Henrik Husmo Høidal

Integrated power and propulsion design for zero-emission vessels with hydrogen fuel

a Case study of an aquaculture vessel

Masteroppgave i Marinteknikk
Veileder: Mehdi Zadeh
August 2023

Masteroppgave

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Abstract

In recent years, the growing interest in zero-emission solutions has prompted a shift in approaching the design of emission-free vessels. This thesis addresses the design of a marine power system to ensure excellent sustainability and zero emissions. The study focuses on a 15 m work vessel operating in Norway's coastal waters for the aquaculture industry.

An initial cost analysis of three different designs reveals that despite the substantial investment cost of the hydrogen system, it can still prove profitable in a hybrid configuration with adequate subsidizing. The hydrogen hybrid system is selected for its emission-free operation and extended range.

The thesis includes a preliminary design, incorporating a suggested load profile based on benchmark vessel data. Properly sized components are integrated into the electric system, with a simplified SLD provided. Furthermore, a comprehensive evaluation of the physical integration of the system is conducted, including the placement of key components such as the hydrogen tank, fuel cell, and battery pack.

Subsequently, the design is assessed based on fuel consumption, emissions, and sustainability. Results underscore the significance of the fuel cell's baseload in achieving a sustainable hydrogen hybrid system. The finalized design is a refined version of the preliminary design, taking sustainability into account. An estimation of the operational costs for the recommended design concludes the thesis.

The suggested design includes a Lithium-ion battery pack, supported by a PEMFC. Results show that the lifetime of the battery pack is dependent on the base load of the fuel cell, the system is designed with this in mind. The return on investment compared to a conventional design is estimated at 7 years, with subsidizing from Enova.

Preface

The master thesis was written in the second quarter of 2023 at the Norwegian University of Science and Technology, Department of Marine Technology. Written by me Henrik H. Høidal for the company Moen Marin, supervised by Professor Mehdi Zadeh.

This master thesis is the result of many hours of hard work and discussions, with my supervisor and employees at Moen Marin. I would like to take this moment to thank all the people involved in helping me with this thesis. A thank you goes out to my supervisor Mehdi Zadeh, for his patience and guidance through this project. The data I received and the discussions I had with colleagues at Moen Marin were invaluable to the progress and finalization of this thesis. I personally thank Benny Kilhavn and Jan Tore Ysland for your continued support and willingness to answer my questions, no matter how foolish.

Trondheim 31.07.2023

Henrik Høidal

Henrik Husmo Høidal

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List of Symbols and Abbreviations

$\%MCR$ Percentage of Max Continuous Rating

η_{el} Electrical Efficency

$\rho_{GE})$ Gravimetric Energy Density

ρ_{VE} Volumetric Energy Density

AC Alternating Current

AIP Approval In Principle

BL Base load

BoP Balance of Plant

$CAPEX$ Capital Expenditures

DC Direct Current

DP Dynamic Positioning

EMS Energy Management System

EoL End of Life

EP Electric propulsion

$EPHPS$ Electric Propulsion with Hybrid Power Supply

ERV Emergency Release Valve

ESS Energy Storage System

FC Fuel Cell

GA General Arrangement

GHS Gas Hydrogen Storage

HP Hybrid Propulsion

$HPHPS$ Hybrid Propulsion with Hybrid Power Supply

HPS Hybrid power supply

HPS Hybrid power system

HPU Hydraulic Power Unit

ICE Internal Combustion Engine

IMO International Maritime Organization

$Li - ion$ Lithium Ion

$MCFC$ Molten Carbonate Fuel Cell

$MILP$ Mixed Integer Linear Programming

$OPEX$ Operational Expenditures

$PEMFC$ Proton Exchange Membrane Fuel Cell

$PEMS$ Power and Energy Management System

PMS Power Management System

PRV Pressure Reduction Valve

PS Portside

ROI Return on Investment

RPM Rotations Per Minute

$SFOC$ Specific Fuel Oil Consumption

SLD Single Line Diagram

SoC State of Charge

$SOFC$ Solid Oxide Fuel Cell

SOG Speed Over Ground

SoH State of Health

STB Starboard

THS Tank Holding Space

$TPRD$ Thermal Pressure Relief Device

1 Introduction

1.1 Background

International shipping is responsible for 2% of the world's energy-related CO_2 emissions. New policies put in place by the International Maritime Organization (IMO) entails the transition to new sources of propulsion and fuel. For the international shipping industry to adhere to these policies and meet Net Zero Emissions by 2050, a 15% reduction in emissions from 2021 to 2030 is required. [4]

In later years, hybrid systems have become a hot topic for maritime applications, guiding the industry towards a power system that integrates multiple sources of energy with an energy storage system. Making the hybrid system economically feasible using optimization algorithms, rulesets, and dedicated load distribution has been the topic of many research projects, both in the automobile industry and the maritime field. Showing the economic potential of environmentally friendly solutions is an important part of getting the industry on board with these new solutions. Since hybrid systems first were introduced they have long since seen many drastic changes to their topology, fuel, and electric storage systems.

This thesis aims to design a zero-emissions power system for a small work vessel for the aquaculture industry, with enough range and low enough costs to make it an attractive alternative to diesel solutions. This is done through analytical estimations and high-level decision-making. The aquaculture industry falls under the jurisdiction of IMO and although the impact of the Norwegian aquaculture industry on global emissions is almost negligible, a change to hybrid or fully electric solutions can prove economically beneficial as shown in [5].

1.2 Objective

The objective of this master thesis is to suggest a zero-emission design for a smaller work vessel, using analytical estimations and design approaches. The objectives of this thesis can be summarized as follows:

- Investigate and explain components in marine hybrid power system through a literature review
- Perform a feasibility study and present different design scenarios
- Suggest a preliminary design
- Decide on a design, with an emphasis on emission reduction and sustainability

1.3 Vessels used in thesis

1.3.1 Frøyblikk - benchmark vessel

In cooperation with Moen Marin, a vast amount of data has been collected from an operating vessel. The vessel that is used as a benchmark for further investigations in this thesis, is the vessel depicted in Figure 1. This is a catamaran work vessel designed for the fish farm industry, with the purpose of maintaining the functionality of different aquaculture sites in the operational area of coastal waters in Norway.

Figure 1: Benchmark vessel, Frøyblikk

The main particulars of the vessel are mentioned in Table 1. Frøyblikk is equipped with an electric propulsion where a battery and two gensets provide power to the driveline, the details are provided in Table 2. On paper, this is a hybrid vessel, but results show that Frøyblikk is operated closer to a diesel-electric vehicle than a hybrid one.

Table 1: Frøyblikk dimensions

Vessel dimension	Value
Length o.a.	14.99m
Length p.p.	14.69m
Breadth mld.	12.0 m
Depth mld.	3.60m

Table 2: Components of Frøyblikk

Component	Model	Size	Location
Main engine	Danfoss Editron Electric motor	370kW	PS and STB
Battery	Akazem 15 OEM	462 kWh	STB only
Genset 1	CAT C18	500 ekW @ 2100 rpm	STB
Genset 2	CAT C9.3	325 ekW @ 1800 rpm	STB
Propeller	Helseth 4H90	1300mm	PS and STB

The data from this vessel is mainly used for the development of a load profile for the design vessel.

1.3.2 Pilot E - Designvessel

This thesis focuses on designing a power system for a smaller vessel compared to Frøyblikk. Utilizing available resources, the objective of designing a more efficient power system for this vessel emerged as the most favorable option

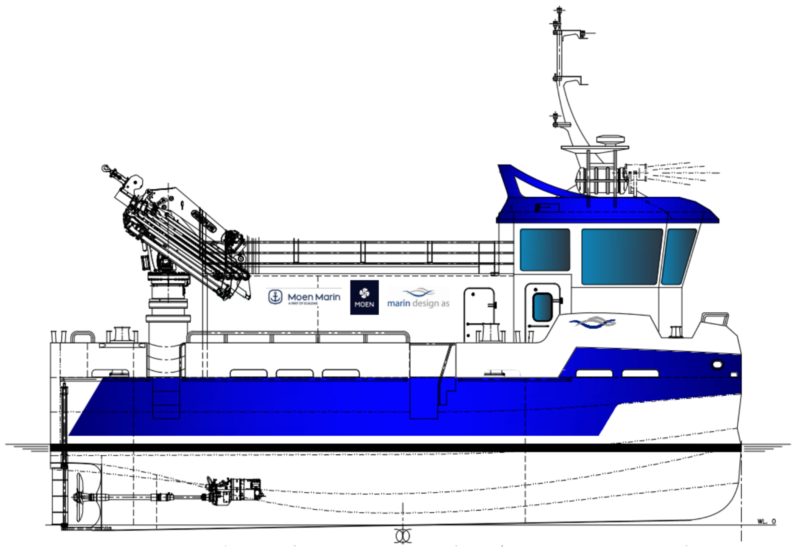

Figure 2: Drawing of the design vessel

Table 3: Dimensions of design vessel

Vessel dimension	Value
Length o.a.	14.99m
Length p.p.	14.69m
Breadth mld.	9.00 m
Depth mld.	3.20m

The vessel's distinctive feature is its non-overnight stay at the site, simplifying the design process by allowing for overnight charging.

This vessel is part of a collaborative project, Pilot E, involving Moen Marin, Moen Verft, and Marin Design, collectively developing a hydrogen-powered vessel for the aquaculture industry. The author of this thesis had a unique opportunity to contribute to the Pilot E project, and many decisions in this study are informed by the experiences gained from this collaboration.

1.4 Structure of thesis

The remaining structure of the thesis, with a description of each chapter, is presented here.

Chapter 2 - Literature review

All relevant theory required to understand the thesis and its approach is presented here. The aim is to have a better understanding of different components within the marine power system, as well as researching state-of-the-art solutions for optimization. A lot of the material here is sourced from a project thesis written by the author in December 2022.

Chapter 3 - Design scenarios and feasibility

This chapter aims to focus on a couple of design suggestions with an emphasis on some different scenarios. A cost estimate is presented for the different scenarios, followed up by a feasibility study. The feasibility study is governed by high-level decision-making, no sizing or dimensioning is done here, but a general design is suggested.

Chapter 4 - Preliminary design

Compared to Chapter 3, Chapter 4 goes more into the details of the system. Sizing components, suggesting a load profile and the physical integration of the system are included here.

Chapter 5 - Sustainable design and operations

Chapter 5 makes minor adjustments to the design suggested in the previous chapter. Here, an analytic estimation of the sustainability of the design is performed, to evaluate its profitability.

Chapter 6 - Conclusion and further work

Results and findings are presented here, along with suggestions for further work. This includes looking further into developing a control algorithm and a cost and sustainability function for a hydrogen hybrid system.

2 Literature review

2.1 Economics and emissions in shipping

2.1.1 CAPEX & OPEX

CAPEX and OPEX are two essential financial concepts that companies use to track and manage their investments and expenses. CAPEX, short for Capital Expenditures, refers to the funds invested by a company in acquiring or upgrading its physical assets, such as property, vehicles, and equipment. These are typically long-term investments that are expected to generate returns over several years.

OPEX, short for Operating Expenses, refers to the day-to-day expenses incurred by a company to operate its business, such as salaries, utilities, supplies, and maintenance. These are typically short-term expenses that are necessary to maintain the company's operations.

In addition to tracking and managing investments and expenses at a company level, it is also possible to calculate the CAPEX and OPEX of specific operations, such as operating a vessel. This approach can provide valuable insights into the costs associated with running a vessel and help companies make informed decisions about their investment and expense strategies. Calculating the CAPEX of operating a vessel involves identifying the costs associated with acquiring or upgrading the vessel, including the purchase price, installation costs, and any modifications or upgrades made over its lifetime. OPEX, on the other hand, includes the day-to-day costs of operating the vessel, such as fuel, maintenance, repairs, crew wages, and insurance. [6]

2.1.2 Emission taxes

The current emission taxes that exist in Norway, are mostly indirect emission taxes, like the carbon tax on gasoline. In 2020, the European Commission introduced 82 measures that in the coming years, are supposed to turn the transport sector into a more greener- and environmentally friendly sector. These measures had a direct impact on the maritime sector, where all vessels over 5000 gross tonnage, have to pay 800 NOK per ton of CO_2. This doesn't directly affect smaller work vessels but in the future, a tax for the entire fleet instead of each single vessel is not unrealistic and such a tax could be right around the corner. [7] [8] [9]

By Norwegian law, all vessels that have propulsion machinery that combined, exceeds 750kW, are required to pay an emission tax on NO_x. This tax requires that vessels report their direct emissions based on a source-specific emission factor, F. This emission factor is calculated from the engine's EIAPP certificate, which is a certificate that gives accurate measurement data approved by a governing body. [10]

$$F(\text{kg NO}_x/\text{ton of fuel}) = \frac{\text{NO}_x \text{ specific emissions(g/kWh)} \cdot 1000}{\text{Specific fuel oil consumption(g/kWh)}} \tag{1}$$

The NO_x emissions are then calculated by multiplying $F \cdot totalfuel(tonnes)$. As of 2023, the current tax on NO_x is 24.27 NOK per kg. This tax is currently the only applicable one for smaller work vessels, but by turning other emissions (like CO) into CO_2 equivalents it is possible to generate a theoretical tax for CO_2. The main purpose of this theoretical tax is to get a feeling for what such a vessel might have to pay in the future and construct a robust way of calculating this expense.

Table 4: Emission taxes

Emission	Tax [NOK]
CO_2	800 per ton
NO_x	24.27 per kg

2.1.3 Enova subsidizing

Enova, a state enterprise, plays a crucial role in driving green innovation projects through subsidies. This support has become a catalyst for companies to prioritize environmentally friendly solutions, as they no longer need to worry about the financial burden of implementing new technologies. Without Enova's backing, the advancements in emissions reduction and climate change mitigation that have been achieved today would not have been possible.

Until early 2023, Enova's subsidy amount regarding battery hybrid solutions was primarily based on the size of the battery system installed on ships. This led to a surge in battery hybrid solutions, with many companies transitioning from conventional power systems to hybrid ones. The battery hybrid configuration, combining a diesel engine with a set of batteries, quickly became the industry standard, despite the substantial costs associated with batteries. However, Enova has now shifted its focus away from battery hybrid solutions as these systems are increasingly seen as a viable alternative to diesel-electric power systems.

In general, Enova supports innovative and sustainable projects by covering up to 50% of the additional costs related to adopting new technologies. This means that Enova will fund the difference between the expense of conventional technology and the cost of the innovative and sustainable technology, up to a maximum of 50%. [11]

Enova's support has effectively incentivized companies to invest in cleaner and more efficient technologies, such as electric propulsion systems and renewable energy solutions. By alleviating the financial burden, Enova has accelerated the adoption of environmentally friendly practices across various industries.

