these cases it may be different to see the effect that these carriers would have had regardless of their applicability. The lessons learned form this may then be applied to vessels that have a different mission profile which does not rule out these technologies. For the second experiment the power plant configuration will be changed. Two different fuel cell types will be used with different fuels. In the third experiment a hybrid configuration with an ICE and a fuel cell will be used. The variable in this experiment is the balance between both these energy converters. From the sensitivity analysis in section 5.3.1 it appeared that the required maximum velocity may have a large effect on the potential solution space. To explore this effect the maximum speed will thus be changed incrementally in the fourth experiment.

## 6.7. Design variation results

In this section the results of the four experiments will be presented. In addition to the graphs in this section the tables with more data on all the experiments is available in appendix C.

### 6.7.1. Experiment 1: current configuration

In this first experiment a number of different technologies will be compared whilst keeping the operational profile and the power plant layout constant. This means that the operational profile of the vessels as established in the vessels system plans will be used. There is only one problem which must be addressed. The fuel capacity of the vessels is based on the required range at a given speed. This is also how the reference model is made. For the actual effectiveness it is important however to consider the expected operational profile which is much more varied. In order not to stray from the original dimensions of the reference model the endurance for the model using the operational profile is calculated using equation (6.25). The first part of this equation corrects for the difference in the average power which is used. The second part of the equation corrects for the difference in the efficiency of the different prime movers used. This is necessary because the transit operation of the LCF the gas turbine is not used but over the entire operational profile it does perform work. The autonomy which results from this will be used as the autonomy for the design variations throughout the experiments.

$$Aut_{op} = \frac{Aut_{ref} \cdot P_{frac,ref}}{P_{frac,op}} \cdot ((1 - Bias_W) \cdot \frac{\eta_2}{\eta_1} +_w \cdot \frac{\eta_1}{\eta_1}) \tag{6.25}$$

Once the new autonomy is established the different experiments are further detailed. For the LCF the original combined diesel or gas (CODOG) is used with a host of different fuels. Although these converter/energy carrier combinations may not always be optimal (it is very unlikely to happen upon a gas turbine fueled with hydrogen) but do give a clear idea of the potential implications. For the LPD the same is done with the current diesel powered integrated fully electric propulsion (IFEP). The consequences for the displacement can be seen in figures 6.7 and 6.8. The hypothesis that the energy

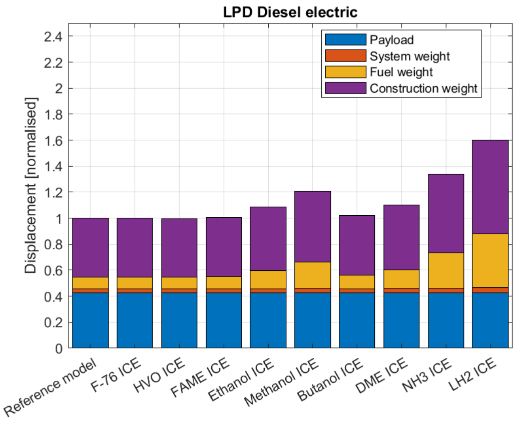


Figure 6.7: LPD: current configuration with different fuels

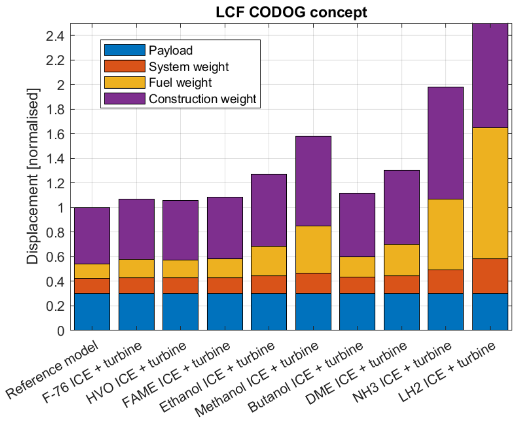


Figure 6.8: LCF : current configuration with different fuels

denser fuels have a smaller effect on the displacement is indeed true. Especially the gaseous fuels which were left in for comparison have a large effect on the increase of displacement. It can also be noted that the increase in displacement is generally smaller for the LPD than for the LCF. This can likely be explained by the relative difference in the contribution of the fuel and system to the total displacement of the vessels. In the fuel and system weight are a relatively large part of the total displacement a 10% increase of the fuel weight will have a relatively large effect on the total displacement which subsequently has a relatively large effect on the increase in required power.

### 6.7.2. Experiment 2: single converter configurations

In the second experiment the current power plant configuration is replaced by a single fuel cell. Both the SOFC and the LT PEMFC have been used for this experiment. This selection is based on the technical characteristics and the readiness of both technologies. In figure 6.9 the first bar on the chart represents the LCF not in its current configuration but in a configuration with only a diesel engine as an energy converter. Note that the displacement is only marginally (<5%) than the displacement with the conventional configuration. Although the system weight has increased by almost 50%, the higher efficiency significantly lowers the weight of the fuel which is taken on board. When considering the fuel cell configurations it appears that the lower power density of the fuel cells in combination with the fuel preformers increases the displacement and the installed power enormously. Although the accuracy of the exact results can no longer be guaranteed since the limits the constant admiralty coefficient are no longer respected. When approaching a displacement of 5 times the original the length of the vessel would have increased by about 70%. This means that instead of approaching a Froude number of 0.4 at the maximum velocity, the Froude number and the relative resistance would be lower which would dampen the effect on the displacement. However, it may be clear that even with a large margin of error, the increase in displacement would be consequential for the design and operating cost. Due to the high power requirement and the high system weight relative to the total displacement the increase in displacement when using only a fuel cell would be enormous. The results for the LPD are much less unfavourable as can be seen in figures 6.10 and 6.11. The combination of a limited maximum velocity and a relatively low contribution of the system weight to the total displacement limit the weight increase. It can be seen for instance that the displacement of a methanol fuelled LPD with an ICE is only about 5% lower than that with a LT PEMFC. Additionally the application of the SOFC also looks more promising. Although the total displacement increases somewhat (+-2%) the needed fuel decreases by 15%. This means that although the vessel is slightly heavier, it uses less fuel. For the LCF this effect was much smaller than the increase in the weight of the system. It should also be observed that the application of a LT PEMFC generally does not lead to a decreased fuel weight when an energy carrier that requires a preformer is installed due to the preformer efficiency.

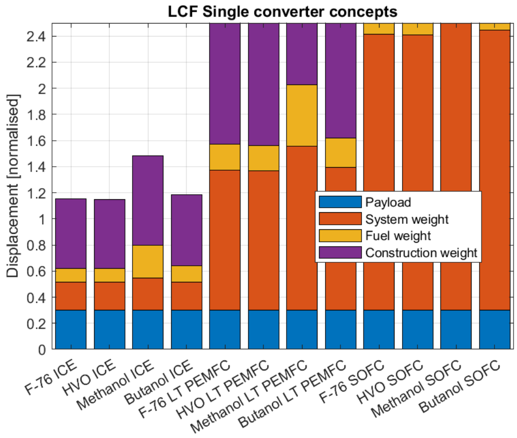


Figure 6.9: LCF fuel cell configurations

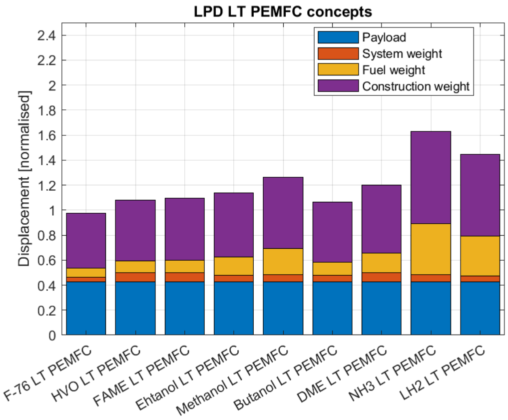


Figure 6.10: LPD: low temperature PEMFC

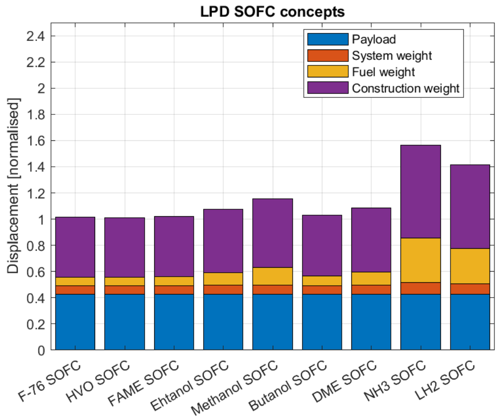


Figure 6.11: LPD: SOFC

### 6.7.3. Experiment 3: hybrid configurations

In the third experiment another configuration is tested. A hybrid power plant with an ICE and a fuel cell. The balance of these two systems is systematically varied so that the effect of different combinations is visible. For both the LPD and the LCF the experiment is executed using both methanol and butanol. It can again be observed that the influence of a low power density fuel cell is much more pronounced on the frigate design than on the LPD which is in line with the conclusions which have been drawn so far. On the figures on page 77 it can be observed that for the LPD there appears to be an optimum ratio $r_{P,fc}$ where the nett displacement is reduced. This can be explained by the increase in efficiency which leads to a lower fuel weight. For some energy carriers and $r_{P,fc}$ ratios this outweighs the increase in system weight. For the configuration fuelled with methanol this occurs at $r_{P,fc} = 0.65$ while for butanol it occurs around $r_{P,fc} = 0.35$. Additionally, the reduction in displacement compared to the $r_{P,fc} = 0$ case is much larger for cases with energy carriers that have a low energy density. The displacement at the optimum $r_{P,fc}$ in the methanol case is 94% of the displacement at $r_{P,fc} = 0$, while the displacement of the optimum using butanol is 98% of the $r_{P,fc} = 0$ point. In the case of butanol however, this small reduction in weight does allow the vessel to be marginally smaller than the reference design. For the LCF it is clear that any significant $r_{P,fc}$ as part of a combined fuel cell and internal combustion engine (COFAICE) system is unlikely to result in efficiency gains which outweigh the increased system weight. The high required power and relatively high system and fuel weight compared to the total displacement lead to a sharp increase of required power.[5] The optima can be illustrated more clearly when plotting the weight separately which is done in figures 6.14 and 6.15.

[5]A difference between the hybrid concept with $f_{P,ICE} = 1$ and the single converter concept with an ICE can be observed, this is because the former is a diesel electric configuration, while the latter is a geared configuration.

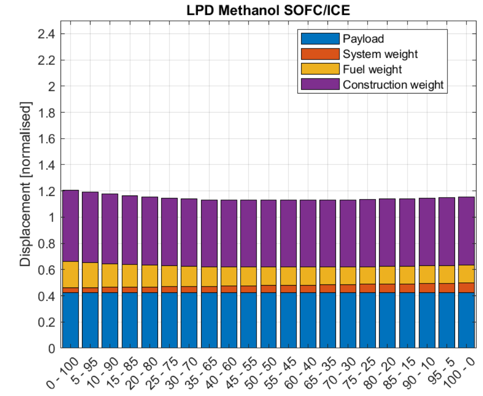


Figure 6.12: LPD: Hybrid methanol configuration

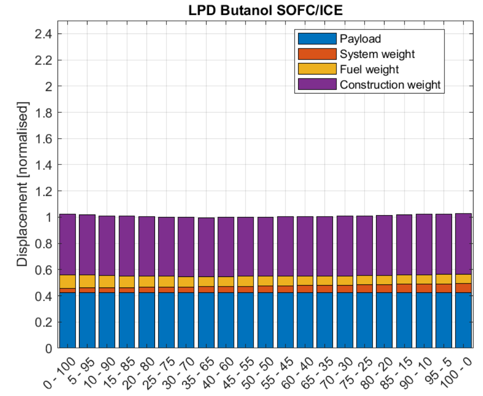


Figure 6.13: LPD: Hybrid butanol configuration

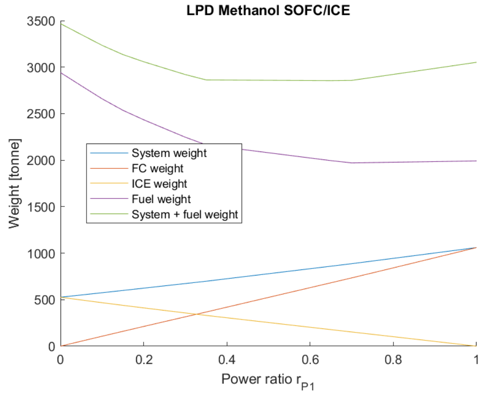


Figure 6.14: LPD: Hybrid methanol configuration

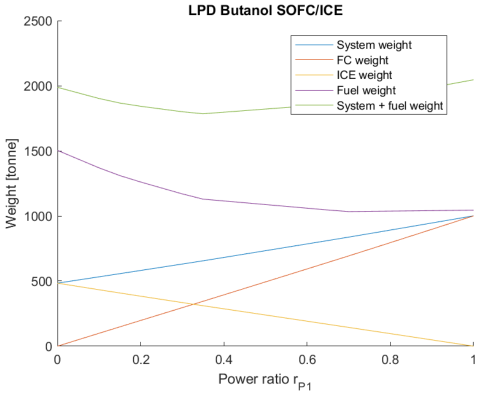


Figure 6.15: LPD: Hybrid methanol configuration

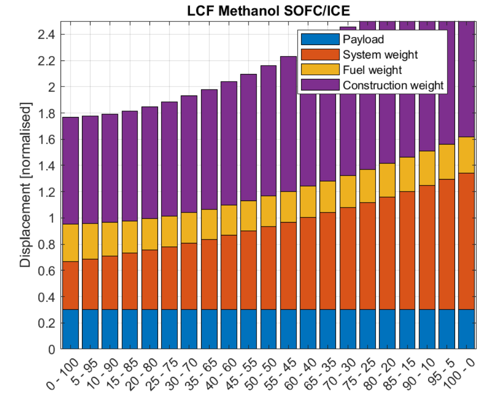


Figure 6.16: LCF: Hybrid methanol configuration

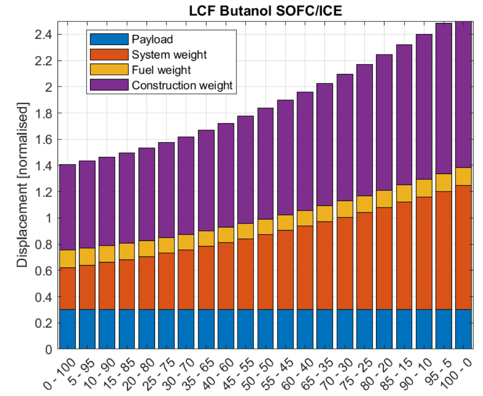


Figure 6.17: LCF: Hybrid butanol configuration

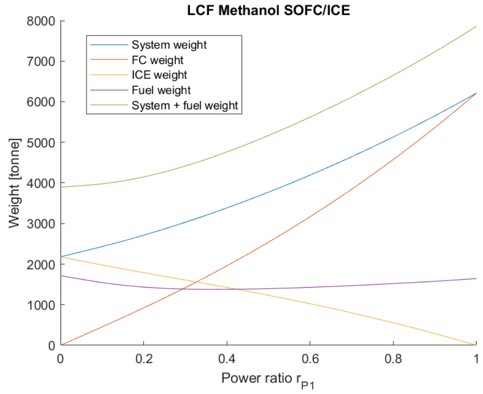


Figure 6.18: LCF: Hybrid methanol configuration

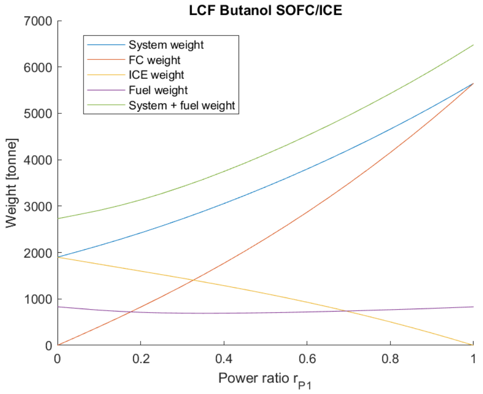


Figure 6.19: LCF: Hybrid butanol configuration

### 6.7.4. Experiment 4: Profile variation

So far quite a stark difference between the LCF and the LPD has been observed. This is likely due to a combination of factors, but the fact that the admirality constant of the LCF is so much lower and the required power thus much higher is one possible explanation. In the previous chapter a sensitivity analysis was already conducted into the required speed of the vessel and it was expected that a lower required top speed would greatly reduce the influence which a switch to alternative energy carriers would have. In order to validate this, the influence of the required speed the maximum velocity of both vessels will be varied in the parametric model as well. This experiment is conducted using two configurations for both vessels. For both vessels the experiment will be conducted with a hybrid 20-80 configuration using methanol and a LT PEMFC as the first configuration, a methanol hybrid 50-50 configuration as the second and a butanol ICE as the third configuration. Since the sensitivity analysis in the previous chapter also pointed in the direction of the maximum vessel speed as an important factor it may be that this experiment will indeed lead to some interesting results.

