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Alternative Energy Carriers in Naval Vessels: Design implications for RNLN large surface vessels

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Abstract

In order to reduce fossil fuel consumption of the Royal Netherlands Navy (RNLN) by 70% in 2050, the use of alternative fuels on the large naval surface vessels are examined. This paper examines the implications for the design and operational effectiveness of these vessels by performing two case studies of the Zeven Provinciën air defence and command frigate (LCF) and the Johan de Witt landing platform dock (LPD). In the case studies an operational analysis, a parametric design study, and an effectiveness assessment are performed on multiple proposed designs. It is found that it is possible to reduce the fossil fuel consumption of the RNLN by almost 70%. This does affect the design of the vessels, however. It was also concluded that the LPD is more suitable for the application of low-energy-density fuels than the LCF, due to its missions requirements. Both the LPD and the LCF show a significant increase in displacement and fuel cost, but it is possible to reduce effects on the operational effectiveness to a minimum.

Keywords: Naval vessel design, Alternative fuels, Systems engineering, Fuel consumption, Feasibility study.

1 Introduction

The Dutch Ministry of Defence has expressed the ambition to reduce the fossil fuel consumption for operational use by 70% in 2050 (Bijleveld-Schouten and Visser, 2019). To achieve this, multiple projects have already been started such as the design of methanol fuelled support vessels and the use of HVO as an additive to the F-76 fuel. The challenge at hand is so severe however that it is necessary to consider more substantial measures. In this paper, therefore, the application of alternative energy carriers and alternative energy converters onboard Royal Netherlands Navy large surface vessels will be considered. This paper attempts to answer the following question: How are the design and the operational effectiveness of RNLN vessels affected using alternative energy carriers and energy conversion technologies that are needed to reduce the fossil fuel consumption of the Netherlands armed forces? In the first section, a short literature review will be presented to explain some of the necessary concepts. The second section will shortly explain the methods which will be used and present the different case study subjects. In section 3 an operational analysis is performed for both vessels to decide which of the measures of effectiveness are most important. In the fourth section, a parametric design tool is used in a systematic design variation of the case study subjects.

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2 Methodology

The effects which the application of alternative energy carriers will have on the design of large surface naval vessels will be assessed through a design study. Two case study subjects will be selected for this design study so that potential differences between vessel types may be observed. In this section, the different steps of the design study and the selection of the vessel on which the study will be performed are explained. The design study follows several distinct steps of a systems engineering approach and focuses mainly on concept exploration and the first phase of concept definition.

2.1 Case study selection

In this subsection, the selection of the two case study subjects is explained. Considering the replacement schedule (Ministry of Defense, 2020) and the prognosis of the fossil fuel consumption of the RNLN fleet it is apparent that significant action has to be taken sooner rather than later. For several future designs, the design process has already progressed to a stage where it is no longer possible, or too costly, to consider such actions. Therefore the vessels delivered before 2030 are not considered. The most suitable subjects for a case study, therefore, are the LPD and the LCF. The design study exists of three separate design steps. In each step more detail is added to the design whilst the number of alternative designs is reduced.

2.2 Effectiveness assessment

The most important constraint in the DEOS concerns the operational effectiveness, which must be maintained or increased. To guarantee this constant effectiveness it is important to define the operational effectiveness and devise a way in which the operational effectiveness can be assessed. For naval vessels, this can be a complex task. Effectiveness assessment of many commercial transport vessels is relatively straightforward. The amount or value of goods transported from A to B is generally a sufficient metric for the effectiveness. If this is then divided by the duration, amount of fuel, or the total cost of the trip, a transport efficiency is obtained (Papanikolaou, 2014). For the second class of vessels, this is not so straightforward. These vessels are so-called service vessels, and many naval vessels fall within this category. Service vessels often have a wide array of different tasks and it is sometimes difficult to measure the output. Furthermore, the design of naval vessels is often a complex matter, sometimes described as a wicked problem. This means that it is difficult or impossible to state the requirements, independently of a solution direction (Coyne, 2005). By extension, this means that it is difficult to define what the contributions to effectiveness are. Within the design approach of systems engineering, there are multiple ways in which the effectiveness can be assessed depending on the design phase Brown (2013).

For a finished design, it is possible to run extensive simulations of different scenarios and operational environments to obtain an effectiveness for certain missions (Michalchuk and Bucknall, 2014). These can then be combined in overall effectiveness models to obtain the overall effectiveness. In the early design phases, it may be more suitable to define a number of measures of effectiveness and judge these measures qualitatively for different designs. This method is simpler and allows for comparison between different designs in the design exploration phase. The first step in the design process will be to establish a suitable set of measures of effectiveness (MoE), and to judge the priority of these measures for the different vessels within the RNLN fleet.

2.3 parametric design study

The second step in the design process is a systematic design variation. Using a design tool adapted from the SPEC tool by MARIN (Netherlands, 2020), various design parameters can easily be changed to examine the influence on the design of the vessels. In this parameter study, the independent variables will mainly be the power plant configuration and the energy carrier. The aim of this study is to obtain an estimate of the main dimensions of the vessels and to uncover the relations between the selected energy carriers and the other design parameters.