2.2 Energy carriers and power sources

2.2.1 Energy Storage Systems

There are many ways of storing energy, all of which have different fields they excel in. The introduction of ESS to the conventional diesel-electric engine topology has greatly increased the efficiency of certain vessels. The combination of the economically efficient diesel-electric engine, and the flexible ESS is now implemented as a standard in the industry. Most commonly used today are Lithium-Ion batteries, which are preferred due to their high efficiency and lifetime.

Batteries have been the industry standard in the automotive industry for many years. Therefore, it is natural that the maritime sector takes advantage of the already existing technology. The rise in electric and hybrid cars with Li-ion batteries has caused the price of such batteries to be lowered quite significantly over the last few years. [12]

The life expectancy of batteries is unfortunately still quite low, which affects the economic advantages of having a hybrid power system since the cost of replacing such batteries is high. The average life expectancy for a Lithium-ion battery is between 1000-4000 cycles. The life expectancy of the battery is dependent on several factors, for example, the so-called 'calendar fade' of the battery, referring to the cell degradation in the battery over time. The calendar fade is dependent on a few factors, among them the temperature of the battery, and will reduce the rated capacity of the battery over time. Another factor that can influence the life expectancy of the battery is the operative state of charge (SoC) of the battery. Meaning, if the battery is operated outside its optimal SoC it can affect the life expectancy. Therefore, measures are put into place to make sure the battery is operated in safe conditions, this is handled by the Power and Energy Management System (PEMS).

Other energy storage solutions like the supercapacitor, favored due to its high discharge and charge rate, are a viable option for dealing with high transient loads. In addition, the supercapacitor has a long life expectancy, with an estimated length of minimum 100 000 cycles [13]. The disadvantage of the high discharge and charge rate is the low energy density that the supercapacitor has, which means that it has to be supported by an additional ESS to make it feasible for stored power supply systems. However, for instances where a high power density over a short amount of time is needed, the supercapacitor is much more favorable to use than the battery. This could for example be applied to lifting operations of a marine vessel, where a high power demand is in effect over a short amount of time (time is short compared to vessel operating time).

Supercapacitors have already been tried out in real-world applications, like this ferry in France [14], the 'Ar Vag Tredan' which is a passenger vessel operating short transport trips in the Bay of Lorient. The supercapacitors are beneficial here since the ferry can charge during the loading and unloading of passengers.

Although the supercapacitor has potential and could be applied to certain scenarios, the battery is favored due to its versatility and industrial maturity. Supercapacitors and their use in marine applications should be investigated further, especially with the combination of another ESS like the Li-ion battery.

2.2.2 Internal Combustion Engine

The internal combustion engine has been around for many years and is by no means new technology. The ICE first got introduced in the 1800s, and the basics of this engine remain the same to this day. [15] The engines create transverse motion by mixing fuel and air, compressing them in a chamber, and then igniting, to generate a power stroke. The transverse motion is turned into rotary motion, connected to the drivetrain.

Although the ICE has been around for a long time, they have never been as effective as they are today. This is mainly due to advances in thermodynamics, digitization of technology, and the addition of gensets to help distribute the load. Though the efficiency of the engines has surely increased over the years, the effective range of diesel engines still stays at 80-100% of the rated power of the engine, as shown in Figure 3

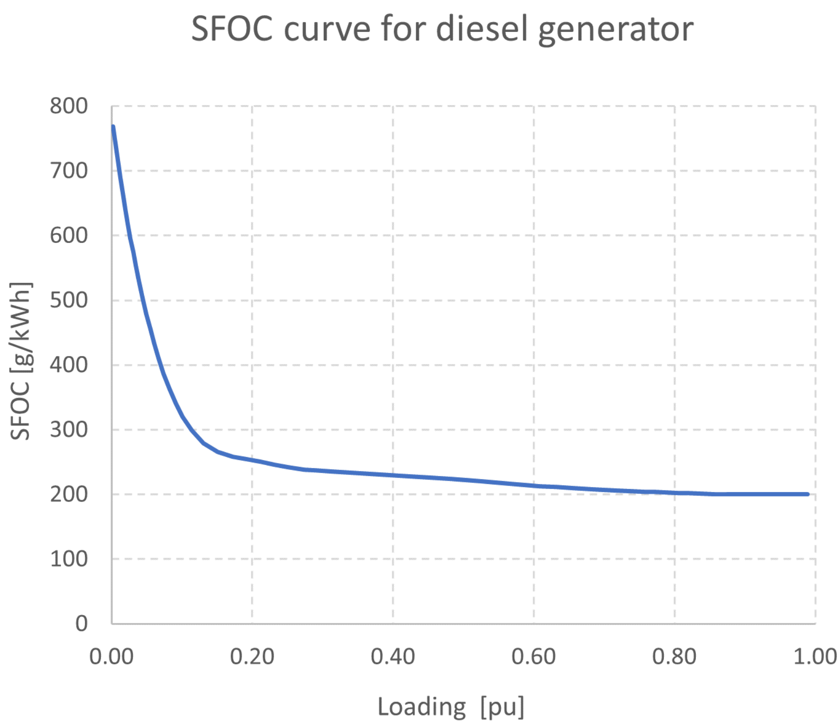

Figure 3: SFOC Curve for fixed speed engine, constructed from a manufacturer's acceptance and certification tests. Data extracted from [1]

This indicates that diesel engines are best equipped for handling operations with a stable load profile, like the transport of cargo or passengers. Vessels with varying load profiles, like offshore supply vessels or trawlers, can't utilize the diesel engine to its full potential due to their varying load demands. Which in turn, makes them less fuel efficient than the aforementioned transport vessels.

Adding gensets to help distribute the load from the main engine, effectively decreases fuel consumption if done correctly. To do this, a governing system needs to be installed, that decides when and how many gensets should operate at any given time, this is what is referred to as the PEMS.

2.2.3 Fuel cell

The combination of a diesel-electric power system and a battery-focused ESS should not be ruled out as the only viable solution to the hybrid power supply system. Fuel cells that run on hydrogen are being researched as a viable alternative to the diesel-electric system but are in their current state mostly viable for short-sea shipping. Fuel cells have a higher theoretical efficiency than ICEs due to the difference in energy conversion. Contrary to the diesel engine a fuel cell converts fuel to energy with an electrochemical reaction and using, for example, hydrogen as a fuel is a much better solution in terms of emissions. [16] State-of-the-art fuel cells (PEMFC) require high-purity hydrogen, to avoid carbon monoxide poisoning, which with current technology makes it hard to apply to long sea vessels. [17]

That being said, if the technology for fuel cells can catch up with batteries, a combination of these two could prove highly beneficial as shown in [14], where a potential fuel saving of 30% for an all-electric vessel is estimated. As mentioned, the optimal fuel cell for a surface vessel is the proton exchange membrane fuel cell (PEMFC), but this FC type requires refined hydrogen which can prove difficult to acquire. In addition, hydrogen has low density, so storing enough hydrogen for full-scale deep-sea travel requires a lot of storage space. To get around this, one could use other FC types, utilizing other fuels like diesel or gas. These FCs are typically not as effective and have a slower start-up than hydrogen-based FCs.

The molten carbonate fuel cell (MCFC) or the solid oxide fuel cell (SOFC) are currently the two preferable solutions to fuel cells on marine vessels, especially for power-demanding operations. However, the PEMFC has higher energy density and cleaner emissions and has been tried out more, especially for submarine vessels.

2.2.4 Balance of Plant

The Balance of Plant (BoP) is a comprehensive term encompassing all non-core components within a system, including optimization and cooling elements. In the context of this paper, the BoP specifically pertains to the auxiliary components surrounding a fuel cell system. It comprises all elements except the fuel cell stack itself. The BoP plays a crucial role in ensuring the optimal functioning, efficiency, and reliability of the fuel cell system, making it a focal point for enhancing overall performance and longevity.

The fuel supply system is responsible for delivering the appropriate fuel to the fuel cell stack, ensuring a steady and controlled flow to maintain the required chemical reactions within the cell. It involves considerations such as fuel storage, distribution, and regulation to match the varying demand from the fuel cell stack accurately. Any imbalance in the fuel supply system could lead to inefficiencies, underutilization of fuel, or even disruptions in power generation.

The air management system, on the other hand, is responsible for supplying the required amount of oxygen to the fuel cell's cathode, where it participates in the electrochemical reaction. Similar to the fuel supply system, maintaining a balanced air supply is vital for maintaining efficient and stable fuel cell performance. It is essential to ensure the proper ratio of air to fuel for optimal electricity generation and to avoid excess air leading to energy losses.

The thermal management system plays a crucial role in maintaining the fuel cell stack at the appropriate operating temperature. Fuel cells operate efficiently within specific temperature ranges, and deviations can adversely affect their performance and lifespan. The thermal management system is designed to distribute heat evenly, prevent overheating, and maintain the necessary temperature levels for the fuel cell stack, contributing to a well-balanced and reliable system.

Additionally, the BoP encompasses power electronics, which act as an interface between the fuel cell stack and the electrical load. The power electronics system ensures that the generated electricity is efficiently transferred to the load, minimizing losses and maximizing the system's overall efficiency. Sophisticated control strategies are often employed to manage the power flow and adapt to varying electrical demands, further contributing to the system's balance and stability.

2.2.5 Hydrogen as fuel

Hydrogen, with its abundant availability and high energy density, has emerged as a promising solution to the global emissions challenge. As concerns about climate change and air pollution intensify, hydrogen has captured significant attention as a clean and sustainable fuel option. With an energy density of approximately 34 kWh/kg, hydrogen surpasses conventional fuels like diesel, which typically ranges between 12 and 14 kWh/kg in terms of energy density. This exceptional energy density, coupled with its widespread availability, positions hydrogen as a potential key player in transitioning towards a more environmentally friendly and efficient energy system.

However, hydrogen poses challenges in terms of both volumetric density and storage. As a gas, it has low volumetric density, requiring significant storage space. To overcome this, researchers have explored the use of liquefied hydrogen, which significantly increases its volumetric density. However, liquefaction requires extremely low temperatures (-253°C or -423°F) and poses technical and safety challenges, which is why hydrogen in gas form is still preferred in marine applications.

2.3 Propulsion systems

Marine propulsion systems are used to power marine vessels. These systems typically consist of a propulsion mechanism, such as a propeller or jet, and a power source, such as an engine or electric motor. Marine propulsion systems are designed to provide efficient, reliable, and safe power for a wide range of vessels, from small boats to large ships. The main types of marine propulsion and their respective benefits and challenges are presented in the following chapters.

2.3.1 Mechanical propulsion

A mechanical propulsion system typically consists of a prime mover, such as an internal combustion engine (ICE), that powers the propeller directly or through a gearbox. As mentioned in Chapter 2.2.2, the ICE is the preferred choice for its high fuel efficiency. Auxiliary loads are typically handled by a separate AC system with diesel generators.

Mechanical propulsion systems are generally simple, requiring fewer conversion stages, which results in low conversion loss in the system. This simplicity also leads to a low initial cost, making it an attractive option for vessels that operate at steady speeds. When the system operates at 80-100% of its capabilities, it not only has high efficiency but also lowers emissions significantly.

The mechanical system has some challenges, as a result of its simplicity. Lacking a governing management system for the engine can result in increased maintenance due to inefficient loading of the engine, especially at high static and dynamic loads. As mentioned, the ICE suffers from low efficiency at lower RPMs, which directly affects the efficiency of the mechanical propulsion system, making it a sub-optimal solution for vessels with varying speeds. This is also true for the NO_x emissions of the engine, which increase the lower the RPM of the engine gets. Also, with this system, a failure of one component will cause a loss of propulsion, which can be crucial for sensitive operations.

2.3.2 Electrical propulsion

Electrical propulsion differs from the mechanical system, in that the generators are now the main prime movers of the propeller. The propeller is run by an electric motor drive, usually through a transformer. Generators now handle both propulsion power and auxiliary power needs.

Using more than one power source as the prime mover has proven very beneficial for vessels with varying speed or load profiles. Having differently sized generators allows each genset to operate closer to its optimal range. During low-load operations, most gensets are switched off, which results in the gensets' life expectancy increasing. The NO_x emissions are also lowered due to gensets operating within their optimal range. Contrary to mechanical propulsion, which suffers from loss of propulsion after component failure, the electric propulsion system is more reliable, because several generators can propel the vessel.

Although the increase in components is good for the availability of the system, it increases conversion losses. In addition, when performing sensitive operations like DP, the gensets operate under their optimal range, leading to worse efficiency and increased emissions. The system also has a chance of shutting down during voltage and frequency swings under fault operations, but the reliability is still considered to be higher than the mechanical propulsion system. [18] It should be noted that the electrical propulsion system is most beneficial when the auxiliary load demands are high.

2.3.3 Hybrid propulsion

Hybrid propulsion is a system that combines elements of both electrical and mechanical propulsion. It typically consists of an ICE and an electric motor connected to the shaft. The ICE is responsible for powering the vessel at high speeds, while the electric motor handles lower speeds. This type of propulsion system offers the benefits of both electrical and mechanical systems, allowing for increased efficiency and flexibility. Hybrid propulsion can save a lot of weight compared to electric propulsion, whilst having many of the benefits the electric propulsion system offers. The electric motor also handles the auxiliary loads.

However, as with any system that involves a compromise, it is not possible to achieve all the benefits of both systems simultaneously. Therefore, the main challenge in designing a hybrid propulsion system is to find the right balance between the advantages and disadvantages of each system, to create a configuration that is well-suited to the specific needs of the vessel. This requires careful consideration of factors such as the vessel's intended use, operational requirements, and available resources.

2.3.4 Hybrid power system

In the previous section, several different propulsion systems were discussed, each of which relies on one or several power supply units to operate. In some cases, these power supply units may be based on different types of technology, such as combustion engines or fuel cells or stored energy sources like batteries or supercapacitors. When a propulsion system is powered by two or more different sources of power, it is referred to as a hybrid power supply system. This type of system offers several advantages over propulsion systems that rely on a single source of power, including increased reliability and efficiency.

The hybrid power supply can be applied to the electrical- or hybrid propulsion, depending on the load profile and demands of the vessel. The power supply can come from sources mentioned in Chapter 2.2, but as mentioned the technology for some of these power sources is still immature. Typically, for smaller work vessels, the hybrid power supply consists of a diesel-electric engine coupled with a Li-ion battery.