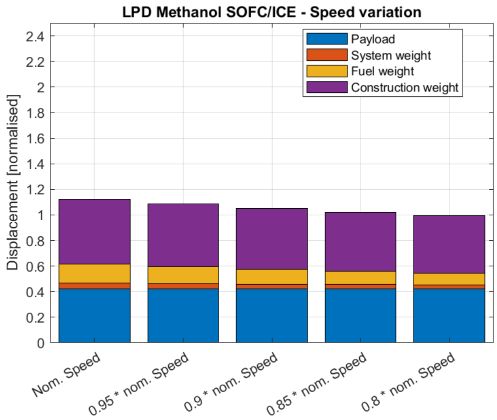


Figure 6.20: Variation of operational profile with 30-70 methanol hybrid configuration

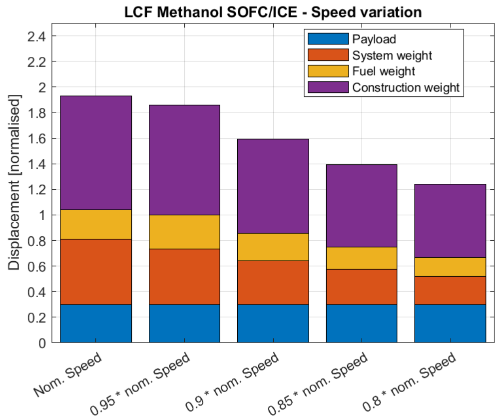


Figure 6.21: Variation of the operational profile of the LCF with 30-70 methanol hybrid configuration

## 6.8. Validation

In the paper *Potential of COFAICE for naval ships* Sapra et al [35] employ a similar method to look at the feasibility of a hybrid system of fuel cells and ICEs for naval vessels. In the paper two cases are considered: a large surface combatant and a landing platform dock. Given the similarity between the cases in the paper and the cases in this research project the results can be used for validation and discussion. It must be noted that the cases are not entirely identical. The landing platform dock in the paper has a total installed power of 22.000 kW while the case study subject, the 'Johan de Witt' has an installed power of 14.800 kW, but the configuration is the same for these two. The surface combatant in the paper has a similar installed power but differs in the configuration. There is a total of 4000 kW of installed auxiliary power, compared to 6000 kW in the *Zeven Provincien* klasse LCF. The LCF meanwhile has 11000 kW of power for the propulsion diesels and 36000 kW of power with the gas turbines, but only one of these run at the same time. The High-end Surface Combatant has 30.000 kW of gas turbine power and 8.000 kW of diesel power which can be used at the same time. The paper subsequently considered LNG as a fuel. Although LNG is not considered in this project since it is a fossil fuel, LNG as an energy carrier can be implemented in the model for validation purposes. For the LPD in the paper it was found that there is an optimum power split at $r_{P,1} = 0.55$ as can be seen in figure 6.25 from the paper.

From the comparison in the two figures it appears that there is a similar trend. In the paper the optimum was found to be around 55% load sharing, while with the adapted design algorithm the optimum appears to be around 35-40%. This difference is due to the variation between the two vessels, but also due to the operational profile. As the author confirms[6] this is likely due to the difference in the operational profile. From figure 6.25 it is also visible that the system weight is almost constant between 20%

[6]In e-mail correspondence with Dr. Sapra he confirms that the operational profile has an important influence on the optimum load sharing percentage.

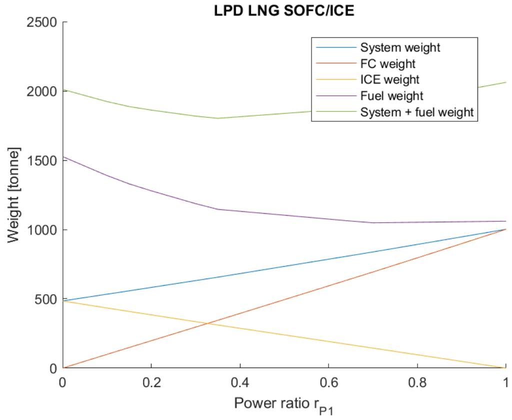


Figure 6.22: System and fuel weight for the LPD in this project

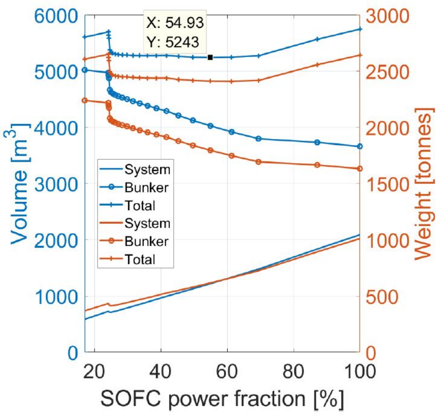


Figure 6.23: System weight for the LPD in the paper by Sapra [35]

and 70% loadsharing. This most likely means that small differences in the operational profile quickly move the optimum within that range. It was also found that at this optimum load sharing percentage the system weight was almost double that of the configuration in which no SOFC is present. When considering a load sharing percentage of 50% in the adapted design algorithm the system weight is close to double the weight of the reference design. The steeper incline of the system weight in figure 6.25 is likely due to the different weight contributions that are included in the system weight. In the design tool presented in this project a significant quantity of auxiliary equipment is included in the system weight. This has as an effect that the relative difference between the power density of an SOFC and an ICE is smaller than in the paper where just the converters themselves are included. When weighing the similarities and differences against each other it seems that the results point to the same broader conclusions.

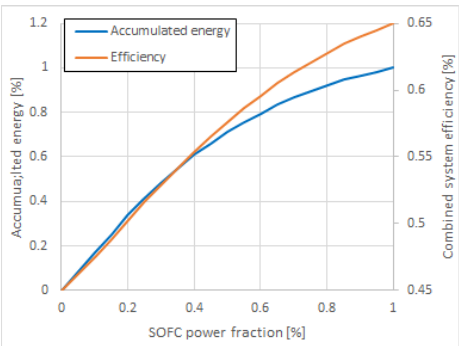


Figure 6.24: System and fuel weight for the LPD in this project

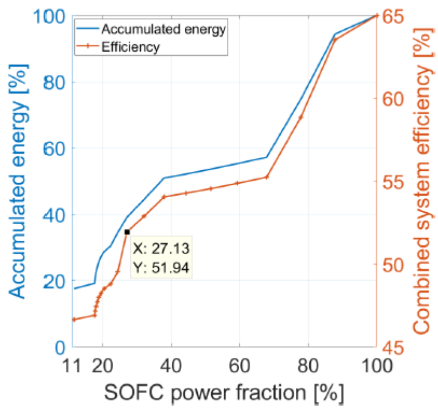


Figure 6.25: System weight for the LPD in the paper by Sapra [35]

The results for the LCF and the High-end surface combatant can also be compared. The results of the paper and this research project are more divergent than with the LPD. After careful consideration it appears that there are three major factors contributing to this. The first is that the authors of the discussed paper have looked at the operating points of the various converters in more detail instead of using a constant efficiency. Also included are the potential efficiency gains that are achieved by using a gasdrive system in which the anode off gas of the fuel cell is combined with the LNG which fuels the ICE. This may lead to an efficiency increase of 5%-8% for the combined system [35]. Although the efficiency curves in figure 6.22 and 6.23 do not have the same shape (due to differences in the operational profile), they do fall within the same range and there are no large discrepancies. The second big difference is in how the size f the vessel and the drive configuration is included in the calculations. In the adapted design algorithm a increase in weight inevitably leads to an increase in resistance (as illustrated in figure 6.1. It is not clear whether the authors of the paper have looked at the vessel as a whole, or just at the power generation configuration. When it is not the power generated by the various converters that is maintained constant, but the power delivered to the consumers (i.e. the propellers and the hotel load) the efficiency of the distribution drive has to be included. When the configuration changes from a geared drive to an electric drive the transmission efficiency in some of the operational points is reduced. It is not clear whether the authors have included this effect in the paper, but it seems likely that this at least partially explains why the conclusions regarding the LCF and the HSC do not align.

## 6.9. Conclusion

In this chapter a parametric design variation was employed to get a better understanding of the influence that different energy carriers and energy converters have on the different ships in the case study. The design algorithm has been developed specifically for this purpose but is largely based on Marins SPEC design tool which is developed with the same aim. Using the developed design algorithm a series of 4 experiments has been conducted on both case study subjects. It was immediately clear that the consequences for the displacement of the LCF are much more severe than for the LPD when using alternative energy carriers and energy converters. Both due to the higher speed requirements and the relatively large fuel and system weight the designs with fuel cells and energy carriers with a low energy density quickly increased the displacement of the LCF by anything between 50% and 500%. For the LCF the application of a fuel cell does not seem to reduce the reduce the displacement when compared with the use of ICEs. The use of alternative energy carriers also appears to have a very drastic impact on the vessels size. Proper integration of a GasDrive system using a high density energy carrier may result in a net reduction of fuel consumption for the LCF. This means that the only suitable candidate at the moment is butanol. For the LPD it seems that there is a benefit to using a hybrid configuration composed of a SOFC and an ICE. Although the use of methanol as a fuel leads to an increase in displacement this increase is much smaller than with the LCF. Using a combination of a SOFC and ICE may further reduce the displacement increase and reduce the nett fuel consumption of the vessel. The optimum ratio $r_{P,fc}$ for the landing platform dock is around 35% for butanol, and 65% for methanol. There does not seem to be an optimum $r_{P,fc}$ for the LCF in the configurations which were initially examined. In order to limit the system weight while maintaining the vessels high top speed it is likely that an alternative design will be a configuration with a gas turbine, a reciprocal engine and possibly a fuel cell. The influence of low energy density fuels on the total displacement of the LCF were also shown to be drastic. It is thus most likely that either bio-fuels such as HVO, or synthetic fuels such as butanol may be applied.

## 6.10. Discussion

In this chapter it was shown that changing the energy carriers and converters on a vessel may have profound implications for the main dimensions of those vessels, and it was also shown that there the quantity of those effects can greatly differ between vessel types. It was also apparent that some modelling decisions must be made which can greatly influence the accuracy and applicability of such a tool. The SPEC tool which is developed by MARIN for instance is a very simple tool which generates a large quantity of output with a minimal amount of input data. Such a tool can be very useful when looking at general relations and dependencies in ship design but when narrowing the scope its usefulness quickly diminishes. The adapted design algorithm which was developed for the purpose of this thesis is a next step up. With more freedom in the design input it is possible to achieve greater accuracy for the vessel types which are considered here. In section 6.8 it became apparent that another step in accuracy can be achieved by considering the different operating points of the individual energy converters instead of using constant values for a converter. More specific input information is needed for this step again and while the accuracy increases the range of different vessels to which the model is applicable also decreases. From the results of the two LPD cases it appeared that the model in the paper by Sapra [35] does not diverge far from the results in this project. When the design becomes more critical and the margins become smaller the added accuracy is seems to make a large difference as was seen in the comparison of the LCF and the high-end surface combatant (HSC).

# 7

# Concept Design

The previous chapters resulted in a clear indication of the expected results with regards to the main dimensions of the two case study subjects. Other than the main dimensions no detailed consequences have been examined so far. This chapter will delve deeper into the specific, technical functioning of the vessels and how the adaptation to different power generation concepts affects the operational effectiveness. Consequences that may not have been directly clear from the result of the parametric study will be examined in this chapter. For each of the two case studies, the most promising concepts from chapter 6 are further refined so that a more detailed design is obtained. For the LPD a COFAICE configuration operating on methanol was found to have significant but manageable effect on the displacement of the vessel and will therefore be examined in this chapter. There was not such a clear preference for the LCF. Low energy density fuels were found to lead to a direct ad high increase of the displacement. Butanol would then be a promising alternative[1] and will therefore be used in this chapter.

The first section of this chapter is aimed at further refining the power generation and propulsion concept and an initial power plant configuration will be presented for both vessels.

Section 7.2 aims to make an initial evaluation of the feasibility of a general arrangement using the proposed configuration by examining the volume needed for all the different spaces of the vessel.

The proposed power plant designs differ from more conventional configurations in multiple ways. Safety concerns are amongst these differences and these will therefore be evaluated in section 7.3.

The eventual goal of the proposed design alterations is to achieve a significant reduction in fossil fuel consumption and exhaust gas emissions. The effect of the separate technologies on exhaust gas emissions has already been established in chapter 3, but section 7.4 will quantify the combined effects of the proposed configurations.

In section 7.5 the prioritization of the different MoEs which was made in chapter 5 is used to qualitatively evaluate the operational effectiveness of both proposed designs before finishing this chapter with the conclusion.

## 7.1. Power plant configuration

The parametric design variation resulted in the main dimensions and an indication of what the power plant configuration will look like, but no physical representation of the configuration has been made yet. Nuances in the design decisions may have far-reaching consequences on the achieved efficiency, system weight, and reliability. In this section, a proposed configuration for the power plants of the LPD and LCF will be presented.

### 7.1.1. Landing platform dock power plant configuration

The selected configuration for the LPD is a COFAICE system. In the previous chapter it was determined that there is no clear optimum for the ratio $r_{P,1}$ when solely considering displacement. In figure 7.2 this is again shown. The trade-off between these options primarily seems to be between OPEX and CAPEX.

[1]Although availability and cost are still a problem.

Similar to the paper by Sapra [35], the optimum with the smallest total displacement will be selected. In table 7.1 the two optimal points are shown together with the reference design and a ICE driven methanol fuelled design.

Table 7.1: Changes in weight and installed power of three concepts compared to the reference model

| | Reference model | ICE methanol | Design 1 | Design 2 |
|---|---|---|---|---|
| $r_{P,fc}$ | 0 | 0 | 0.35 | 0.7 |
| Displacement | 1 | 1.21 | 1.13 | 1.13 |
| System weight | 1 | 1.10 | 1.46 | 1.85 |
| Fuel weight | 1 | 2.20 | 1.62 | 1.48 |
| Construction weight | 1 | 1.21 | 1.13 | 1.13 |
| Installed power | 1 | 1.10 | 1.06 | 1.06 |
| Installed power | 14800 | 15942 | 15430 | 15426 |
| Fuel cells | 0 | 0 | 5400 | 10798 |
| ICE's | 14800 | 15942 | 10029 | 4628 |
| Pods | 11000 | 12142 | 11630 | 11626 |
| Speed on fuel cells [kts] | 0 | 0 | 12.17272 | 16.52098 |

The power plant configuration will resemble the schematic illustrated in figure 7.1. As the installed power has increased by 4% compared to the reference design the installed power is now roughly 15.400 kW which of which the fuel cells supply 5400 to 10800 kW and the ICE the rest. Since the vessels displacement has increased, the resistance and thus the necessary delivered power to the pods also increases as can also be observed in table 7.1.

There is still freedom in the exact number of fuel cells and ICEs. The low capacity of individual fuel cells warrants the use of a high number of fuel cells for this design. The current maximum capacity of a single fuel cell module lies around 300-500 kW [52]. This means that between 10 and 20 modules must be installed for the first design, and 20 to 35 for the second design. This large number presents both challenges and opportunities with regards to the layout. It is also possible to determine the maximum

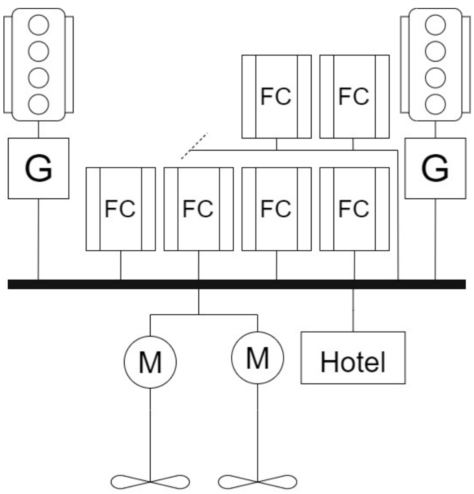


Figure 7.1: LPD power plant configuration

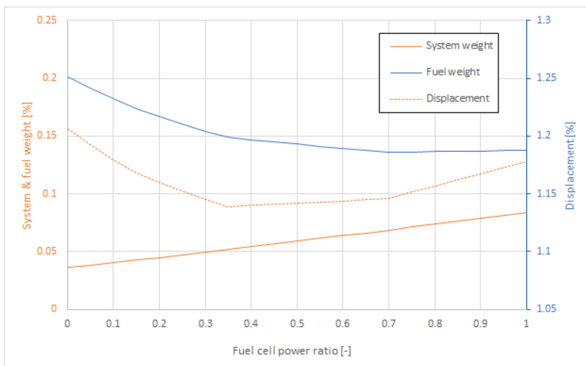


Figure 7.2: LPD power plant configuration

achievable speed while sailing solely on fuel cell power by rewriting equation 6.12 into equation (7.1) and (7.2)

$$V_{fc,max,1} = \sqrt[3]{\frac{(P_{fc} - P_{aux}) \cdot C_{adm}}{\Delta^{\frac{2}{3}}}} \approx 12kts \tag{7.1}$$

$$V_{fc,max,2} = \sqrt[3]{\frac{(P_{fc} - P_{aux}) \cdot C_{adm}}{\Delta^{\frac{2}{3}}}} \approx 16kts \tag{7.2}$$

which leads to maximum speeds of roughly 12 and 16 knots for the two proposed configurations.

