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Zero-emission systems for maritime vessels in the aquaculture industry

Nullutslippssystemer tilknyttet maritime fartøy innenfor oppdrettsnæringen

Bachelor's thesis in Engineering, Renewable Energy
Supervisor: Ignat Tolstorebrov
Co-supervisor: Erlend Vaktskjold / Kristian Holmefjord
May 2024

Bachelor's thesis

NTNU
Norwegian University of Science and Technology
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Preface

This bachelor's degree thesis is written by four students studying engineering, and renewable energy at the Norwegian University of Science and Technology (NTNU). The members of the group have specialization in energy storage and efficient energy use. The report is written in cooperation with Corvus Energy as the main partner, which is leading the way for zero-emission solutions for marine vessels. The goal of this report was to provide information regarding the feasibility of zero-emission systems in the maritime industry.

During the writing of this report, guidance and insight provided by internal supervisor, Ignat Tolstorebrov has been of utmost importance. Weekly meetings, with almost no exceptions, including feedback on the report, as well as coffee breaks have been key factors in the completion of the report. A plethora of resources and contacts would not have been available without the help given.

In our collaboration with Corvus Energy, two external supervisors were provided to us. Kristian Holmefjord and Erlend Vaktskjold have contributed resources regarding components, topics for investigation, and other relevant industry contacts. Cooperating with industry has been a new and valuable experience for the group and we are thankful for the opportunity given to us by everyone in Corvus Energy.

In the process of gathering information for the report, numerous organizations and people have been contacted. As a result of this, several e-mails and meetings have been written and conducted, where the ones contacted have been of great pleasure to communicate with, and been important assets during the writing of this report.

Trondheim 22.05.2024

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Abstract

This thesis aims to evaluate the feasibility of carbon reductive energy systems aboard wellboats in the maritime industry using simulations. Initially, a short introduction presents the motivation behind the report, as well as giving a short overview of the structure. The introduction covers the rising need for decarbonizing modern society as climate change approaches. As the maritime sector faces the green shift, wellboats have been observed as a source of greenhouse gas emissions where improvements can be made.

Following the introduction is a chapter including theory. This covers technology and standards in today‘s maritime industry, aiming to show the different advantages and disadvantages that influence the operation of wellboats today. Parameters for calculation and working principles are shown to give an understanding of the related consequences of alternative energy systems and storage methods.

The different systems simulated in this report revolve around carbon-reductive energy systems. The various energy carriers are presented to show what aspects are advantageous as well as the affiliated obstacles. Hydrogen and batteries are the main technologies presented as they have the potential to be entirely green. The derivatives of hydrogen, e.g. ammonia and methanol are displayed in a smaller extent, along with biodiesel and liquid natural gas, given that they are not entirely emission-free during operation.

Thereafter the problem is defined more specifically along with the goals of the report, as well as the boundaries and limits. A strategy for accomplishing this is then presented. The goal being informing the industry about carbon reductive systems is to be achieved by simulation and system modeling The boundaries and limits showcase the scope as well as the restraints shaping the report.

Subsequently, the methods used for producing results are presented. The methods cover data gathering, simulation, and calculation strategies. Using the methods presented makes it easy to replicate the results given similar datasets. Assumptions related to calculations are also mentioned to justify the end results produced.

The results obtained from the literature study and the methods used are then presented and discussed. The discussion aims to reveal the benefits and complications surrounding the different solution proposals, with a basis in numerical results. Using the numerical foundation, a perspective concerning logistics, emissions, cost, and infrastructure is investigated. Most of the results indicate the same outcome, where the feasibility of carbon reductive systems suffers heavily from high costs and low energy densities compared to traditional fuels. Sources of error are then addressed to give reason to different assumptions and possible non-representative values. Factors such as uncertain data, approximations and placeholders are some of the sources discussed.

The thesis concludes that carbon reductive systems suffer from several factors such as infrastructure and cost, and that the feasibility of these systems remains questionable, until the aforementioned reasons and market changes, to better support the various carbon reductive energy bearers. However, the possibility of a transitory period is more promising but still requires a technological and economic push to be realized.

Sammendrag

Denne rapporten vurderer egnetheten til forskjellige karbonreduserende energisystemer i maritim industri ved hjelp av simulering. Det er først skrevet en innledning med formål om å presentere motivasjonen bak, og oppbygningen av rapporten. Introduksjonen tar for seg problemet med den maritime industriens klimautslipp og legger til grunn for hvordan brønnbåter kan være et punkt for forbedring i møte med det grønne skiftet.

Følgende blir relevant teori vist for å gi en oversikt over dagens teknologiske standard for fartøy, da spesielt brønnbåter, med fordeler og ulemper knyttet til industriens metoder. Parametere som er relevante for beregninger og prinsipper blir også inkludert i dette kapitlet. Med teorien presentert skal konsekvensene knyttet til de forskjellige teknologiene være enkle å begripe.

De forskjellige systemene simulert i denne rapporten benytter seg av hver sin energibærer eller en hybrid bestående av to. De forskjellige lagringsmediene blir gått igjennom for å vise forskjellige utfordringer og særskilte konkurransefortrinn. Hydrogen og batterier er energibærerene som blir presentert i størst grad ettersom de har potensialet for fullstendig grønn drift. Derivatene av hydrogen, altså amoniakk og methanol, samt flytende naturgass og biodisel, blir presentert men til en mindre grad ettersom de ikke er fullstendig grønne i drift.

Problemstillingen til rapporten blir deretter definert tydelig sammen med oppgavens mål, omfang og begrensninger. Strategien for gjennomførelse blir også presentert her. Omfanget tar for seg utslippene, energibehovet, kostnadene, infrastrukturen, og logistikken knyttet til drift av en brønnbåt ved bruk av forskjellige energibærere.

For at resultatene skal kunne enkelt replikeres med liknende datasett, presenteres metodene brukt i rapporten. Beregninger, datainnsamling, samt simuleringsparametere blir gjort rede for og diverse antakelser forbundet med beregninger blir også tatt opp for å gjøre rede for resultatene som er produsert.

Resultatene som er produsert og innhentet med de nevnte metodene blir deretter presentert, og diskutert. Diskusjonen tar for seg de forskjellige energisystemene i et energi- og miljøorientert perspektiv. Med de tidligere nevnte simuleringssystemene, måles energisystemene opp mot dagens referansesystem drevet med diesel som brennstoff. Utslipp, energitetthet, logistikk og infrastruktur er viktige aspekter som tas opp i dybden.

Oppgaven konkluderer med at grønne alternative energisystemer sliter med å konkurrere mot dieselsystemer på grunn av en lav energitetthet, høye kostnader og et skjørt rammeverk som støtter disse alternativene. Muligheten for et transitorisk system som ikke nødvendigvis er fullstendig grønt viser seg å være en mer realistisk mulighet, sammenliknet med å konvertere uten sikkerhetsmarginer. Selv om det er mer realistisk, kreves det fortsatt en stor investering i marked og infrastruktur for å realisere dette.

Abbreviations

Abbreviation	Meaning
AC	Alternating current
AIS	Automatic identification system
CCS	Carbon capture and storage
CH_2	Compressed hydrogen gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CH_3OH	Methanol
DC	Direct current
DoD	Depth of discharge
GHG	Green house gas
H_2	Hydrogen
H_2O	Water
HVO	Hydrogenated vegetable oil
ICE	Internal combustion engine
LCA	Life cycle assesment
LH_2	Liquid hydrogen
LHV	Lower heating value
LIB	Lithium-ion battery
LNG	Liquid natural gas
MGO	Marine gas oil
NH_3	Ammonia
nm	Nautical miles (1.852 km)
NO_x	Nitrous oxides
PEMFC	Proton exchange membrane fuel cell
RTE	Round-trip-efficiency
SoC	State of charge
SOFC	Solid oxide fuel cell
SO_x	Sulphur oxides
H_2O	Chemical formula for water
B100	100% biodiesel
ft	feet

Symbols

Symbol	Meaning
ρ	Mass density
V	Volume or voltage
$\dot{V}$	Volume-flow
$\dot{m}$	Mass flow
P	Power
t	Time
P_f	Packing factor
η	Efficiency

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1 Introduction

As the earth gradually approaches an irreversible climate change the challenge of reducing emissions has become increasingly important. One of the most important measures is transitioning away from fossil fuels, which currently dominate most of the global industry. [117]

Being a mature technology and boasting a large energy density, diesel is the fuel of choice for heavy-duty machinery, such as wellboats in the maritime industry. Being able to supply the necessary power and energy, as well as being convenient in practice, diesel is put in a position where it is hard to replace [163]. New technology within energy storage is making alternative solutions to fossilized fuels, with little to no climate gas emissions. The relevancy of new storage technologies becomes bigger, as the energy density and efficiencies increase, but they are not yet competitive without compromising cost, and practice in the industry. Long charge times, low efficiencies, and poor infrastructure make for great challenges given the current circumstances. [30]

This report investigates the potential scenario where conventional diesel vessels are either retrofitted or replaced entirely with carbon-reductive energy bearers. Including mediums such as hydrogen, ammonia, methanol, liquid natural gas (LNG), and biodiesel, with the aim of reducing the maritime industry's carbon footprint. With extensive literature search and dialogue with several companies within the industry, data has been gathered to simulate carbon reductive proposals to the current fossilized systems. Utilizing software such as Python, the data has then been presented to give an overview of the different advantages and disadvantages of various configurations.

The theory behind wellboats is presented to give an insight in why the problems connected to the green shift arise, covering topics such as current technology used aboard a boat in the industry. Information regarding the wellboat in question is given by an anonymous partner of this report. The technology necessary for the green transition is also covered, showcasing the potential as well as shortcomings.