2.4 Concept design

In the final design step, a concept from the systematic design variation will be selected for both vessels. Using these concepts, the feasibility of all the different objectives mentioned in the introduction will be assessed. Next to an effectiveness assessment and design summary of the individual case study vessels, a prognosis will be made for the fossil fuel consumption, GHG emissions and fuel cost for the entire RNLN fleet until 2050. For the final effectiveness assessment, the influence of the design changes on the MoE's will be examined for each MoE, before making a judgement on the overall effectiveness.

3 Operational analysis

To assess how alternative energy carriers may influence the design and operation of the vessel an operational analysis is performed as the first design step. In this operational analysis, the different missions which the RNLN vessels are expected to perform have been examined, together with the capabilities required to execute these missions successfully.

3.1 Measures of effectiveness

From the analysis of the missions, tasks, and capabilities which the vessels must fulfil, a list of systems that provide those capabilities can be made. Each of these systems will influence the effectiveness in a multitude 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 Brown and Andres (1980):

- Speed
- Stability
- Strength
- Seakeeping
- Style
  - Stealth
  - 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 fundamentals of maritime operationsMiddendorp (2014) and on the international level in the NATO Capability Codes & Capability Statements North Atlantic Treaty Organization (2020). 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 fundamentals of maritime operations, this list is based mainly on conversations with DMO colleagues Verbaan (2020). 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 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.

3.2 Mission profiles & capability requirements

The missions which the RNLN vessels perform may be subdivided into three categories: maritime assistance, maritime security operations, and maritime combat operations. In the fundamentals of marine operations, the maritime doctrine of the Dutch Armed Forces is presented. In the table in appendix A1 all the different missions which are considered in this paper are shown. To establish the mission profile it is important to first know which vessels are designed to execute certain operations.

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 appendix A1, a table is provided in which an estimation of the different mission profiles of various RNLN vessels is presented. The weights in this table represent the importance each mission has for the design and the role of the vessel. A mission profile may also be based on the time which a vessel spends performing certain operations, but the uncertain nature of naval operations means that this would lead to a bias towards peacetime operations. A similar table may be constructed for the mission capability requirements. This table is also found in the appendix and gives an estimation of the importance of certain MoEs for the success of each mission. Both these tables have been constructed through the use of the GMO(Middendorp, 2014) and CCCS(North Atlantic Treaty Organization, 2020), and with help of colleagues at the DMO(Verbaan, 2020). Nonetheless, these tables remain a subjective interpretation of different priorities and must not be interpreted as absolute truths.

3.3 Capability prioritization

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, the importance of a certain capability for a vessel may be calculated. The result of this process is a capability prioritisation that is found in the table below. In order to illustrate and more easily distinguish between the priorities for different capabilities, a colour scale has been added. Dark green is considered the most important capabilities while dark red is 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 to 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

TABLE 1: Add caption

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

and displacement. The correlation matrix in the appendix shows how each measure of effectiveness is influenced by another.

3.4 Results

3.4.1 LCF

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. 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. 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 onboard 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.

3.4.2 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 to accommodate cargo, 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. 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 the vessel would thus lend itself quite well for the application of fuel

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4 Parametric design

In this section of the paper, a systematic design variation will be performed. A parametric design tool has been developed based on the Ship Power & Energy Concept (SPEC) tool developed by the Maritime Research Institute of the Netherlands (MARIN). In this design tool, it is possible to select different energy carriers and power plant configurations for a vessel and obtain a first indication of the size, and several other design parameters of the vessel. A short explanation of the design tool is first provided, after which the experiments setup and preliminary results will be provided.

4.1 Design tool

The design tool is developed to be used as a preliminary design tool. With a relatively small quantity of design data, it is possible to assess the influences of, and relations between different parameters. The application of energy carriers with different power densities may affect the vessel dimensions significantly. If the range, payload, and operational profile remain constant, an energy carrier with a lower energy density will lead to a larger fuel mass. This increases the displacement and leads to an increased resistance, a higher required power and higher fuel consumption. This mechanism, shown in figure 1, makes it difficult to estimate the vessel dimensions without an iterative process. The design

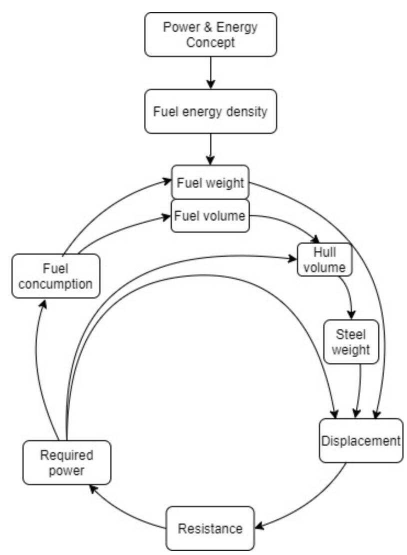

FIGURE 1: A reduction in energy density leads to an larger increase in the ships displacement

tool aims to automate this process. To achieve this, a number of simplifications and assumptions is used within the mathematical model. The complete mathematical model can be seen in appendix A2. The most important of the simplifications are the following:

- The entire displacement is divided into four weight groups.
- A constant admiralty coefficient based on the brake power at the maximum velocity.
- A constant hull shape.
- Efficiencies are taken as constants.