### 7.1.2. Air Defence and Command Frigate power plant configuration

The configuration for the LCF is somewhat more complicated. Due to the large negative effect of low power density energy carriers and energy converters, it was established that in order to maintain the required top speed of 29 knots without an excessive increase of displacement, the gas turbines in the installation must be preserved in the proposed design. Although there was no clear optimum load sharing ratio $r_{P,1}$ from a displacement point of view, a combined configuration using fuel cells, ICEs and gas turbines are proposed. In this way, a design with a higher fuel economy can still be explored. One of the problems of the parametric design tool was that it is difficult to consider all the different possibilities there are with regards to the configuration of a more complex power plant. In figures 7.3 through 7.6 the current and the different proposed configurations are shown. In all the proposed configurations a fraction of the power otherwise generated by an ICE. Configuration 1 in figure 7.4 would stay the closest to the current configuration. The main difference between the four configurations shown is the implementation of electric propulsion. The higher transmission efficiency of a geared transmission increases the total efficiency at high speeds when the engines are operating in design conditions. In off-design conditions however an electric transmission may be more efficient. Engine efficiency quickly decreases in part-load conditions, but the generator set in an electrical propulsion system can always operate at nominal speed. The current and the first proposed configuration show a CODOG propulsion configuration. Due to the fact that the ICE in proposed configuration 2[2] is replaced by a generator set and electric motors, this also means that both the reciprocating engine and the turbines can deliver propulsive power at the same time without the need for more intricate and complex gearboxes. This means that the gas turbine can be smaller in size and that the total system efficiency at top speed increases since the inefficient gas turbines have a lower energy ratio $r_E$ (see equation B.16). Both configuration 2 and 3 also allow the vessel to sail while operating only the fuel cells and electric motors which dramatically reduces the acoustic signature. Depending on the actual power ratio $r_{P,fc}$ that is

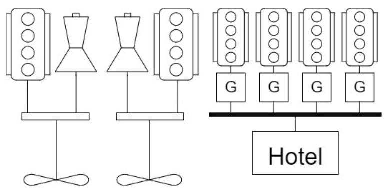


Figure 7.3: LCF current CODOG configuration

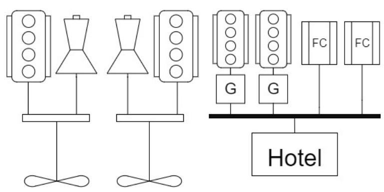


Figure 7.4: LCF proposed Configuration 1: CODOG + FC

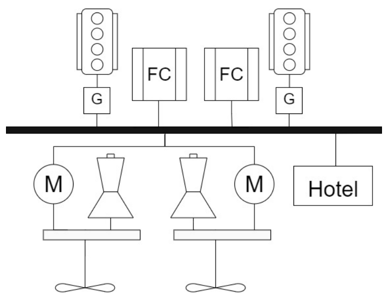


Figure 7.5: LCF proposed Configuration 2 CODLAG + FC

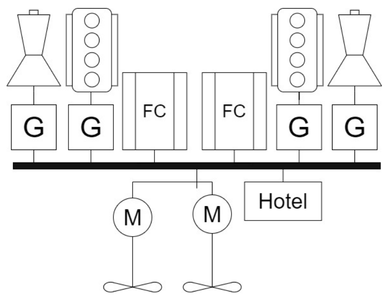


Figure 7.6: LCF proposed Configuration 3: IFCFEP

selected, configuration one is of limited use as the maximum output power of the fuel cell is lower than the installed auxiliary power in this configuration. It also does not offer the benefit of silent operation, and

[2]The naming convention becomes a bit complex when fuel cells enter the equation. Although COFAICE covers some instances, abbreviations are more likely to complicate than facilitate matters when speaking of a system comprised of fuel cells, reciprocating engines, gas turbines and electric motors of which some have a geared transmission and others an electric transmission in addition to the choice to either operate them together or one at the time.

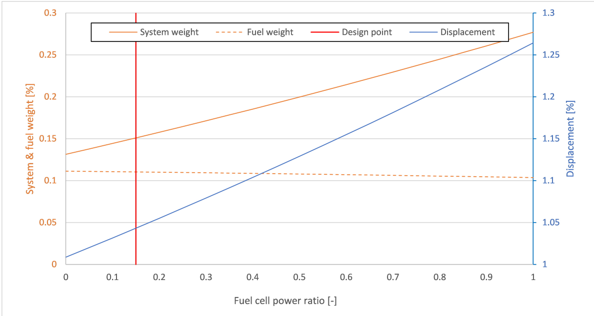


Figure 7.7: Displacement, system & fuel weight as percentage of reference design displacement

a higher fuel economy would be its only benefit. The second configuration benefits from the fact that it can sail on the electric power of the fuel cells and ICEs. The geared gas turbines subsequently provide propulsive power for higher speeds. The final proposed configuration is configuration three, which is an IFEP configuration where all energy converters supply electric power and the propulsion is supplied by electric motors. One of the benefits of such a system is that no complex shaft or gearbox arrangements are required and there is a high freedom with regard to the placement of individual components. The total system efficiency will be lower than that of the second system however, as the gas turbines are not directly delivering their power to the propellers. It is readily apparent that for the same power split, many different design possibilities still remain. Although these choices influence many different properties of the vessel this project is not about the best possible configuration, but the influence of the application of different energy carriers and converters. To be able to use the full potential benefits of a fuel cell configuration concept 3 and 4 as proposed will be used for the remainder of this chapter. Of the two, the configuration in figure 7.5 is more optimized towards high vessel speeds whilst the configuration in figure 7.6 may be better suited to a highly varying on board energy demand[3]. Although these configurations were not extensively tested in the parametric variation due to limitations in the model it may still be interesting to consider their implications for the operational effectiveness of the vessel. In figure 6.8 it was shown already that the use of any but the most energy dense fuel would result in dramatic increase in the displacement. This is without even considering the application of the three configurations discussed above. Given these facts the energy carrier considered for this application will be butanol. Configuration 2 in figure 7.5 will be used for this analysis. In figure 7.7 the development of the weight of different components is presented. As mentioned earlier there is a considerable margin with the exact system weight as the parametric design tool is not suited for the complex configurations which are necessary for the frigate. The figure nonetheless shows the development of the weight when a larger portion of the power is delivered by a fuel cell. For this configuration, three different design points are selected for further assessment. These design points are at $r_{P,fc} = 0.15$, $r_{P,fc} = 0.3$ and $r_{P,fc} = 0.45$ respectively. It must be noted that in this case the power ratio does not include the gas turbine and thus denotes the power split between the reciprocal engine and the fuel cell (and thus not the gas turbine). Since large fuel cell power ratios were found to have an unfavourable influence on the vessels displacement only lower power ratios are selected here. This will allow for assessment of the influence on operational effectiveness whilst limiting the negative influence on the displacement.

## 7.2. Payload carrying capacity

To judge whether all the systems of the current vessel will fit in the proposed designs it is important to consider the spatial arrangement of these systems within the vessels. In the parametric design variation of the previous chapter the algorithm was primarily driven by the total vessel displacement and weight of the different systems and components. Although the algorithm does calculate the theoretical system and fuel volumes, these were not used as objectives in the mathematical solver. The simple fact that the displacement of the vessel is sufficient to accommodate the weight of the payload, system, fuel, and construction does not mean that all components spatially fit within the vessel. The density of methanol is lower than the density of F-76 and for SOFCs the gravimetric power density is not only lower than for ICEs, the volumetric power density also is. Although it would be ideal at this stage to make a detailed

[3]possibly for the use of direct energy weapons or charging of batteries and super capacitors.

Table 7.2: proposed designs for the LCF

| | Reference model | Design 1 | Design 2 | Design 3 |
|---|---|---|---|---|
| $r_{P,fc}$ | 0 | 0.15 | 0.3 | 0.45 |
| Displacement | 1 | 1.03 | 1.08 | 1.12 |
| System weight | 1 | 1.19 | 1.41 | 1.58 |
| Fuel weight | 1 | 0.95 | 0.94 | 0.93 |
| Construction weight | 1 | 1.03 | 1.08 | 1.12 |
| Installed power | 1 | 0.87 | 0.89 | 0.91 |
| Installed power [kW] | 53000 | 46680 | 47922 | 48879 |
| Fuel cells [kW] | 0 | 1497 | 4611 | 7055 |
| ICE [kW] | 17000 | 13476 | 10760 | 8623 |
| GT [kW] | 36000 | 31707 | 32551 | 33201 |
| EM [kW] | 0 | 10973 | 11371 | 11678 |
| Speed on fuel cells [kts] | | 0 | 10 | 14 |

layout design and consider how different spaces interact to see whether or not all objects fit, this is a cumbersome process. In the layout design of complex vessels the devil is in the detail and it is therefore not achievable in this project to generate a complete general arrangement. In order to judge whether or not the systems fit in the design a more high level volume analysis will be performed. In this procedure the dimensions of the adapted designs will be used. These are shown in table 7.1 and 7.2.

In this volume analysis the total enclosed volume of the proposed vessel designs will be compared to the sum of the volumes of all individual components. For the volume analysis the hull is scaled up by the same factor as the displacement provided in tables 7.2 and 7.1 to obtain the larger vessel while maintaining a constant hull shape. This leads to the following mathematical description of the enclosed hull volume:

$$V_{enclosed,2} = V_{hull,1} \cdot \frac{\Delta_2}{\Delta_1} + V_{superstructure}. \tag{7.3}$$

To obtain the volume and the purpose of different spaces in the original design the general arrangement plan and the FIDES models are used. There are 4 main categories for which the volume needs to be determined:

- Propulsion & power generation
- Fuel storage
- Payload volume (operational rooms, accommodation, cargo space)
- Auxiliary spaces (workshop, hallways, HVAC, auxiliary systems)

From the volumetric power densities found in chapter 3 and the installed power the volume of the system in de new designs can be obtained. However, this represents the volume of the converters, pre-reformers and auxiliary equipment which is not the same as the volume of the spaces which need to fit onboard. The machinery spaces around the equipment are not included in this. In order to get an indication of the required size of the equipment rooms the volume of all spaces related to propulsion & power generation in the original DMO model is multiplied by the ratio between the volume of the systems of the reference model and the proposed model.

$$r_{v,sys} = \frac{V_{sys,2}}{V_{sys,1}} \tag{7.4}$$

Where:

$V_{sys,1}$ is the system volume from the reference model
$V_{sys,2}$ is the system volume from the proposed model

$$V_{space,2} = V_{space,1} \cdot r_{v,sys} \cdot f_{c1} \cdot \frac{1}{f_{c2}} \tag{7.5}$$

Where:

$V_{space,2}$ is the total volume of the machinery spaces int he proposed model

$V_{space,1}$ is the total volume of the machinery spaces of the FIDES model
$f_{c1}$ is a correction factor for layout differences between systems
$f_{c2}$ is a measure for the fill rate of machinery rooms

The factor $f_{c1}$ is a proposed correction factor which can be used to account for the differences in layout design that result from different systems. When this factor is equal to 1 it is the assumption that a machinery space with a fuel cell needs the same amount of space as a machinery space with a ICE. This is space that may be used for auxiliary equipment, safety equipment, space for easy access during maintenance or other activities. For now this factor is assumed to be equal to 1. The factor $f_{c2}$ is a similar factor which is used to indicate the fill rate. The fill rate of the machinery rooms on the LPD is much lower than that of the machinery rooms on the LCF and a higher fill rate results in a lower machinery space volume for the same power. For the fuel, a similar ratio can be determined:

$$r_{v,fuel} = \frac{V_{fuel,2}}{V_{fuel,1}}. \tag{7.6}$$

In the two following subsections the ratios $r_{v,sys}$ and $r_{v,fuel}$ will be determined for both case study subjects. Subsequently, a comparison is made between the total enclosed volume, according to (7.2), and the sum of the volumes of all the system categories to evaluate the effect on the volumetric payload capacity.

### 7.2.1. Landing Platform Dock internal volume

For the LPD the total enclosed volume of the vessel has increased by roughly 10% (the hull volume increases by 13% and the superstructure volume remains constant) for both proposed designs. Using the volume of the system and fuel from appendix C and equations (7.2) and (7.2) the volumes of the system and fuel for both designs are calculated and presented in table 7.3. Apart from the system and fuel some of the other values change, while some remain constant. The ballast capacity for example has to increase by 13%, the same as the increase in the displacement in order to retain the docking capability and submerge to the correct draught.The volume needed for auxiliary equipment, accomodation, operational spaces, and payload does not change. Table 7.3 shows the results of this quick comparison and it is readily apparent that although the vessel meets the requirements of the payload weight, there is not enough space on board the vessel to place all the necessary components.

Table 7.3: Volumes of different spaces in the LPD (relative to the total volume of the reference design)

| | Reference | Design 1 | Design 2 |
|---|---|---|---|
| $r_{P,fc}$ | 0 | 0.35 | 0.7 |
| $r_{v,sys}$ | - | 1.93 | 2.8 |
| $r_{v,fuel}$ | - | 1.74 | 1.58 |
| Total encolsed volume | 1 | 1.09 | 1.09 |
| Ballast | 0.06 | 0.08 | 0.08 |
| Auxiliary | 0.15 | 0.15 | 0.15 |
| Accomodation | 0.19 | 0.19 | 0.19 |
| Payload & operational spaces | 0.50 | 0.50 | 0.50 |
| Fuel | 0.013 | 0.02 | 0.02 |
| Systems | 0.09 | 0.17 | 0.25 |
| Required volume | 1.01 | 1.12 | 1.19 |
| Deficit | 0.01 | 0.11 | 0.20 |

The deficit[4] in the bottom row is the difference between the required volume and the enclosed volume of the vessel. In order to fit in the required volume, the payload carrying volume would have to be decreased by $1 - \frac{0.5-0.11}{0.5} = 22\%$ and $1 - \frac{0.5-0.20}{0.5} = 39\%$ respectively for the two design shown here. To maintain the operational effectiveness the cargo volume will have to be maintained as well. This means that the vessel will have to increase in size. This will again lead to an increase in the steel

[4]There is a small discrepancy between the required volume and the enclosed volume since one is sourced from the FIDES model and the other from the reference model of the parametric design tool which is a simplified representation of the real design.

weight. Using the following equation it is seen that for the first design the vessel displacement will increase by another 3 percentage point to 1.16 times the original displacement to satisfy not just the condition of equal payload weight, but also payload volume.

$$\Delta_1' = \Delta_1 + V_{deficit,1} \cdot SWL = 1.13 + (\frac{V_{encl}}{0.11} \cdot 0.11)/V_{encl} = 1.13 + 0.01 = 1.14 \quad (7.7)$$

In the instance of the first design this only adds another percentage point to the displacement. For the second design the deficit in the volume is larger and will thus lead to an increase in the displacement of 7 percentage point. this results in a final displacement of 1.2 times that of the reference design. It must be noted that the deficit in the internal volume can also be solved in another manner. The fill rate of the machinery rooms can also be increased since the fill rate of machinery rooms in the LPD is generally relatively low. Such a solution does have consequences for the building cost and maintainability however.

### 7.2.2. Air Defence and Command Frigate internal volume

The process of determining whether or not the internal volume of the different designs of the LCF is sufficient to accommodate all the different systems is the same as the process for the LPD. In table 7.4 the ratios with which the different volumes increase, as well as the volumes of the different systems is shown.

Table 7.4: Volumes of different spaces in the LCF (relative to the total volume of the reference design)

| | Reference | Design 1 | Design 2 | Design 3 |
|---|---|---|---|---|
| $r\_P,fc$ | 0 | 0.15 | 0.3 | 0.45 |
| $r\_v,sys$ | - | 1.12 | 1.33 | 1.55 |
| $r\_v,fuel$ | - | 1.38 | 1.36 | 1.35 |
| Total encolsed volume | 1 | 1.06 | 1.09 | 1.12 |
| Ballast | 0.01 | 0.01 | 0.01 | 0.01 |
| Auxiliary | 0.2 | 0.2 | 0.2 | 0.2 |
| Accommodation | 0.28 | 0.28 | 0.28 | 0.28 |
| Payload & operational spaces | 0.35 | 0.35 | 0.35 | 0.35 |
| Fuel | 0.03 | 0.04 | 0.04 | 0.04 |
| Systems | 0.13 | 0.15 | 0.2 | 0.3 |
| Required volume | 1 | 1.03 | 1.08 | 1.18 |
| Deficit | 0 | -0.03 | -0.01 | 0.07 |

What is most notable for these results is that it the weight appears to increase faster than the volume up to a point. For the first two proposed designs the growth in enclosed volume is larger than the growth in the required volume this leading to a surplus volume. However, the margin is very small. As was already discussed, the accuracy of the parametric design tool is not very high with such complex configurations and it is therefore not possible to conclude that there is a significant saving in volume. For the third design it is apparent that the increase in volume due to the significant $r_{P,fc}$ becomes larger than the increase in weight. For this last design it would thus be necessary to increase the size of the vessel further to maintain the operational effectiveness since the volume of payload & operational spaces has decreased by $1 - \frac{0.35-0.07}{0.35} = 20\%$. In order to compensate for this the vessel will again have to be enlarged. This will add another 4 percentage point in steel weight (as was demonstrated in equation (7.2.1)) to the displacement of the vessel resulting in a displacement of 1.16 times the original.

## 7.3. Safety concerns

Besides an indication of the general installed power, volume and weight of the different components of the power plant there are multiple other factors that differentiate the two selected power plants from more conventional power plants. A number of those factors is associated with the safety issues surrounding the proposed alteration. This subsection will examine the safety issues concerned with fuel cell and low flashpoint fuels. Although these safety concerns may already been touched upon in chapter 3, this section also aims to offer risk mitigation strategies and evaluate what the influence on the operational effectiveness is expected to be.