2.3.5 Electric propulsion with hybrid power system

Electric propulsion with a hybrid power system (EPHPS) is a concept that has been adapted from the automotive industry, where it is commonly used to improve the efficiency of vehicles. In this type of system, the braking power that is typically dissipated into thermal energy is instead stored in batteries. Although marine vessels don't dissipate as much energy by braking as automotive vehicles, the battery can be charged during low-load operations, where the generators or the engine operate at almost full capacity, effectively charging the battery with most of its power. In addition, the battery can also assist with the efficiency of the system by load leveling or peak shaving, which can decrease fuel consumption by as much as 2-3% for a bulk carrier, as shown in [19]. The battery can also be useful as a backup to the ICE, if it were to fail, increasing the reliability of the system. It should be noted that if the vessel is performing sensitive- or large-load operations, the battery size should be designed to handle these operations alone if failure were to incur.

With that said, the EPHPS still has some challenges. One of these challenges is the increased complexity of the system due to the presence of multiple power sources, such as batteries and traditional power generators. The PEMS then has to manage the charging of batteries and load distribution of the power sources. Another challenge is the expense of batteries, which increases the initial cost of implementing the EPHPS. Despite these challenges, the EPHPS is often seen as a valuable addition to vessels with high auxiliary loads, such as offshore supply vessels, trawlers, and drill vessels. This is because the benefits of the EPHPS tend to outweigh the challenges.

2.3.6 Hybrid propulsion with hybrid power supply

As mentioned in Chapter 2.3.3, hybrid propulsion utilizes the simplicity of the mechanical shaft connection coupled with the electrical engine. The efficient ICE and mechanical drivetrain handle high speeds, while the electrical motor handles lower speeds and auxiliary loads. Like the hybrid propulsion system, the benefits and challenges of this system will depend on the operational criteria of the vessel. In simple terms, the system will benefit from the simplicity of the mechanical drive but is not adept at handling high auxiliary loads. HPHPS is mostly applicable for vessels that operate with varying loads that are rooted in vessel speed, like a tug boat, where the engine is not running at full capacity after the structure being tugged has been set into motion.

In Table 5 the different benefits and challenges of EP, HP, EPHPS and HPHPS are compared.

2.3.7 Power system topology

The topology of the power system greatly depends on the components and the intended use of the system. Traditionally, an AC grid has been used for marine vessels, as the diesel-electric engine and the electric generator produce AC power. With the introduction of ESS to HPS, DC grids should be considered a viable alternative, as it brings quite a few benefits with them. That being said, the AC grid has its uses, modern vessels often use a combination of AC and DC components.

AC topology has a lot of benefits, but also some setbacks that the DC topology could do better. Using an AC grid in a HPS requires two converters between the ESS and the battery, as told by [20]. In addition, the required components for the AC grid are usually quite bulky and heavy, meaning that the deadweight of the vessel increases with AC topology. The system is also dependent on both the voltage of the circuit and the frequency, which means that the system is dependent on the constant speed of the prime mover. However, the safety system surrounding this topology is very well developed due to its use in other commercial applications.

The DC topology differs from the AC topology in several ways. Firstly, the DC topology requires the use of components that convert AC sources to DC, such as rectifiers and inverters, whereas the AC topology requires the opposite. This means that the energy storage system in a DC topology only requires one converter. Secondly, the DC system is controlled solely by the voltage, allowing the prime movers to operate at variable speeds and removing the frequency constraint that the AC system experiences. This makes the DC topology more versatile and efficient. Additionally, the

DC topology is lighter, as it requires fewer AC components. However, one potential issue with the implementation of the DC topology is the ripple effect, which can cause heating in conductors.

As stated in [20] the DC system, especially the variable speed DC system, provides better efficiency than the AC system. It is therefore natural to assume that a DC system is optimal for the HPS.

2.3.8 Comparison of HPS optimization methods

The selection of appropriate solutions for the HPS have been extensively studied in the literature and the author of this paper does not claim to have exhaustive knowledge on the topic. The selected approaches are based on the findings of previous simulation studies and the expertise of other authors within their fields of research.

The following tables provide a detailed comparison of the different components of a power system, listing their respective advantages and disadvantages. These tables will be instrumental in conducting a feasibility study later in this thesis, ultimately leading to the formulation of an appropriate design for further research.

Table 5: Propulsion and supply system comparison, adopted from [2].

Technology	Benefits	Challenges
Mechanical propulsion	• Low conversion losses • High efficiency at design speed • Low emissions at design speed • High industrial maturity	• High emissions below design speed • Increased maintenance due to inefficient loading • Handles part loads poorly • Low availability (if the main engine fails, propulsion is halted)
Electrical propulsion	• Handles high auxiliary loads well • Reduced noise • Less GHG emissions at low speeds	• Conversion losses decreases efficiency at higher speeds • Risk of failure at constant load
Hybrid propulsion	• Low loss at design speed • Robustness • Load and engines matched at low speeds	• Increased complexity
Electrochemical power supply	• Air independent • No operative emissions • High efficiency	• Limited range • Safety
Stored power supply	• Air independent • No operative emissions	• Very limited range • Safety
Hybrid power supply	• Load leveling or peak shaving • Storing regenerated energy • Reduced operating time of gensets • Handles transient loads well • Reduced fuel consumption • Volumetric efficiency	• System complexity • Safety due to battery • Initial cost of battery • Constant generator speed

Table 6: Comparison of different ESS and power sources.

Technology	Benefits	Challenges
Batteries	• High energy density • Industrial maturity • Handles load fluctuations well • Potential for no operational GHG emissions	• Medium life expectancy • Adds a lot of weight • Medium energy density
Flywheel [21]	• High efficiency • Low maintenance cost • Almost no performance loss from cycling • Fast charge & discharge rate • No operational GHG emissions	• Low energy density • Little flexibility in physical footprint • Energy capacity is highly size dependent • Very high self-discharge rate
Supercapacitor	• Very high efficiency • No operational GHG emissions • High power density • Long life expectancy • Very fast charge & discharge rate	• Low energy density • Needs to be supported by additional ESS • High self-discharge rate
Internal combustion engine	• High efficiency • Reliable • Long life expectancy • High industrial maturity	• High emissions below rated power • Potential efficiency has flattened out • Efficiency greatly affected by transient loads
Fuel cell	• No operative GHG emissions (fuel dependent) • Very high efficiency • Air independent • Technological maturity (due to submarine use)	• Limited range (limited by fuel density) • Requires high-purity hydrogen • Safety

2.4 Power and Energy Management System

As mentioned earlier, a governing system that distributes energy according to certain demands, also referred to as the PEMS, can help reduce fuel consumption. The PEMS consists of the power management system (PMS) and the energy management system (EMS), where the EMS's main task is to operate the PMS as efficiently as possible. The PMS is responsible for keeping the required energy available at all times, this includes decreasing the stress on components through optimal load cycling, effectively reducing the maintenance or replacement costs of the system.

Research shows that most vessels are operating outside of their optimal range. By introducing a more accurate PEMS and improving the algorithm, this paper [1] showed a decrease in fuel consumption by 12.6% for a platform supply vessel, by introducing mixed integer linear programming (MILP).

Most research surrounding the PEMS today is focused on minimizing the fuel consumption of the vessel, which is highly relevant when discussing the optimization of diesel-electric- or hybrid power systems. The general idea is to have gensets with different power ratings so that when the required power is low, the gensets with low-rated power handle the load at close to their maximum capacity. This maximizes the efficiency, in theory, of the vessel. In reality, this is harder to achieve than on paper, since knowing the load profile for the vessel is vital for this approach to work.

There are mainly two categories regarding the strategies to optimize a vessel's energy use, namely the rule-based strategy and optimization-based strategies. These are covered in short in the following chapters.

2.4.1 Rule-based EMS

A rule-based EMS is a common EMS strategy today. The main idea behind a rule-based strategy is that an operator or system architect applies a set of rules to the system based on previous experience or knowledge. These rules range from the distribution of the power demand among the gensets, to deciding how many hours each genset or battery should be run/charged to ensure as little maintenance as possible.

The rule-based strategy is easier to implement than most existing optimization strategies and is generally quite reliable. However, as mentioned earlier, some vessels operate outside of their optimal range, despite having a rule-based EMS in place. This indicates that a strategy customized for each vessel and its corresponding load profile should be designed. Ships that experience varying or unpredictable loads may have a tougher time with a rule-based strategy than a vessel with a predictable load profile. This is the case for most OSV's where marine operations and dynamic positioning are a regular occurrence.

2.4.2 Optimization-based EMS

This strategy is divided into offline and online optimization strategies. There are many explored strategies within offline optimization, but the main problem with offline optimization persists. For offline optimization to be viable, an accurate load profile is required, which is impossible to come by in marine vessels. Therefore, online optimization is looked upon as the future of EMS systems, and albeit complicated, it has great potential.

The general idea of the online optimization strategy is to have a system in place that takes real-time load profiles, to decide the most optimal loading condition of each component in the system. This can be done by a learning-based system as suggested by [22], where M. Zadeh suggests that the controller autonomously learns the optimal load distribution and improves the system in real-time. Zadeh shows that the learning-based controller can improve performance and could result in a higher control reward compared to conventional approaches.[22]

3 Design scenarios and feasibility

A feasibility study is done in the preliminary stage of ship design, before the details are worked out, the feasibility study is done to check how viable the design is. This is done in regard to existing laws and regulations, the operational profile of the vessel, and the cost estimation of designs. The scope of design for this vessel is mainly focused on components or optimizations that significantly increase efficiency and sustainability, whilst decreasing emissions from the vessel. For the sake of simplicity, it is assumed that some components of the electrical system, such as the electric propulsion engine, thrusters, cooling system, and associated elements, remain constant and are sourced from Frøyblikk.

3.1 Design and operational assumptions

An operating profile estimation for the vessel is an important step in the process of designing the governing power system. Knowing where the ship will operate, estimating how much of the day it will be in transit, and the required load of each operation, are all factors that help make decisions regarding design. The operating profile for the workboat in question will be sourced from the Pilot E project from Moen Marin, covered in Chapter 1.3.2.

The work vessel will be operated on a 7-hour day shift, with up to 45 min of transit time to and from the location, resulting in an operating time of 8.5 hours. On location, the ship will have a load demand of 30kWh, which is the hotel load plus the load demand of the hydraulic system. During transit, for the ship to maintain the desired cruising speed of 4 knots, the *two* electric propulsion engines have an estimated demand of 70kW. Therefore, the total energy demand throughout a normal operation day will be,

$$P_{tot} = p_{transit} \cdot t_{transit} + p_{location} \cdot t_{location} = 2 \cdot 70kW \cdot 1.5h + 30kW \cdot 7h = 420kWh \quad (2)$$

The estimated energy demand is likely higher than necessary, but due to the unpredictable nature of weather and operations, it is more prudent to take a cautious approach. If the vessel moves beyond its assumed operating area and encounters rougher water conditions or if operations are demanding, there is a possibility that the current power system may not be sufficient anymore.

Table 7: Design parameters and their associated importance

Design parameter	Importance
Safety	Very high
Deck space	High
Emissions	High
Sustainability	High
Range	Medium
The efficiency of power system	Medium

3.2 Design and operational scenarios

When referring to design and operational scenarios, emphasis is put on high-level decision-making. Meaning, the selection of power sources, energy storage devices, fuel selection, and sizing of components.

Hydrogen-fuelled vessels are a topic of debate and the issues surrounding the storage, safety, and volumetric energy density of hydrogen are some of the main arguments against its use. The energy density mainly affects the range of the vessel, since there exists a limit to how much hydrogen one can store on a ship.

3.2.1 Usual life scenario

For vessel dimensions and a detailed power system, refer to Chapter 1.3.1. Frøyblikk is expected to do various tasks related to the fish farms in its operational area. The tasks include everything from transit to and from the site to crane operations. In other words, the vessel is experiencing transient loads throughout the day, which Frøyblikk is equipped to handle with its hybrid power system, consisting of two gensets and a battery pack. It should be noted that the power system of Frøyblikk is not designed based on the operational profile mentioned earlier. A simplified SLD of the power system of Frøyblikk is presented below

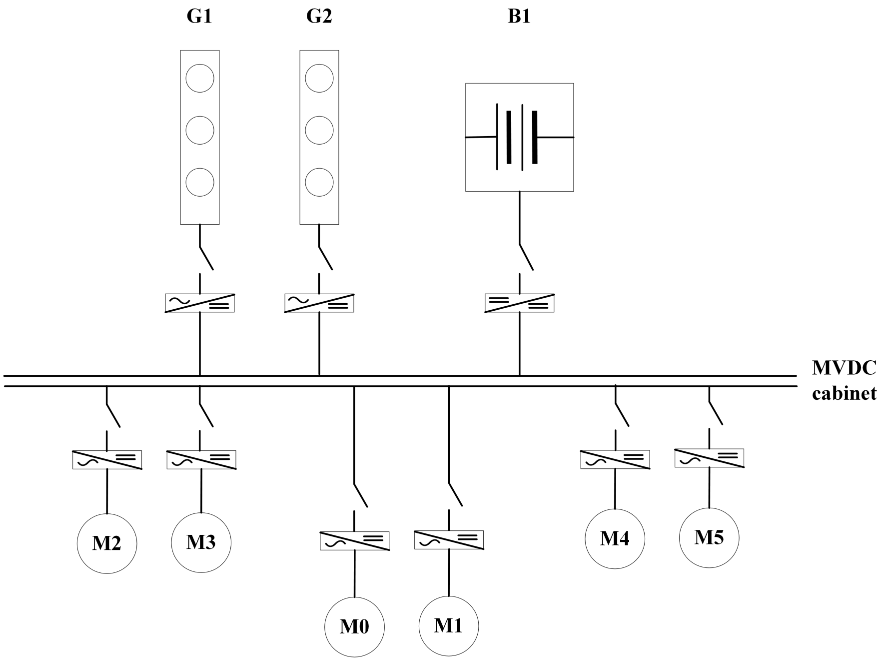

Figure 4: SLD of Frøyblikk drive line (simplified)

Table 8: List of components in SLD

SLD Component	Description
G1	Genset 1
G2	Genset 2
U1	14 batteries coupled in parallel (33kWh each)
M0	Propulsion motor port side
M1	Propulsion motor starboard side
M2	HPU engine 1
M3	HPU engine 2
M4	Bowthruster motor 1
M5	Bowthruster motor 2

where 14 battery packs are parallel coupled and connected to the switchboard, which provides storage and power to the six different motors. The propulsion engines, placed in each bow, two thrusters and two HPU motors.

The current power system of Frøyblikk provides robustness through the two diesel generators, which charge batteries, provide propulsion power in transit, and act as a failsafe so that a failure in the system does not result in loss of propulsion power or loss of operational ability. The battery ensures that the transient loads are handled effectively by assisting the generators at loads that are either higher or lower than the recommended $\%MCR$. Theoretically, this is done by peak shaving or load leveling where the PEMS controls each respective unit. However, the battery system supplier informed the author that the energy demand and power division is entirely user controlled. Currently, the PEMS exists mostly as a suggestion to the user and not a governing control algorithm. The effect of this can be seen in Chapter 4.1.1 where both generator one and generator two are operated below their optimal $\%MCR$. This could result in increased costs and emissions for the vessel.