Objectives are presented to show the motivation of the report. Showcasing the goal, scope, and wanted effects of this report. The methods are then showcased to explain the analysis and computation of data necessary for producing results. The necessary assumptions are also shown so the results can be replicated using any set of similar data.

The results of computation and research are displayed giving a comparative foundation for potential solutions. Discussion revolving around the different problems in transitioning to a green system is then reasoned for, explaining the advantageous as well as disadvantageous effects the solution can inflict. The report then concludes with important findings, notes, and a final perspective on the matter reviewed, providing an evaluation of the feasibility of the various systems.

2 Theory

The term **zero-emission** systems in this report is defined as **any system trying to achieve a major reduction in greenhouse gas emissions**. This section covers the technology used in these systems.

This chapter provides the necessary background theory used to carry out the methods, as well as produce and understand the results. It includes an overview of the aquaculture industry, along with wellboat operations. The theory of relevant energy carriers and systems is provided, including logistics, infrastructure, and current status in the marine industry.

2.1 The Norwegian aquaculture industry

The maritime fish farming industry is facing tremendous challenges related to carbon footprint and sustainable implementation. Zero-emission systems are a key aspect of a future green society. This section explores the theoretical framework that shapes the aquaculture industry,

Since its beginning in the early 1970s, the Norwegian aquaculture industry has grown to deliver more than half of the world's farmed salmon. In 2023 alone, salmonoid fish had an export value of nearly 128 billion NOK, making it one of Norway's most important trades [142]. Furthermore, there is a strong political will for further growth. [107]

2.1.1 Life cycle of the farmed salmon

The production cycle of salmonids, from eggs to finished products, takes an average of three years. The cycle is illustrated in Figure 1.

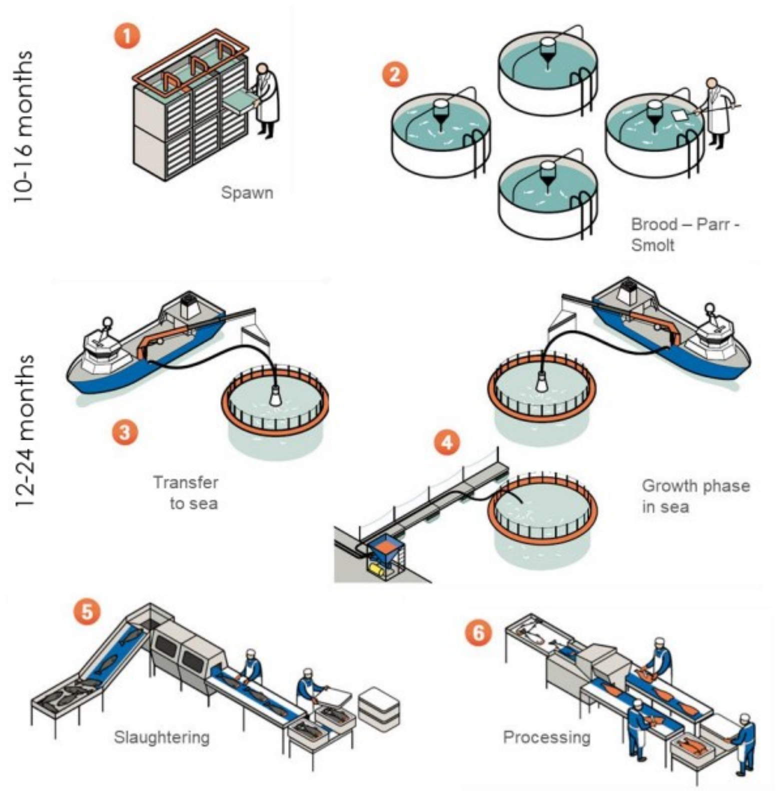


Figure 1: Production cycle, illustration from Mowi. [112]

The land-based process of breeding the fish up to a desired size takes between $10 - 16$ months. After this, wellboats transport fish to the sea location. The fish spend the next $12 - 24$ months in seawater cages/pens. Here, they are grown to approximately $4 - 5$ kg. When the fish have reached their preferred weight, they are slaughtered, either at land-based processing plants or aboard specialized ships. [112]

Most of the smolt in Norway is released in sea cages during spring and autumn, although some are released at different locations all year round. The harvesting of fish is spread across the year, with a higher frequency in the last half. After harvesting, the site is laid fallow $2 - 6$ months before new fish are introduced, to minimize disease. [112]

2.1.2 Environmental impacts

Despite the industry's beneficial impact on Norway's economy, there are environmental concerns. In a life cycle analysis (LCA) conducted by Asplan Viak in 2021, the total emissions from the fish-farming industry were estimated to be 8.46 $Mton\ CO_2e$. It is possible to divide the emissions into two categories: direct emissions related to the production, and emissions related to the processing and transportation of the finished product. The emissions from processing and European as well as intercontinental transportation are estimated to be a total of 1.2 $Mton\ CO_2e$ according to Asplan Viak. [121]

Asplan Viak's calculations show that the biggest environmental impact stems from the production of fish. The feeding of fish contributed the most with a total of 5.82 $Mton\ CO_2e$. They also estimated the total direct CO_2e emissions from the energy use in the fish farming industry to be 570 $Mton\ CO_2e$. When including the indirect emissions, from the production of fuel and electricity, the total was estimated to be a total of 697 $Mton\ CO_2e$. The wellboats are the main contributor of greenhouse gas emissions (GHG), with a total of 384 $Mton\ CO_2e$ [121].

Other concerns regarding the aquaculture industry are organic waste affecting local ecosystems, animal welfare, and how escaped salmon are cross-breeding with wild salmon [137]. In this report, only GHG emissions will be investigated. Several of the big aquaculture industry companies have pledged to cut emissions in line with the Paris Agreement, including the world's biggest salmon manufacturer Mowi. [80]

2.1.3 Vessels used in the aquaculture industry

In 2021, Asplan Viak conducted a mapping of the vessels associated with the aquaculture industry. This was partly based on updated numbers from a previous statistic where Apoint, Doxacom, and Kontali examined smaller boats, as well as the larger vessels in the industry. The results are given in Table 1. [121]

Table 1: Number of vessels in the aquaculture industry. [121]

Vessel	Fossilized fuel consumers	Hybrid-electric / electric [a]	Total
Wellboat	75	15	90
Service vessel >15 m	35	9	44
Work-/servicevessel <15 m	297	3	300
Workboat	609	4	613
Smaller vessels	697	1	698
Total	**1713**	**32**	**1745**

[a] Only a few work-/servicevessels are pure electric. The remaining vessel uses hybrid solutions

This overview has certain shortcomings, as several types of vessels are excluded. These include feeding boats, diving boats, process boats, and feeding barges [121]. Despite this, it provides a useful indication of the fuel system distribution in the aquaculture industry.

The feeding barge is a stationary on-site vessel. It contains living quarters for the workers, control rooms, feeding and lighting systems for the pens, as well as other equipment for day-to-day work. A master thesis from 2019, focusing on the electrification of a feeding barge in Trøndelag, investigated the power and energy consumption from a feeding barge during summer and winter. Some of the results from the report are shown in Figure 2. There is both daily and seasonal variation in the demand. The seasonal changes in both power and energy demand are mostly affecting the base load, whereas the daily change is due to production operations. [109]

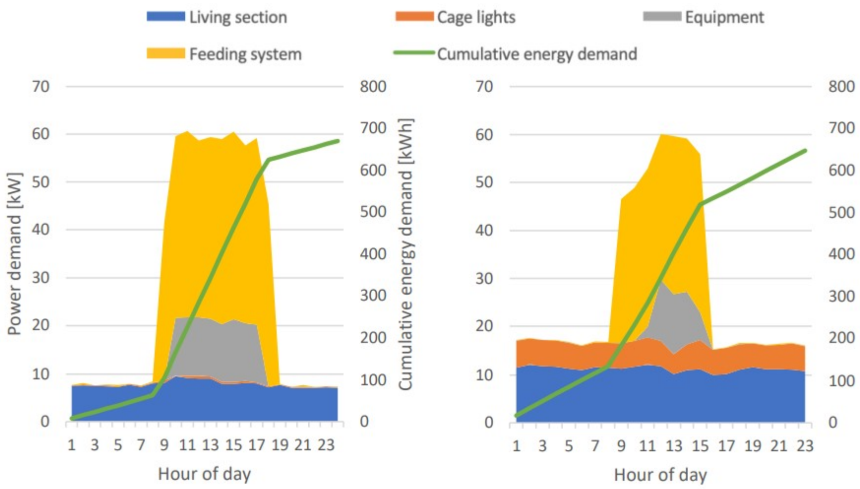


Figure 2: Power and energy consumption from a feeding barge. [109]

Previously, all feeding barges were run on diesel generators. In recent years, shore power has been increasingly common. In 2021, it was estimated that 57% of the feeding barges used shore power, 6% used diesel generators in combination with batteries, and 37% used only diesel generators as their power supply. [3] A master thesis from 2019 concluded that given energy efficiency measures, 83% of Trøndelag's feeding barges could be electrified without triggering grid investments [109]. A similar thesis examining feed barges in Finnmark had similar findings, where the degree of electrification could be increased from 62% to 80% with a positive economic impact [111]. The main difficulties related to shore power are associated with too low capacity in the local power grid, and/or the feeding barges being too far away from the grid. [3, 109, 111]

There are roughly 700 small boats in the aquaculture industry, with their main purpose being the transportation of people and smaller equipment to the fish farms. Based on the summary from Asplan Viak, the use of electrical/hybrid propulsion systems on these boats is close to non-existent. Each boat has an estimated yearly average fuel consumption of 15.000 − 18.000 liters of fuel, resulting in a total of over 10 million liters of fuel each year. [121]

The work and service vessels have similar tasks. Work vessels are the smallest of the two, at lengths varying between 10 and 15 meters. They are typically associated with a specific fish farm, performing daily tasks such as supervision, cleaning, feeding, handling dead fish, light lifting, etc. The work vessels are commonly owned by the company that operates the fish farm. [18].