- Energy converter volume and weight are linearly dependent on the required power.

The algorithm evaluates two different functions that both estimate the total displacement of the vessel. The first is derived from the main dimensions of the vessel whilst the second formula is a simple addition of the four different weight groups.

$$\Delta_1 = L_{wl} \cdot B \cdot T \cdot C_b \tag{1}$$

$$\Delta_2 = W_{strcut} + W_{fuel} + W_{system} + W_{rest} \tag{2}$$

Three of the four weight categories in the second displacement estimate are in their turn a function of the vessel size, operational profile, and the technical properties of the energy carriers and converters. The algorithm is implemented in Matlab and uses a solver to bring the error in the displacement down to zero.

$$\epsilon_\Delta = \Delta_1 - \Delta_2 \tag{3}$$

Using this procedure, the main dimensions and weights of the weight groups are determined. Given the simplifications and assumptions that are used it is not realistic to expect a 100% accurate calculation. There is still a large design margin, irrespective of the results of this calculation. Furthermore, the design tool has not been developed to obtain a final design, but to assess the relations and influences between parameters, and to find a starting point for the next phases in the design process.

4.2 Verification

A verification of the design tool has been performed using reference models. To obtain this reference model the design parameters of the actual vessels have been used as input for the design tool. The difference between the output of the design tool and the dimensions and weights of the real vessels will then shed more light on the accuracy of the design tool. In the table below the dimensions and weight of the real vessels and the reference design are presented side by side. It can be observed that all parameters of the reference design fall within a 5% margin of the real design.

This means that within a certain range, the design tool is sufficiently accurate for the purpose which it serves.

4.3 Experiment selection

The experiments that have been selected for this paper serve two purposes. The primary is the selection of a suitable design with which the design process can continue. The secondary purpose is to understand more about the relation between the design choice in energy carrier and converter, and the effect they have on the vessel dimensions. In the table below an overview is given of the different experiments which have been performed. In each experiment, the power plant configuration is treated as the independent variable, while the operational profile, range, and rest weight are kept constant.

TABLE 2: Verification of reference designs with SPEC and the new adapted design tool

	LCF		LPD	
	DMO design	Reference	DMO design	Reference
W_{struct}	1	1.01	1	0.90
W_{sys}	1	0.98	1	1.01
W_{fuel}	1	1.00	1	1.08
W_{rest}	1	1	1	1
Δ	1	1.031	1	0.981

TABLE 3: Selected experiments

	LCF	LPD
Experiment 1	Conventional configuration, different fuels	Conventional configuration, different fuels
Experiment 2	IFEP: ICE, SOFC, PEMFC	IFEP: SOFC, PEMFC
Experiment 3	Hybrid electric: ICE & SOFC	Hybrid electric: ICE & SOFC
Experiment 4	Hybrid SOFC & ICE and direct gas	

The first experiment is equal for both vessels. The current configuration is used for a selection of different fuels: F-76, FAME, HVO, ethanol, methanol, butanol, ammonia, DME and liquid hydrogen (Streng, 2021). In the second experiment, other power plant configurations are also tested. A fully integrated electric plant (IFEP) is used, powered by an ICE, SOFC, and PEMFC. The original configuration of the LPD is already diesel-electric, so this configuration is not added. The third experiment considers a hybrid electric plant in which both ICEs and SOFCs are used to deliver the electric power. Different power ratios are also used ranging from 100% of the power delivered by the ICE ($r_{P,fc} = 0$) to 100% of the power delivered by the fuel cell ($r_{P,fc} = 1$). The fuels used in this experiment are butanol and methanol. For the LCF a fourth experiment is conducted. Given the high-speed requirement of the LCF, a configuration using a geared drive gas turbine and electric motor, combined with a SOFC ICE electric power plant is tested. This concept is tested using methanol, butanol, and F-76.

4.4 Results

Experiment 1
In the figures below is it quite clear that the contained energy densities have a drastic impact on the total displacement of the vessel. The two biofuels HVO and FAME have an energy density closer to that of F-76 and similarly sized vessels are thus expected. It is also readily apparent that the gaseous fuels ammonia and liquid hydrogen will result in a considerably larger vessel. The effects of the alcohol fuels are more moderate and fall in between the two extremes. The most remarkable however is the difference between the two vessels. The increase in displacement of the LPD is much smaller than that of the LCF. This can likely be attributed to two things. The relatively small contribution of the fuel weight to the total displacement of the LPD results in a smaller increase of displacement for the same increase in fuel weight. The high relative fuel weight of the LCF means that the mechanism explained in figure () leads to an increase in the total displacement of the vessel more quickly.