### 7.3.1. Risk associated with methanol

Methanol is a low flashpoint fuel. This means that under atmospheric conditions, methanol will ignite at ambient temperatures if exposed to an ignition source. The flashpoint of methanol lies at 11 °C which is significantly lower than average temperatures in the engine room. Until recently, only fuels with a flashpoint higher than 60°C were allowed for use onboard to reduce the risk of explosion or fire [92]. Apart from the low flashpoint methanol has other properties that further exacerbate the risks associated with it. It's vapour density is higher than that of air, allowing it to pool up within a vessel which adds to the risk of explosion [92]. Conventional fire fighting methods may not always be suitable to fighting methanol fires either. Methanol and methanol vapour is also toxic to humans and ultimately, methanol can be corrosive. These three factors, low flashpoint, toxicity, corrosiveness, make the application of methanol much more difficult but mitigative measures can be put in place. For methanol these mitigative measures mainly consist of designing a gas-safe machinery space and storage space meaning that all piping should be double walled and gas tight, and that sufficient ventilation and an inert gas system should be present [68]. These measures ensure that under normal conditions the risks associated with using methanol are as low as those associated with a system being fuelled by a fuel with a flashpoint higher than 60 °C. In combat situations however it is likely that the effectiveness of double-walled piping is significantly diminished in the case of an impact whilst the effect of an explosion or fire remain the same. It is thus presumable that the survivability would decrease in combat situations. In order to determine whether this holds a more comprehensive risk assessment or failure modes effect analysis should be conducted.

### 7.3.2. Risk associate with butanol

Buranol has significant benefits when compared to methanol. The first is the higher flashpoint. Although the flashpoint of butanol is still below the 60C°threshold which is generally used in regulations for low flashpoint fuels, 35C°is below the generally expected environmental temperature. In machinery rooms the temperature may well rise to the flashpoint, as well as in several geographic areas in which operations may be conducted. The risk associated with butanol is therefore smaller than that of methanol but higher than that of F-76. Mitigative measures should be expected to be vastly more effective however, especially when environmental temperatures are well below 35C°. When compared to methanol, the miscibility of butanol is much lower which is conducive to fuel stability and indirectly to recoverability. When following the same safety precautions as with methanol, the use of butanol may thus create additional design implications, but the risk should be significantly lower.

### 7.3.3. Fuel cell safety

Similar to methanol fuel cells have their own associated risks, although not a s serious as those associated with methanol. Depending on whether the system is is outfitted with external pre-reforming or (in)direct internal reforming there will always be some systems and section of piping with highly combustible hydrogen gas. When employing a GasDrive system this problem is exacerbated as the anode of gas is supplied to the ICE meaning that the hydrogen gas is no longer contained within the fuel cell module. In the commercial shipping sector this configuration would full under gas fuelled vessel and thus necessitate gas-safe machinery spaces. Similarly to methanol this means that fuel pipes have to be double walled and there must be the possibility to purge fuel tanks and pipes.

### 7.3.4. Safety measure influence on design

It appears that both for the use of methanol and fuel cells it is possible to lower the risk to acceptable thresholds under normal circumstances. These mitigation measures put in place however may influence the design freedom in certain ways. Double-walled pipes and purging installations of pipes and tanks make the installations heavier and larger than conventional installations. The use of double-walled pipes increases the weight of auxiliary systems which likely gives an incentive to cluster fuel cells and ICEs together. This means that the cost of spatial separation is higher.

## 7.4. Emissions

Given the proposed change in both the energy carriers and the energy converters it is necessary to examine what the effect of these configurations is on the fuel consumption and emissions of the two case study vessels. In this section the absolute fuel consumption, $NO_x$, $SO_x$, PM, and GHG equivalent emissions will be determined. Table 7.5 shows how these emissions vary for different fuels and combustion methods[5].

Table 7.5: Well to wake emissions [g/kWh of finished fuel] (adapted from [92], [53], [89] & [99])

| | F-76 | Methanol | | Butanol | | |
|---|---|---|---|---|---|---|
| | | ICE | SOFC | ICE | SOFC | GT |
| GHG (green) [kg CO2 eq/kWh] | N.A. | 4.4 | 4.4 | 66.75 | 66.75 | 66.75 |
| GHG (grey) [kg CO2 eq/kWh] | 89 | 97.65 | 97.65 | N.A. | N.A. | N.A. |
| SOx [g/kWh] | 0.36 | 0.007 | - | /* | - | - |
| NOx [g/kWh] | 3 | 5 | - | 3 | - | -* |
| PM [g/kWh] | 0.23 | 0.034 | - | /* | - | -* |

### 7.4.1. LPD emissions

Given the proposed COFAICE configuration on the LPD the emissions are not only determined by the chemical composition of methanol but also by the conversion processes of the ICE and the SOFC. The well-to-wake GHG emission is also determined by the source of the methanol. Since it is difficult to determine what the state of the methanol market will be in 2050 the GHG emissions for both green and grey methanol. When using methanol in a fuel cell a number of emissions is reduced by a large amount. Since an SOFC requires a relatively pure fuel supply all sulphur must already be removed from the fuel, fortunately, the sulphur content of methanol is almost negligible to begin with. The same goes for particulate matter as heavy hydrocarbons also poison the fuel cell [53]. And since the conversion process is based on electrochemical conversion instead of high temperature combustion the $NO_x$ emissions of a fuel cell are also negligible [53]. In table 7.5 the specific emissions of a diesel fueled ICE and a methanol fuelled ICE and SOFC are shown. It is readily apparent that switching the methanol only has a positive effect on GHG emissions if green methanol is used. The ability of the LPD to sail on only the fuel cells diminish the $NOx$ emissions sufficiently to comply with the IMO tier III emissions regulations without the need for an SCR.

### 7.4.2. LCF emissions

The emissions of the LCF are as of yet a different story. The well-to-wake GHG emissions of bio-butanol are much higher than those of methanol because the production process is more energy intensive [89]. This means that the potential of GHG emission reduction is lower. However, as the absolute amount of fuel is not much higher than when using F-76, the 70% reduction of GHG emissions stipulated by the IMO is still achieved. Since the use of butanol as a standalone fuel is not as common yet, it is difficult to obtain accurate information about the secondary emissions of butanol in gas turbines. However, given the chemical composition of the fuel and the trends that are seen for other fuels when combusted in gas turbines the assumption is made that the $NO_x$ and $SO_x$ emissions of butanol are insignificant.

## 7.5. Design selection & effectiveness assessment

Having established how the different design choices that were made for the proposed design may influence the general operations of machinery spaces and the vessel it is now possible to assess not only how individual MoEs are affected but also how the effectiveness of the two case study vessels is affected. In table 7.6 the prioritization of the different MoEs is again presented, now showing only the rows of the two case study subjects. In the parametric design variation the design speed, the vessels range and the payload weight of the vessels were maintained constant. A second iteration in which the focus was on the payload volume was also performed. This means that these measures have not been affected greatly in the design and it is thus considered that these have remained constant for this

[5]* Some values for butanol were difficult to obtain. The assumptino was made that due to the combustion, the PM and NOx emissions of butanol in a gas turbine would be negligible. For combustion in an ICE, more data would be needed.

effectiveness assessment. In the final effectiveness assessment the changes of the individual MoEs will be judged on a scale of -10 to 10 in which -10 represents a large negative change in effectiveness, 0 signifies a constant effectiveness, and 10 means a large positive change. By using this scale it is possible to judge some values qualitatively, but it also lends itself to a more quantitative assessment when the necessary data is available. In the following subsection, each MoE will be discussed separately.

Table 7.6: Prioritisation of the MOE's for the LPD and LCF (1 = low priority, 9 = high priority)

| | SEWACO | Susceptibility | Vulnerability | Recoverability | Range | Endurance | Top speed | Acceleration | Manoeuvrability | Payload (volume) | payload (weight) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LCF | 8.6 | 4.2 | 6.6 | 6.2 | 5 | 5 | 5.9 | 3.2 | 3.6 | 1.8 | 1.4 |
| LPD | 3.3 | 2 | 4 | 3.4 | 4.8 | 4.8 | 4.2 | 1.8 | 3.7 | 6.2 | 5.5 |

### 7.5.1. Susceptibility

In many of the considered designs it is possible to sail on the power generated by the fuel cells and thus minimize the acoustic signature of the energy converter. The possibility to sail with barely any acoustic signature which would be highly conducive for the susceptibility. Although the acoustic signature is only one part if the greater spectrum of signatures, reducing it will result in a lower susceptibility. Scoring a positive 10 on this MoE would mean that all signatures are diminished completely. Since only the acoustic signatures are reduced up to certain percentage of the vessel speed, the maximum potential is lower. A maximum silent speed of 12 and 16 knots for the LPD is therefore considered to be a 3 and 4 point increase of the susceptibility[6]. Relative to the top speed of the vessel, the silent speed for the different LCF designs are somewhat lower than for the LPD. The three different LCF designs will thus be rated 0, 2 and 3. Although the susceptibility becomes better for the LPD than for the LCF, the effectiveness of the LCF will benefit more from this since the importance of susceptibility is higher in its mission profile. At higher speeds the benefit of low engine noise diminishes as the sound made by the propeller likely becomes more dominant. Both the propeller noise and the other remaining signatures thus contribute to diminishing returns when considering improvements in the susceptibility.

### 7.5.2. Vulnerability

The onboard use and storage of methanol carries considerable risk with it. The combination of corrosiveness, low flashpoint and high vapour density increase the explosion and fire risk on board. These risks can be mitigated to a certain degree by making the involved machinery spaces gas safe and outfitting all fuel lines with double-walled pipes. This ensures that there is no single point of failure and that the frequency of hazardous events is significantly lowered. This initially means that after applying the mitigation measures the survivability is as high as with a conventional fuel. In combat situations however the effectiveness of double-walled piping is diminished significantly whilst the magnitude of the effects of an explosion is still the same, resulting in a higher risk, thus increasing vulnerability. Although the flashpoint of butanol is significantly higher than that of methanol, the main difference between the LPD and LCF is found in the operational environment. As the LPD operates in relatively low conflict environments, the mitigation measures reduce the risk enough that the penalty to vulnerability is small, it is ranked at -2. The combination of a low flashpoint fuel and a high conflict environment means that the penalty to the vulnerability rating will be higher for the LCF, it is ranked at -3.

### 7.5.3. Recoverability

The recoverability of a vessel is mainly an aspect of human performance [72]. However, good design may enhance recoverability. Designing with redundancy and compartmentalization of different systems enhances recoverability. The recoverability may however be influenced by some properties of the

[6] A high positive score thus represents a low susceptibility, which is a positive property.

selected energy carriers. Due to its toxicity, methanol may be harmful to crew when exposed to the fuel. This is only a minor consideration however, as fuel lines are shut of either automatically or remotely in the case of a leak. The toxicity of butanol is comparable to other fuels and thus presents no extra danger. Since the original configurations of both the LPD and LCF are already designed with redundancy in mind, further separation of the systems may not contribute much to the recoverability. The score for the recoverability for the LPD will thus be -1, and 0 for the LCF.

### 7.5.4. Acceleration & manoeuvrability

The acceleration of LCF designs 2 and three, and the first LPD design is somewhat lower due to the fuel cell configuration. For these designs however, the fuel cell power ratio is relatively low and the effect on the acceleration is small. For the second LPD design however, the fuel cell power ratio is quite large and is likely to have a larger influence on the ability of the LPD to accelerate quickly. However, this is not an important MoE for the LPD and the operational effectiveness is thus not influenced significantly. The manoeuvrability of both vessels is somewhat enhanced through the use of hybrid electric configurations. The LCF may have improved manoeuvrability in close quarters due to the quick response of the electric motors. The LPD already has this capability, but the use of fuel cells may make this operation more efficient and more comfortable.

### 7.5.5. Payload carrying capacity

Both the volume and weight available for payload had been maintained equal to that of the original design. There is thus no difference in effectiveness stemming from this MoE.

### 7.5.6. Final effectiveness assessment Landing Platform Dock

For the proposed alternate design for the LPD the increase in displacement initially appeared to be modest when the energy carrier was changed to methanol and the power generation was shared by an ICE and an SOFC. In this proposed design the payload weight, payload volume, speed and range were maintained constant.

The main functions of the landing platform dock are related to amphibic power projection and transport of troops and equipment. To fulfil these functions a large volume is generally needed. In order to conserve the payload capacity of the LPD the displacement has to increase significantly. First due to the added displacement in the parametric design study, and subsequently in the second iteration which ensures compliance with a constant payload volume. The increased susceptibility that results from the ability to sail at a relatively high speed on only the fuel cells is not an important factor for the LPD as the acoustic signature is not a design priority. The expectation is that the use of methanol does not bring added risk with it if the correct mitigative measures are applied as long as the vessel does not operate in the highest end of the spectrum of operations. The large size of the LPD also allows for more effective separation of the fuel cells which increases redundancy and recoverability. It remains to be seen how practical a high degree of separation is due to the added machinery space necessary for double-walled pipes and other measures. Together it can be concluded that the effect on vulnerability and recoverability is neutral. Together the effect of these survivability MOEs on the effectiveness is thus very small. The changes in mobility also have a low impact on the overall effectiveness of the LPD. The top speed is maintained as this was a constant input. The acceleration decreases significantly as a lower share of the total installed power (only 30% as opposed to 100%) exhibits a quick load response. However, since acceleration is not an important MoE this barely influences the effectiveness. The manoeuvrability is wholly maintained since the selected configuration is entirely electric which allows for dynamic positioning. It is assumed that the remaining ICEs deliver enough power on short notice to effectively DP. Although not directly included in the effectiveness, the comfort at anchor or in port may be increased significantly as the auxiliary power can be completely supplied by the fuel cells.

### 7.5.7. Final assessment Air Defence and Command Frigate

For the LCF butanol was selected as a fuel since the previous chapter indicated that any but the most energy dense fuels would lead to an excessive increase in displacement. Although the application of an SOFC did not appear to lead to a beneficial reduction in the fuel consumption three design with varying SOFC load shares were selected for an operational effectiveness assessment. Given the mission profile and the prioritization of the MoEs for the LCF it was observed that the possiblity for a silent

Table 7.7: Change in effectiveness of the proposed LPD design

| LPD effectiveness assessment | SEWACO | Susceptibility | Vulnerability | Recoverability | Range | Endurance | Top speed | Acceleration | Manoeverability | Paylaod (volume) | Payload (weight) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MOE prioritization | 3.3 | 2 | 4 | 3.4 | 4.8 | 4.8 | 4.2 | 1.8 | 3.7 | 6.2 | 5.5 | |
| Change in design 1 | 0 | 3 | -2 | -1 | 0 | 0 | 0 | -2 | 2 | 0 | 0 | -1.6 |
| Change in design 2 | 0 | 5 | -2 | -1 | 0 | 0 | 0 | -4 | 2 | 0 | 0 | -1.2 |

operation would benefit the operational effectiveness greatly. For this reason the higher load shares have a higher increase in operational effectiveness. The first design does not generate enough power on the fuel cells alone to sail at any significant speed. The other design however do allow the vessel to sail at respectively 10 and 14 knots with a lowered acoustic signature. It can be imagined that this would benefit an anti-submarine warfare frigate to an even greater degree. The penalty to vulnerability that is incurred with an increasingly large SOFC system, and thus with increasing complexity dampens this benefit considerably.

Table 7.8: Effectiveness assessment of the LCF designs

| LCF effectiveness assessment | SEWACO | Susceptibility | Vulnerability | Recoverability | Range | Endurance | Top speed | Acceleration | Manoeverability | Paylaod (volume) | Payload (weight) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MOE prioritization | 8.6 | 4.2 | 6.6 | 6.2 | 5 | 5 | 5.9 | 3.2 | 3.6 | 1.8 | 1.4 | |
| Change in design 1 | 0 | 0 | -3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -19.8 |
| Change in design 2 | 0 | 3 | -3 | 2 | 0 | 0 | 0 | -1 | 1 | 0 | 0 | 5.6 |
| Change in design 3 | 0 | 5 | -3 | 2 | 0 | 0 | 0 | -2 | 1 | 0 | 0 | 10.8 |

## 7.6. Conclusions

In this chapter the resulting design form the parametric study were further refined by adding more detail to the power plant configuration. All aspects of the proposed design were then evaluated and their effect on the various MOEs was established. With this effect and the design priorities for the two vessels an effectiveness assessment was conducted. From this assessment it can be concluded that the potential for the application of alternative energy carriers and energy conversion methods on the LCF is negligible. The application of methanol and SOFCs on board the LPD would be possible, but some cost would be incurred. For the proposed design the displacement increased by 14% while the fuel weight increased by 60%. Although the payload weight, range and operational profile were maintained, the payload volume decreases which has a significant negative impact on the vessels operational effectiveness. The alterations do almost completely reduce the majority of the emissions however. The fuel cells allow the vessel to sail almost without any emissions and thus be IMO tier III compliant.

Table 7.9: Assessment of the proposed alternative designs

| | LCF | | | LPD | |
|---|---|---|---|---|---|
| | Design 1 | Design 2 | Design 3 | Design 1 | Design 2 |
| Fuel cell power ratio | 0.15 | 0.3 | 0.45 | 0.35 | 0.7 |
| Displacement | +3% | +8% | +16% | +14% | +20% |
| Operational effectiveness | Slight negative effect | Equal | Small positive effect | Equal | Equal |
| GHG emmissions | -75%* | -75%* | -75%* | -92%* | -93%* |
| IMO Tier III compliant | Yes | Yes | Yes | Yes | Yes |
| Fossil fuel consumption | -100%* | -100%* | -100%* | -100%* | -100%* |
| Total fuel consumption | -5% | -4% | -3% | +62% | +48% |
| Investment cost | + | ++ | +++ | ++ | +++ |

# 8

# Constructing a roadmap

To achieve the goals regarding fossil fuel consumption it is imperative to look beyond just the technical potential and design implications for individual vessels. Although this is a start, it is not possible to draw extensive conclusions with regards to the recommended strategy for the RNLN in order to achieve the goals stipulated in the DEOS. In this chapter a broader perspective will be adopted. An attempt will be made to project the lessons learned in the case studies on the entire RNLN fleet over the coming decades. This way the conclusion from the two case studies may help to provide insights which may prove useful both across the different vessels of the fleet and across the 30 years which remain before the DEOS goals must be achieved. This chapter will begin by considering directly how the lessons learned in the case studies may be translated to different ship types. In the second section of this chapter some consideration will be given to the potential developments of the coming years and how these may affect the conclusions so far. In section 8.3 factors will be discussed that have so far been relegated to the background, but are nonetheless of vital importance for any long term strategy. In the next section a prognosis is made for the future fuel consumption of the RNLN. In this prognosis the advantages and disadvantages of different scenarios will be discussed.