Service vessels, such as the one shown in Figure 3, are generally larger, ranging from 15 − 30 meters, and operate between different fish farms. They perform heavier work, which includes heavy lifting, high-pressure washing, delousing, changing of fishing nets, etc. Part of the industry's service vessel fleet is owned by separate service companies, who rent out their services and crew. Service vessels can also be used as dive boats, and may have equipment for emergency slaughter of fish. [18]

Figure 3: A 24-meter service vessel. [55]

Both work and service vessels are used in the day-to-day operations, close to the fish farms. During nighttime, both vessel types tend to moor either in port or at the fish farm. The reports from ABB/Bellona and Sintef Ocean identified a high electrification potential for this category of vessels. However, a feeding barge connected to shore power is a prerequisite. For H_2-driven vessels, additional infrastructure would be required. [3, 88]

In 2017, the first two electric aquaculture workboats were delivered. "GMV Zero" a fully electric vessel, and "Elfrida" with a backup diesel generator [88]. In later years fully electric and hybrid workboats have increased in numbers, although, as shown in Table 1, they only counted less than 2% of the total fleet in 2021 [3].

A 15-meter H_2-electric working vessel for the aquaculture industry is currently being developed in Norway. It will use H_2 in compressed form, produced by a local pilot facility. The project aims to pave the way for a larger H_2 hub in the region and gain insights into the performance of H_2 as an energy carrier for such a vessel. A concept drawing is shown in Figure 4. [68, 49]

Figure 4: Concept drawing of a H_2-fueled work vessel. [68]

Specialized vessels are used for slaughtering and processing the fish. The smallest are typically used for small-scale operations or emergency slaughter and can have overlapping functions with service vessels for other uses, while newer concepts for process vessels include a large ship that slaughters and transports the fish directly abroad. Varying sailing routes and operations indicate that the different vessels have different needs in terms of energy storage. [88]

2.2 Wellboats

As this thesis aims to evaluate possible alternative fuels for wellboats, this type of vessel will be more thoroughly explained in this section. This includes the status of today, certain trends for the future, their typical operational pattern, and a more thorough explanation of the delousing.

Most wellboats today use diesel as their only energy supply, but low-emission solutions are becoming increasingly popular, particularly battery-hybrid solutions. Besides lowering fuel consumption, large battery packs are expected to decrease engine maintenance, enhance working conditions, and become increasingly economically favorable. One wellboat currently use liquid natural gas (LNG) in combination with a battery pack [113], and a wellboat using NH_3 (NH_3) as its fuel source is currently in early development [144, 88]

2.2.1 Operational pattern

Wellboats are larger ships transporting live fish, and one is shown in Figure 5. They transport both smolts from land-based facilities to sea locations, mature fish ready for slaughter back to land, and fish between different locations. Boats specialized for transporting smolt are considerably smaller than those transporting mature fish in the 4-5 kg range, with the latter including some of the biggest ships in the aquaculture industry. The fish are transported in onboard wells with circulating water. [28]

Figure 5: Illustration of a wellboat. [59]

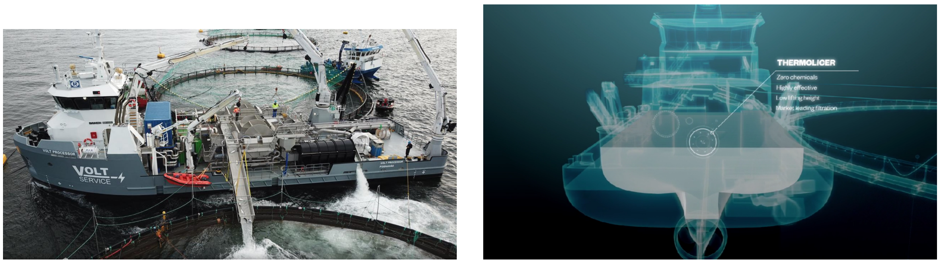
Long sailing routes for these large vessels in combination with energy-demanding operations result in the largest fuel consumption of the mapped vessels shown in Table 1. Ranging from 312 000 to 2 400 000 liters, with an average of 1 700 000 liters per boat per year, they contribute to a significant part of the industry's pollution [18].

Where wellboats previously were dedicated to fish transport, they have become increasingly complicated in recent years. Modern wellboats have equipment for disinfecting the water coming in and out of the cargo hold, delousing, counting, and sorting fish. However, current trends now indicate a higher degree of specialization, not only for different-sized fish but also for lice treatment. This trend will have a direct impact on their energy demand, which will vary even more than with today's fleet. [88]

2.2.2 Delousing

Delousing is a process that removes salmon lice, *Lepeophtheirus salmonis*, from the skin of the fish. There are various approaches to delouse the fish. The three most common methods are mechanical and thermal delousing, as well as freshwater baths. Chemical delousing were previously carried out, but are being phased out [29]. The Norwegian Institute of Marine Research recently indicated that freshwater baths had the best results for both delousing and animal welfare, which could suggest that this will be more common in the years to come. [129]

The mechanical delousing consists of either low-pressure (LP) water jets, brushes, or a combination of these. During thermal delousing, water is heated up to $28 - 34°$, and the salmon is treated for 20-30 sec. This process heats the lice enough for the muscles to relax and let go of the skin [62]. Different companies have different solutions and varying capacities in terms of tonne fish they delous per hour. In Figure 6 shown two different concepts, where Optimars solution is shown in Figure 6a and Thermolicers solution shown in Figure 6b [128, 158]. From a welfare perspective, neither is ideal, as bleeding fish with several wounds are frequently reported from mechanical delousing, and the salmon shows signs of pain at temperatures above $28°C$ [129].



(a) Optimars delouser in operation. [128] (b) Thermolicers delousing concept. [158]

Figure 6: Two different thermal delousing systems.

2.3 Power generation

Onboard power is a crucial part of today's ships, which include systems such as internal combustion engines (ICE), generators, and fuel cells.

2.3.1 Internal combustion engine

The ICE is responsible for generating mechanical power. The typical peak efficiency of a modern diesel engine is approximately 50%, with losses mainly due to heat. [166] Diesel ICEs can be modified to run on biodiesel without major modifications. [168]

The ICE works by compressing injected fuel to its ignition point. As the fuel ignites, pressure is generated to exert force on pistons mounted on the engine axle, resulting in rotational movement. Due to the varying thermodynamic properties of different fuels, ICEs have certain differences, such as spark plugs or the use of pilot fuels to start the ignition. The product of the combustion is exhaust, which is pushed out of the system. The process is shown in Figure 7.[27]

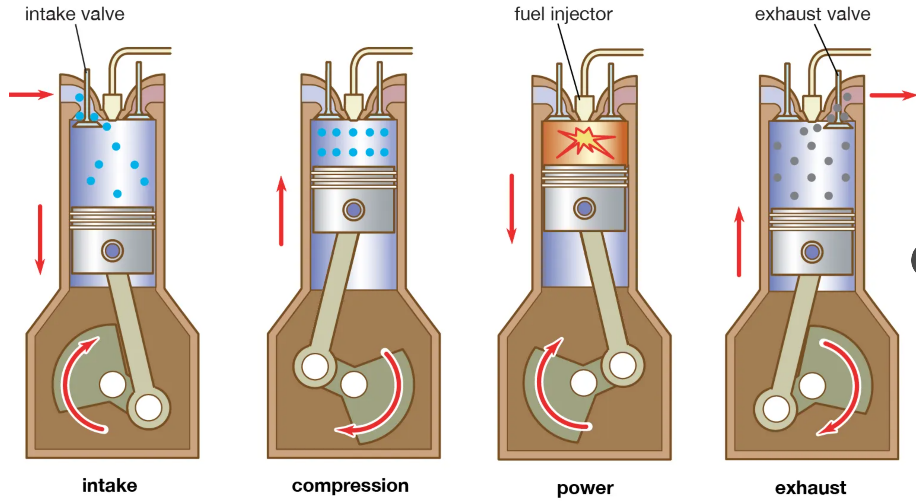


Figure 7: ICE process schematic. [27]

2.3.2 Electrical machines

To convert the chemical energy stored in fuels to electric power, a generator can be used. First, it is converted to mechanical energy like the ICEs, before an alternator is used to further convert the mechanical energy into electric energy. The electricity can then be used for a variety of onboard equipment. In summary, the chemical energy of the diesel is converted to mechanical energy in the engine, and consequentially into electrical power using the alternator.

The electrical alternative to diesel engines is the three-phase alternating current (AC) asynchronous and synchronous machines. Three-phase motors work by applying electrical power to wound coils to induce a rotating electromagnetic field. This rotating field then pulls the rotor around either by interlocking with the rotor magnets in a synchronous machine or by inducing another electromagnetic field in the squirrel cage in an asynchronous machine. [83]

Typical efficiencies are $85 - 96\%$ and $92 - 97\%$ for asynchronous and synchronous machines respectively [153, 44]. Direct current (DC) machines provide high control and starting torque but are not very relevant due to their low efficiency of approximately $50 - 80\%$ [138], compared to their AC counterparts. The aforementioned machines can be used as generators by reversing the process of induction.