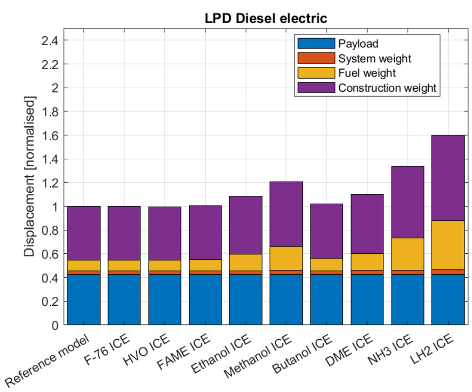

FIGURE 2: LPD: current configuration with different fuels

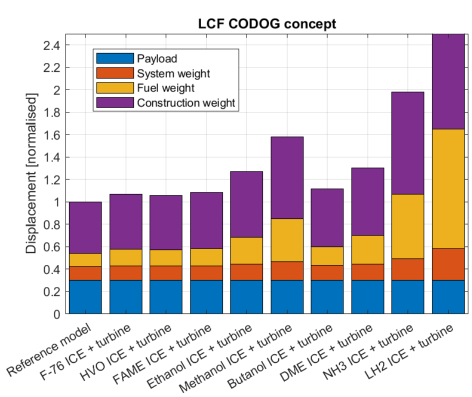

FIGURE 3: LCF: current configuration with different fuels

Experiment 2
In the following figures (4 and 5) it can be observed that the application of fuel cells increases the vessel displacement further. Especially the LCF, which has a high installed power relative to its size grows uncontrollably due to the lower power density of the fuel cells. The pre-formers which are needed for the LT-PEMFC also negate the efficiency gain which is achieved by using fuel cells. The total system efficiency of the LT-PEMFC concept is thus similar to that of an ICE. The lower power density however results in a heavier vessel.

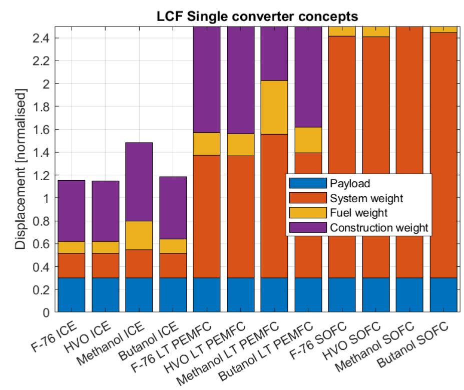

FIGURE 4: LCF fuel cell configurations

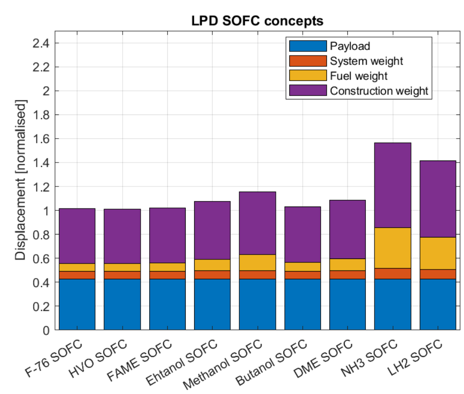

FIGURE 5: LPD: SOFC

Experiment 3
From the previous experiments, it resulted that a system powered by only fuel cells would likely be very heavy. A hybrid system in which a SOFC and ICE are combined may prove to benefit from the advantages of the efficient fuel cell without an excessive increase in the system weight. With increments of 5%, the power ratio of the fuel cell is increased from 0% to 100% for both methanol and butanol. In figure 6, it can be seen that as the fuel cell power fraction increases, the fuel weight decreases fuel to the greater system efficiency. Around $r_{P,fc} = 35\%$ there appears to