## 8.1. Applicability of lessons learned

In the selection of case study subject an effort was made to pick samples which are to some degree representative of the composition of the fleet of RNLN large surface vessels. With the selection of the LPD Johan de Witt and the Zeven Provinciën class LCF two distinct vessel types that are at opposite ends of the mission spectrum this is achieved to some degree. Given that a clear difference was observed between the design implications for the LPD and the LCF it must be contemplated how these conclusions may be translated to other vessels. When looking at the differences between the two vessels it can be roughly stated that the LPD falls within a category of payload driven designs, whilst the LCF falls in the category of velocity driven design. Although more complex subdivisions of design types can be made, these two categories will be used for the RNLN fleet. Using this method a first estimate of the fleet-wide implications of the proposed alterations is achieved.

## 8.2. Fuel consumption prognosis

The design strategy that was adopted uses three fuels, F-76 for the older vessels, methanol for the volume driven designs and butanol for the faster vessels. The fuel consumption of butanol and methanol also changes in comparison to the original vessels that use F-76. In figure 8.1 a prognosis of the fuel consumption is shown. This prognosis is made using the same assumptions as the fuel consumption prognosis that was shown in the introduction, in addition to the results of the design study. It can be seen that with these efforts, the goal of a 70% reduction is not achieved, but only by a small margin. Small fuel savings can still be achieved by mixing F-76 with HVO, or by adapting vessels in their mid-life update. It should thus be concluded that the application of alternative fuels may play a pivotal role in the reduction of fossil fuel consumption of the RNLN.

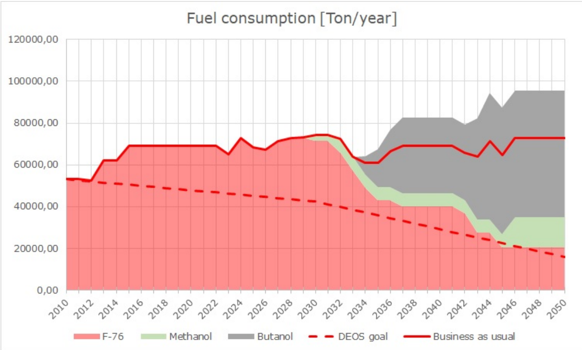


Figure 8.1: Prognosis of absolute fuel consumption

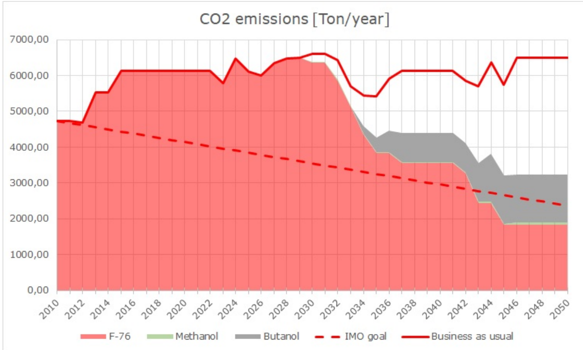


Figure 8.2: Prognosis of GHG emissions

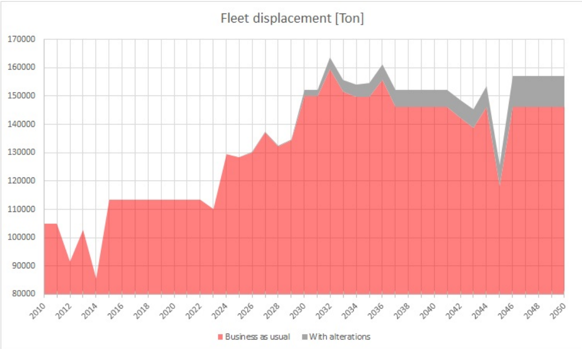


Figure 8.3: Prognosis of vessel tonnage

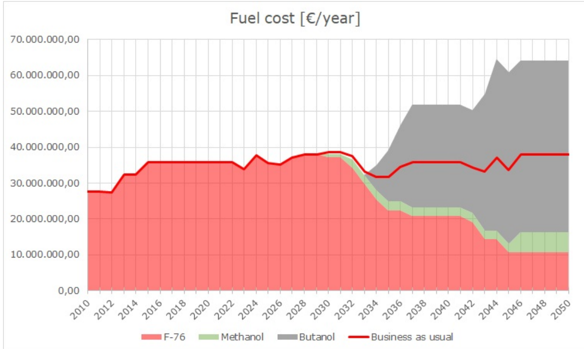


Figure 8.4: Prognosis of fuel cost (using 2020 fuel prices)

## 8.3. Other consequences

The scope of the thesis is focussed towards the design implications of naval vessels such as the increase in displacement, the fuel consumption and the operational effectiveness. The application of alternative energy carriers have a profound influence on other aspects of the operations of the RNLN as well. This section will shortly consider factors as cost, logistics & operational independence.

### 8.3.1. Cost

For any military acquisition project their are tight budget restriction in the design of new naval vessels. As explained in chapter 2 the design process is often a cost-effectiveness trade off. The proposed design alterations are of influence on both the CAPEX and the OPEX. The CAPEX is influenced by the higher cost of the fuel cells compared to conventional combustion engines. The increased vessel size also increase steel cost. Finally the added complexity of the power generation system with a complex balance-of-plant and necessary safety measures also add to the initial investment. With the high level concept design as it is right now it is difficult to make accurate estimates as to the cost of the new vessels. Likewise it is difficult to asses the change in the OPEX over any meaningful period of time. Although prices for different fuels are available at this moment it is difficult to predict how these prices may develop in the coming 10, let alone 30 years. In figure 8.4 the development of fuel cost over the next 30 years is shown using the 2020 prices for F-76, methanol and butanol. Although these prices are predicted to decrease by up to xx% by 2050 there is a large margin of error and it is clear that operations will be considerably more expensive.

### 8.3.2. Availability & logistics

Logistics play a key role in any military operation. The fuel capacity obviously plays a limiting role in this respect. Although the range of the individual vessels was maintained in the case studies, the vessels must also be seen in the larger system of which they are part. Larger naval groups are often accompanied by tanker vessels which are an integral part of any navy. This is reflected by the replenishment capacity of the RNLN. The JSS and CSS are both vessels that supply in this need for fuel replenishment, and other NATO allies also have such a capacity. Using multiple fuels presents a problem in this regard, since compatibility issues may arise. The NATO standardization office publishes strict guidelines on fuel quality so that navies can work together seamlessly. Switching from F-76 to other fuels will therefore reduce the inter-operability of the RNLN vessels and catastrophically influence the glsrnln effectiveness. Besides the compatibility of the RNLN fleet with NATO allies, the problem of fuel availability also comes into play when refuelling in foreign ports. Marine diesel fuel is found virtually anywhere on earth [1], methanol and butanol bunkering will for the foreseeable future be limited to only well developed areas connecting large shipping routes. These factors of logistic compatibility and availability influence the operability of the RNLN vessels regardless of the design changes. In addition to this, it was seen that the absolute fuel consumption of some of the vessel increased as much as 40%. This means that even in the situation where the logistics system is equipped with the means to transport methanol, more or larger tankers will be needed to sustain a mission. For butanol this is not an issue, as it was seen that with the right configuration, the absolute fuel consumption of butanol fuelled vessels will be roughly equal to the current fuel consumption of those vessels.

## 8.4. Decision making process

The scope of this thesis was mainly limited to the design implications of individual vessels. Both in the literature review and in the previous sections of this chapter an attempt was made to capture the extent of the complex system in which the vessels operates. The decisions to implement the proposed, or other measures, in order to achieve the goals set in the DEOS is in the end a political decision. In such difficult situations, it may be helpful to use a more structured approach. Within systems engineering there is a host of decision support systems that can facilitate such decisions. Kossiakoff's [48] decision framework (table 8.1) provides insight into the suitable support tools.

Table 8.1: Decision framework by Kossiakoff

| | Scope of control | | | |
|---|---|---|---|---|
| Decision type | Operational | managerial | Strategic planning | Technology needed |
| Structured | Known procedures<br>Algorithms | Policies<br>Laws<br>Trade-off analysis<br>Logic | Hystroical analysis<br>Goal-oriented rask analysis | Information systems |
| Semistructured | Tailered procedures<br>Heuristics | Tailored policies<br>Heuristics<br>Logic | Causality ORI analysis<br>Probabilities | Decision support systems |
| Unstructured | Intuition<br>Experimental | Intuition<br>Experimental | Intuition<br>Creativity<br>Theory | Expert systems |

In general there are three types of decision that can be distinguished: structured, semi-structured and unstructured. The difference between these problems depend on the degree of routine involved in the problem and the similarity to other problems that are encountered more often. Unstructured decisions are unique and within the realm of systems engineering often concern the adoption of new technologies.As more experience and knowledge is gained these decision may become semi-structured [48]. The decision regarding which technologies to use onboard naval vessels falls between the semi-structured and unstructured kinds. The consequences of the problem are relevant for each scope of control. This also means that different decisions have to be made for each scope of control and that one support tool is not sufficient. This thesis considered mostly the operational scope of control. The answers which this thesis provides (which will be elaborated on in chapter 9) are thus not the definitive answer to the challenge of fossil fuel reduction. The problems of cost and logistics partially fall within the managerial and strategic planning scope, and it is therefore important that any strategy to reduce the fossil fuel consumption of the RNLN is developed with every scope of control in mind.

[1] Although it might not be up to spec with the requirements of F-76 fuel, availability is not often a problem.

# 9

# Conclusions & recommendations

This research was conducted to examine the potential of alternative energy carriers on the large seagoing surface vessels of the RNLN. In this chapter the main conclusions that have been drawn will be presented. In addition to the conclusions, a discussion will shed light on the way in which the conclusions may, or may not be applied to the real world. Finally some recommendations for future research are presented.

## 9.1. Conclusions

In this thesis it was shown that it is possible to use alternative energy carriers to reduce the fossil fuel consumption by nearly 70% through design changes for future vessels. Additional energy saving measures and the mixing of F-76 with HVO or other bio-fuels may further reduce the fossil fuel consumption to achieve the stated goal of 70% reduction. Using these additional measures it is also possible to comply with the GHG emissions reduction goals of the IMO. It was also seen however that this does have profound implications for the design of the glsrnln large surface vessels. In this section the main research question will be answered:

> *How is the design and the operational effectiveness of RNLN vessels affected by the use of alternative energy carriers and energy conversion technologies that are needed to reduce the fossil fuel consumption of the Netherlands armed forces?*

This will be done by revisiting and answering the different sub questions which were presented in the introduction. Since the MoD has expressed the need to maintain operational effectiveness for the fleet the the first sub question will be related to defining the operational effectiveness:

> 1. How is the operational effectiveness of RNLN surface vessels defined and how is it influenced by changes in energy carrier & converter?

The first chapter of the literature review was dedicated to understanding the concept of operational effectiveness. It was established that in naval vessel design it is often impossible to assess the effectiveness, without having detailed information about the solution direction. In systems engineering (the method used at the DMO) there are multiple phases of the design where more detail is added. For the most detailed design an effectiveness assessment can be performed by modelling and simulating the exact scenarios which may be encountered during operations. In a less detailed design the effectiveness may be assessed by defining multiple MoEs. Even for more abstract designs, the influence of design changes on any MoE may be assessed quantitatively. For this thesis the relevant MoEs are those which are related to the power generations and energy storage. The following MoEs were selected for this purpose.

- Offensive capabilities
- Survivability
  - Susceptibility
  - Vulnerability

- Recoverability
- Mobility
  - Top speed
  - Acceleration and deceleration
  - Mobility
- Range
- Endurance/autonomy

In chapter 5 a operational analysis was performed for the RNLN large surface vessels with an emphasis on the two case study vessels. For this operational analysis the RNLN maritime doctrine and system plans for the different vessels were analysed. This information was used to make a subjective assessment of the importance of each MoE for different missions, and the mission profile for each vessel. In this way an indication of the prioritization of MoEs was obtained for the case study subjects. This prioritization is a good guide and can help the designer to make well informed decisions throughout the design process.

Table 9.1: Prioritisation of the MOE's for the LPD and LCF (1 = low priority, 9 = high priority)

| | SEWACO | Susceptibility | Vulnerability | Recoverability | Range | Endurance | Top speed | Acceleration | Manoeuvrability | Payload (volume) | payload (weight) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LCF | 8.6 | 4.2 | 6.6 | 6.2 | 5 | 5 | 5.9 | 3.2 | 3.6 | 1.8 | 1.4 |
| LPD | 3.3 | 2 | 4 | 3.4 | 4.8 | 4.8 | 4.2 | 1.8 | 3.7 | 6.2 | 5.5 |

2. Which energy carriers and conversion methods exist for marine applications and what are their characteristics?

In chapter 3, the second chapter in the literature review an extensive overview of the different ways in which to reduce fuel consumption and GHG emissions was presented. Different operational, human, and technological factors were discussed. The focus was on the available energy carriers and energy conversion methods ranging from marine diesel to liquid hydrogen, and from gas turbines to high temperature fuel cells. For the most viable technologies the physical properties and their potential influence on the earlier described MoEs were estimated. The result of this is shown in an overview in table 9.2 which was already presented in chapter 3.

Table 9.2: An initial estimate of how different energy technologies influence technical capabilities

| | Carriers | | | | | | | | | | Converters | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F-76 | LNG | Hydrogen | Ammonia | HVO | FAME | Ethanol | Methanol | Butanol | Batteries | Diesel | Turbine | Fuel cell | Electic motor |
| Survivability | | | | | | | | | | | - | - | + | + |
| Susceptibility | | | | | | | | | | | - | - | + | + |
| Acoustic | Depends on converter | | | | | | | | | | – | - | ++ | + |
| IR | | | | | | | | | | | - | - | - | + |
| Vulnerability | ++ | - - | - - | - - | ++ | ++ | - | - - | + | - | + | - | - | + |
| Recoverability | ++ | - - | - - | - - | ++ | +- | - | - - | + | - - | - | - | ++ | +- |
| Mobility | | | | | | | | | | | + | ++ | - | + |
| Top speed | Depends on converter | | | | | | | | | | + | ++ | - | + |
| Acceleration | | | | | | | | | | | + | ++ | - | ++ |
| Manoeuvrability | | | | | | | | | | | Depends on configuration | | | |
| Volume | ++ | - - | - - | - - | + | + | - | - | +- | - | + | ++ | +- | + |
| Displacement | ++ | - - | - - | - - | + | + | - | - | +- | - | + | ++ | +- | + |
| Logistics | ++ | - - | - - | - - | ++ | + | + | +- | ++ | | Depends on fuel | | | |
| Maintenance | ++ | - - | - - | - - | + | + | - | - | + | +- | + | - | ++ | + |
| Cost | Not in scope | | | | | | | | | | ++ | - | - | + |

On the basis of this table a first indication about the influence of different technologies on the various MoEs can be made.

3. What design changes should be applied to which vessels in order to achieve the perceived goals?

In the introduction it was already seen that drastic changes in the fossil fuel consumption of almost all vessels need to be realised to achieve the goals set in the DEOS and by the IMO. In the final chapter of the problem statement a method for the further thesis is presented. In this chapter the LPD and LCF were discussed as suitable case study subjects since these are the first vessels scheduled to be delivered for which no significant design progress has been made yet (and thus there is still the option to apply novel technologies). When further analysing the fuel consumption prognosis it was established that all the vessels delivered after 2030 would have to be virtually fossil fuel free. This means that for all vessels scheduled to be delivered after 2030 it is not enough to look only at increasing efficiency but zero carbon energy carriers will have to be applied. The design changes which are explored should thus be aimed at completely eliminating the fossil fuel consumption. Furthermore, the design changes should be tailored to the operational- and mission profile of the specific vessel. The specific design changes that were selected were different for both vessels. For the LPD a configuration with both fuel cells and ICEs was selected. The power ratio $r_{P,FC}$ was chosen at 35%, which means that 35% of the total power is delivered by the SOFCs. Methanol is chosen as a suitable fuel for the LPD. For the LCF a more complex configuration was deemed suitable. This configuration uses two gearboxes with a gas turbine and electric motor connected to each. The electric load for the on board systems and the electric motors is supplied by a combination of ICEs and SOFCs.

4. How do these changes influence the general design and operational effectiveness of the ship?

For both vessels it was seen that it is possible to use alternative energy carriers while maintaining many of the operational capabilities. In the case studies two vessels were designed which have the same range, endurance, operational profile and operational effectiveness as the original designs. For these designs, this came at the cost of an increased displacement. Table 9.3 once again summarizes the different designs, with the selected designs highlighted in green. For the LPD the displacement increased by 14% while the fuel consumption increased by 60%. Due to the use of butanol, the displacement of the LCF increases only by 6% and the fuel consumption is almost constant.