3.2.2 Best case scenario

In designing a best-case scenario for a work vessel, it is essential to consider not only efficiency but also the availability of deck space. Deck space plays a crucial role in the optimal performance of the ship, as it provides ample room for the crew to work on various tasks.

To create an ideal design, it is important to focus on improving the parameters mentioned in Table 7. Regarding emissions, adhering to the guidelines and goals set by the IMO, a zero-emission design would be considered the best-case scenario. By zero-emission design, it is referred specifically to eliminating emissions from vessel operations, while not taking into account the emissions produced during the manufacturing of components and fuel.

Zero-emission power sources offer various options, such as batteries that can be charged while the vessel is docked or hydrogen-based fuel cells. However, utilizing batteries as the primary power source presents a limitation in terms of their range. Additionally, relying solely on batteries can be problematic if the battery system were to fail, as there would be no backup propulsion power available. On the other hand, fuel-cell-driven vessels face a similar challenge due to hydrogen's relatively low volumetric energy density. To achieve a similar range as a diesel-electric vessel, a fuel-cell-based power system would require sacrificing valuable deck space, which is not an ideal solution. To put it in perspective, if a vessel is run only with hydrogen, it would require 4.29 times as much tank capacity as it would with diesel.

A promising approach could be a hybrid solution that combines the energy storage capacity of batteries with the zero-emission power generation of fuel cells. In this setup, the battery, with its limited range and lack of redundancy, is complemented by the fuel cell. Throughout the day, the fuel cell operates to charge the battery and assists with powering larger loads, while the battery handles transient loads efficiently.

Optimizing all parameters simultaneously can prove challenging, as enhancing one parameter might inadvertently lead to neglecting another.

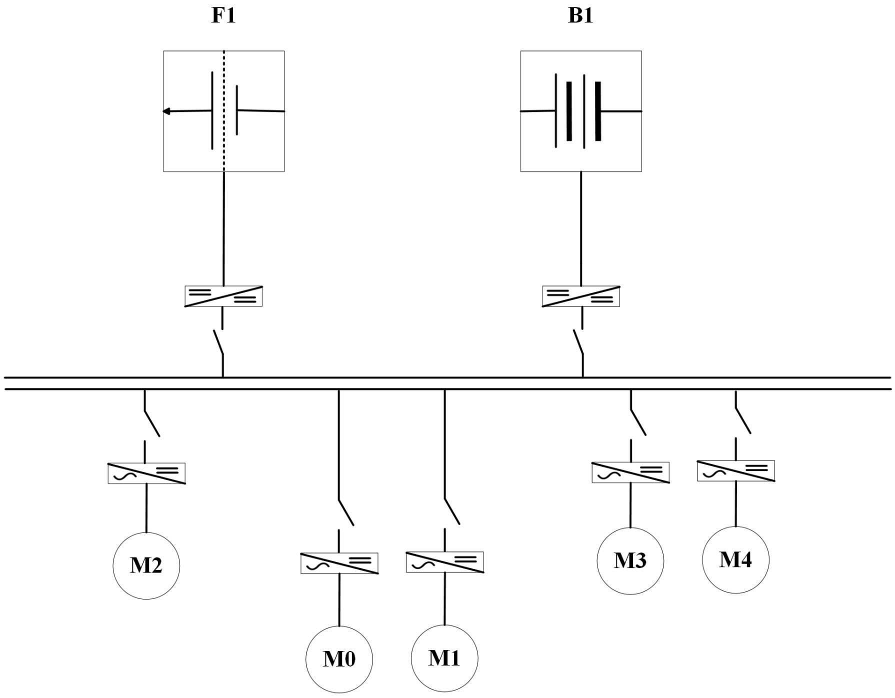

Figure 5: Suggested SLD for a best-case scenario

Figure 5 is similar to Figure 4, but the sizing of the battery pack and the secondary power source is different. Also, there is only one HPU engine on this vessel. The differences are presented in Table 9

Table 9: SLD Components of best case scenario

SLD Component	Description
F1	One fuel cell (100kW)
B1	Three 92 kWh battery packs
All other(s)	Same as Table 8

The suggested design incorporates one fuel cell and a battery system. The battery's role is to handle transit, balance load variations, supply additional power when necessary, and shield the system from frequent load changes. Compared to the fuel cells, the battery exhibits a faster response time, contributing to better system performance. This implementation is expected to reduce maintenance requirements for the fuel cell, as it can operate at a constant load.

The design emphasizes redundancy, emission reduction, and available power, focusing on creating a reliable and efficient energy system. However, it's important to note that the design does not consider the space required for hydrogen fuel storage. The production and storage of hydrogen still face challenges that need to be addressed before hydrogen can be considered a fully viable replacement for fossil fuels. Continued advancements in hydrogen production, storage, and infrastructure will be crucial to further enhance the feasibility and practicality of hydrogen as an alternative energy source.

3.2.3 Market/cost-based scenario

The total cost of a vessel and the profit thereof, is usually what governs whether or not the vessel will be built in the first place. In other words, the project needs to be profitable, either through design or through subsidizing, for a company to consider starting production. This is where the support from Enova, discussed in Chapter 2.1.3, is so important. Here, the designs mentioned in the chapters above are compared (simplified) to a conventional diesel mechanical vessel. The question is then; What concept is the most viable in terms of the market / cost?

Investment cost When referring to investment cost, it is defined as the cost from the contract that has been signed, to the vessel delivered to the customer. For simplicity, it is assumed that costs related to the classification and the approval process are negligible. It is also assumed that all costs, except costs surrounding the power system, remain the same for all designs. This is to better picture the major investment cost difference between the different designs.

Let's say the investment cost of a conventional diesel mechanical vessel is 10 million NOK. Based on pricing data from Moen Marin, a hybrid system, consisting of two gensets and a battery pack (typically somewhere around 150-300kWh) has an increase in investment cost of 45%, which means that the hybrid system would cost 14.5 million NOK. As discussed in Chapter 2.1.3, 30% of this extra cost used to be covered by Enova but as of 2023 that support has been cut. In other words, the extra cost will not change, making a battery-hybrid solution less attractive to customers.

The cost of implementing a hydrogen system is currently higher compared to a diesel hybrid system due to the technological immaturity of fuel cells and hydrogen storage. Moen Marin has undertaken a project that utilizes hydrogen fuel(as discussed in Chapter 1.3.2, and the investment cost is derived from this specific project. It is important to note that this investment cost does not directly represent Moen Marin's actual project costs or financial requirements but serves as a factor increase based on the price difference obtained from Moen Marin's actual pricing. The total investment cost, if the diesel-mechanical design is 10 million, is 23 million which is a 230% increase. With the support from Enova, this value will allegedly shrink to 16.5 million NOK.

Table 10: Overview of estimated investment costs for different designs

Design	Investment cost [NOK]	Enova support	Price increase from D-M
Conventional D-M	10 million	0	0%
Diesel hybrid	14.5 million	0	45%
FC hybrid	23 million	50%	230%

Operating costs As its name indicates, the operating costs are directly related to the cost of operating the vessel during a normal workday or lifespan. To make a valid analysis of the operational costs, an overview of the cost of fuel is necessary.

Table 11: Fuel prices on average, for 2022 [3]

Fuel	Cost(average)
Diesel	16.5 NOK/liter
Electricity	0.7 NOK/kWh
Hydrogen	90 NOK/kg

Considering the operational profile outlined in Chapter 3.1, where the daily total energy demand is 420 kWh, with 210 kWh allocated for transit purposes, it becomes feasible to estimate the annual operational costs for each design. However, several assumptions must be made, particularly concerning the hours of operation, which are challenging to accurately predict. The majority of the data utilized are derived from Moen Marin and subsequently scaled accordingly.

Assuming:

- the vessel operates 8.5 hours a day for 365 days
- of the 8.5 hours, 1.5 are used in transit, resulting in approx. 548 hours

- diesel engines/generators are operating at 50% during transit
- that the gensets operate 250 additional hours throughout the year, assisting/charging the battery
- the FC operates at all times, producing a steady output of 30kW
- the assisting engine of the conventional design operates 50% of total daily use
- no control algorithm is employed for efficient use of power sources (gives a linear approach)
- the lifespan of the FC and battery is not included in the cost

With these assumptions, calculating the operational costs of each design is a simple task. It should be noted that this calculation is an overestimate, as the earn-back time relies heavily on the operational costs of the conventional design, which is highly dependent on varying diesel prices.

Table 12: Estimated 'earn-back' time

Design	Operational costs [thousand NOK]	Earn back time (vs conventional)
Conventional D-M	1964.2	-
Diesel hybrid	998.4	4.6 years
FC hybrid	719.8	5.4 years

In Table 12, the calculated operational costs are presented and tell that the diesel hybrid is the cheapest one to operate. The batteries that both the FC hybrid and the diesel hybrid are equipped with have an expected lifespan of a minimum of 8 years. The total savings for the diesel hybrid during the batteries lifespan is:

$$Op.savings(8y) = (1964.2 - 998.4) \cdot 8 = 7726.4(\text{thousand NOK}) \tag{3}$$

while the total savings for FC hybrid is:

$$Op.savings(8y) = (1610.5 - 719.8) \cdot 8 = 9955.2(\text{thousand NOK}) \tag{4}$$

Assuming that a new battery pack for the vessel will cost 5 million, which is a big overestimate, the operational savings are high enough to cover the expense of a new battery pack. This means that the designs, with the current assumptions, are sustainable and profitable. Even though the hydrogen system is quite expensive to invest in with current technology, this price is expected to fall quite drastically in the following years due to advances and commercialization of fuel cells. This can also be said for the price of hydrogen, which is quite high as of today. The vessel consumes approximately 5000kg of hydrogen during a year, so the price of hydrogen has a huge impact on the operational costs.

From the data presented above, it can be concluded that if the only purpose of the design is to profit over time, the FC hybrid is a favorite. The investment cost of this design is high compared to the conventional design, but with an estimated earn-back time of 5.4 years, the investment pays off soon enough. One aspect that remains unaddressed in terms of the operational costs and sustainability of the FC hybrid design is the lifespan of the fuel cell stack. The lifespan of a PEMFC can range from 5,000 to 30,000 hours, depending on its usage. When employed as the primary power source, it is expected to endure 10,000 hours, equivalent to approximately 3 years of service. In optimal conditions (30,000 hours), it could last up to 10 years (with current assumptions), but this would necessitate continuous operation throughout its lifespan. Currently, the design explicitly states that the fuel cell is operated at all times to generate approximately 30 kW, except being turned off during the night. Consequently, due to uncertainties surrounding the FC's lifespan, the calculation thereof has been omitted from consideration.

3.2.4 Regulation-based scenario

Regulations are put in place to make sure that future vessels being built, adhere to certain safety measures and limitations, that are set based on experience regarding such vessels. Regulations surrounding conventional diesel-electric vessels are well established, and are easy to adhere to, given the extensive knowledge spread among employees and contractors in the ship design business. There are also laws in place to ensure compliance with environmental standards and emissions regulations. However, when it comes to innovative and emerging technologies in ship design, such as alternative fuels or hybrid propulsion systems, regulations may not be as well-defined. In such cases, the challenge lies in striking a balance between encouraging innovation and ensuring safety and environmental sustainability. Therefore, regulatory bodies and industry stakeholders must collaborate to establish comprehensive guidelines that address the unique characteristics and potential risks associated with these new technologies.

About the designs discussed in the preceding chapters, the diesel hybrid stands out as a well-regulated option due to its widespread usage in hybrid vessels. Meanwhile, the conventional diesel-electric vessel holds an even stronger position in terms of established regulations, given its long-standing presence in the industry. On the other hand, the utilization of hydrogen systems in boats remains largely uncharted territory, with only a few exceptions such as research vessels or short-sea passenger ferries. Consequently, regulations for these types of vessels are virtually non-existent.

The first commercial vessel approved for fuel cell technology will play a pivotal role in shaping future vessels and the corresponding regulations. The development surrounding this initial commercial application will serve as a basis for subsequent recommendations and regulations. In essence, being at the forefront of this technological leap will hold historical significance, but it will also entail a highly time-consuming and complex process. The classification society and producers involved will need to design and formulate new regulations as they progress along the way.

3.3 Feasibility

In this chapter, the different parts of the power system will be assessed in terms of their feasibility in marine applications. Load-sharing scenarios will be addressed to discuss the effect of a battery in the power system, and which approach could prove to be the most beneficial.

3.3.1 Load sharing scenarios

The load profile for the work vessel is presented in Figure 6, which is an estimate of the load profile of a standard workday. This will of course vary in a real-life scenario, depending on if the vessel operates at several sites or if the vessel has different operations.

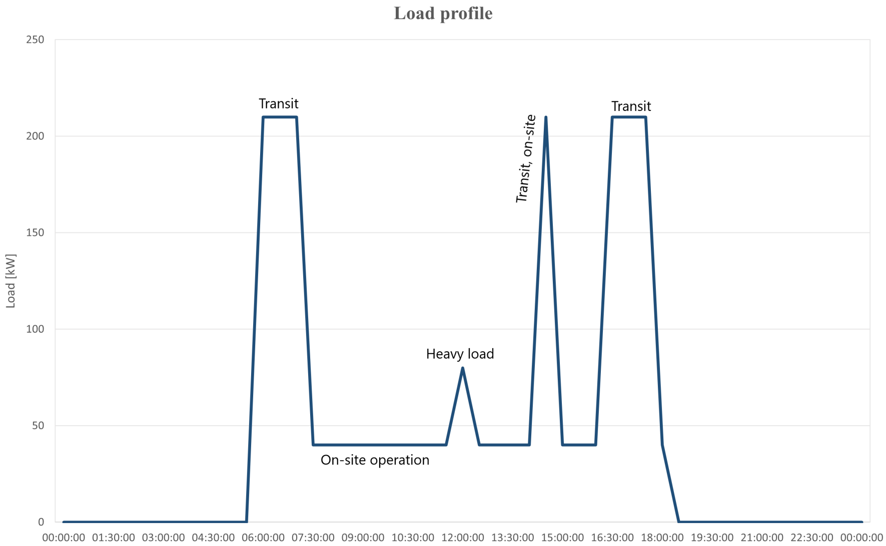

Figure 6: Suggested load profile for the work vessel

The suggested load profile is not meant to be an accurate representation of the loads the vessel will experience but serves as a benchmark for assessing different load-sharing strategies. The loads pictured above are some of the load-demanding operations that a work vessel encounters, and are further described in Table 13.