2.3.3 Fuel cells

A fuel cell generates electric energy through chemical reactions and consists of electrodes covered in an electrolyte. The technological principle behind fuel cells has been known since 1839, but it took more than a hundred years to make operating fuel cells. [70]

Several types of fuel cells exist. The different fuel cells have different operating parameters, with their respective advantages and challenges, and for the last 15 years, proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC) have been discussed for maritime applications. The working principle of a PEMFC, which is the most common is shown in Figure 8. [167]

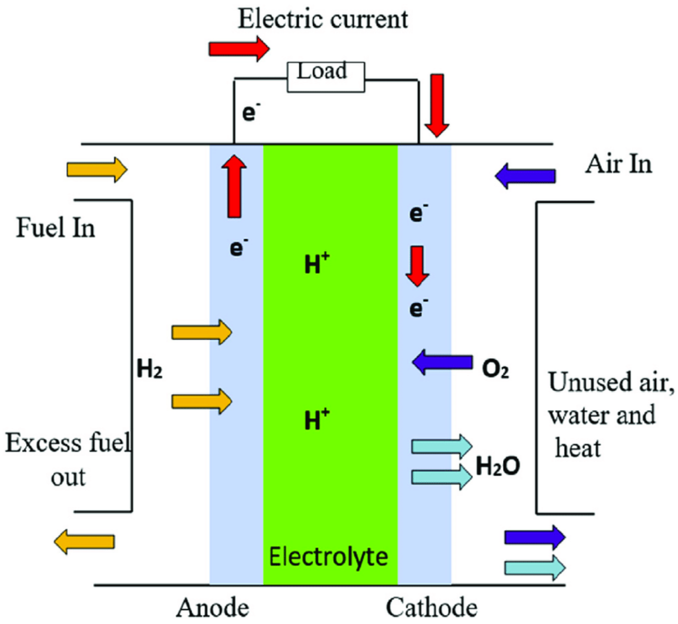


Figure 8: Working principle of a PEMFC [135]

PEMFC has a high dynamic response, relatively high power density, and low operating temperatures compared to many others. Shortcomings include the requirement for an expensive platinum catalyst in the electrode, a relatively low power output, and limitations regarding the fuel input. These limitations have increased the interest in SOFC, as it is more flexible regarding fuel. For SOFC, reformed-, natural-, coal- and NH_3 can be utilized for fuel. The lifetime expectancy is also up to ten times higher for SOFC than PEMFC. The issue of slow dynamic responses can be solved by integrating battery packs to smooth the operations, and equipment to utilize the excess heat from the high-temperature operation can increase the system efficiency. [167]

2.4 Energy carriers and storage

Energy can be stored in a variety of ways such as kinetic or potential energy, as well as heat or chemical energy. Lately, the focus on the development of efficient, and flexible energy storage solutions has been stressed by numerous scientific organizations, with promising results [108, 37], and the energy storage industry has grown significantly in recent times [30]. Norway, amongst other countries, wants to produce batteries in the future, due to its vital position in a low-carbon society [60].

Different energy systems have varying qualities, often being a compromise of either high energy or power density. To be able to compare different technologies, specific energy or power is common to examine. Such comparisons are often shown in Ragone charts, with specific energy on one axis and specific power on the other. Due to the large technological differences between fuels and systems, both axes of the Ragone charts are logarithmic. An example of a Ragone chart is given in Figure 9.

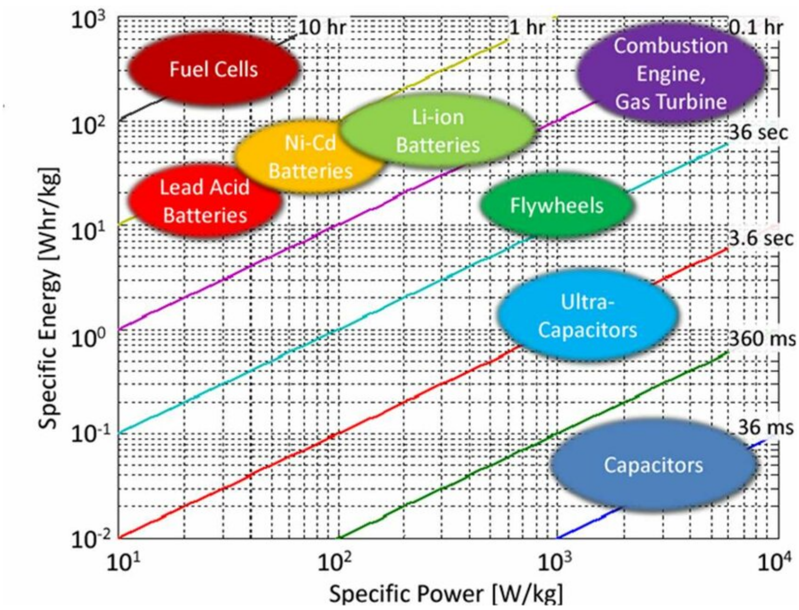


Figure 9: A Ragone plot. [84]

In terms of storage, the necessary volume to store any given amount of energy can be of as much relevance as weight. A comparison between the specific energy density, also called gravimetric energy density, and volumetric energy density can be useful. Such a plot, comparing different gravimetric and volumetric energy densities, is shown in Figure 10. H_2 gas illustrates the need for such a comparison. While it has the highest gravimetric energy density, the volumetric energy density is the lowest of the alternatives [30].

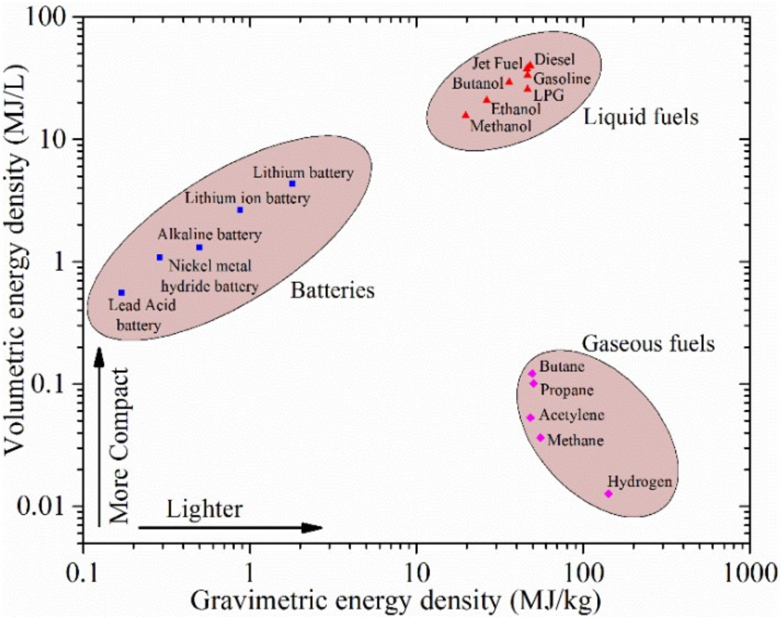


Figure 10: Energy density plot. [99]

In this chapter, the most relevant energy storage solutions will be presented with their respective advantages and disadvantages. The different fuels investigated in this report have values given in Table 2

Table 2: Properties of the different fuels investigated.

Fuel types	Volumetric energy density [MJ/l]	Gravimetric energy density [MJ/kg]
MGO	36.6	42.8
LNG	22.2	48.6
Biodiesel	34.8	37.8
Compressed H2	2.16 [a]	120
Liquid H2	8.5	120
NH_3	13	18.6
Liquid NH_3	15.6	18.6
Methanol	16	19.9

[a] Obtained using the density of hydrogen from Figure 1.6 in a report from Sofoklis S. Makridis [94] at 250 bar and 25 °C.

2.4.1 Diesel

Diesel is supported by a solid infrastructure as a consequence of its long history and mature technology. In the US alone, the estimated consumption of diesel for transport was 473 million liters per day in 2022 [163].

Marine gas oil (MGO) is a mix of distillates, that has a slightly higher density than diesel and is the most common fuel for marine applications [127]. As shown in Figure 10, diesel‘s volumetric energy density surpasses every other relevant storage medium. With diesel being a superior energy storage medium in terms of volumetric energy density, available infrastructure, and price, it is challenging for emerging low-carbon solutions to provide a good alternative. The main issue regarding the use of MGO is the GHG emissions, as one kg of MGO emits approximately 3.206 $kg\ CO_2$. [36]

2.4.2 Biodiesel

A potentially more environmentally friendly option than fossil fuels is biodiesel. Like fossil diesel, biodiesel can be used in ICEs, both as pure biodiesel or in a mixture with regular diesel. The percentage of biodiesel in the blend is expressed in the name, with B100 being pure biodiesel and B30 having 30% biodiesel, etc. Although biodiesel has a slightly lower LHV, the similarities to diesel are to such an extent that the difference in power output of an engine is less than 1%. Furthermore, they are suitable for existing diesel systems such as storage tanks[24]

Biodiesel is derived from organic sources and is potentially carbon-neutral, however, this depends on the production method. Biodiesel made from crops is considered challenging in terms of sustainability, as it harms food production and land area, as opposed to biodiesel made from bi-products, algae, or microorganisms. If produced according to the EU's sustainability criteria, biodiesel can be considered carbon-neutral and not contributing to global warming [25]. When comparing emissions from combustion, the difference between fossil diesel and biodiesel both CO_2 and NO_x-emissions is small, with different studies presenting different results. These results vary between a slight increase to decrease in emissions, and with the percentage of biodiesel in the fuel mix. However, biodiesel shows a significant reduction in SO_x-emissions. [24]

2.4.3 Liquid Natural Gas

Liquid natural gas (LNG) has 600 times higher energy density compared to its gaseous form, making it suitable for transportation and as a fuel source. When used as fuel, LNG consists of at least 90% methane, with other carbon structures as the remaining 10%. It has been used as a fuel on LNG tankers since the 1970's either in pure LNG or dual-fuel ICE engines. To liquefy natural gas, a temperature of $-162°C$ is required, which stresses the need for well-insulated storage tanks. Input heat from the external environment causes LNG to re-evaporate, and due to losses during LNG's life cycle, CO_2-emissions are nearly the same as MGO. However, LNG has the potential to reduce GHG emissions by 15% compared to MGO. SO_x emissions are drastically lowered or eliminated with LNG, and NO_x-emissions are reduced. [24]

2.4.4 Batteries

Batteries play an increasingly large role in decreasing the maritime industry's emissions through hybridization with other fuel sources. Through peak shaving and load stabilization, maintenance costs and fuel consumption are reduced compared to running on different fuels alone [88].