Table 9.3: Final assessment of the proposed alternative designs

| | LCF | | | LPD | |
|---|---|---|---|---|---|
| | Design 1 | Design 2 | Design 3 | Design 1 | Design 2 |
| Fuel cell power ratio | 0.15 | 0.3 | 0.45 | 0.35 | 0.7 |
| Displacement | +3% | +8% | +16% | +14% | +20% |
| Operational effectiveness | Slight negative effect | Small positive effect | Small positive effect | Equal | Equal |
| GHG emmissions | -75%* | -75%* | -75%* | -92%* | -93%* |
| IMO Tier III compliant | Yes | Yes | Yes | Yes | Yes |
| Fossil fuel consumption | -100%* | -100%* | -100%* | -100%* | -100%* |
| Total fuel consumption | -5% | -4% | -3% | +62% | +48% |
| Investment cost | + | ++ | +++ | ++ | +++ |

In the different experiments that were conducted, it was observed that there is a significant difference between the potential for the use of alternative energy carriers for the two case study vessels.

The final conclusion that can be drawn from these two case studies is that there is potential for the application of alternative energy carriers and energy conversion methods on the RNLN large surface vessels from a technical perspective, but some cost related to the vessel design, fuel cost, and logistics must be incurred. The consequences of such applications are also quite clear and can be summarized in a few main points:

1. Different vessel types require different solutions
2. Vessels with a high speed requirement and a relatively high system weight incur a high weight penalty when low energy/power density technologies are applied
3. Vessels with a lower top speed and system weight have the potential to decrease the fuel consumption significantly

4. For some vessels, an optimum load share between conventional combustion engines and an SOFC is observed. Energy carriers with a lower energy density have a more pronounced optimum.
5. The effect of the application of the considered technologies on the operational effectiveness is heavily dependent on the mission profile of the vessel

Beyond the conclusions that are related to the technical functioning of the isolated vessel it was also observed that the consequences for the broader system in which the vessels operate, especially on the logistics, are heavily affected. Using the proposed solution, the total fuel consumption and the fuel cost would likely increase significantly. Using multiple fuels with different properties on different vessels is also not conducive to the operations, as the logistics and the tanker capacity is not suited to this.

## 9.2. Discussion

Throughout the thesis various assumptions and simplifications have been made to arrive at the conclusions which were presented here. Some of these assumptions may not hold in different scenarios or result in inaccuracies in the results. In this discussion these points will again be presented. More importantly, the way in which these assumptions influence the validity or the applicability of the results in the real world must also be examined critically.

In the three progressive steps of the case study design choices were made which added an increasing level of detail to the design. This simultaneously limits the possibility to assess other alternatives. The final conclusion of this thesis is thus wholly dependent on these design choices and therefore does not offer a complete image. Various energy carriers which were abandoned in early stages may affect the design in other ways than were seen here. An effort was made to include all relevant factors as much as possible. Due to the limitations in both time and resources for a masters thesis it was not possible to complete detailed designs for all different energy carriers and different configurations. Besides this important point concerning the design strategy, there are other points in the method which must be discussed.

### 9.2.1. Operational analysis

The operational analysis in this thesis was conducted using a short list of MoEs. Using such a list unavoidably leads to an over simplification of reality when designing a vessel. When designing a vessel this is normally solved by performing more elaborate and more accurate performance assessments as the design progresses. In this thesis the designs did not progress to such a phase. One benefit of such an abstract concept design is that it is truly the energy carrier which is assessed instead of other design choices which are made throughout the process. Another reason why an effectiveness assessment on the basis of a select set of MoEs is a suitable approach is the comparative nature of the case studies. In the case studies, there were no vessels designed from scratch. By comparing the altered designs with the original design, it is possible to assess the change in effectiveness.

### 9.2.2. Parametric design study

In the parametric design study the goal was to create a simple design tool. Simple here refers to the required input. The design tool gives quick and easy insight into the relations between different design parameters and provides initial indications of the main dimensions and properties of a vessel. As such, the development of the design tool is a trade off between simplicity and accuracy. As was discussed in chapter 6, the results of the design tool lacks in accuracy for certain complex power plant configurations. Additionally, the accuracy decreases as the displacement diverges further from the reference model. This is due to the assumption of a constant admiralty coefficient, which is only valid for constant Froude numbers. As the top speed of the vessel is maintained constant, but the vessels size increases, the Froude number decreases. This likely leads to an overestimation of the required power for larger vessels. This overestimation itself again results in a larger vessel. Besides physical inaccuracies of the design tool, there is also a large design margin which is not represented here. Design choices may lead to different weight distributions than are presented in the results. The design tool thus is applicable only as a tool for obtaining first estimates, for understanding relations between different parameters, and for observing trends within certain designs.

## 9.3. Recommendations for future work

The work in this thesis is by no means definitive. The nature of the research questions means that many different subjects are touched upon while few are mastered. In this section therefore, a number of recommendations for future research will be provided. The recommendations will focus on 5 subjects: operational analysis, parametric design variation, layout design, marine engineering, and design integration.

### 9.3.1. Operational analysis

The most limiting restrictions for any strategy to achieve a lower fossil fuel consumption is the restriction of *maintaining operational effectiveness*. In this thesis the operational effectiveness was assessed at the vessel level, for vessels that are similar in mission profiles to the current fleet. By making this choice a host of novel operational concepts is disqualified. More intensive use of unmanned vehicles, swarms, AI may dramatically change the operations and the associated fuel consumption. Continuous development of military doctrine and new naval vessel concepts will likely go hand in hand.

### 9.3.2. Parametric modelling

The assumptions made for the parametric design variation have already been discussed extensively. It may be clear that there is still a lot to be gained by further extending the design tool. A more robust implementation of different configurations and a direct coupling between the operational profiles and the design algorithm will increase the accuracy of the results. The input data may also still be improved. Especially the power densities of auxiliary systems are needed before a more accurate result can be presented. In addition to this, the parametric model should be applied to more different vessels. Although it was shown that there is a clear difference between the two vessels studies, it would be interesting to consider vessels which share characteristics of both the LPD and the LCF.

### 9.3.3. Layout design

The proposed designs still lack in detail. Although there is significant knowledge of the interactions between conventional machinery and the machinery spaces on board vessels this knowledge is still lacking when it comes to more novel configurations. The influence of the placement and mitigation measures in hybrid configurations using fuel cells and combustion engines is something which should be examined into more detail.

### 9.3.4. Marine engineering

Besides the spatial layout the marine engineering component of the proposed configurations is also an area in which much progress is still to be made. Although significant research into these subjects is being performed, both at the TU Delft and other institutions, there is often a high variance amongst the resulting values. Small variations in properties such as specific fuel consumption, power density, fuel utilization, and pre-reformer utilization will all have their influence on the final design. Some of these values may change depending on the selected energy carriers as well. Further dynamic modelling of the hybrid configurations using various energy carriers may yet lead to interesting insights.

# 10
# Critical reflection

In this chapter I will attempt to offer a critical reflection on the work which I have performed over the past 10 months. The opportunity to work on a project exploring alternative fuels at the Defence Materiel Organisation presented me with two interesting topics, sustainability and naval vessel design, between which the overlap was not obvious to me at the beginning.

Although at first I held a sceptical attitude towards the push for sustainability within the RNLN this is a position which has become more and more nuanced throughout the graduation process. At first I was lead by the thought that the navy should be optimally equipped for any potential combat situation. This classical realist[1] interpretation assumes that a military is solely an instrument for the projection of hard power. It may be argued however, that in the present day the projection of soft power is as important, or even more important a diplomatic tool for The Netherlands. Part of this soft power is the use of state owned assets to lead in the energy transition. Making the Dutch armed forces more sustainable is not only a question of effectiveness in combat situations, but also a case of leading by example. What better proof of concept than a navy operating without fossil fuels. It must immediately be said however, that the continued integration and pacification after the end of the cold war has seemed to grind to a halt in the past years. The highly debated 'peaceful' rise of China and increased assertiveness of the Russian Federation has made the NATO allies painfully aware of the importance of an effective military. During the project I have attempted to stay within the scope of *effectiveness* as it is interpreted in the literature study. The feasibility of the proposed design changes however revolve around the metric used for effectiveness: is the military a tool for the projection of *hard power* or *soft power*? This is in the end a political question which has been in the back of my mind at many times.

The subject subsequently has challenged, and changed my perception of marine technology as an exact science. Especially in the research which I've performed into the operational effectiveness and the requirements of naval vessels it is clear that no single solution is necessarily optimal. The uncertain nature of the operation of not just naval vessels, but also other military assets can be seen on all levels: technical, tactical, operational, and political. It is important to keep in mind that the purpose of a military is essentially political. This idea is excellently captured in the aphorism that "*war is the continuation of politics by other means*" [98]. The translation of these broad political goals to a technical product such as a naval vessel is something which has fascinated me.

The many different alternative technologies are also thought provoking. It is undeniable that fossil fuels simply have excellent technical properties (although these might be so excellent, simply because our technologies have evolved around them), and that in the search for a replacement of fossil fuels, mankind is restricted by certain physical limitations. It is also apparent however, that these limitations can be overcome, albeit at a certain cost. The cost can be financial, or it can be expressed in a certain risk, and overcoming these limitations certainly requires a degree of vision and commitment. When considering which energy carrier will be dominant in the maritime industry in 2050 there are many "ifs" and "buts". But it is also clear from my literature review that there is no shortage of bright minds working to develop and enhance alternatives to fossil fuels.

Although I've attempted to offer a clear and concise answer to the question whether or not alternative

[1] *Realist* here refers to the family of theories called *realism* within international relations [7]

fuels have place in naval vessels, the answer is still debatable. When telling people about my project, whether they were colleagues, fellow students, family or friends, some were inclined to quickly state that naval vessels will continue to use fossil fuels for the foreseeable future without much argumentation. By performing this research, I hope to contribute to this debate by providing an indication of what to expect if this route is chosen. Without knowing what the costs will be, it is difficult to make any decisions, even one that may seem trivial. Additionally, by looking at all the potential applications of alternative energy carriers, and not just the most obvious, it is possible to understand what the limitations currently are.

# Bibliography


[1] Toekomst van de krijgsmacht lijst met vragen en antwoorden.

[2] Abdalla M Abdalla, Shahzad Hossain, Ozzan B Nisfindy, Atia T Azad, Mohamed Dawood, and Abul K Azad. Hydrogen production, storage, transportation and key challenges with applications: A review. *Energy conversion and management*, 165:602–627, 2018.

[3] Avinash Kumar Agarwal. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in Energy and Combustion Science*, 33(3):233–271, 2007.

[4] A.J. Andrews. Marine requirements elucidation and the nature of preliminary ship design. *Int. Journal of Maritime Engineering*, 2011.

[5] David Andrews. Warship Design. In *Encyclopedia of Maritime and Offshore Engineering*. John Wiley & Sons, Hoboken, 2017. ISBN 9781118476406.

[6] W.E. Astley, A. Grasman, and D.B. Stroeve. The impact of alternative fuels on short sea shipping and inland shipping. In *International Naval Engineering Conference and Exhibition*, 2020.

[7] Joh Baylis. *The Globalization of World politics*. Oxford University Press, Oxford, 2017.

[8] Tulay Berk. Energietransitie defensie: Terugkoppeling opdracht. Presentation, 2018.

[9] Volker Bertram, Jean Jacques Maisonneuve, Jean Caprace, and Philippe Rigo. Cost assessment in ship production. *RINA*, 01 2005.

[10] M. M.K. Bhuiya, M. G. Rasul, M. M.K. Khan, N. Ashwath, and A. K. Azad. Prospects of 2nd generation biodiesel as a sustainable fuel - Part: 1 selection of feedstocks, oil extraction techniques and conversion technologies. *Renewable and Sustainable Energy Reviews*, 55:1109–1128, 2016.

[11] Krzysztof Biernat. *Storage Stability of Fuels*. InTechOpen, London, 2014.

[12] Linder Biert. *Solid oxide fuel cells for shipsSystem integration concepts with reforming and thermal cycles*. PhD thesis, Delft University of Technology, 2020.

[13] Drs. A. Th. B. Bijleveld-Schouten. Defensienota 2018: Investeren in onze mensen, slagkracht en zichtbaarheid. Technical report, Ministry of Defence, March 2018.

[14] Drs. A. Th. B. Bijleveld-Schouten. Jaarverslag en slotwet ministerie van defensie 2019. Technical report, Ministry of Defence, May 2020.

[15] Drs. A. Th. B. Bijleveld-Schouten and Drs. B. Visser. Operationale energiestrategie. Technical report, Ministry of Defence, 2015.

[16] Drs. A. Th. B. Bijleveld-Schouten and Drs. B. Visser. Defensie energie en omgevingsstrategie. Technical report, Ministry of Defence, 09 2019.

[17] Jelle Bos. *Towards Energy Efficient Shipping*. PhD thesis, Delft University of Technology, 2020.

[18] Evert A. Boumand, Elizabeth Landstad, Agathe I. Rialland, and Adners H Stromman. State-of-the-art technologies, measures, and potential for reducing ghg emissions from shipping - a review. *Transportation Research Part D*, 52:408–421, 2017.

[19] J Boumeester. *De effecten van Hydrotreated Vegetable Oil (HVO) op dieselmotoren van de marine*. PhD thesis, Hogeschool Windesheim, 2017.

[20] Nick Bradbeer and Alistair Greig. Warship Machinery Constraints. In *Encyclopedia of Maritime and Offshore Engineering*. John Wiley & Sons, Hoboken, 2017. ISBN 9781118476406.

[21] Alan J Brown. Application of operational effectiveness models in naval ship concept exploration and design. *Ship Science & Technology*, 7, 2013.

[22] D.K. Brown and D.J. Andres. The design of cheap warships. In *Proceedings of International Naval Technology Expo*, Rotterdam, June 1980.

[23] J.S. Carlton. *Marine Propellers and Propulsion*. Butterworth-Heinemann, 2018.

[24] Christos Chryssakis, Océane Balland, Hans Anton Tvete, and Andreas Brandsæter. Alternative fuels for shipping. Technical report, DNV GL AS Maritime, 2014.

[25] Walt Cooper and Richerd Lee. Computing fully burdened costs of energy – fuel (fbce-f). In *2013 International Cost Estimation & Analysis Association Conference*, 2013.

[26] Richard Coyne. Wicked problems revisited. *Design Matters*, 26:5–17, 2005.

[27] A.E. de Gaaij. *Applying parametric optimisation in the concept exploration phase on naval support vessels*. PhD thesis, Delft University of Technology, 2019.

[28] Niels de Vries. *Safe and effective application of ammonia as a marine fuel*. PhD thesis, Delft University of Technology, 2019.

[29] Da Deng. Li-ion batteries: basics, progress, and challenges. *Energy Science & Engineering*, 3, 09 2015.

[30] Eric Dion. *Synergy: A Theoretical Model of Canada'S Comprehensive Approach*. iUniverse, Bloomington, 2017.

[31] DNV GL. Future Fuels and Fuel Converters. Technical report, DNV GL AS Maritime, no date.

[32] Jon Anders Ryste DNV GL. Alternative marine fuels study. Technical report, DNV GL AS Maritime, 2019.

[33] Etienne Duchateau. *Interactive evolutionary concept exploration in preliminary ship design*. PhD thesis, Delft University of Technology, 2016.

[34] Douglas W. Elmendorf. The cost-effectiveness of nuclear power for navy surface ships. Technical report, Congress of the United States Congressional Budget Office, 2011.

[35] Harsh Sapra et al. Potential of combined drive of fuel cell and internal combustion engine (cofaice) for naval ships. In *15th International Naval Engineering Conference & Exhibition*, 2020.

[36] Rinse Geertsma, 2020.

[37] Rinse Geertsma and Klaas Visser. Energy as a weapon, part ii. In *EAAW VII Symposium Proceedings*, 2017.

[38] Agnieta Habben-Jansen. *A Markov-based vulnerability assessment of distributed ship systems in the earlydesign stage*. PhD thesis, Delft University of Technology, 2020.

[39] Frank Hendrickx, Tom Maes, Britta de Meyer, Tine van Suetendael, and Chris Peeters. De koninklijke marine als matitieme leader firm. Technical report, Nederland Maritiem Land, Delft, 2003.

[40] IMO. Annex 5: 2014 guidelines on the method of calculation of the attained energy efficiency design index (eedi) for new ships. Technical Report RESOLUTION MEPC.245(66), april 2014.

[41] International Maritime Organisation. Adoption of the initial imo strategy on reduction of ghg emissions from ships and existing imo activity related to reducing ghg emissions in the shipping sector. Technical report, International Maritime Organisation, London, April 2018.

[42] Lv Jian-wei, Wu Gang, and Xie Zong-ren. The approaches to simplification of effectiveness-cost analysis of navy vessel life cycle and its application. In *2013 International Conference on Management Science and Engineering 20th Annual Conference Proceedings*, pages 434–440, 07 2013.

[43] A.A. Kana, C.P.F Shields, and D.J. Singer. Why is naval design decision-making so difficult? In *Warship 2016: Advanced Technologies in Naval Design, Construction, & Operation*, Bath, 2016.

[44] Jaime Karreman. Patrouilleschip zr.ms. groningen vertrekt zondag voor twee jaar naar caribisch gebied, April 2019. URL `https://marineschepen.nl/nieuws/Zr-Ms-Groningen-zondag-voor-twee-jaar-naar-Caribisch-gebied-100419.html`.

[45] Jaime Karreman. Doorbraak in dossier vervanging m-fregatten, june 2020. URL `https://marineschepen.nl/nieuws/Doorbraak-in-dossier-vervanging-M-fregatten-230620.html`.

[46] Sander Knegt. *Winning at sea: developing a method to provide insight in early stage naval fleet design requirements*. PhD thesis, Delft University of Technology, 2018.

[47] Otto C. Kopp. Fossil fuel, 2020. URL `https://www.britannica.com/science/fossil-fuel`.

[48] Alexander Kossiakoff, William N. Sweet, Samuel J. Seymour, and Steven M. Biemer. *Systems Engineering Principles and Practice*. John Wiley & Sons, New Jersey, 2011.