Table 13: Operational description

Operation	Description
Transit	Transit to and from the operational area, usually somewhere 30-60min to and from the site.
On-site operations	Hotel load, plus load demand from HPU (crane operations, etc.)
Heavy operation	A combination of operations that could result in a 'heavy operation'
Transit, on-site	Shorter transit time than to and from the site, usually between barge and cage

Diesel Hybrid A diesel hybrid work vessel for the fish farm industry employs specific load-sharing alternatives. In larger vessels, the genset is typically supported by the battery during high-load demand scenarios with a transient load profile, such as DP. However, in the case of the vessel in question, which does not utilize DP, the highest load demand occurs during transit. During transit, the main genset operates close to optimal efficiency and is designed to handle most, if not all, of the load. As a result, the battery remains mostly inactive during this phase. The battery may however assist the genset with start and stop operations due to its faster response and load delivery time compared to the diesel generator. The battery on these vessels is primarily responsible for handling the load during on-site operations, where the most demanding task is typically a crane lift, with a load that generally does not exceed 80 kW.

In Figure 7, a more detailed load profile is shown for the diesel hybrid vessel, specifying the load provided by each power source. When the battery charge goes below zero, it indicates that the battery is charging, as shown in the graph. It is important to note that the provided numbers are approximate and do not account for conversion losses within the system.

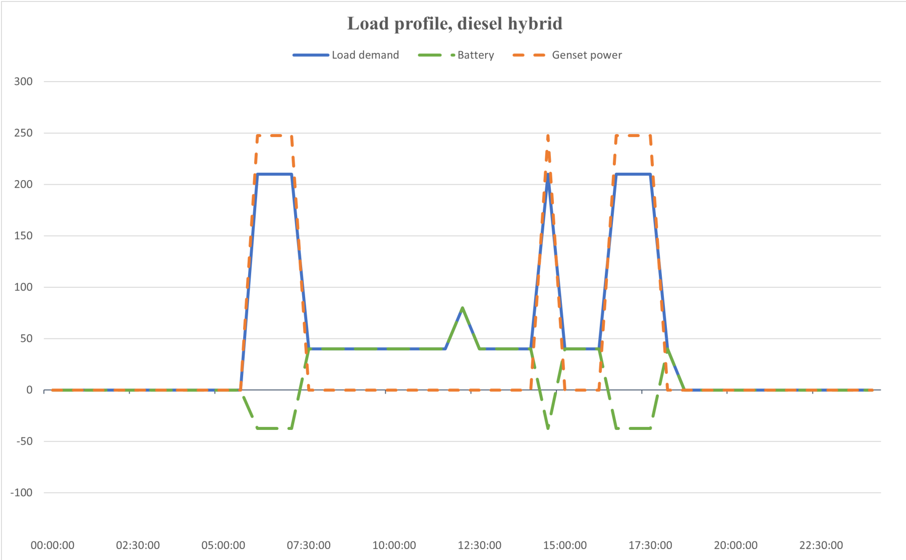

Figure 7: Load profile for Diesel Hybrid

As depicted in the figure, during transit, the genset provides more load than necessary for propulsion, effectively charging the battery with excess power. Ideally, the battery should be fully charged from shore power before the transit begins, eliminating the need for charging during the initial part of the journey. This requires lowering the $\%MCR$ of the genset by approximately 16%. However, this adjustment has a negligible impact on the SFOC of the genset. For instance, reducing the $\%MCR$ from 80% to 64% would result in an increase of only 4 g/kWh in the SFOC.

Hydrogen hybrid The hydrogen hybrid work vessel shares a similar load profile with the diesel hybrid, with the highest load demand occurring during transit to and from the site. However, the hydrogen hybrid differs in terms of its operation strategy aimed at maximizing the lifetime of the PEMFC stack. In this case, the FC should run for as much time as possible. Therefore, even during on-site operations where the load demand is lower than the power supplied by the fuel cell, the FC will remain active, charging the battery with the excess power provided. The battery then handles most of the load required for propulsion, with assistance from the FC.

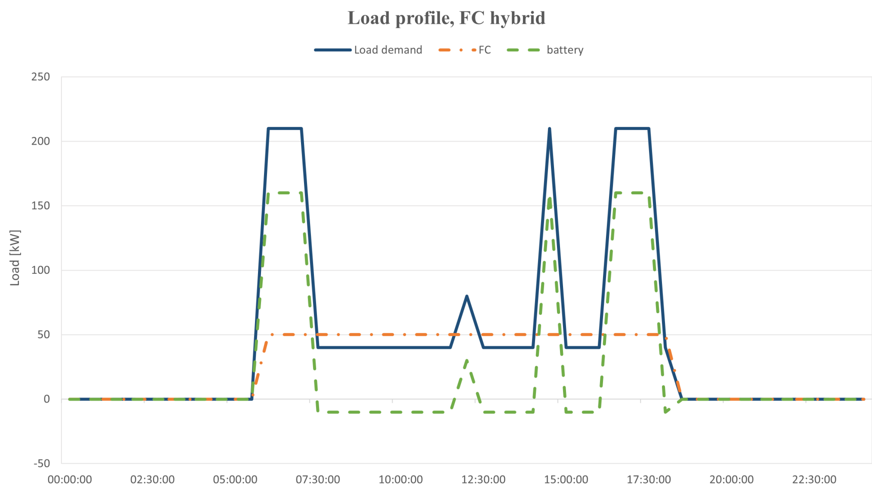

Figure 8: Load profile for FC Hybrid

Figure 8 illustrates the load profile for the FC hybrid vessel, highlighting the contribution of the fuel cell and battery. As shown, the fuel cell covers the majority of the load during on-site operations.

However, during instances of sudden load increase, the battery assists by providing the required power. This load-leveling function performed by the battery allows the fuel cell to operate as stably as possible, thereby increasing the estimated lifetime of the stack. The power supplied to the system by the fuel cell is set to 50kW, as this is where the fuel cell is estimated to run most efficiently. The hotel load, including the HPU load, should be covered by the fuel cell supply unless a heavy lift occurs.

3.3.2 Hydrogen integration

Hydrogen, while not yet commonly employed in maritime applications, holds promise for the future. However, due to its limited usage in this domain, regulations about the storage and integration of hydrogen within vessels are yet to be fully established. As previously mentioned, one notable characteristic of hydrogen is its high energy density, although it does suffer from a relatively low *volumetric* energy density. This poses a challenge when it comes to storing hydrogen onboard ships.

When considering hydrogen storage options for maritime use, two primary choices emerge, liquid or gas storage. Liquid hydrogen storage involves cooling hydrogen to extremely low temperatures, transforming it into a liquid state for denser storage. On the other hand, gas storage entails keeping hydrogen under high pressure within specialized tanks. The main issue with storing the hydrogen in liquid form is that it needs to be kept at temperatures below -253 °C, which calls for advanced cryogenic containers, further complicating the system. In other words, the preferred method, currently, is hydrogen in gas form.

The integration of Gas Hydrogen Storage (GHS) in the vessel includes the integration and placement and fuel cell, which is further discussed in Chapter 3.3.3. Generally, pressurized tanks are considered a safety concern that needs to be addressed through preemptive methods. Hydrogen as a gas is extremely flammable when combined with oxygen, and leakage or fire on the vessel could prove catastrophic for all crew onboard. The combination, pressurized tanks containing hydrogen gas, is likely the largest safety concern of the vessel.

Even though hydrogen is highly flammable when combined with oxygen, hydrogen is still lighter than air, which means that it disperses quickly if it were to leak. With this in mind, it is natural to theorize that placing the hydrogen storage on deck is better than having it in the hull, as dispersing it in the free air is safer than keeping it contained in a room. The question that remains, is where on the vessel the tanks could be placed without being a hindrance for the crew, whilst also having access to free air. To be able to argue for the placement of the hydrogen storage, it is necessary to estimate the needed size of the storage.

Sizing of hydrogen storage and filling philosophy Earlier, the consumption of hydrogen during normal operation was briefly touched upon. Generally, if the load on the stack is 30kW, it will consume 1.6kg of hydrogen per hour, resulting in a consumption of 13.6 kg per day (assuming 8.5 hours of operation time). A normal diesel-mechanical vessel might refill one to two times a month, depending on how much time it spends in transit. Considering hydrogen has 4.29 times lower volumetric energy density than diesel(as mentioned in Chapter 3.2.2), a reasonable conclusion is to say that the refilling of hydrogen should happen once a week. The weekly consumption of hydrogen is $13.6kg \cdot 7days = 95.2kg/week$ which means the tank capacity should be a minimum of 100kg. Looking into hydrogen storage solutions, state-of-the-art hydrogen tanks for maritime applications have a capacity of 9kg, 32kg, 153kg, or 189kg. The two largest models are 11.6m in length, which does not fit well on the vessel. It is therefore reasonable to think that the 32kg tank is a good fit for the vessel, as it is approx. 5.69 m long, about a third of the design vessel's length. Four tanks are required to cover the minimum tank capacity of the vessel, giving a total hydrogen fuel capacity of 128 kg, which, in theory, will result in a refill every 9 days.

Placement of hydrogen tanks There are now four 5.69 m tanks, each with a diameter of 0.69m that needs to be placed somewhere sensible on the vessel. The GA below illustrates a suggested area where the tanks could be placed, without obstructing critical work space for the crew.

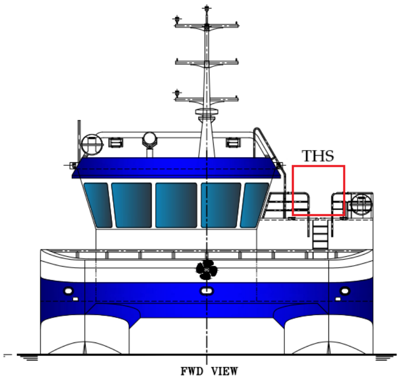

Figure 9: Front view

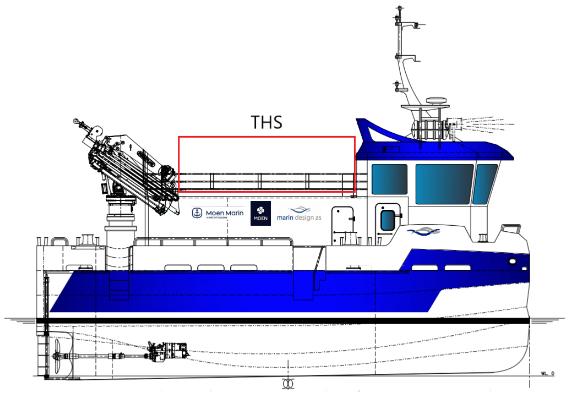

Figure 10: Starboard side view

The starboard side of the vessel is typically used for work, cranes, and other hydraulic equipment. This is to make it easier for the crew on board to work, as the vessel now has one dedicated lift and work side. In other words, the starboard side is a no-go for tank placement, as this is a highly active work area.

3.3.3 Fuel cell & BoP

The implementation of the FC and assessment of the BoP requires consideration of the energy and power demand. The energy demand has already been discussed in earlier chapters, where a total demand of 420 kWh throughout a normal day of operations is needed. Most of this is supplied by the battery pack, but the FC is also a contribution that needs to be accounted for. In Chapter 3.3.2 the FC power supply was set to 50 kW, based on the hydrogen consumption at this power level. The power demand during on-site operation is assumed to be 30-40kW, based on historical data from other ships built by MM of the same size. With a power supply of 30-50 kW, the excess power can be used to charge the battery, which has a depleted SoC after the transit load demand.

With this in mind, a FC with its optimal range covering the interval of 40-50kW should be considered, as this is the best fit for this vessel under the current assumptions. There are currently no PEMFCs designed for marine use, at least not of this size, so the designer should look elsewhere to find a suitable FC. The fuel cell should be placed in a separate room, due to safety concerns discussed in Chapter 3.3.4.

An example of FC placement is illustrated in the image below.

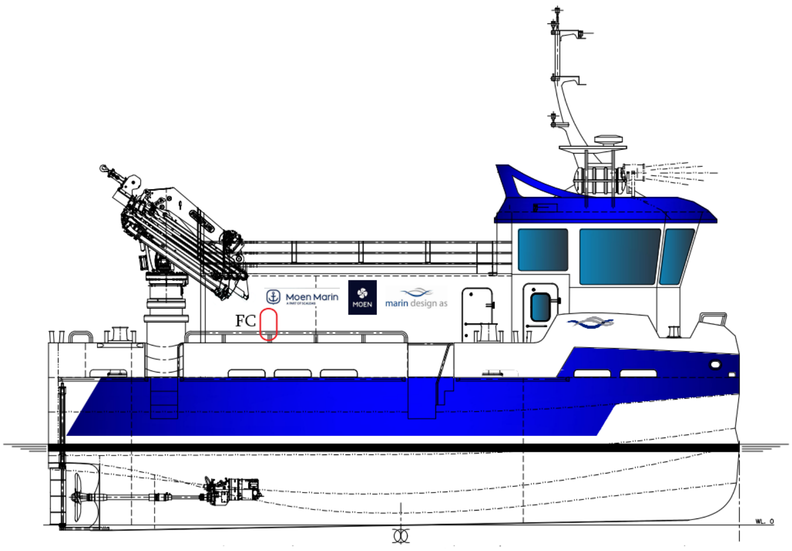

Figure 11: Suggested FC placement

BoP The Balance of Plant, is everything needed for the fuel cell system to operate, except for the fuel cell stack itself. In Figure 12 the BoP for the current design is suggested. This is a simplified diagram, to show the general idea of the BoP, a table containing a description of the various components is presented in Table 14