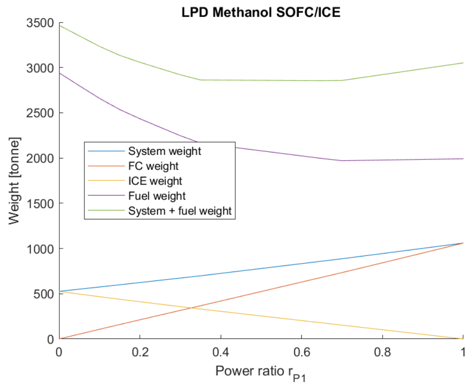

FIGURE 6: LPD: Hybrid methanol configuration

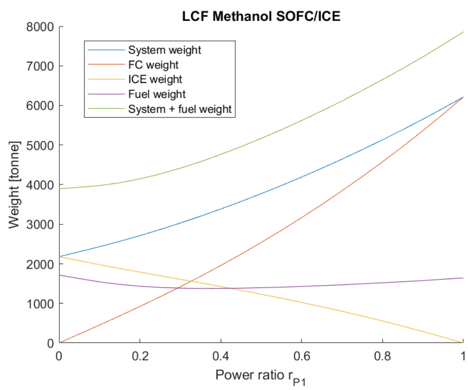

FIGURE 7: LCF: Hybrid methanol configuration

be an optimum. As the average efficiency approaches a maximum the reduction of fuel weight becomes smaller. However, the system weight continues to increase almost linearly. For the LCF the picture is quite different. Although the efficiency increases, the fuel weight does not decrease as much. This can again be attributed to the relatively high installed power. An increase in the system weight also has a significant effect on the resistance and thus the fuel consumption. There is thus no optimum to be observed. Additionally, it can be noted that for the LPD, there is an important difference between the use of butanol and methanol. Although both show the same trend with a minimum in the displacement around $r_{P,fc} = 35\%$, the difference between the minimum displacement and the maximum displacement is almost negligible with the use of butanol and much more pronounced with the use of methanol.

Experiment 4
The three experiments so far considered are not sufficient for the LCF. For a comparison with the current design, it is also necessary to assess a design that also uses a gas turbine. In figure 15 the results from this experiment are presented. In this experiment, the fuel cell power ratio depicts only

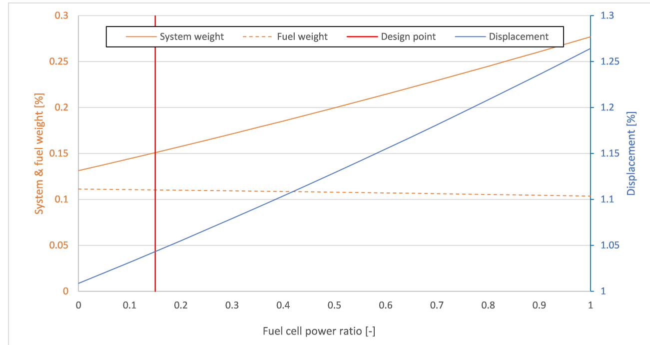

FIGURE 8: Displacement, system & fuel weight as percentage of reference design displacement

the power ratio between the generator set and the fuel cell. The gas turbine is considered to be used only for propulsion and is directly driven. In this experiment, it can be seen that although the total system efficiency does increase, the increased weight of the fuel cell is much higher. An optimum comparable to the LPD is not found.

5 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. One configuration from the previous design step is selected for continuation into the concept design phase. For the LPD this is the hybrid SOFC ICE methanol concept depicted in figure 9. For the LCF it is the hybrid electric design with an SOFC, ICE, and gas turbine depicted in figure 13. For both vessels, several design points are selected which will be evaluated further. After the evaluation and final design iteration an effectiveness assessment is performed.

5.1 Landing platform dock power plant configuration

The selected configuration for the lpd is a cofcaice 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 10 this is again shown. The trade-off between these options primarily seems to be between OPEX and CAPEX. Similar to the paper by Sapra et al. (2020), the optimum with the smallest total displacement will be selected. In table 4 the two optimal points are shown together with the reference design.

TABLE 4: Changes in weight and installed power of three concepts compared to the reference model

	Reference	ICE	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	16

The power plant configuration will resemble the schematic illustrated in figure 9. 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 4.

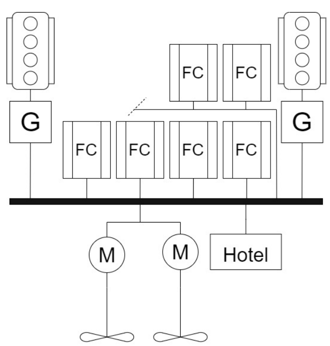

FIGURE 9: LPD power plant configuration

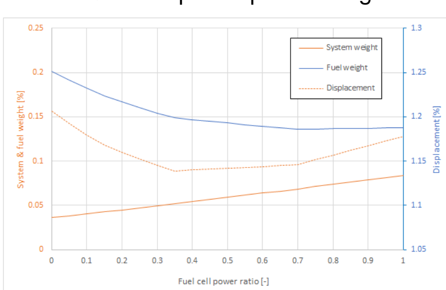

FIGURE 10: LPD power plant configuration

It is also possible to determine the maximum achievable speed while sailing solely on fuel cell power using equation (4) and (5)

$$V_{fc,max,1} = \sqrt[3]{\frac{(P_{fc} - P_{aux}) \cdot C_{adm}}{\Delta^{\frac{2}{3}}}} \approx 12kts \tag{4}$$

$$V_{fc,max,2} = \sqrt[3]{\frac{(P_{fc} - P_{aux}) \cdot C_{adm}}{\Delta^{\frac{2}{3}}}} \approx 16kts \tag{5}$$

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

5.2 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, ICE 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 11 through 14 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 12 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 CDOG propulsion configuration. Due to the fact that the ICE in proposed configuration 2[1] 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

[1]The naming convention becomes a bit complex when fuel cells enter the equation. Although COFCAICE 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.