Batteries store chemical energy which can be converted into electric energy. They are divided into two main groups, namely primary and secondary batteries. Primary batteries are not rechargeable and are disposed of after use, as opposed to secondary batteries. Primary batteries are not relevant for large-scale applications, and for the rest of the report "batteries" will refer to secondary batteries. [30]

With batteries becoming a more optimized field, the availability, cost, and performance are improving. The energy density of a battery can hardly compete with diesel in terms of output but has the possibility of being a zero-emission energy storage medium. The infrastructure is constantly improving, allowing for easier implementation. [30] The working principle of a battery is based on an anode, cathode, and separator as well as an electrolyte being responsible for the transport of charges. This is presented for a Lithium-ion battery in Figure 11. [30]

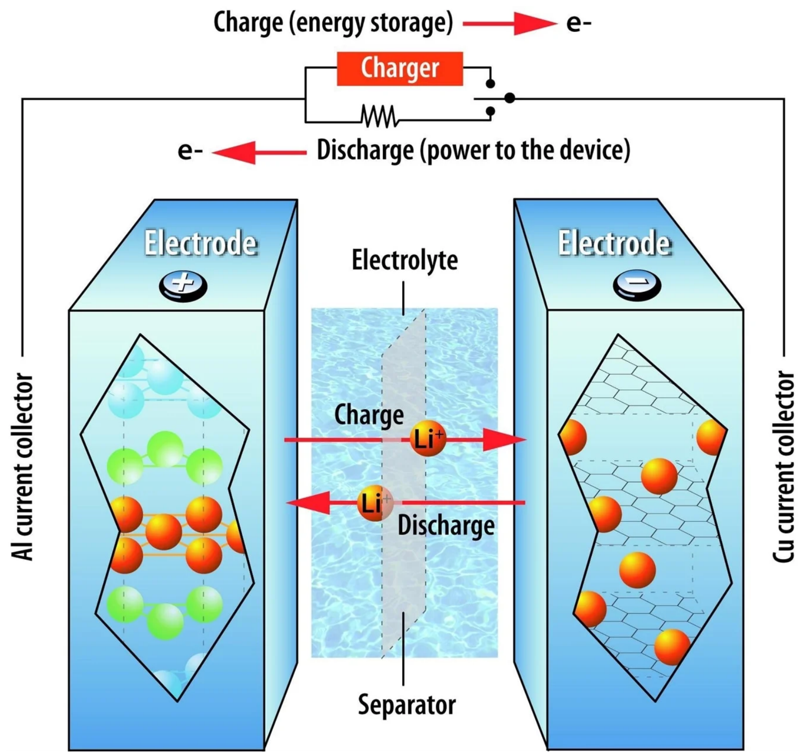


Figure 11: Working principle of Li-ion battery. [20]

C-rate is a measurement of how fast a battery either charges or discharges. A C-rate of 1 indicates a charging or discharging rate of 100% in one hour, whereas a C-rate of 0.5 indicates 50% charge or discharge in one hour etc [30]. During battery use, the state of charge (SoC) and depth of discharge (DoD) describe the amount of charge left in the device, and the relation between them is given in 1. The state of the battery during storage and use impacts how fast the battery deteriorates. Leaving a battery with a SoC over 80%, or discharging the battery below $10 - 20\%$ SoC exerts unnecessary electrochemical stress on the battery, reducing its lifetime. [47]

$$SoC = 1 - DoD \tag{1}$$

2.4.5 Hydrogen

Hydrogen (H_2) as an energy carrier can be made using several methods. Green H_2 is produced using water electrolysis, which splits H_2O with the help of electricity and has the potential of having no emissions using green renewable energy. Other methods involving emissions, e.g. steam reformation can produce grey H_2. With the addition of Carbon Capture Storage (CCS) technology, it is then called blue H_2. While green hydrogen is the most environmentally friendly, it is also the most expensive, up to four times the price of grey hydrogen. [120, 154, 30, 24]

H_2 can be stored in a variety of ways, and the most common storage methods are shown in Figure 12. Several other methods exist, such as metal hydrides and liquid organic H_2 carriers, but have different challenges that are currently being researched. [164] Due to currently unsolved obstacles, these storage methods, as well as cryo-compressed, are not further elaborated in this thesis.

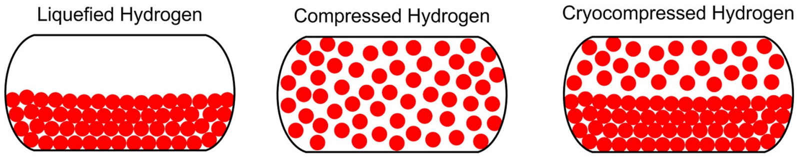


Figure 12: Different storage methods for H_2. [164]

Compressed hydrogen gas (CH_2) stored under high pressure is the most common solution, and a 10% energy loss can be assumed in the process. The storage pressure greatly affects its volumetric energy density, as shown in Table 3 Whereas CH_2 in atmospheric pressure (1 bar) has roughly 0.01 MJ/l, the volumetric energy density is nearly 300 times greater at 350 bar. Further increasing the pressure to 700 bar increases the energy density by a factor of roughly 1.7. [21, 164]

Table 3: Volumetric energy density for pure H_2 stored in different ways. [164]

	Volumetric energy density (MJ/L)
Compressed H_2	
1 bar, room temperature	0.01
250 bar, room temperature	2.16[a]
350 bar, room temperature	2.94
700 bar, room temperature	4.97
Liquid H_2	
1 bar, -253 °C	8.5

[a] Obtained using the density of hydrogen from Figure 1.6 in a report from Sofoklis S. Makridis [94] at 250 bar and 25 °C.

A potential problem that can occur during CH_2 storage is hydrogen-embrittlement, where hydrogen diffuses into the metal structure and compromises its strength and integrity. Certain metals withstand this to a much larger degree and are thus better suited for CH_2 storage. CH_2 storage tanks are divided in four main categories, based on their material compositions. A simplification of the tanks are shown in Figure 13, and a rough comparison of cost and weight is given in Table 4. [164]

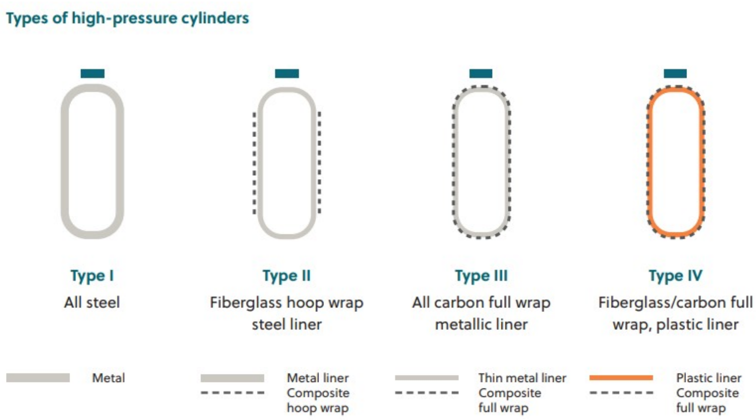


Figure 13: A simplified illustration of the different tank types for H_2 storage. [72]

Liquefied hydrogen (LH_2) has a volumetric energy significantly higher than for CH_2, thus reducing the required storage space. H_2 has a boiling temperature of $-253°C$, and the low temperature is considered a major challenge for this method of storage. Due to heat from the environment, some H_2 vaporizes in the tank. Daily losses due to this phenomenon, called boil-off, are estimated to be between $1,5 - 3\%$ of the LH_2 depending on insulation and tank size. Well-insulated tanks are

Table 4: A comparison of the different tanks. [110]

	Cost	Max storage pressure [bar]	Weight
Type I	Cheapest	500	Heaviest
Type II	150%· Type I	1000+	65%· Type I
Type III	300%· Type I	450	30%· Type I
Type IV	Most expensive	1000	Lightest

thus a prerequisite for storing LH_2 over time, and a larger tank where the volume-to-surface ratio is high is also beneficial.

2.4.6 Ammonia

NH_3 has been used as a fuel for decades [76], and be used in both fuel cells and ICEs. It contains 1.7 times the amount of H_2 by volume compared to molecular H_2 and is an effective H_2 carrier. Liquid ammonia (LNH_3) has a higher volumetric energy density than both LH_2 and CH_2. The temperature at which NH_3 liquefies is $-33°C$, compared to $-253°C$ for H_2. [24]

NH_3 is conventionally used in ICE systems, where it can operate at high compression ratios, and a competitive efficiencies compared to diesel engines. [24]

When NH_3 is utilized as a fuel, NO_x is released into the atmosphere and contributes to respiratory diseases, ground-level ozone problems, and acidic rain [122]. One kilogram of NO_x has the same damaging potential as 298 $kg\ CO_2$ [119]. The exact emission profile for NH_3 is currently unclear due to the recent introduction of dual-fuel ICE for this fuel.NH_3 does not contain carbon or sulfur, and both CO_2 and SO_x-emissions are thus negligible from pure NH_3 combustion. [100, 24].

A recent literature study evaluated the potential for both NH_3 and H_2 as energy carriers by comparing the total efficiency through a range of pathways where the H_2/NH_3 was stored for 30 days before being used for power production. The results are shown in Figure 14 [116]. An important note for this study is that the energy carriers are assumed to be stored in the liquid phase due to favorable volumetric energy density properties [116], which increases energy losses as previously mentioned in Section 2.4.5.