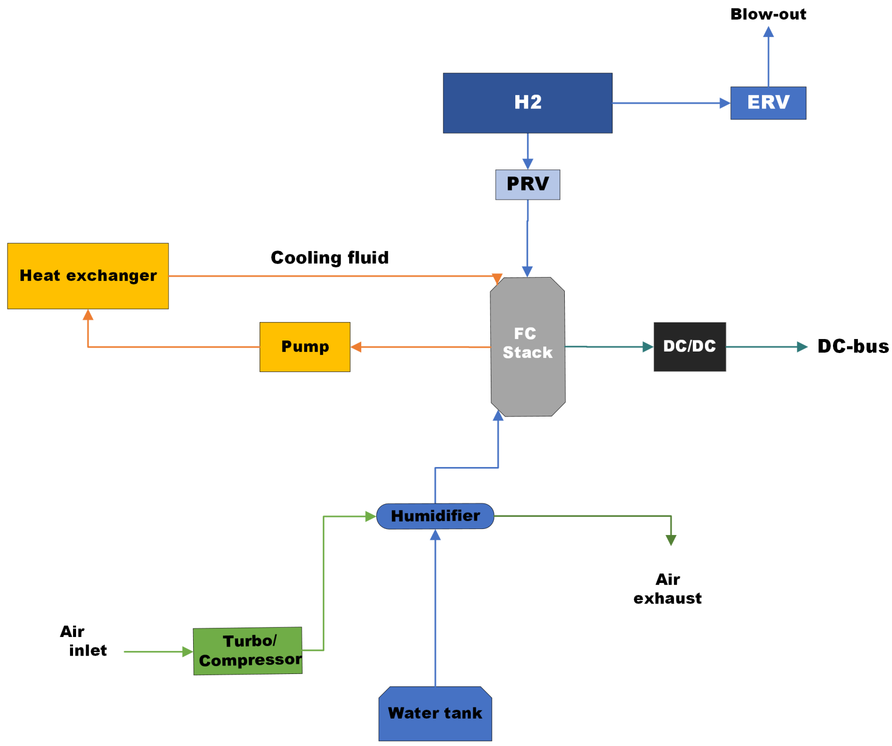

Figure 12: BoP for the fuel cell design

Component	Description
H2	H2 tank, discussed in Chapter 3.3.2
Blow-out	Valve to open into free air for dispersion of hydrogen
ERV	Emergency Release Valve, usually paired with several other fail-safe valves
PRV	Pressure Reduction Valve, reduces pressure from the tank to acceptable levels for FC
Heat Exchanger	Regulates temperature of components within FC system
Cooling fluid	Typically glycol or something similar
Pump	Maintains pressure in cooling system
FC Stack	PEMFC Stack, not scope of BoP
DC/DC	DC-DC converter, voltage regulation / conversion
Humidifier	Maintains moisture in reactant gas, enabling optimal performance
Air inlet	Inlet of reactant gas, in this case, oxygen (sourced from air)
Turbo / Compressor	Supplies the air in a controlled manner
Air exhaust	Exhaust for air supplied to the cathode that did not participate in electrochemical reaction
Water tank	Manages water byproducts and assists in cooling and humidification processes

Table 14: BoP components

3.3.4 Safety of hydrogen

Safety concerns surrounding hydrogen are important to consider early in the design process, as both compressed tanks and the hydrogen itself pose severe threats if exposed to fire or similar hazards. Proper safety measures should be implemented to mitigate the risks associated with handling and storing hydrogen.

To ensure the safe storage of hydrogen, the compressed tanks should be approved by a certified body to ensure compliance with standards for pressurized gas storage at sea. This entails ensuring that the tanks maintain their structural integrity even when exposed to sunlight and seawater. One effective approach is to encapsulate the tanks within a robust frame that can withstand the elements, including sunlight and seawater. Additionally, the tanks should be constructed to withstand the corrosive effects of seawater, reducing the likelihood of leakage due to deterioration.

Gas leakage is a significant concern when dealing with hydrogen due to its high flammability and low ignition energy. To mitigate this risk, it is crucial to use robust tanks and pipelines that undergo regular inspections to detect any potential leaks. In the event of a leakage, measures should be in place to minimize the chances of a fatal accident. Gas detection systems are essential to promptly alert the crew and the system of a leak, triggering appropriate procedures. The response procedures will depend on the location of the leak and the criticality of the affected component. If a gas leakage is detected in the tank area, the procedures should ensure the immediate halt of gas supply to the point of the leak, along with proper ventilation of the area to reduce the risk of ignition. If hydrogen leakage is detected within a closed space, measures should be implemented to inert the area using nitrogen or argon. This can be achieved by opening a valve connected to a gas container to introduce an inert gas.

Another critical concern that should be addressed early in the design process is the risk of a fire event. A fire reaching the pressurized hydrogen tanks would have catastrophic consequences for the crew onboard the vessel and could potentially lead to an explosion. Therefore, it is imperative to implement measures to minimize the likelihood of such an explosion. One approach is to incorporate a Thermal Pressure Relief Device (TPRD) that opens at a predetermined temperature. When activated, this valve should rapidly purge the remaining hydrogen from the system at a safe height where the flames are unlikely to ignite the gas. Additionally, proper fire protection measures should be implemented to safeguard the areas surrounding the hydrogen tanks.

The possibility of tank rupture due to accidents like ship collisions or dropped loads during crane lifts is another critical consideration in the design process. The risk of ship collision in the vessel's operational area should be taken into account, and measures to mitigate the impact of a potential collision should be discussed. Restricting crane movements to prevent operation over the tank area is a reliable method to ensure no loads are dropped on the tank system, enhancing safety.

By addressing these safety concerns early in the design process and implementing appropriate measures, the risks associated with hydrogen handling and storage can be effectively minimized, enhancing the overall safety of the vessel and its crew.

3.3.5 Battery system integration

The battery system is a vital part of the power system of the vessel, as this system is intended to cover the majority of the load demand. This means that the vessel needs to have a sufficiently large battery to cover the energy demand from transit and also enough to cover unexpected loads during on-site operations. The total estimated energy demand of the vessel is 420 kWh, where the FC supplies 30-50kW for 8.5 hours of the day, resulting in 340-425kWh of energy provided by the FC.

The battery needs to handle $210kWh - [30, 50]kWh = [160, 180]kWh$ for the transit. This is a slight overestimate which does not account for charging during on-site operation, as the vessel might require more battery capacity for transit in case of a failure in the hydrogen system. To increase the lifetime of a battery it is suggested that the SoC stays between 20% and 80%, leaving 60% capacity left to use. The vessel then needs to be installed with a battery capacity of,

$$Q_{bat} = (\frac{[160, 180]}{0.6})\text{kWh} = [267, 300]\text{kWh} \tag{5}$$

where the focus should be put on a battery type with high energy.

The most ideal location for the battery pack is in one of the hulls of the vessel, due to its heavy weight. The normal procedure in these vessels is to have them in a cabinet, that is classified as a fire-protected space. Additional fire protection measures should also be put into place, as a fire in battery systems releases dangerous toxins.

3.4 Specific energy density of designs

The specific energy density is a measure of how much energy the powertrain can deliver per unit of measurement. This is useful for design purposes, for example when designing a vessel that needs space, emphasis should be put on a design with a high volumetric energy density(ρ_{VE}).

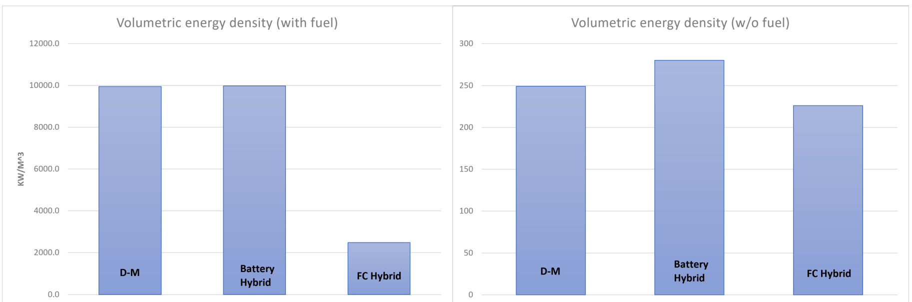

Figure 13: Estimated volumetric density of each design

In Figure 13 it is clear that the hydrogen concept suffers from a low volumetric energy density than the other two. By neglecting the impact of hydrogen as fuel, as shown in the figure on the right, the FC hybrid is not far from achieving the same ρ_{VE} as the diesel mechanical concept, even with its technological immaturity. The battery hybrid is a favorite here due to the high ρ_{VE} of the battery and genset.

The gravimetric energy density, ρ_{GE}, can be used in the design process if the vessel has a focus on efficiency in transit, as the deeper the draught of the vessel, the more energy is needed. Therefore, selecting a design with a high ρ_{GE} could be an optimal design solution.

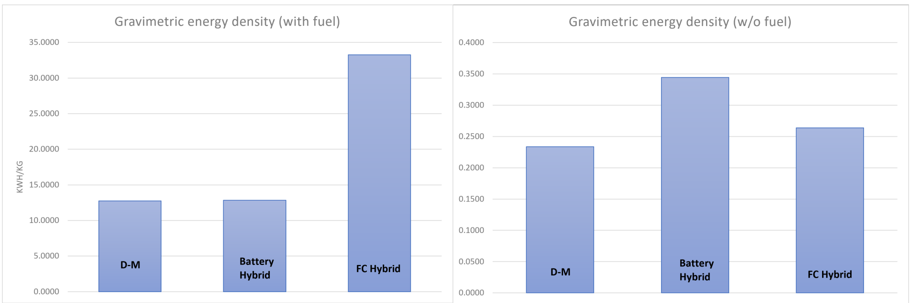

Figure 14: Estimated gravimetric density of each design

The best design, based on Figure 14, in terms of the energy per kg, is the hydrogen hybrid design. That is, if fuel is included, the battery hybrid still comes out on top if fuel is neglected. This is mainly due to that the fuel cell in question has been scaled down, whilst there exist other fuel cells that deliver more energy per kg, they don't have the same efficiency.

Note that the fuel tank weight and the weight of the electrical system have not been included in this calculation, which suggests that the diesel mechanical might come out on top still, in terms of specific energy density.

Based on the estimations and assumptions presented in this chapter, the hydrogen hybrid option has been chosen as the preferred design for the preliminary design process. This decision is primarily driven by its zero-emission characteristic and the authors' existing knowledge and experience in the realm of hydrogen implementation in marine vessels.

4 Preliminary Design

The preceding chapter, Chapter 3, discussed general design ideas focused on high-level decision-making. In this chapter, the attention shifts to the critical aspects of sizing, dimensioning, and integrating various components within the electric system of the vessel. Additionally, the chapter explores the physical system integration from a ship design perspective, including the layout of tanks, and space allocation.

Throughout this chapter, a holistic approach to sizing, dimensioning, and system integration will be employed. By addressing the electric system integration, switchboard selection, development of the SLD, physical system integration, and the layout of tanks, the aim is to establish a comprehensive framework for integrating the hydrogen system smoothly into the vessel's design.

4.1 Sizing and dimensioning

In this chapter, the size of major components and some minor ones are suggested, based on the vessel design mentioned in Chapter 1.3.1. A more precise load profile is presented, based on the historical data of a larger vessel, with a more accurate energy demand from transit.

4.1.1 Load profile based on historical data

As previously mentioned, historical data from MM has been received and processed. Due to the high level of noise and uncertainties surrounding this data, the load profile will be assumed based on the 'active' periods of each component, instead of the magnitude and the active period. Figure 15 depicts the historical load profile and Speed Over Ground (SOG) for a larger vessel than what is designed for in this thesis.

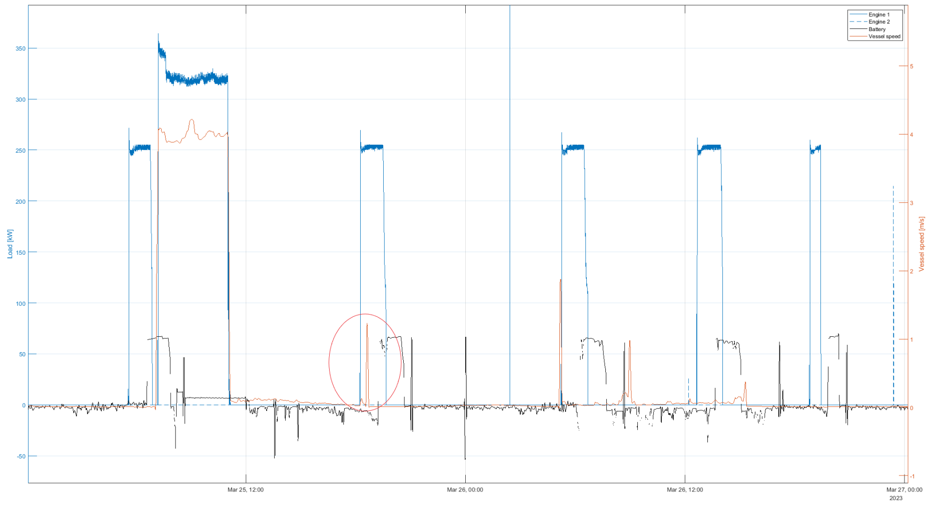

Figure 15: Historical load profile

Both the battery load and the SOG have undergone extensive filtering, resulting in the exclusion of some data points. This filtering process is particularly noticeable in the battery load, where areas with higher rates of increase were restricted by the filter, leading to gaps or missing data. Similarly, the filtering has affected the SOG, as evidenced by the period marked by the circle. During this time, the vessel was in transit, but the low-pass filter resulted in a brief duration of low amplitude for the SOG, failing to capture its true behavior.

However, despite the presence of missing or misrepresented data, it is still possible to derive a more detailed load profile compared to the one mentioned in Chapter 3.3.1.

The work day commences early, with the initiation of genset 1 at 5:30, presumably to recharge the battery above its lower limit. The battery then assists in propelling the vessel, and once the cruising speed of 9 knots is attained, the genset takes over the entire load demand for the transit period. No load is shown beyond this transit phase, likely due to the vessel's minimal hotel load (14kW). During this duration, it is highly probable that work activities are focused on the fish cages or barge, rather than performing operations that require a significant power demand. This low hotel load is efficiently managed by the battery, although it might not be depicted due to the relatively small change in the battery's SoC. (The battery load calculation is based on a generalized Coulomb counting approach.)

Towards the end of the work day, the vessel enters transit again, possibly for a shorter duration to reach a nearby site. Typically, these larger work vessels remain on-site overnight, which is why two operational days serve as a benchmark for analyzing the load profile of this work vessel.

On the subsequent day, the battery exhibits increased activity, characterized by shorter-duration amplitudes during which the genset does not assist. These instances are likely associated with crane lifts. Whenever the genset is active, it is assumed to be either charging the battery pack or utilized for propulsion in some form.

Based on this analysis, the following load profile is hypothesized for the smaller work vessel.