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

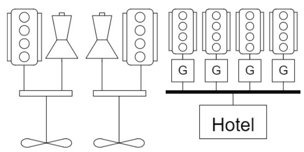

FIGURE 11: LCF current CODOG configuration

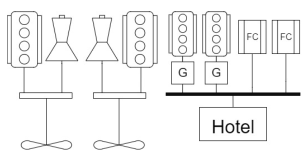

FIGURE 12: LCF proposed Configuration 1: CODOG + FC

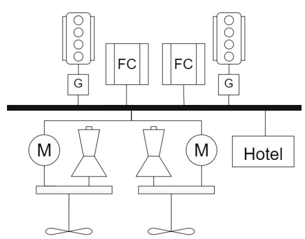

FIGURE 13: LCF proposed Configuration 2 CODLAG + FC

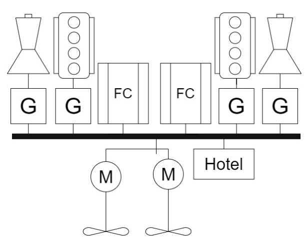

FIGURE 14: LCF proposed Configuration 3: IFCFEP

is 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 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 ICE. 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 13 is more optimised towards high vessel speeds whilst the configuration in figure 14 may be better suited to a highly varying on board energy demand[2]. 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 3 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 13 will be used for this analysis. In figure 15 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.

5.3 Final effectiveness assessment Landing Platform Dock

For the proposed alternate design for the LPDthe 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

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

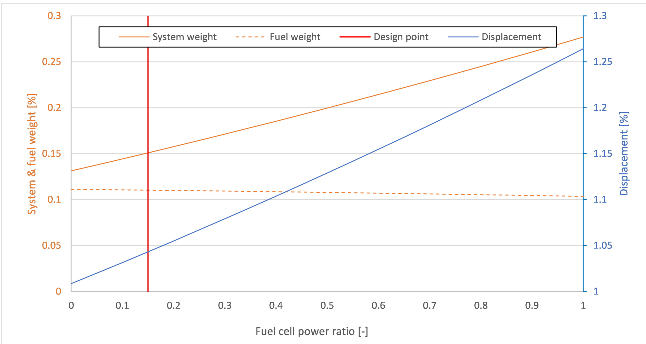

FIGURE 15: Displacement, system & fuel weight as percentage of reference design displacement

TABLE 5: proposed designs for the LCF

	Reference	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

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 mitigation 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 ICE 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.

TABLE 6: Change in effectiveness of the proposed LPD design

	SEWACO	Susceptibility	Vulnerability	Recoverability	Range	Endurance	Top speed	Acceleration	Manoeverability	Paylaod (volume)	Payload (weight)	
MOE	3.3	2	4	3.4	4.8	4.8	4.2	1.8	3.7	6.2	5.5	
Des. 1	0	3	-2	-1	0	0	0	-2	2	0	0	-1.6
Des. 2	0	5	-2	-1	0	0	0	-4	2	0	0	-1.2

5.4 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 prioritisation of the MOEs for the LCF it was observed that the possibility for a silent 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.

6 Results

Given the proposed design alterations to the LPD and the LCF it can now be calculated what the consequences will

TABLE 7: Effectiveness assessment of the LCF designs

	SEWACO	Susceptibility	Vulnerability	Recoverability	Range	Endurance	Top speed	Acceleration	Manoeverability	Paylaod (volume)	Payload (weight)	
MOE	8.6	4.2	6.6	6.2	5	5	5.9	3.2	3.6	1.8	1.4	
Des. 1	0	0	-3	0	0	0	0	0	0	0	0	-19.8
Des. 2	0	3	-3	2	0	0	0	-1	1	0	0	5.6
Des. 3	0	5	-3	2	0	0	0	-2	1	0	0	10.8

be for the fuel consumption of the RNLN. To do this, the consequences for the two vessels (which are also seen in more detail in appendix A4), have been extrapolated to the rest of the fleet. All new frigates and other fast vessels delivered after 2030 are calculated using the approach for the LCF. For all other vessels, the design alterations for the LPD are used. A prognosis for the fuel consumption can be seen in figure 16. Derived from this, the GHG emissions and the fuel cost expectations are also shown. It is clear that with only the proposed design changes, the goal of the fossil fuel consumption and GHG emissions are almost achieved. Further mixing of HVO with the F-76, or other measures to conserve energy will likely result in the achievement of the DEOS goals.