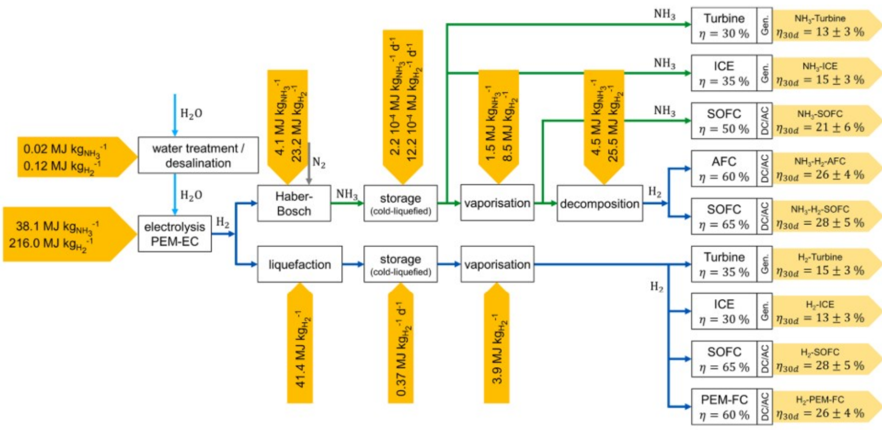


Figure 14: Energy efficiencies for H_2 and NH_3 systems. [116]

2.4.7 Methanol

Methanol (CH_3OH) is an alcohol made through synthesis gas: a mixture of carbon monoxide (CO), CO_2, and H_2. The high hydrogen-to-carbon ratio makes it an effective hydrogen carrier. Today, CH_3OH is most commonly produced through natural gas, but mature technology exists to make synthesis gas, through biological material and waste. A more sustainable concept is shown in Figure 15, where the carbon is captured from industry, and then used for methanol production at a later stage. [79]

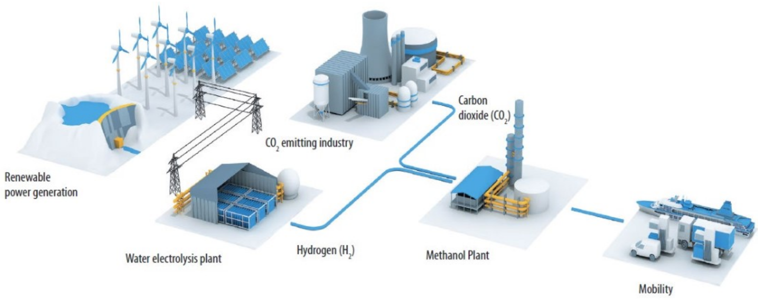


Figure 15: Concept of methanol production. [79]

As an energy storage medium for marine applications, it has several benefits. CH_3OH can be used in both fuel cells and ICEs, with combustion being most common as diesel engines with some adjustments and pilot fuels are suitable. Due to CH_3OH being a liquid at room temperature and atmospheric pressure, transportation is easier than most alternative fuels. However, it is corrosive and has only half the volumetric energy density of diesel fuel.[24]

Combustion of CH_3OH emits 69 $g\ CO_2/MJ$, compared to 74 $g\ CO_2/MJ$ for diesel [33, 134]. However, production of CH_3OH from biomass or green H_2 combined with recycled carbon dioxide could reduce CO_2 emissions by up to 95% and NO_x by up to 80%. [134].

CH_3OH synthesis and distillation processes can have an energy efficiency between 75% and 90% when renewable energy is used [42], and the total energy efficiency from production to power generator is 49%. This is higher than the average of 42-43% for H_2 and NH_3 pathways shown in Figure 14. [133]

2.5 Ships currently operating on alternative fuels

When evaluating whether or not alternative fuel sources can be used on a wellboat, examination of existing ships can give valuable information and insight in possibilities and challenges. As of May 2024, numerous ships are running on alternative fuels, and new projects are currently being developed within all the alternatives introduced above.

2.5.1 Electrical

Batteries are an increasingly popular choice for coastal waters, with technology constantly being improved. The world's first fully electric ferry, MS Ampere, was put into operation in Norway in 2014. The 1090 kWh battery pack covers $5-7$ times the amount of energy one trip requires, and the ferry charges when loading/unloading at port [105, 90].

MS Ampere marked the beginning of the electrification of the Norwegian ferries, and there are currently more than 40 operating ferries [97]. Worldwide, the use of electrical ferries has drawn inspiration from MS Ampere, and there are currently plans for electric ferries with up to 40 MWh installed battery capacity [50].

2.5.2 Hydrogen

Following in the footsteps of MS Ampere is the world's first H_2-powered ferry, MF Hydra. With 400 kW fuel cells and 1356 kWh of battery capacity, it sails on the Norwegian west coast. By charging while loading and unloading passengers, along with its 80 m^3 storage tanks for LH_2, it can sail entirely emission-free. It has a diesel generator for backup. [104]

On May 4th, 2024, the superyacht "Feadship 821", was launched. The yacht has an installed PEMFC of 3 MW and a storage volume of 92 m^3 for liquefied H_2 as its main fuel system. It can use Hydrotreated Vegetable Oil (HVO) as a secondary fuel for longer trips, or no H_2-bunkering locations are available. [86]

Within 2025, two new ferries are set to sail between Bodø and Moskenes, both with an installed power of 6MW in fuel cells. It will run on a minimum of 85% H_2 [71]. Compressed H_2, stored on the deck to make room for cars, will be used due to the lower cost [86]. The project aims to utilize experience from the development of Feadship 821 [56].

(a) Torghatten [67]

(b) The worlds first ferry driven partly on H_2, MF Hydra [81]

Figure 16: Two H_2-operated ships.

It is estimated that the ferries will need between $6-10$ tonnes of H_2 per day, which will be supplied from a new production site outside Bodø. The excess oxygen will be handled and ready for sale to the aquaculture industry, while the excess heat will be used in district heating in Bodø. [159]

Through the Flagship program in the EUEU, which aims to contribute to the H_2 position in the maritime industry, two inland cargo vessels are set to sail with H_2-battery hybrid systems [5]. FPS Waal has a potential sailing time of 20 hours at 13 knots. It is set to have a 1.2 MW installed capacity in fuel cells to utilize its nearly 500 kg of compressed H_2, as well as a battery capacity of 675 kWh. [38]

2.5.3 Methanol

As of today, there are 29 methanol-powered ships, with 228 vessels ordered [87]. These include Ane Maersk, a container ship powered by methanol, servicing between Asia and Europe [93]. Ane Maersk has a main engine of $44,2$ MW and can travel $23,000$ nautical miles (nm) on methanol [11].

Stena Germanica, a Ro-Pax ferry operating between Gothenburg and Kiel, was retrofitted with a dual-fuel methanol diesel engine in 2015. The ferry is 240 meters long and can carry 1300 passengers and 300 cars, with an engine power output of 24 MW. [148].

2.5.4 Ammonia

By 2050, NH_3 is predicted to be the leading fuel source for large cargo ships. Despite this, there are currently no ships sailing on NH_3. However, several large projects are underway. The world's first NH_3 container ship in development is Yara Eyde, which will sail between Norway and Germany from 2026 [157]. A project examining the possibilities for an NH_3-powered wellboat will be carried out in the first half of 2024, with the possibility of using dual-fuel NH_3 and diesel engines promoted as an advantage for this fuel [144, 156]

2.5.5 LNG

LNG is common in the maritime industry, with hundreds of ships using this as fuel. The first wellboat using an LNG-battery hybrid was delivered in Norway in 2021, cutting CO_2-emissions by 30% and NO_x-emissions by 90% [113]. LNG is widely recognized as a suitable fuel during the transition from MGO to alternative fuels, and it is expected that 32% of maritime vessels will use LNG by 2050. [24]

2.6 Logistics and infrastructure

For any fuel, logistics, and infrastructure supporting production, distribution, storage, and fueling is imperative for its success. After decades of use, the infrastructure supporting MGO is as of now better than the alternative fuel sources.

The infrastructure supporting LNG is also well-developed, including bunkering stations on shore and directly from both trucks and specialized ships [78, 63]. An illustration of shore-based bunkering and ship-to-ship bunkering is shown in Figure 17 [140].

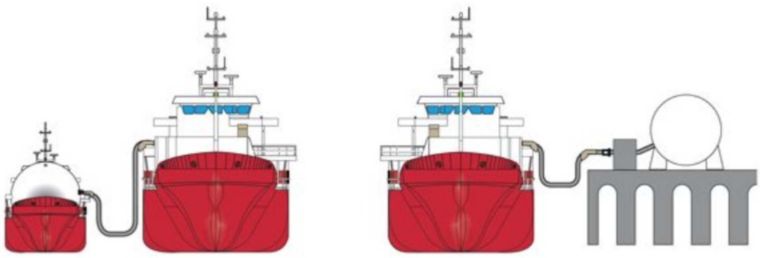


Figure 17: Bunkering methods. [140]

In Norway, the electrification of the ferry fleet has led to a high increase in specialized charging stations along the coast [78]. These high-voltage chargers have charging capacities ranging from $2.5 - 23\ MW$ [8, 57]. To allow other ships to use shore power or charge on-board battery packages, when moored, shore power installations have received state funding since 2016. In total, this funding has enabled nearly 200 shore power facilities [2]. Figure 18 illustrates the geographical distribution of these facilities. Most are in the southern part of the country, while the Helgeland and Finnmark Coasts have relatively few. [52]