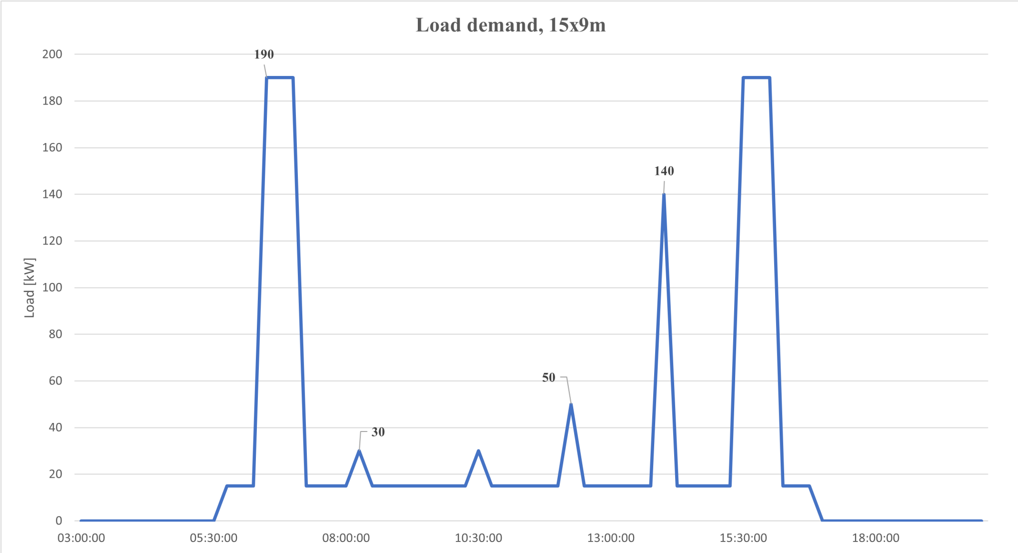

Figure 16: Suggested load profile for vessel

The revised load profile incorporates several key modifications compared to the previously suggested profiles. These adjustments primarily focus on the load demands associated with HPU operations, such as crane lifts, tailored to the size of the vessel. These loads have been adjusted to the HPU load limit, never exceeding 50kW.

Additionally, the hotel load has been recalibrated to 14kW, which is in line with the vessel the historical data has been extracted from. During transit periods, assuming a forward speed of 9 knots, the power demand has been set at 190 kW. These adjustments result in an estimated energy demand of 470kWh, with 320kWh allocated for transit (corresponding to a duration of 1.75 hours) and 150kWh for hotel loads and HPU operations.

The frequency of crane operations is derived from historical data, suggesting an average of approximately 2.5 heavy lifts per day. This updated load profile will serve as the foundation for sizing and dimensioning various components within the power system in the subsequent chapters.

4.1.2 Fuel cell

The fuel cell design for the vessel should incorporate a base load, which needs to be determined based on a new and more detailed load profile analysis. While the average load demand of the vessel is 42.5 kW, it is important to acknowledge that this average is high due to transit, which will primarily rely on the battery system. To ensure efficient operation, a feasible base load for the fuel cell is estimated at 40 kW. This power level is sufficient to meet the majority of the vessel's load requirements, while unexpected high loads can be handled by the battery system.

To facilitate the design process, data from a reputable supplier is utilized. The fuel cell has specific dimensions as listed in Table 15. Due to a lack of existing data, the dimensions are scaled down to match the dimensions of a fuel cell with a rated power of 100kW (scaled down from 200kW). Additionally, key performance parameters provided by the supplier are also considered. The gravimetric energy density of the fuel cell is indicated by the parameter ρ_{GE}, which has a value of 5.35 kg/kWh. The volumetric energy density is denoted by ρ_{VE} and is specified as $138 kWh/m^3$.

Referencing the base load of 40 kW, other important fuel cell characteristics are also provided. The specific fuel consumption (SFC) at the base load is indicated as 33 g/kWh, representing the fuel consumption rate for a unit of electrical energy produced. Furthermore, the electrical efficiency (η_{el}) at the base load is 55%, representing the proportion of electrical energy outputted compared to the total energy input.

Table 15: Fuel cell dimensions

Parameter	Size
Power	100kW
Height	1100mm
Width	730mm
Depth	900mm
Weight	535 kg
ρ_{GE}	5.35 kg/kWh
ρ_{VE}	138 kWh/m^3
Base load	40kW
SFC at BL	33 g/kWh
η_{el} at BL	55%

This fuel cell is selected based on its ease of integration and regulated maritime use.

4.1.3 Battery pack

The new energy demand from transit has been set to 320kWh, assuming that the propulsion engines operate close to full capacity during transit, giving a forward speed of approx. 9 knots. Subtracting the energy delivered by the FC during transit gives a remaining energy demand of

$$E_{transit} = 320kWh - 40kW \cdot 1.75h = 250kWh \tag{6}$$

To ensure a minimum level of safety, the battery pack should be sized to enable the vessel to return to shore in the event of a hydrogen system failure. An event like this is not unlikely, as the hydrogen system will be switched off in case of a leak or any errors. Considering the worst-case scenario where the hydrogen system fails on-site before any battery charging occurs, and the nearest shore is the vessel's home port, the minimum required battery capacity is determined as,

$$Q_{bmin} = (150\,kW \cdot 0.75\,h + 50\,kW \cdot \frac{6\,nmi}{2\,kts}) \cdot \frac{1}{0.8} = 328\,kWh \tag{7}$$

with the following assumptions:

- Power demand for transit for such occasions is 50kW
- Speed of transit is 2 knots
- Distance to cover is 6 nautical miles (nmi)

It is essential to emphasize in the vessel's safety philosophy or operations manual that in the event of a power source failure, the vessel must return to shore immediately. Also, in the case of such an event, the lifetime of the battery pack does not have priority, so the available SoC is 80%.

Considering that the battery pack is normally charged at an average rate of 20 kWh (based on the load profile presented in Chapter 4.1.1), it is determined that the battery should not be sized to provide enough energy for both transit periods. The battery pack size based on transit demand is calculated as follows,

$$Q_b = \frac{150kW \cdot 0.75h + 140kW \cdot 0.25h}{0.6} = 246kWh \tag{8}$$

Here, 0.6 represents the available SoC for the pack. Since $Q_b < Q_{bmin}$, the battery pack should be around 328 kWh. The precise sizing of the battery pack will depend on the cell and pack sizes available from the supplier.

One well-established supplier delivers 124kWh packs, that have the following dimensions,

Table 16: Battery pack dimensions

Parameter	Size
Height	2241mm
Width	865mm
Depth	738mm
Weight	1628kg
ρ_{GE}	13kg/kWh
ρ_{VE}	87 kWh/m^3

where three of these packs would suffice for the vessel in question.

Note that the suggested sizing of the battery pack does not account for conversion losses in the system.

4.1.4 Hydrogen storage

Earlier, the consumption of hydrogen during normal operation was briefly touched upon. According to data in Table 15 if the load on the stack is 40kW, it will consume 33 g/kWh, where the hydrogen consumption is calculated as

$$H_2 = \frac{33g/kWh \cdot 40kW}{1000} = 1.34kg/h \tag{9}$$

resulting in a daily consumption of $1.34, \mathrm{kg/h} \cdot 9\mathrm{h} = 12.1\mathrm{kg}$ hydrogen per day (assuming 9 hours of operation time as stated in Chapter 4.1.1). In comparison, a normal diesel-mechanical vessel may refill one to two times a month, depending on its transit time.

Considering that hydrogen has 4.29 times lower volumetric energy density than diesel (as mentioned in Chapter 3.2.2), a reasonable estimate is that the refilling of hydrogen should occur once a week. The weekly consumption of hydrogen is $12.1\mathrm{kg} \cdot 7\mathrm{days} = 84.7\mathrm{kg/week}$, which means the tank capacity should be a minimum of 85 kg.

State-of-the-art hydrogen tanks for maritime applications have capacities of 9 kg, 32 kg, 153 kg, or 189 kg. The two largest models are 11.6 m in length, which does not fit well on the vessel. Therefore, it is reasonable to think that the 32 kg tank is a good fit for the vessel, as it is approximately 5.69 m long, about a third of the design vessel's length. Three tanks are required to cover the minimum tank capacity of the vessel, giving a total hydrogen fuel capacity of 96 kg. It is however recommended to use 4 tanks, to improve stability and ease of implementation of the tank holding space. This results in a total fuel capacity of 128kg, which will theoretically require a refill after 10 days.

4.2 Electric system integration

This chapter presents the sizing of different electrical components, along with a more detailed SLD.

4.2.1 Switchboard

As discussed in Section 2.3.7, AC power systems are generally considered simpler and more robust than DC systems, but they lack the variable frequency capability that DC systems offer. DC power, on the other hand, is better suited for variable frequency power sources. Additionally, components used in DC systems tend to be lighter compared to their AC counterparts.

Given that the fuel cell is considered the prime mover in the vessel's power system, one could argue that it is theoretically frequency stable. However, in practical operation, the fuel cell's load may vary, as the user will likely have control over the fuel cell load. Therefore, opting for a DC topology for the power system and implementing a DC Switchboard in the vessel is justified.

In designing the DC Switchboard, it is ideal to have its voltage equal to or higher than that of the components it interfaces with. This choice reduces resistive losses by decreasing the current magnitude, subsequently leading to smaller component sizes. The fuel cell, with a voltage rating of 800V, stands as the highest-rated component in terms of voltage. Consequently, setting the switchboard voltage to 800V is reasonable to avoid challenges in obtaining components rated for a voltage higher than 800V.

4.2.2 Inverters and converters

In the given DC-based system, the inclusion of an inverter between the propulsion motors and the switchboard is necessary. This inverter must be appropriately sized based on the switchboard voltage and the power requirements of the propulsion motor. As each inverter receives 800V from the switchboard, it is imperative that the inverter's voltage rating aligns with this value. Moreover, the inverter must also be sized to accommodate the power rating of the motor it is intended to drive. The rated power of each motor is presented in Table 17

Table 17: Rated power of motors

Motor	Rated power
Propulsion motor	100kW
HPU	50kW
Thruster motor	70kW

To ensure proper power supply from the fuel cell to the switchboard and from the battery to the switchboard, DC-DC converters should be positioned between each pair of components. While a unidirectional DC converter from the fuel cell to the switchboard is sufficient, the battery necessitates a bi-directional converter, as it will both supply and receive power. Both converters should be appropriately sized to accommodate the specific power requirements.

The updated (SLD) for the vessel is depicted in Figure 2, showing adjustments made to one of the HPU motors due to the smaller size and fewer cranes compared to Frøyblikk,

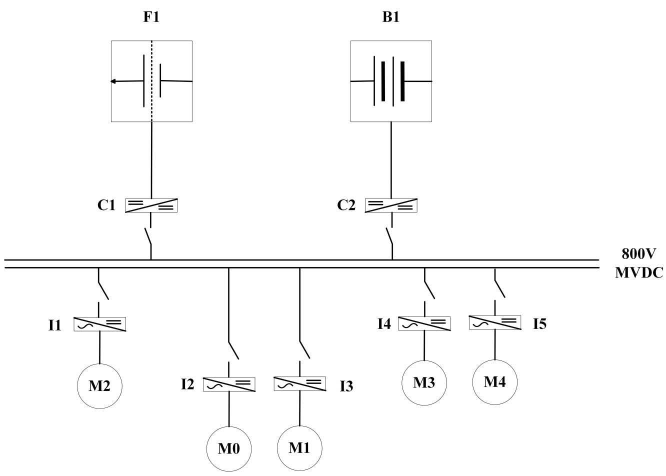

Figure 17: Updated SLD

with the description of the 'new' components and their sizing below.

Table 18: Sizing and placement of inverters and converters

Component	Description	Sizing
C1	Unidirectional DC converter, FC	800V, 100kW
C2	Bi-directional DC converter, Battery (3 pcs.)	800V, 92kW
I1	DC-AC Inverter, HPU	800V, 50kW
I2, I3	DC-AC Inverter, Propulsion	800V, 100kW
I4, I5	DC-AC Inverter, Thruster	800V, 70kW

4.3 Physical system integration

4.3.1 Placement of hydrogen tanks

There are now four 5.69 m tanks, each with a diameter of 0.69m that needs to be placed somewhere sensible on the vessel. The starboard side of the vessel is typically used for work, cranes, and other hydraulic equipment. This is to make it easier for the crew on board to work, as the vessel now has one dedicated lift and work side. In other words, the starboard side is a no-go for tank placement, as this is a highly active work area. The tanks should be placed according to the standards put in place by the class society, or go through an approval process during the Approval in Principle (AIP).

Since no relevant regulations exist regarding the placement of such tanks yet, the tank placement shown in Figure 9 is recommended. Exact measurements on where to place the tank should be decided after careful consideration and cooperation with a class society.

4.3.2 Fuel cell integration

Considering the characteristics and safety requirements of the fuel cell system, it is advisable to allocate a separate room dedicated to the fuel cell installation. While the FC itself has a relatively small footprint compared to the hydrogen tanks, certain safety measures need to be implemented, as discussed in Chapter 3.2.4.

Creating a designated FC room allows for focused safety measures to be put in place without impacting other areas of the vessel. One significant consideration is the need to inert the FC room with nitrogen in the event of a leakage, which can be costly and challenging to implement in a larger space like the hull. Additionally, the FC room must meet stringent fire insulation requirements (A60), which can be particularly expensive to achieve in aluminum hulls.

By having a separate FC room, maintenance and stack replacement at the end of the fuel cell's life cycle become more convenient. Furthermore, locating this room under the hydrogen tanks can help streamline the piping work required for hydrogen supply, reducing complexity and potential installation challenges.

An extension of an existing workshop area, specifically designed to accommodate the separate FC room, is a practical consideration. This arrangement allows for a focused approach to safety measures and facilitates maintenance activities. For illustration, refer to Figure 11.

4.3.3 Battery system integration

To ensure optimal stability and weight distribution in the vessel, it is crucial to position the battery system as low as possible. Given the substantial weight of the battery pack, placing it lower in the vessel helps to lower the center of gravity, enhancing stability during operation.

The hull of the vessel provides a suitable location for the battery pack, as it allows for effective weight distribution and balance. By positioning the battery pack in one hull, the weight can be counterbalanced by the ballast tank or other components located in the opposite hull. This even distribution of weight helps maintain the vessel's stability, reducing the risk of tilting or imbalance.

Ensuring adequate protection against electrical fires is of paramount importance when placing the battery system within the hull of the vessel. The chosen hull should possess sufficient safety features to mitigate the risk of electrical fire incidents and minimize their potential consequences.

To enhance cost efficiency and safety measures, it is advisable to consider locating other components, like the control cabinet and switchboard in the same area as the battery system. This proximity reduces the need for excessive cable lengths and simplifies the overall wiring layout. By consolidating the battery system and other components in the same location, potential safety hazards associated with long cable runs and interconnecting various compartments can be minimized.

Furthermore, by centralizing these components, it becomes more convenient to implement comprehensive safety measures, such as fire suppression systems and thermal monitoring devices. Adequate fire-rated insulation and fireproof enclosures can be employed in the designated area to further enhance the protection against electrical fires.

4.3.4 Summary of preliminary design

Throughout this chapter, a preliminary design has been proposed, encompassing the sizing and selection of various components discussed in detail. The objective of this chapter is to provide a summary of the key design considerations and decisions made during the process of formulating the preliminary design.