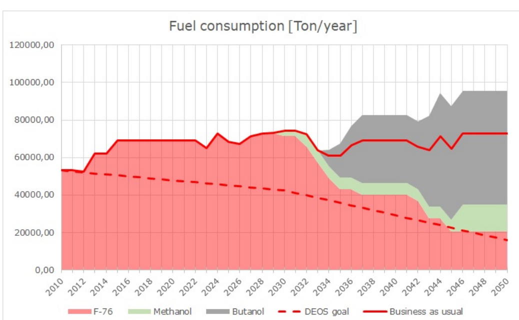

FIGURE 16: Prognosis of absolute fuel consumption

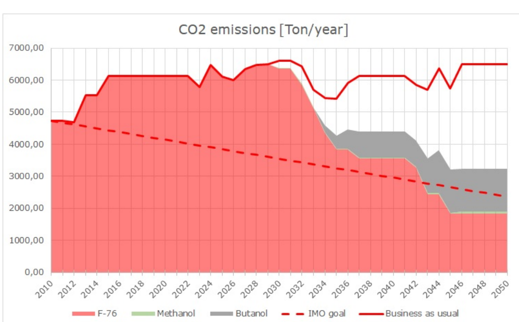

FIGURE 17: Prognosis of GHG emissions

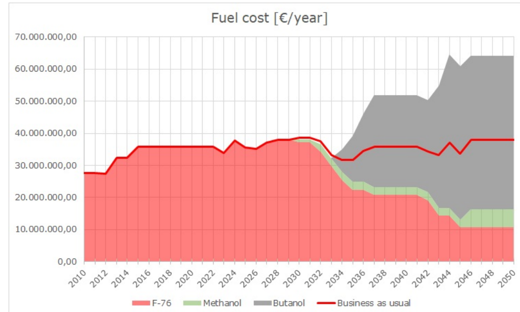

FIGURE 18: Prognosis of fuel cost (using 2020 fuel prices)

7 Conclusions

In this paper, the potential of alternative energy carriers onboard naval vessels were examined. By answering the question: "*How are the design and the operational effectiveness of RNLN vessels affected using alternative energy carriers and energy conversion technologies that are needed to reduce the fossil fuel consumption of the Netherlands armed forces?*" it may be possible to optimise a design strategy for the future naval vessels of the RNLN. It was shown that by adapting the design of future naval vessels, it is possible to reduce the fossil fuel consumption by almost 70%. If other vessels are adapted during their midlife update, or if HVO is mixed with the F-76, it is possible to achieve a reduction of 70%. Additionally, this would ensure compliance with the IMO goals regarding GHG and NOx emissions. Achieving these goals, without reducing the operational effectiveness comes at a cost. The designs of the LCF and LPD both have an increased displacement. The mechanism behind this increased displacement is similar, but there are differences between the vessels as well. The conclusion can be summarised in the following points:

1. **Different vessel types require different solutions.** Depending on the operational requirements and the subsequent design priorities, the cost of reducing the fossil fuel consumption will be higher for certain vessels than for others.
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**. Vessels that have a high top speed and a long-range generally have a relatively high fuel and system weight. The same increase in the fuel weight will thus induce a larger increase in the displacement than for a vessel with a low fuel weight. This increase in the displacement further necessitates a higher installed power.
3. **Vessels with a lower top speed and system weight have the potential to decrease the fuel consumption and displacement significantly through the use of fuel cells.** Vessels with a low top speed and fuel

weight have the potential to reduce their fuel consumption (compared to a vessel with the same fuel but no fuel cell) through the application of a relatively large fuel cell power ratio. Although the fuel cells increase the system weight, the increased energy efficiency of the system reduces the fuel weight by a larger amount.

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.** The reduction of the displacement is not seen in every vessel type or for every operational profile. When fuels with a higher energy density (e.g. butanol) are used, the difference between the minimum and maximum displacement is lower. A high fuel cell power ratio is thus best suited for vessels using a fuel with a lower energy density.

5. **The effect of the application of the considered technologies on the operational effectiveness is heavily dependent on the mission profile of the vessel.** A net negative effect on the operational effectiveness can be prevented in most situations. In some situations, the application of fuel cells may provide a slight improvement to the susceptibility.

8 Discussion & recommendations

In this paper multiple simplifications and assumptions have been made that may affect the accuracy and applicability of the results and a short discussion is therefore in order. A number of recommendations for future research can also be provided.

The operational analysis was performed using measures of effectiveness which have been selected specifically to assess the implications concerning alternative energy carriers and energy converters during operations. This list is by no means a complete representation of the design priorities of a naval vessel and only served to highlight the main differences. Such a list is a feasible tool in this approach since it was mainly used to highlight the differences between the original design, and the adapted designs. The subjective nature of the operational analysis is also a point of improvement. With a higher level of detail, a more comprehensive effectiveness assessment may be performed.

Another area for which the results must be discussed is the parametric design tool. The tool is developed on the basis of an earlier tool developed by MARIN and although much improvement has been made, the tool does lack in accuracy in some areas. Given the constant hull form, the assumption is made that the admiralty coefficient is also constant. This assumption is only valid for constant Froude numbers however. This means that as vessels get much larger than the reference design, the estimation of the required power is higher than it would be in reality. This means that as displacement increases, accuracy decreases. Also, when considering more complex power plant configurations with three or more different energy converters that do not distribute their power in the same manner, the results lack in accuracy. The results can still be used to observe trends and examine relations between different design parameters, but the indication as to the main dimensions of the vessels may not be representative. Since the model is not developed for naval vessels, but with any vessel type in mind, further improvement of this model may prove valuable for future design studies.