[49] J.J. le Poole. *Integration of aboard logistic processes in the design of logistic driven ships during concept exploration*. PhD thesis, Delft University of Technology, 2018.

[50] Ungtae Lee. *Improving the Parametric Method of Cost Estimating Relationships of Naval Ships*. PhD thesis, Massachusetts Institute of Technology, 2014.

[51] Horng-Jang Liaw, Chien-Tsun Chen, and Vincent Gerbaud. Flash-point prediction for binary partially miscible aqueous–organic mixtures. *Chemical Engineering Science*, 63(18):4543 – 4554, 2008.

[52] P.V. Linder van Biert; M, Godjevac; Klaas Visser; Aravind. A review of fuel cell systems for marine applications. *Journal of Power Sources*, pages 345–364, 2016.

[53] Kristine Bruun Ludvigsen and Elrik Ovrum. Fuel cell position paper. Technical report, DNV GL AS Maritime, 2012.

[54] Edward Luttwak. *Strategy: the logic of war and peace*. Harvard University Press, Cambridge, 2002.

[55] Hongrui Ma, Koen Steernberg, Xavier Riera-Palou, and Nigel Tait. Well-to-wake energy and greenhouse gas analysis of sox abatement options for the marine industry. *Transportation Research Part D*, 17(4):301–308, 2012.

[56] B. W. Michalchuk and R. W. G. Bucknall. Co2 reduction design strategies for naval ships. In *Proceeding of the 12th International Naval Engineering Conference*, 2014.

[57] T.A. Middendorp. Fundamentals of maritime operations: Netherlands maritime military doctrine. Technical report, Ministry of Defence, February 2014.

[58] Ministry of Defense. 2019: balanceren tussen investeren, moderniseren en herstellen, may 2020. URL `https://www.defensie.nl/actueel/nieuws/2020/05/20/jaarverslag-2019-defensie-het-jaar-van-investeren-moderniseren-en-herstellen`.

[59] Alvar Mjelde, Oyvind Endresen, and Magnus S. Eide. Asean ship emission inventory. Technical report, DNV GL AS Maritime, 2018.

[60] G.A. Nahar and S.S. Mdahani. Thermodynamics of hydrogen production by the steamreforming of butanol: Analysis of inorganic gasesand light hydrocarbons. *international journal of hydrogen energy*, 2010.

[61] Maritime Research Institute Netherlands. Sustainable power marin. Technical report, Maritime Research Institute Netherlands, 2020.

[62] CBS News. Real cost of gas at afghan bases: $400/gal. Newspaper article, 12 2011. URL `https://www.cbsnews.com/news/real-cost-of-gas-at-afghan-bases-400-gal/`.

[63] North Atlantic Treaty Organization. Bi-sc capability codes and capability statements. Technical report, January 2020.

[64] NATO Standardization Office. Anep-41: Ship costing. Technical Report 41, North Atlantic Treaty Organisation, 2006.

[65] NATO Standardization Office. Nato standard aflp-1385: Guide specification (minimum quality standards) for naval distillate fuels (f-75 and f-76). Technical report, North Atlantic Treaty Organisation, march 2017.

[66] NATO Maritime Capability Group 6 on Ship Design and Maritime Mobility. Specialist team on ship systems engineering. Technical report, North Atlantic Treaty Organisation, 2011.

[67] H. C. Ong, A. S. Silitonga, H. H. Masjuki, T. M.I. Mahlia, W. T. Chong, and M. H. Boosroh. Production and comparative fuel properties of biodiesel from non-edible oils: Jatropha curcas, Sterculia foetida and Ceiba pentandra. *Energy Conversion and Management*, 73:245–255, 2013.

[68] International Maritime Orginaisation. Draft interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel. Technical report, International Maritime Organisation, 09 2019.

[69] Daniel R. Palo, Robert A. Dagle, and Jamie D. Holladay. Methanol steam reforming for hydrogen production. *Chemical Review*, 107:3992–4021, 2007.

[70] Apostolos Papanikolaou. *Ship Design: Methodologies for Preliminary Design*. Springer, Dordrecht, 2014.

[71] Rachel J Pawling. Introduction — What Makes a Warship ? In *Encyclopedia of Maritime and Offshore Engineering*. John Wiley & Sons, Hoboken, 2017.

[72] Alexander Spyro Piperakis. *An Integrated Approach to Naval Ship Survivability in Preliminary Ship Design*. PhD thesis, University College London, 2013.

[73] Cornelis Posthumus. Oes maatregelen css, November 2018.

[74] Cornelis Posthumus, 2020.

[75] H. W. Rittel and M. M. Webber. Dilemmas in a general theory of planning. *Policy sciences*, pages 155–169, 1973.

[76] J. M. Ross. A practical approach for ship construction cost estimating. 2004.

[77] Mark Roth. *Analysis of General Arrangements created by the TU Delft Packing Approach*. PhD thesis, Delft University of Technology, 2017.

[78] Scaled Agile. Scaled agile framework. URL `https://www.planview.com/resources/articles/lkdc-set-based-design/`.

[79] Noelle Eckley Selin. Renewable energy, 2020. URL `https://www.britannica.com/science/renewable-energy`.

[80] Paresh Chandra Sen. *Principles of electric Machines and Power Electronics*. John Wiley & Sons, Hoboken, 2013.

[81] David Jacob Singer and Norbert Doerry. What is set-based design? *Naval Engineers Journal*, 2009.

[82] Devendra Singh, K. A. Subramanian, and S. K. Singal. Emissions and fuel consumption characteristics of a heavy duty diesel engine fueled with Hydroprocessed Renewable Diesel and Biodiesel. *Applied Energy*, 155(April 2003):440–446, 2015.

[83] Matthew J Smith. *Updating MIT's cost estimation model for shipbuilding*. PhD thesis, Massachusetts Institute of Technology, 2008.

[84] Douwe Stapersma. *Reader WB4408B Diesel Engines Volume 4 Emissions and Heat transfer*. Delft University of Technology, Delft, 2010.

[85] Douwe Stapersma. Some thoughts on an Energy Efficiency Design Index for naval ships. 2013.

[86] Douwe Stapersma and hans Klein Woud. *Design of Propulsion and Electric Power Generation Systems*. The Institute of Marine Engineering, Science and Technology, London, 2002.

[87] Roxana Tiron. $400 per gallon gas to drive debate over cost of war in afghanistan. Newspaper article, 10 2009. URL https://thehill.com/homenews/administration/63407-400gallon-gas-another-cost-of-war-in-afghanistan-.

[88] M. Kotek V. Hönig and J. Mařík. Use of butanol as a fuel for internal combustion engines. *Agronomy Research*, 2014.

[89] S. Vaisanen, J. Havukainen, V. Uusitalo, M. Havukainen, R. Soukka, and M. Luoranen. Carbon footprint of biobutanol by abe fermentation from corn and sugarcane. *Renewable Energy*, pages 401–410, 2016.

[90] L. van Biert, K. Visser, and P.V. Aravind. A comparison of steam reforming concepts in solid oxide fuel cell systems. *Applied Energy*, 264, 2020.

[91] Martin van Hees. *Quaestor: Expert governed parametric model assembling*. PhD thesis, Delft University of Technology, 1997.

[92] P.S. van Lieshout, V. de Jonge, R. Verbeek, A.W. Vredeveldt, and S. Finner. Green maritime methanol: Wp3 factsheet and comparison with diesel and lng. Technical report, TNO, 2020.

[93] Bart van Oers. *A Packing Approach for the Early Stage Design of Service Vessels*. PhD thesis, Delft University of Technology, 2011.

[94] Bart van Oers. Consulted: 13-08-2020, 2020. Head life cycle modelling, DMO.

[95] Bart van oers; Erik Takken; Etienne Ducheteau; Ruben Zandstra; Siebe Cieraad; Wendy van den Broek de Bruijn; Michel Janssen. Warship concept exploration and definition at the netherlands defence materiel organisation. *Naval Engineers Journal*, 130(2):61–82, 2018.

[96] Huibert Jan Verbaan, 2020.

[97] R Verbeek and M Verbeek. Lng for trucks and ships: fact analysis review of pullutant and ghg emissions final. Technical report, TNO, 2015.

[98] Carl von Clausewitz. *On War [Vom Krieg]*. 1832.

[99] BENJAMIN R. WIGG. *A STUDY ON THE EMISSIONS OF BUTANOL USING A SPARK IGNITION ENGINE AND THEIR REDUCTION USING ELECTROSTATICALLY ASSISTED INJECTION*. PhD thesis, University of Illinois, 2011.

# A

# Vessel replacement schedule

Table A.1: Replacement schedule for surface vessels in service after 2010

| Type | Name | In service | out of service |
|---|---|---|---|
| Supply | Zuiderkruis | 1975 | 2012 |
| MBV | Makkum | 1985 | 2024 |
| MBV | Schiedam | 1986 | 2025 |
| MBV | Urk | 1986 | 2026 |
| Torpedewerkschip | Mercuur | 1987 | 2026 |
| MBV | Zierikzee | 1987 | 2027 |
| MBV | Vlaardingen | 1989 | 2028 |
| MBV | Willemstad | 1989 | 2029 |
| M-Fregat | Karel Doorman | 1991 | 2006 |
| M-Fregat | Willem van der Zaan | 1991 | 2005 |
| DVT | Cerberus | 1992 | 2026 |
| DVT | Argus | 1992 | 2026 |
| DVT | Nautilus | 1992 | 2027 |
| DVT | Hydra | 1992 | 2027 |
| M-Fregat | Tjerk Hiddes | 1993 | 2006 |
| M-Fregat | Abraham van der Hulst | 1993 | 2004 |
| M-Fregat | Van Amstel | 1993 | 2023 |
| M-Fregat | Van Nes | 1994 | 2008 |
| M-Fregat | Van Galen | 1994 | 2009 |
| Supply | Amsterdam | 1995 | 2014 |
| M-Fregat | Van Speijk | 1995 | 2025 |
| LPD 1 | Rotterdam | 1998 | 2028 |
| MOV | Van kinsbergen | 1999 | 2025 |
| LCF | Zeven provincien | 2002 | 2032 |
| HOV | Snellius | 2003 | 2033 |
| LCF | Tromp | 2003 | 2033 |
| HOV | Luymes | 2004 | 2034 |
| LCF | De Ruyter | 2004 | 2034 |
| LCF | Evertsen | 2005 | 2035 |
| OVT | Pelikaan | 2006 | 2030 |

Table A.2: Replacement schedule for surface vessels in service after 2010 (continues)

| Type | Name | In service | out of service |
|---|---|---|---|
| LPD 2 | Johan de Wit | 2007 | 2037 |
| OPV | Holland | 2012 | 2042 |
| OPV | Friesland | 2013 | 2043 |
| OPV | Zeeland | 2013 | 2043 |
| OPV | Groningen | 2013 | 2043 |
| JSS | Karel Doorman | 2015 | 2045 |
| CSS | Den Helder | 2024 | 2054 |
| rMCV | | 2025 | 2055 |
| rMT | | 2025 | 2055 |
| rMCV | | 2026 | 2056 |
| rSS | | 2026 | 2056 |
| rMCV | | 2027 | 2057 |
| rMFF | | 2027 | 2057 |
| rMCV | | 2028 | 2058 |
| rMFF | | 2028 | 2058 |
| rMCV | | 2029 | 2059 |
| rLPD 1 | | 2030 | 2060 |
| rMCV | | 2030 | 2060 |
| rLS | | 2030 | 2060 |
| rLPD 2 | | 2032 | 2062 |
| rHOV | | 2033 | 2063 |
| rHOV | | 2034 | 2064 |
| rLCF | | 2034 | 2064 |
| rLCF | | 2035 | 2065 |
| rLCF | | 2036 | 2066 |
| rLCF | | 2037 | 2067 |
| rOPV | | 2043 | 2073 |
| rOPV | | 2043 | 2073 |
| rOPV | | 2044 | 2074 |
| rOPV | | 2044 | 2074 |
| rJSS | | 2046 | 2076 |

# B

# Design algorithm

In this appendix a mathematical description of the adapted design algorithm will be presented.

$$L_{wl} = B \cdot LoB \tag{B.1}$$

$$T = \frac{B}{BoT} \tag{B.2}$$

$$FBD = T * FoT \tag{B.3}$$

$$\Delta_1 = L_{wl} \cdot T \cdot B \cdot C_b \tag{B.4}$$

$$V_{hull} = \frac{\Delta_1}{\rho} + L_{wl} \cdot B \cdot FBD \cdot C_{wp} \cdot C_f \tag{B.5}$$

$$P_{prop} = \frac{\Delta_1^{2/3} \cdot V_{max}^3}{C_{adm}} \tag{B.6}$$

$$\eta_{drive,rel} = \frac{\eta_{drive}}{\eta_{drive,ref}} \tag{B.7}$$

$$P_{inst} = \begin{cases} \frac{P_{prop}+P_{aux}}{max(r_p)} \cdot \frac{1}{\eta_{drive,rel}} & \text{when } drive = or \\ P_{prop} \frac{1}{\eta_{drive,rel}} + P_{aux} & \text{when } drive = and \end{cases} \tag{B.8}$$

$$P_{avg} = P_{inst} \cdot P_{frac} \tag{B.9}$$

$$P_1 = P_{inst} \cdot r_(p, 1) \tag{B.10}$$

$$P_2 = P_inst \cdot r_(p, 2) \tag{B.11}$$

$$r_{P,1} + r_{P,2} = 1 \tag{B.12}$$

$$P_{frac} = \left( \sum_{i=1}^{n} (P_i + P_{e-load}) * T_i \right) / P_{inst} \tag{B.13}$$

$$E_{req,n} = P_{avg} \cdot Aut \cdot \frac{r_{E,n}}{\eta_{sys,n}} \tag{B.14}$$

$$\eta_{sys,n} = \eta_{conv,n} \cdot \eta_{pref,n} \tag{B.15}$$

$$\eta_{sys,total} = \frac{1}{\frac{r_{E,1}}{\eta_{sys,1}} \frac{r_{E,2}}{\eta_{sys,2}}} \tag{B.16}$$

$$W_{fuel} = \sum_{n=1}^{2} \frac{E_{req,n}}{U_{cont,n}} \tag{B.17}$$

$$W_{sys,1} = P_1 \cdot SP_1 \tag{B.18}$$

$$W_{sys,2} = P_2 \cdot SP_2 \tag{B.19}$$

$$SP_n = SP_{con,n} + SP_{aux,n} + SP_{drive} + SP_{pref,n} \tag{B.20}$$

$$W_{sys} = W_{sys,1} + W_{sys,2} \tag{B.21}$$

$$W_{struct} = V_{hull} \cdot SWL \tag{B.22}$$

$$\Delta_2 = W_{struct} + W_{sys} + W_{fuel} + W_{rest} \tag{B.23}$$

$$\mathrm{E}_{\Delta} = \Delta_1 - \Delta_2 \tag{B.24}$$

Using equations B and B, the algorithm obtains two estimates fo the displacement of the vessel. The first is based on the dimensions of the vessel and the second on the total weight of the weight groups. This second estimate is also a function of the vessels resistance, the operational profile, the selected energy carrier and more. The algorithm finally solves the equations by finding the solution to:

$$E_{disp}(B) = 0. \tag{B.25}$$

This is the point at which both displacement estimates are equal, which provides the relevant data.