Table 19: Components and sizes of preliminary design

Component	Description	Size	Comment
Fuel Cell	PEMFC selected based on availability	100 kW	Base load at 40 kW
Battery	Li-ion battery pack, high energy density	372 kWh	Three 124kWh packs
Hydrogen storage	THS, containing hydrogen in gas form	128kg	Refill after 10 days

Table 19 summarizes the main components of the work vessel. Design decisions are mainly based on ease of implementation and availability of components. Where information or regulations are lacking, assumptions have been made which should be reassessed at a later stage.

5 Sustainable design and operations

This chapter revolves around emissions reduction, optimization strategies, and diverse design approaches as its central themes. A key aspect explored here is the comparison of fuel consumption among various power system configurations to determine the most optimal load-sharing scheme. Additionally, a thorough assessment of the vessel's lifetime, based on different design evaluations, is conducted to ensure its optimal longevity.

Furthermore, this chapter presents valuable insights into cost considerations and potential cost improvements. Drawing on findings from the preceding sections on fuel consumption and lifetime estimation, practical suggestions are put forward to enhance the cost-effectiveness and overall economic viability of the vessel.

5.0.1 New assumptions

To make more accurate decisions, it is not viable to depend on the calculations and assumptions presented in Chapter 3.2.3. The assumptions there, state the vessel operates for 365 days a year for

8.5 hours a day. With the new load profile presented in Chapter 4.1.1, the following assumptions are adjusted along with some new ones.

Assuming:

- the vessel operates for **9** hours a day for **261 days**
- of the 9 hours, **1.75** are spent in transit, resulting in approx. **457** hours
- the FC operates at all times, producing a steady output of **[30,40,50,60]kW**
- **the assisting power source (battery) operates 50% of on-site operations, at 20kW**
- the lifespan of **the battery is** included in the cost, fuel cell is not

5.1 Power Management System

As mentioned in Chapter 2.4, most vessels are operated outside their optimal range, and introducing a more accurate PMS system can greatly improve the efficiency of the vessel. Frøyblikk, on which a lot of the data in this thesis is based, operates with a rule-based EMS that suggests the most optimal way to utilize each power unit, using load sharing and peak shaving to lessen the fuel consumption of the system. However, whether or not the recommended load-sharing strategy is employed, is entirely user controlled.

There are already known flaws with a rule-based system, due to the generalization of rules being made, as making a new rule-based algorithm for each vessel can prove to be costly and demanding. In addition, the rule-based system fails to capture the ever-changing characteristics of the fuel cell and battery, due to aging and degradation. Other approaches to managing the PEMS should be considered, like MILP or an optimization-based EMS.

A monitoring system has been established for a small amount of vessels in the fish farm industry and the continued extension of this approach is necessary to optimize the usage of a hydrogen hybrid vessel. For future vessels, online learning-based optimization is suggested, due to its high accuracy and constantly improving optimization curve. This approach can further decrease fuel consumption and increase the total efficiency of the system.

5.2 Fuel consumption and emissions

The new policies put in place by IMO require a 15% reduction in emissions from 2021 to 2030. A hybrid design for vessels that operate with highly varying load profiles should theoretically be able to cover this reduction, but in reality, a lot of these hybrid vessels are not utilized optimally. This means that the focus should be on retrofitting existing vessels to zero-emission alternatives to reach said goal set by IMO. For that to be a reality, the technology needs to be further developed and vessels need to be built. This requires support and subsidized by the government as mentioned in Chapter 2.1.3.

The hydrogen system suggested for the small work vessel has zero operational emissions. The production of hydrogen is energy-demanding and can be the cause of significant emissions if not regulated properly. In other words, for this to be a true zero-emission design, regulations need to be put in place for the production of batteries and hydrogen, as these are currently emission-heavy productions.

5.2.1 Emissions

The operational emissions from the FC hybrid design are zero. Therefore, the emissions from the diesel hybrid design are presented to compare how much can be saved by switching over to an emission-free design. Also, since there are zero emissions from the FC hybrid design, the different sizings and power-sharing scenarios won't be compared here.

Compared to the hydrogen hybrid, the diesel hybrid has significant emissions, due to the gensets handling the load demand that comes during transit. Based on numbers from Frøyblikk, the estimated emissions for a month are,

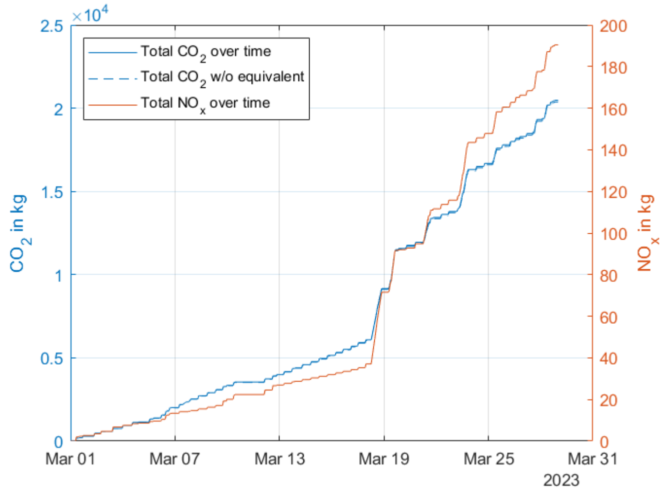

Figure 18: Emissions from Frøyblikk

where the CO_2 equivalent, is the small relative amount of CO emissions. It is important to keep in mind though, that the hull of Frøyblikk and the design hull of the vessel in question are different. The hull of Frøyblikk is built for space, whilst the design vessel hull is built for efficiency. It is estimated that these emissions can be reduced by 30-35% based on the difference in propulsion engines and hull shape.

This results in total emissions from a diesel hybrid vessel equal to $CO_2 = 14.3tonnes$ and $NO_x = 133kg$ in a month. Assuming the same operation through a year gives,

Table 20: Emissions from a diesel hybrid design for a year

Emission gas	Total (tonnes)
CO_2	171.6 tonnes
NO_x	1.6 tonnes

5.2.2 Fuel- and power consumption

Three different power-sharing methods will be compared, where the fuel cell operates at a different base load. This will show the difference in fuel consumption for each scenario, further arguing for which case is the most reasonable. The scenarios are a baseload of 30kW, 40kW, 50kW, and 60kW, and all have the same amount of hours operated.

Table 21: Hydrogen fuel consumption

Base load	SFC (g/kWh)	Total fuel in a year
30 kW	27.75	1955 kg
40 kW	33.52	3150 kg
50 kW	38.81	4558 kg
60 kW	44.79	6312 kg

As shown in Table 21 the fuel consumption increases quite fast with the baseload. To argue for a baseload of 60kW, a new FC would have to be installed, with a larger rating than the one this vessel has been designed for to lower the SFC. Additionally, given that the estimated peak load, not counting transit, is 50kW, means that designing a FC with a base load higher than this is unnecessary. The difference between a base load of 30kW and 40kW in terms of hydrogen consumption, results in *1195 kg* in a year. In other words, in terms of pure hydrogen consumption, the 30kW scenario is favored.

The estimated power consumption is presented in Table 22, assuming:

- when baseload is 30 kW, FC needs assistance from the battery for 75 % of on-site operations
- when baseload is 40 kW, FC needs assistance from the battery for 50% of on-site operations (20 kW load)
- when baseload is 50 kW, FC needs assistance from the battery for 25% of on-site operations (10 kW load)
- when baseload is 60 kW, no assistance from battery needed

These assumptions give the following result,

Base load	Battery power consumption (1 year)	Total power consumption (1 year)
30 kW	125 932 kWh	196 402 kWh
40 kW	87 435 kWh	181 395 kWh
50 kW	68 676 kWh	186 126 kWh
60 kW	59 378 kWh	200 318 kWh

Table 22: Power consumption

where there is a clear difference in power consumption of the different designs. The difference in total power consumption could be caused by an overestimation of how much the battery is used during on-site operations. Still, the battery is expected to be deployed for some operations, especially with its low ramp time compared to the fuel cell. Ideally, if the designs and assumptions were perfect, the power consumption would be equal for all designs. The fact that a 60 kW baseload has a much larger power consumption than the other three, indicates that it is way oversized for this design.

5.3 Lifetime

The estimated lifetime of the selected fuel cell, even operating under varying conditions, has an expected lifetime of 25 000 operating hours. This means that the FC will have an estimated life expectancy of 10.6 years.

Generally speaking, Li-ion batteries have an expected lifetime of 8 years or 4000 cycles. The EoL for these batteries is defined as 80% state of health (SoH).

Given that the FC will operate at a steady baseload, with the same operating hours across all three configurations, it is assumed that the life expectancy will stay the same. The main thing a change in baseload will affect is the life expectancy of the battery, as the number of cycles will decrease with a higher base load. It is assumed that the battery has a minimum of 1 cycle in 24 hours. Table 23 shows the estimated amount of cycles,

Table 23: Battery cycles at different base loads

Base load	Cycles per day	Cycles in a year	Cycles in 8 years	Estimated lifetime
30 kW	2.93	765	6116	5.2 years
40 kW	2.45	638	5105	6.3 years
50 kW	2.12	554	4432	7.2 years
60 kW	1.96	512	4099	7.8 years

where the difference in cycles dependent on base load is evident. The base load of the fuel cell has a significant impact on the lifetime of the battery, under the assumptions mentioned earlier. If the estimated lifetime of the battery pack is 4000 cycles, the 60kW baseload is the only design that coincides with the estimated lifetime. The other baseloads can still be argued to be a better fit for the design, if the cost weighs up for it, and will be further investigated in the following chapter on cost and cost improvement.

5.4 Cost and cost improvement

The estimated cost of three different designs has been presented in Chapter 3.2.3, where assumptions have been made to simplify the calculations. In this chapter, the aim is to present more accurate estimates of the operational costs of the design, along with ways to minimize the cost.

5.4.1 Results

The relative lifetime cost of the battery is calculated by estimating the cost of a new battery pack to be 1.5 million NOK. EoL for the battery back is set to 4000 cycles when the battery pack reaches 80 % SoH. This includes an estimated effect of calendar fade. Table 24 presents the yearly operational costs at different baseloads.

Table 24: Operational costs and lifetime cost at different base loads of the FC

Base load	Yearly op. cost	Relative lifetime cost of battery	Yearly cost with cost of battery
30 kW	256 987 NOK	286 707 NOK	543 695 NOK
40 kW	344 697 NOK	239 294 NOK	583 990 NOK
50 kW	458 285 NOK	207 776 NOK	666 062 NOK
60 kW	609 663 NOK	192 514 NOK	802 177 NOK

Table 25: Return of investment for the hydrogen hybrid design

Design	Investment [NOK]	Operating Cost [kNOK]	ROI
Conventional	10 million	1483	-
Hydrogen hybrid (without Enova)	23 million	584	14.46 years
Hydrogen hybrid (with Enova)	16.5 million	584	7.23 years

Table 25 provides a comprehensive presentation of the estimated Return on Investment (ROI) for the hydrogen hybrid design, compared to a conventional alternative. The findings from this table distinctly underscore the indispensability of Enova's support and assistance in the inception and realization of these innovative initiatives.

5.4.2 Discussion

Results in Table 24 argue for what was found in Chapter 5.3, where the FC base load influences the lifetime of the battery pack. The 30 kW scenario is the cheapest one but also has the shortest battery lifetime, coming in at only 5.2 years. If cost was the only thing considered, this would be the favorable base load to set the FC at. However, considering the emission and resource-heavy production of Li-ion batteries, it would be irresponsible to willingly lower the expected lifetime by this much.

The 40 kW baseload is only 40k NOK more expensive than the 30 kW one, but already increases the lifetime of the battery by a full year. This is also the original suggested design based on the average base load of the vessel. It is recommended that the vessel is designed with this baseload, to minimize costs related to fuel consumption and battery lifetime. The difference in yearly cost between the 40 kW baseload and the other two suggestions is too large to be considered viable alternatives.

6 Conclusion and further work

6.1 Conclusion

This thesis presents a proposed power system design tailored for a work vessel intended for application in the fish farm industry. The design selection is based on criteria centered on sustainability, emissions reduction, and cost-effectiveness. While giving due consideration to technology availability and regulations, priority has been emissions and sustainability. The suggested design entails a hydrogen hybrid configuration, combining the excellent gravimetric energy density of hydrogen with the mature technology surrounding Li-ion batteries. Analytical estimations indicate that the operational costs of a hydrogen hybrid outperform those of a diesel hybrid, implying that anticipated advancements in fuel cell technology will render the hydrogen hybrid an attractive alternative to conventional diesel hybrids.

Furthermore, estimated load profiles are provided for the work vessel, derived from existing data obtained from a slightly larger work vessel. Under normal operational conditions with the suggested design, the fuel cell is projected to have an estimated lifetime of 10.6 years, while the battery's estimated lifetime stands at 6.3 years. Notably, the battery lifetime is highly dependent on the base load of the fuel cell, emphasizing the importance of selecting an appropriate base load to achieve long-term sustainability for the vessel.

The recommended design entails a 100 kW fuel cell with a base load of 40 kW, complemented by a 371 kWh battery pack. These specific design details aim to strike a balance between power capacity, efficiency, and sustainability.

6.2 Further work

The conclusions drawn and decisions made in this thesis primarily rely on estimations due to the limited availability of comprehensive raw data. To achieve greater accuracy in the results, obtaining more relevant data, particularly regarding the State of Health (SoH) and power delivery of the battery pack, would prove invaluable. The methods and decision-making approaches presented here, could potentially be applied to larger ships and warrant further investigation.

Moreover, a thorough examination of the impact of the hydrogen system on the vessel's stability and weight, particularly for monohull vessels, is imperative. Placing a heavy tank in such an elevated position is likely to significantly influence the vessel's stability, necessitating an in-depth analysis.

Exploring and refining a control algorithm specifically tailored for these vessels is crucial since the fuel cell and battery pack's lifetime significantly impacts the overall yearly cost. The development or incorporation of a PEMS that accurately captures the dynamic characteristics of the fuel cell and battery pack would be highly beneficial, and the effects of its implementation should be documented.

In addition, developing a comprehensive cost and sustainability function applicable to hydrogen systems could prove invaluable. A well-derived function could be readily applied to various vessel designs incorporating hydrogen systems, streamlining and expediting the design process significantly. There also might be some errors surrounding the calculation of the earn-back time of the initial designs. Ensuring that the expected lifetime of the vessel exceeds the earn-back time, is vital to prove the design profitable.

Finally, it is estimated, at the time of writing of this thesis, that regulations surrounding hydrogen hybrid systems will be ready in a couple of years. As the regulatory landscape becomes more transparent, it will be vital to ensure that the design remains aligned with the latest guidelines and best practices.

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