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Appendix

A1: Operational analysis

TABLE 8: Mission profiles

	Maritime Assistance		Maritime Security			Maritime Combat				Maritime Sustainability			
	Maritime Assistance 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
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
heightOPV	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

TABLE 9: Mission capability requirements

	Maritime Assistance		Maritime Security			Maritime Combat				Maritime Sustainability			
	Maritime Assistance 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
Paylaod (weight)	1	7	1	3	3	1	1	1	7	9	5	7	3
heightTotal	23	35	23	31	31	61	55	51	55	43	37	43	43

TABLE 10: Capability correlation matrix

	Susceptibility	Vulnerability	Recoverability	Range	Endurance	Top speed	Acceleration	Manoeverability	payload (volume)	payload (weight)
Susceptibility	x					-	-	-	+	+
Vulnerability		x							-	
Recoverability		-	x							
Range				x						-
Endurance					x					
Top speed	-					x			-	- -
Acceleration	-						x			- -
Manoeverability	-							x	-	-
Volume	+	-				-		-	x	++
Displacement	+	-		-		- -	- -	-	++	x

A2: Mathematical model

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

$$L_{wl} = B \cdot LoB \tag{6}$$

$$T = \frac{B}{BoT} \tag{7}$$

$$FBD = T * FoT \tag{8}$$

$$\Delta_1 = L_{wl} \cdot T \cdot B \cdot C_b \tag{9}$$

$$V_{hull} = \frac{\Delta_1}{\rho} + L_{wl} \cdot B \cdot FBD \cdot C_{wp} \cdot C_f \tag{10}$$

$$P_{prop} = \frac{\Delta_1^{2/3} \cdot V_{max}^3}{C_{adm}} \tag{11}$$

$$\eta_{drive,rel} = \frac{\eta_{drive}}{\eta_{drive,ref}} \tag{12}$$

$$P_{inst} = \begin{cases} \frac{P_{prop}+P_{aux}}{max(r_p)} \cdot \frac{1}{\eta_{drive,rel}} & \text{when } drive = or \\ P_{prop}\frac{1}{\eta_{drive,rel}} + P_{aux} & \text{when } drive = and \end{cases} \tag{13}$$

$$P_{avg} = P_{inst} \cdot P_{frac} \tag{14}$$

$$P_1 = P_{inst} \cdot r_(p, 1) \tag{15}$$

$$P_2 = P_inst \cdot r_(p, 2) \tag{16}$$

$$r_{P,1} + r_{P,2} = 1 \tag{17}$$

$$P_{frac} = \left(\sum_{i=1}^{n} (P_i + P_{e-load}) * T_i \right) / P_{inst} \tag{18}$$

$$E_{req,n} = P_{avg} \cdot Aut \cdot \frac{r_{E,n}}{\eta_{sys,n}} \tag{19}$$

$$\eta_{sys,n} = \eta_{conv,n} \cdot \eta_{pref,n} \tag{20}$$

$$\eta_{sys,total} = \frac{1}{\frac{r_{E,1}}{\eta_{sys,1}} \frac{r_{E,2}}{\eta_{sys,2}}} \tag{21}$$

$$W_{fuel} = \sum_{n=1}^{2} \frac{E_{req,n}}{U_{cont,n}} \tag{22}$$

$$W_{sys,1} = P_1 \cdot SP_1 \tag{23}$$

$$W_{sys,2} = P_2 \cdot SP_2 \tag{24}$$

$$SP_n = SP_{con,n} + SP_{aux,n} + SP_{drive} + SP_{pref,n} \tag{25}$$

$$W_{sys} = W_{sys,1} + W_{sys,2} \tag{26}$$

$$W_{struct} = V_{hull} \cdot SWL \tag{27}$$

$$\Delta_2 = W_{struct} + W_{sys} + W_{fuel} + W_{rest} \tag{28}$$

$$\Delta = \Delta_1 - \Delta_2 \tag{29}$$

Using equations 8 and 8, 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:

$$E_{disp}(B) = 0. \tag{30}$$

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

A3: Design tool input parameters

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 **??** 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 11: 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 12: 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 13: 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

TABLE 14: Well to wake emissions [g/kWh of finished fuel] (adapted from van Lieshout et al. (2020), Ludvigsen and Ovrum (2012), Vaisanen et al. (2016) & WIGG (2011))

	F-76	Methanol		Butanol		[t]
		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	-	/*	-	-* [b]

A4: Selected design and design consequences

In table 15 the outcome of the complete analysis of all five designs can be seen. The designs which have been selected for the further analysis of the GHG emissions and fuel consumption are highlighted in green.

TABLE 15: Proposed design changes for the LDP and LCF

	LCF			LPD	[t]
	Design 1	Design 2	Design 3	Design 1	Design 2 [b]
Fuel cell power ratio	0.15	0.3	0.45	0.35	0.7
Displacement	+3%	+8%	+16%	+14%	+20% [t]
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	+	++	+++	++	+++ [b]