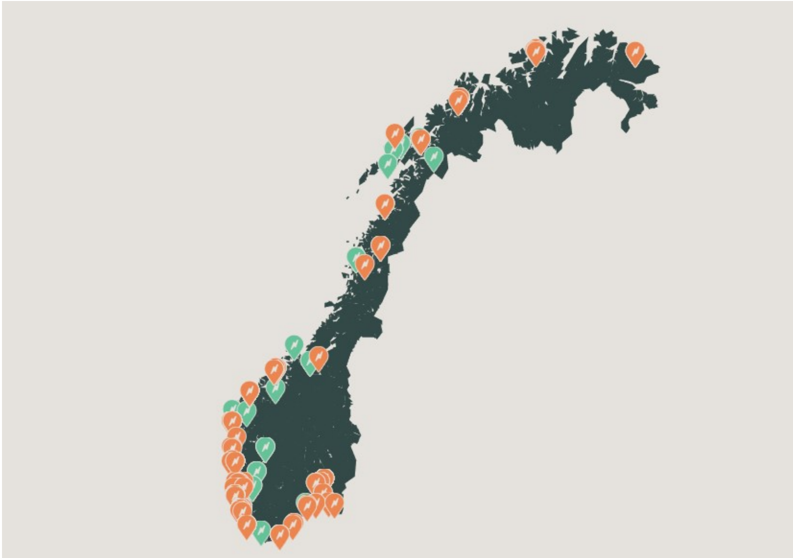


Figure 18: Shore power facilities in Norway. Green indicates a facility under construction, while orange is currently operating. [52]

Shore power charging technology is quickly improving, and in 2024 there are several different charging technologies available. Several companies offer charging for ferries, with wireless charging using electromagnetism being common. Wärtsilas ferry charging concept is shown in Figure 19, and can charge up to 2 MW, with a vacuum plug keeping the ship in place [32]. Similar solutions are offered by Wabtecs Ferrycharger, with capacities going as high as 23 MW [57].

Figure 19: Wireless charging concept. [32]

The first H_2 fueling facility dedicated to the marine sector in Norway had its first tests in early 2024. Despite successful H_2 production and pressure testing on the facility, the companies responsible will do further improvements and testing before the full launch [165]. Despite this being the first of its kind, several ongoing projects are aimed at these H_2 hubs, such as HyFuel by Ocean Hyway Cluster [73].

NH_3 is a widely traded product due to its usage in fertilizer production, and supply chains for the substance already exist close to several ports. Currently, over 120 ports worldwide has infrastructure for the import and export of NH_3, but local options are necessary. An option is to use ship-to-ship fueling similar to LNG, which could enable NH_3 use in more remote areas. [63]

In 2023 the Norwegian Hydrogen Forum identified 51 active projects associated with H_2 and 75 associated with NH_3 [45]. Figure 20 illustrates how these and projects for methanol and e-fuels, are spread in Norway. The burgundy-colored dots represent projects that have reached their final investment decision, while the turquoise has not. [155]

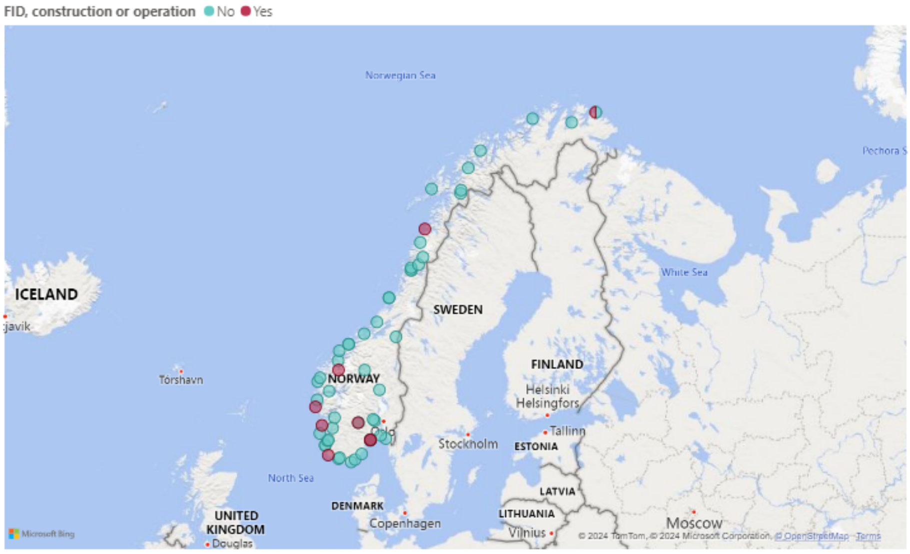


Figure 20: A map of projects related to the production or consumption of hydrogen-based fuels or e-fuels, by the Norwegian H_2 Forum. [155]

Fueling time is another important factor, as excess time in port contributes to the ship's downtime. Current bunkering time as informed by the crew, is between $50 - 200$ m^3/h, depending on the port. The fueling of methanol is very similar to MGO [98]. LNG bunkering stations have a similar bunkering time, varying from $133 - 200$ m^3/h. Truck-to-ship bunkering has lower fueling times, making it less suitable for larger ships [89]. For NH_3, bunkering time may increase from 6-60% compared to MGO [169]. Currently, the maximum allowed fueling rate for H_2 gas is 216 kg/h, due to safety issues, with an expected increase to 480 kg/h in the near future [101], this applies to long haul trucks. In relation to the H_2 station shown in Figure 4, it is estimated that it will be technologically possible to fuel up to 1 ton/h [68].

As of today, there is only one port in Norway where ships can bunker methanol from onshore facilities [78], with a total of 122 worldwide in April 2023. However, both trucks and tank ships can be used. The methanol-powered ship Proman Stena Bulk has conducted successful bunkering with onshore facilities, trucks, and other ships. The latter is shown in Figure 21. [102]

Figure 21: Ship-to-ship bunkering of methanol. [102]

2.6.1 Safety considerations

Different energy storage mediums represent varying risks in terms of their ability to cause damage to humans and their surroundings. Regardless of which energy storage medium is used, there is going to be a certain risk involved. However, with proper handling as well as education of relevant personnel, the risks are within accepted limits. Although this report‘s main focus is on the technology and implementation of it, some of the underlying safety hazards will be mentioned. Further examination of the topic goes beyond the scope of this thesis and would require further work.

A major concern regarding H_2 is its highly combustible nature, with its flammability limit ranging from $4 - 75\%$ [116], a leakage can therefore be dangerous, especially within closed spaces. H_2's explosive nature was shown in the Sandvika explosion in 2019, and underline the consequences of accidents. [123]. Although NH_3 also is a hydrogen carrier, the hazards vary significantly from pure H_2. Rather than being a highly flammable and explosive substance such as H_2 gas, NH_3 is highly toxic and corrosive. Being exposed to high concentrations of NH_3 in the air causes immediate burning of the eyes, nose, throat, and respiratory tract and can result in blindness, lung damage, or death. [69] Methanol has its safety concerns regarding the toxicity to human and low flashpoint along with the fact that it has an invisible flame [126].

The main issue concerning LIBs is related to fire hazards. Battery fires are often a consequence of improper storage, charging, and use, where a LIB can become unstable and self-ignite. Compared to other battery technology, the particular reason why the LIB is so dangerous is its highly volatile electrolyte. In the case of overheating, the phenomenon of thermal runaway may occur. Thermal runaway is when the battery reaches temperatures where an internal reaction takes place. In the case of a fire, this reaction sustains the fire, thus making it more dangerous. As an additional obstacle, fire extinguishers do not work in the case of a battery-ignited hazard. Other safety concerns include the corrosiveness of the electrolyte. [162]

3 Objectives

The objective of this thesis is to evaluate alternative energy systems solutions to reduce climate gas emissions from wellboats used in the aquaculture industry. The alternative energy systems investigated are mostly based on H_2, as it is one of the fastest-developing fuel technologies and has the potential for an entirely green future. Other mediums that are not necessarily completely green are also investigated to a lesser extent.

The evaluation utilizes a numerical approach to examine how different energy systems compare to currently used systems and their potential consequences. Supported by an extensive literature search, relevant parameters and information have been gathered to make analysis possible.

3.1 Problem and research question

The problem with decarbonizing wellboats is connected to the low energy density in energy carriers such as hydrogen and batteries. In addition to the poor energy density, the infrastructure surrounding carbon reductive fuels is inadequate in terms of availability and cost compared to MGO.

The research question shaped by these problems is then:
How feasible are different zero-emission systems on a wellboat, in a techno-economical, operational, and sustainable perspective?

3.2 Goals

The goal is to reduce climate change caused by aquaculture, targeting wellboat emissions and informing the industry of the different alternatives available and in development. This thesis evaluates different energy system proposals for wellboats and asses their affordability and performance.

3.3 Boundaries and limits

Wellboats are highly complex vessels, containing numerous components and processes. a study of the whole system in depth is too ambitious for the time period of this project. Thus the thesis will only study the energy system onboard. MGO is compared to alternative fuels, with a main focus on H_2-based solutions. Other fuels are included in the calculations and simulations to provide valuable comparison results, but due to higher uncertainties regarding components and price, they are not investigated to the same extent.

As the marine industry is highly competitive, gathering information regarding components provided by manufacturers is difficult as sensitive information regarding price and performance is not public information.

3.4 Strategy

This thesis will evaluate the impact different energy systems will have on a chosen wellboats operational profile. This will be done through a simulation, where the energy demand of the different systems will be calculated based on a simulated trip. Based on the energy demand, the required mass and volume of the different fuels can be calculated, further indicating the necessary storage volume. By comparing this to the examined ship, the impact regarding bunkering intervals will become clear, paving the way for discussion

Utilizing libraries for thermodynamic properties, a Python script is to be made with the intention of presenting data and behaviors of different systems compared to a reference system.

4 Methods

In this section, the methods used to construct a relevant trip simulation are presented. To properly evaluate different emission-reducing fuels while highlighting their impact on the operational profile, relevant data and technical information have been gathered and analyzed. Furthermore, the parameters of the simulations had to be set, including certain calculations and assumed equipment used.