# C
# parametric design results

## C.1. Landing Platform Dock results

Table C.1: Normalised results LPD design variation

| Displacement | Rest weight | System weight | Fuel weight | Construction weight | Installed power | Converter 1 | Converter 2 | Carrier 1 | Carrier 2 | Name |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.00 | 1 | 1.00 | 1.00 | 1.00 | 1.00 | Medium speed CI ICE | None | F-76 | F-76 | Reference model |
| 1.00 | 1 | 1.00 | 1.00 | 1.00 | 1.00 | Medium speed CI ICE | None | F-76 | F-76 | F-76 ICE |
| 1.00 | 1 | 1.00 | 0.97 | 1.00 | 1.00 | Medium speed CI ICE | None | HVO | HVO | HVO ICE |
| 1.01 | 1 | 1.00 | 1.04 | 1.01 | 1.00 | Medium speed CI ICE | None | FAME | FAME | FAME ICE |
| 1.09 | 1 | 1.04 | 1.51 | 1.09 | 1.04 | Medium speed CI ICE | None | Ethanol | Ethanol | Ethanol ICE |
| 1.21 | 1 | 1.10 | 2.20 | 1.21 | 1.10 | Medium speed CI ICE | None | Methanol | Methanol | Methanol ICE |
| 1.02 | 1 | 1.01 | 1.13 | 1.02 | 1.01 | Medium speed CI ICE | None | Butanol | Butanol | Butanol ICE |
| 1.10 | 1 | 1.05 | 1.59 | 1.10 | 1.05 | Medium speed CI ICE | None | DME | DME | DME ICE |
| 1.34 | 1 | 1.16 | 2.98 | 1.34 | 1.16 | Medium speed CI ICE | None | NH3 | NH3 | NH3 ICE |
| 1.60 | 1 | 1.27 | 4.50 | 1.60 | 1.27 | Medium speed CI ICE | None | LH2 | LH2 | LH2 ICE |
| 1.05 | 1 | 1.70 | 1.05 | 1.05 | 1.02 | LT PEMFC | None | F-76 | F-76 | F-76 LT PEMFC |
| 1.05 | 1 | 1.70 | 1.02 | 1.05 | 1.02 | LT PEMFC | None | HVO | HVO | HVO LT PEMFC |
| 1.06 | 1 | 1.71 | 1.09 | 1.06 | 1.03 | LT PEMFC | None | FAME | FAME | FAME LT PEMFC |
| 1.27 | 1 | 1.87 | 2.31 | 1.27 | 1.13 | LT PEMFC | None | Methanol | Methanol | Ehtanol LT PEMFC |
| 1.27 | 1 | 1.87 | 2.31 | 1.27 | 1.13 | LT PEMFC | None | Methanol | Methanol | Methanol LT PEMFC |
| 1.07 | 1 | 1.72 | 1.18 | 1.07 | 1.04 | LT PEMFC | None | Butanol | Butanol | Butanol LT PEMFC |
| 1.16 | 1 | 1.79 | 1.67 | 1.16 | 1.08 | LT PEMFC | None | DME | DME | DME LT PEMFC |
| 1.67 | 1 | 2.29 | 4.56 | 1.67 | 1.30 | LT PEMFC | None | NH3 | NH3 | NH3 LT PEMFC |
| 1.45 | 1 | 1.44 | 3.53 | 1.45 | 1.21 | LT PEMFC | None | LH2 | LH2 | LH2 LT PEMFC |
| 1.11 | 1 | 3.02 | 0.91 | 1.11 | 1.05 | SOFC | None | F-76 | F-76 | F-76 SOFC |
| 1.10 | 1 | 3.01 | 0.89 | 1.10 | 1.05 | SOFC | None | HVO | HVO | HVO SOFC |
| 1.11 | 1 | 3.03 | 0.95 | 1.11 | 1.05 | SOFC | None | FAME | FAME | FAME SOFC |
| 1.19 | 1 | 3.13 | 1.37 | 1.19 | 1.09 | SOFC | None | Ethanol | Ethanol | Ehtanol SOFC |
| 1.30 | 1 | 3.28 | 1.98 | 1.30 | 1.14 | SOFC | None | Methanol | Methanol | Methanol SOFC |
| 1.13 | 1 | 3.05 | 1.02 | 1.13 | 1.06 | SOFC | None | Butanol | Butanol | Butanol SOFC |
| 1.20 | 1 | 3.15 | 1.44 | 1.20 | 1.10 | SOFC | None | DME | DME | DME SOFC |
| 1.64 | 1 | 3.82 | 3.82 | 1.64 | 1.29 | SOFC | None | NH3 | NH3 | NH3 SOFC |
| 1.44 | 1 | 2.89 | 2.98 | 1.44 | 1.20 | SOFC | None | LH2 | LH2 | LH2 SOFC |
| 1.00 | 1 | 1.00 | 1.00 | 1.00 | 1.00 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 0 - 100 |
| 1.01 | 1 | 1.07 | 1.01 | 1.01 | 1.00 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 10 - 90 |
| 1.01 | 1 | 1.14 | 1.02 | 1.01 | 1.01 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 20 - 80 |
| 1.02 | 1 | 1.21 | 1.03 | 1.02 | 1.01 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 30 - 70 |
| 1.02 | 1 | 1.28 | 1.03 | 1.02 | 1.01 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 40 - 60 |
| 1.03 | 1 | 1.35 | 1.03 | 1.03 | 1.01 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 50 - 50 |
| 1.03 | 1 | 1.42 | 1.04 | 1.03 | 1.02 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 60 - 40 |
| 1.04 | 1 | 1.49 | 1.04 | 1.04 | 1.02 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 70 - 30 |
| 1.04 | 1 | 1.56 | 1.04 | 1.04 | 1.02 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 80 - 20 |
| 1.05 | 1 | 1.63 | 1.05 | 1.05 | 1.02 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 90 - 10 |
| 1.05 | 1 | 1.70 | 1.05 | 1.05 | 1.02 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 Hybrid 100 - 0 |
| 1.21 | 1 | 1.10 | 2.20 | 1.21 | 1.10 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 0 - 100 |
| 1.22 | 1 | 1.18 | 2.23 | 1.22 | 1.10 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 10 - 90 |
| 1.22 | 1 | 1.25 | 2.25 | 1.22 | 1.11 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 20 - 80 |
| 1.23 | 1 | 1.33 | 2.27 | 1.23 | 1.11 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 30 - 70 |
| 1.24 | 1 | 1.41 | 2.28 | 1.24 | 1.11 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 40 - 60 |
| 1.24 | 1 | 1.48 | 2.28 | 1.24 | 1.12 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 50 - 50 |
| 1.25 | 1 | 1.56 | 2.29 | 1.25 | 1.12 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 60 - 40 |
| 1.25 | 1 | 1.64 | 2.30 | 1.25 | 1.12 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 70 - 30 |
| 1.26 | 1 | 1.72 | 2.30 | 1.26 | 1.12 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 80 - 20 |
| 1.27 | 1 | 1.79 | 2.31 | 1.27 | 1.13 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 90 - 10 |
| 1.27 | 1 | 1.87 | 2.31 | 1.27 | 1.13 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid 100 - 0 |
| 1.02 | 1 | 1.01 | 1.13 | 1.02 | 1.01 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 0 - 100 |
| 1.03 | 1 | 1.08 | 1.14 | 1.03 | 1.01 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 10 - 90 |
| 1.03 | 1 | 1.15 | 1.15 | 1.03 | 1.02 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 20 - 80 |
| 1.04 | 1 | 1.22 | 1.16 | 1.04 | 1.02 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 30 -70 |
| 1.04 | 1 | 1.29 | 1.16 | 1.04 | 1.02 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 40 - 60 |
| 1.05 | 1 | 1.36 | 1.17 | 1.05 | 1.02 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 50 - 50 |
| 1.05 | 1 | 1.43 | 1.17 | 1.05 | 1.03 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 60 - 40 |
| 1.06 | 1 | 1.50 | 1.17 | 1.06 | 1.03 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 70 - 30 |
| 1.06 | 1 | 1.58 | 1.18 | 1.06 | 1.03 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 80 - 20 |
| 1.07 | 1 | 1.65 | 1.18 | 1.07 | 1.03 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 90 - 10 |
| 1.07 | 1 | 1.72 | 1.18 | 1.07 | 1.04 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol Hybrid 100 - 0 |
| 1.23 | 1 | 1.33 | 2.27 | 1.23 | 1.11 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid full speed |
| 1.17 | 1 | 1.16 | 1.97 | 1.17 | 0.96 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 0.95 speed |
| 1.12 | 1 | 1.01 | 1.72 | 1.12 | 0.84 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 0.9 speed |
| 1.08 | 1 | 0.88 | 1.50 | 1.08 | 0.74 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 0.85 speed |
| 1.04 | 1 | 0.78 | 1.32 | 1.04 | 0.65 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 0.8 speed |
| 1.21 | 1 | 1.10 | 2.20 | 1.21 | 1.10 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 0 - 100 |
| 1.20 | 1 | 1.30 | 2.08 | 1.20 | 1.09 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 10 - 90 |
| 1.20 | 1 | 1.50 | 2.01 | 1.20 | 1.09 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 20 - 80 |
| 1.20 | 1 | 1.71 | 1.96 | 1.20 | 1.10 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 30 - 70 |
| 1.21 | 1 | 1.93 | 1.94 | 1.21 | 1.10 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 40 - 60 |
| 1.23 | 1 | 2.14 | 1.94 | 1.23 | 1.11 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 50 - 50 |
| 1.24 | 1 | 2.36 | 1.94 | 1.24 | 1.11 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 60 - 40 |
| 1.25 | 1 | 2.59 | 1.94 | 1.25 | 1.12 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 70 - 30 |
| 1.27 | 1 | 2.81 | 1.96 | 1.27 | 1.13 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 80 - 20 |
| 1.28 | 1 | 3.04 | 1.97 | 1.28 | 1.13 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 90 - 10 |
| 1.30 | 1 | 3.28 | 1.98 | 1.30 | 1.14 | SOFC | Medium speed CI ICE | Methanol | Methanol | Methanol Hybrid SOFC 100 - 0 |

Table C.2: Normalised results LCF design variation

| Displacement | Rest weight | System weight | Fuel weight | Construction weight | Installed power | Converter 1 | Converter 2 | Carrier 1 | Carrier 2 | Name |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | Medium speed CI ICE | Gas Turbine | F-76 | F-76 | Reference model |
| 1.02 | 1 | 1.01 | 1.09 | 1.02 | 1.01 | Medium speed CI ICE | Gas Turbine | F-76 | F-76 | F-76 ICE + turbine |
| 1.01 | 1 | 1.01 | 1.06 | 1.01 | 1.01 | Medium speed CI ICE | Gas Turbine | HVO | HVO | HVO ICE + turbine |
| 1.04 | 1 | 1.02 | 1.14 | 1.04 | 1.02 | Medium speed CI ICE | Gas Turbine | FAME | FAME | FAME ICE + turbine |
| 1.19 | 1 | 1.12 | 1.74 | 1.19 | 1.12 | Medium speed CI ICE | Gas Turbine | Ethanol | Ethanol | Ethanol ICE + turbine |
| 1.44 | 1 | 1.27 | 2.73 | 1.44 | 1.27 | Medium speed CI ICE | Gas Turbine | Methanol | Methanol | Methanol ICE + turbine |
| 1.06 | 1 | 1.04 | 1.24 | 1.06 | 1.04 | Medium speed CI ICE | Gas Turbine | Butanol | Butanol | Butanol ICE + turbine |
| 1.22 | 1 | 1.14 | 1.85 | 1.22 | 1.14 | Medium speed CI ICE | Gas Turbine | DME | DME | DME ICE + turbine |
| 1.75 | 1 | 1.45 | 3.99 | 1.75 | 1.45 | Medium speed CI ICE | Gas Turbine | NH3 | NH3 | NH3 ICE + turbine |
| 2.58 | 1 | 2.06 | 7.19 | 2.58 | 1.88 | Medium speed CI ICE | Gas Turbine | LH2 | LH2 | LH2 ICE + turbine |
| 1.00 | 1 | 1.29 | 0.70 | 1.00 | 0.79 | Medium speed CI ICE | None | F-76 | F-76 | F-76 ICE |
| 2.05 | 1 | 5.45 | 1.21 | 2.05 | 1.34 | LT PEMFC | None | F-76 | F-76 | F-76 PEMFC |
| 2.31 | 1 | 4.21 | 3.73 | 2.31 | 1.45 | LT PEMFC | None | LH2 | LH2 | LH2 LTPEMFC |
| 2.58 | 1 | 6.28 | 2.80 | 2.58 | 1.55 | LT PEMFC | None | Methanol | Methanol | Methanol PEMFC |
| 2.10 | 1 | 5.54 | 1.37 | 2.10 | 1.37 | LT PEMFC | None | Butanol | Butanol | Butanol PEMFC |
| 4.26 | 1 | 14.87 | 1.61 | 4.26 | 2.12 | SOFC | None | F-76 | F-76 | F-76 SOFC |
| 4.49 | 1 | 12.86 | 4.77 | 4.49 | 2.19 | SOFC | None | LH2 | LH2 | LH2 SOFC |
| 5.10 | 1 | 16.67 | 3.63 | 5.10 | 2.38 | SOFC | None | Methanol | Methanol | Methanol SOFC |
| 4.35 | 1 | 15.07 | 1.82 | 4.35 | 2.15 | SOFC | None | Butanol | Butanol | Butanol SOFC |
| 1.66 | 1 | 2.89 | 2.09 | 1.66 | 1.18 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 0 - 100 |
| 1.74 | 1 | 3.17 | 2.18 | 1.74 | 1.22 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 10 - 90 |
| 1.83 | 1 | 3.47 | 2.25 | 1.83 | 1.25 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 20 -80 |
| 1.91 | 1 | 3.77 | 2.32 | 1.91 | 1.29 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 30 -70 |
| 1.99 | 1 | 4.08 | 2.38 | 1.99 | 1.32 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 40 - 60 |
| 2.08 | 1 | 4.41 | 2.45 | 2.08 | 1.36 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 50 - 50 |
| 2.17 | 1 | 4.75 | 2.52 | 2.17 | 1.39 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 60 - 40 |
| 2.27 | 1 | 5.11 | 2.58 | 2.27 | 1.43 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 70 - 30 |
| 2.37 | 1 | 5.49 | 2.65 | 2.37 | 1.47 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 80 - 20 |
| 2.47 | 1 | 5.87 | 2.72 | 2.47 | 1.51 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 90 - 10 |
| 2.58 | 1 | 6.28 | 2.80 | 2.58 | 1.55 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 100 - 0 |
| 1.36 | 1 | 2.56 | 1.03 | 1.36 | 1.05 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 0 - 100 |
| 1.42 | 1 | 2.81 | 1.07 | 1.42 | 1.08 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 10 - 90 |
| 1.49 | 1 | 3.06 | 1.11 | 1.49 | 1.11 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 20 -80 |
| 1.55 | 1 | 3.33 | 1.14 | 1.55 | 1.14 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 30 -70 |
| 1.62 | 1 | 3.60 | 1.17 | 1.62 | 1.17 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 40 - 60 |
| 1.70 | 1 | 3.89 | 1.20 | 1.70 | 1.20 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 50 - 50 |
| 1.77 | 1 | 4.20 | 1.23 | 1.77 | 1.23 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 60 - 40 |
| 1.85 | 1 | 4.51 | 1.27 | 1.85 | 1.26 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 70 - 30 |
| 1.93 | 1 | 4.84 | 1.30 | 1.93 | 1.30 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 80 - 20 |
| 2.02 | 1 | 5.18 | 1.33 | 2.02 | 1.33 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 90 - 10 |
| 2.10 | 1 | 5.54 | 1.37 | 2.10 | 1.37 | LT PEMFC | Medium speed CI ICE | Butanol | Butanol | Butanol hybrid 100 - 0 |
| 1.32 | 1 | 2.52 | 0.91 | 1.32 | 1.03 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 0 - 100 |
| 1.39 | 1 | 2.76 | 0.94 | 1.39 | 1.06 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 10 - 90 |
| 1.45 | 1 | 3.01 | 0.98 | 1.45 | 1.09 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 20 -80 |
| 1.51 | 1 | 3.28 | 1.00 | 1.51 | 1.12 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 30 -70 |
| 1.58 | 1 | 3.55 | 1.03 | 1.58 | 1.15 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 40 - 60 |
| 1.65 | 1 | 3.83 | 1.06 | 1.65 | 1.18 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 50 - 50 |
| 1.72 | 1 | 4.13 | 1.09 | 1.72 | 1.21 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 60 - 40 |
| 1.80 | 1 | 4.44 | 1.12 | 1.80 | 1.24 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 70 - 30 |
| 1.88 | 1 | 4.76 | 1.15 | 1.88 | 1.28 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 80 - 20 |
| 1.96 | 1 | 5.10 | 1.18 | 1.96 | 1.31 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 90 - 10 |
| 2.05 | 1 | 5.45 | 1.21 | 2.05 | 1.34 | LT PEMFC | Medium speed CI ICE | F-76 | F-76 | F-76 hybrid 100 - 0 |
| 1.91 | 1 | 3.77 | 2.32 | 1.91 | 1.29 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid full speed |
| 1.63 | 1 | 2.98 | 1.83 | 1.63 | 1.02 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 0.95 speed |
| 1.41 | 1 | 2.38 | 1.46 | 1.41 | 0.81 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 0.9 speed |
| 1.25 | 1 | 1.92 | 1.18 | 1.25 | 0.65 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 0.85 speed |
| 1.12 | 1 | 1.56 | 0.96 | 1.12 | 0.53 | LT PEMFC | Medium speed CI ICE | Methanol | Methanol | Methanol hybrid 0.8 speed |

# D

# Overview of model input data

## D.1. System power densities

Broadly speaking there are two different methods to calculate the power density of the total system. The most accurate method is to work bottom-up and include every system component. This method is also very time consuming however. The second method is to use more general system level relations which can be derived from reference vessels. The data used for the parametric design tool has been derived using the second method and is based on reference vessels within the RNLN fleet and values used by MARIN for the SPEC tool. An attempt was made to differentiate between different distribution drive systems. As was explained in chapter 7 the exact configuration and design choices still have a significant impact on the final system weight and the values below should only be used for preliminary design.

Table D.1: Energy carrier contained energy densities

| Name | Gravimetric energy density [MJ/kg] | Volumetric energy density [MJ/L] |
|---|---|---|
| F-76 | 30.09 | 34.03 |
| HVO | 30.8 | 31.9 |
| FAME | 28.92 | 30 |
| Ethanol | 20.72 | 18.5 |
| Methanol | 15 | 14 |
| Butanol | 27 | 21 |
| DME | 19.8 | 13.3 |
| NH3 | 11.7 | 9 |
| LH2 | 8.5 | 5 |
| LNG | 30 | 14 |
| None | 0 | 0 |

Table D.2: Energy converter power densities

| Name | Power density [kg/kW] | Volumetric power density [l/kW] | Efficiency [-] |
|---|---|---|---|
| Medium speed CI ICE | 15 | 16 | 0.45 |
| High speed CI ICE | 5 | 6 | 0.35 |
| Gas Turbine | 2.5 | 5 | 0.25 |
| LT PEMFC | 20 | 60 | 0.55 |
| SOFC | 60 | 120 | 0.65 |
| None | 0 | 0 | 1 |

Table D.3: Auxiliary system power densities

| Name | Gravimetric power density [kg/kW] | Volumetric power density [l/kW] | Efficiency |
|---|---|---|---|
| Direct | 5 | 9 | 0.95 |
| Geared | 7 | 15 | 0.9 |
| Electric | 18 | 20 | 0.8 |
| Hybrid | 10.5 | 16.6 | 0.82 |
| None | 0 | 0 | 1 |