4.1 Data gathering

To perform a realistic simulation for different energy systems being used in wellboats, information regarding operational profiles and sailing patterns is essential.

To uphold the agreement of anonymity, data in this thesis have been censored out like this: [redacted].

Through contact with relevant industry stakeholders, data covering the energy consumption of a wellboat were given under the condition of anonymity. The data includes yearly energy consumption and necessary power for different operations, and are shown in Table 5.

Table 5: Yearly energy consumption [12]

Activity	Hours/year	%/year	Propeller load [kW]	Base load (Burner) [kW]	kWh/year	L/year
Sailing 12kn	210	2%	1360	1200	1 194 667	119 467
Sailing 11kn	550	6%	950	1200	2 627 778	262 778
Sailing 10kn	950	11%	685	1200	3 979 444	397 944
Slowsteam	1050	12%	350	250	1 400 000	140 000
Manouevering	1164	13%	300	1200	3 880 000	388 00
Delousing	1662	19%	300	1200 (300)	6 094 000	609 400
Del. heat.	104	1%	300	1200 (2000)	577 778	57 778
Fetching	390	4%	200	1100	1 126 667	112 667
Delivering	780	9%	200	1100	2 253 333	225 333
Port	1900	22%	0	250	475 000	47 500
	8760	**100%**			**23 608 667**	**2 360 867**

4.1.1 Current power system

The ship currently has an installed power capacity of over 6 MW. This is divided between the main engine and three auxiliary generators. Installed capacity and dimensions for each component are given in Table 6. For the sake of anonymity, all numbers are rounded and deviate slightly from the real values.

Table 6: Installed power and dimensions.

	Power [kW]	Lenght [mm]	Width [mm]	Height [mm]	Weight [tons]
Main engine	2600	4500	1850	3700	33.5
Generator 1	1600	6600	2300	2600	24
Generator 2	1600	6600	2300	2600	24

4.1.2 Operational pattern

Although the data in Table 5 provides yearly energy values and operational distribution, it does not provide detailed information. In order to obtain a better understanding of how the ship is operating, the ship's automatic identification system (AIS) log during one year was examined through Marine Traffic [96].

To gain an understanding of the ship's sailing pattern, data recorded each time the vessel arrived or departed from the port were analyzed. The ship conducted 315 trips, with its mean, median, and maximum time at sea and in port shown in Table 7.

Table 7: Time spent in port.

	Port stay [h]	**At sea [h]**
Mean	10,54	15,87
Median	5,46	11,49
Max	85,01	95,50

Both for time in port and at sea, there is a large deviation between the mean and median, where the mean is between $40 - 50\%$ larger. This indicates that there are a fewer number of trips/stays significantly greater than the mean, thus increasing it.

Every port stay was logged throughout the year. $93,3\%$ of the stays were at five ports, which has been censored for the sake of anonymity. Out of the five locations in Table 8, Port A, C, and D are close to each other, with roughly $15 - 40$ km between them. Port B and E are located relatively far away from the rest but in close proximity to each other.

Table 8: Port stay information

	Number of stays	**% of stays**
Port A	130	41,3
Port B	73	23,2
Port C	50	15,9
Port D	29	9,2
Port E	12	3,8
Combined ABCDE	294	93,3
Total	**315**	**100%**

Ports D and E are the largest ports and are located on the mainland. There exist plans for hydrogen production relatively near both these ports, which further indicates that they have the best prerequisites for large-scale hydrogen storage.

Marine Traffic does not provide information about operations carried out by the ship, but through the AIS log it was possible to observe when the ship stopped at sea. The location of these stops was compared to the Norwegian Directorate of Fisheries map of currently active aquaculture locations [9], as well as satellite images and nautical charts. It was then possible to estimate how often the ship visited fish farms. Figure 22 shows the ship's AIS log over a nautical chart, indicating that the stop was related to operations at aquaculture locations. Whether the ship was conducting fish transportation or delousing is not clear from Marine Traffic [96].

Figure 22: AIS data confirms a stop at an aquaculture location. The different colors of the track indicate different speeds.

As the ship conducted numerous trips throughout the year, not every trip was examined closely enough to identify operations at aquaculture locations. To gain a representative selection, the first week of each month throughout the year was closely examined. This provided information about both sailing distance and speed.

Some key information derived from the examined trips is shown in Table 9. Certain trips were pure transit between ports, although most were from port to fish farm and back to port. The distance in Table 9 is based on the total sailing distance, and varied from 14 to 285 *nm*, with the median being 75 *nm*. There was no coherence between longer sailing distances and longer times at aquaculture locations, and the ship's stops at fish farms varied between 1,5 and 45 hours.

Table 9: Key data from the closer examined trips.

	Total distance [nm]	**Time at fish farms [h]**
Mean	85,7	6,8
Median	75	2,8
Max	285	45

4.2 Simulation parameters

The parameters include the defined systems, equipment used, the designed trip, and relevant calculations. The calculations will be done in Python.

4.2.1 Equipment

The fuel cells used in simulations will be based on the Pelican Marine Fuel Cell System provided by Corvus Energy. The specifications of the fuel cell are given in Table 10.

Figure 23: Corvus Pelican Fuel Cell System [39]

The fuel cells were reported to perform better at loads not exceeding 50%. When running the fuel cells close to 50% load, the fuel cells are assumed to have a life expectancy of five years, which corresponds with common intervals for ship maintenance. Furthermore, it is assumed that high loads decrease the life expectancy of the system.

Table 10: Pelican system specifications. [**39**]

Pack Power Size	340 kW (4 x 85 kW FC module)
System Power Range	340 kW - 10 MW
Output Voltage	400-750 VDC1,2
Pack weight (+/-15)	3100 kg
Pack Dimensions (±5%)	Height: 2300 mm Width: 1400 mm Length: 2100
Electrical Connection	Parallel connection 4 FC modules in FC pack

In this system both the packs and modules can operate separately from each other, meaning that it is possible to run as little as $85 - 340\ kW$ even though the total system has several MW installed capacity.

The battery pack used to simulate hybrid solutions is based on the Corvus Dolphin Energy NxtGen marine energy storage system. The specifications are given in Table 11.

Cell chemistry	Lithium-ion NMC-graphite
C-rate peak (discharge/charge)	1,1C/1,0C for 10 seconds
C-rate continuous (discharge/charge)	0,5C/0,5C
Single module size	8.2 kWh
Single module capacity	190 Ah
Single string range	33-197 kWh
Max gravimetric density	168 Wh/kg
Max volumetric density	212,5 Wh/l

Table 11: Corvus energy dolphin specifications.[41]

The electrical engine is assumed to have a similar installed capacity as the current engine, 2600 kW. The size is based on an engine shown in Figure 24 from Mship.no is shown in Figure 24.[115]

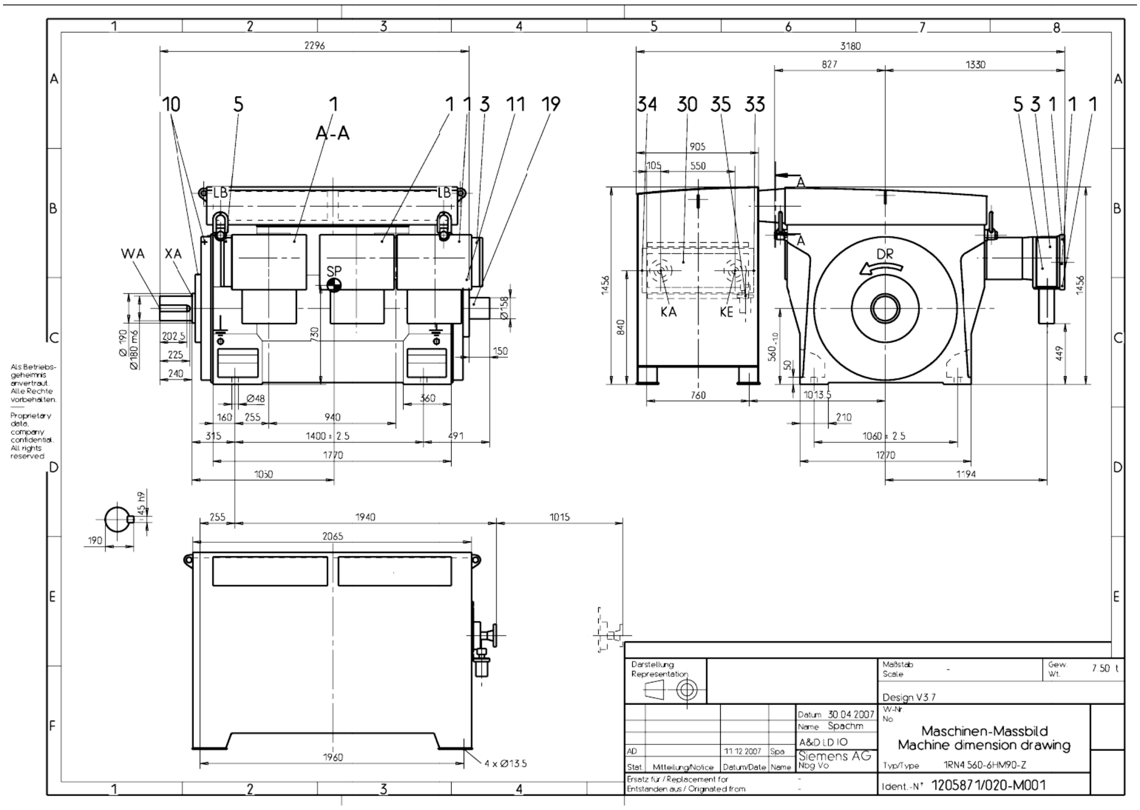


Figure 24: Electrical motor 2600kW. [115]

For components related to the use of other alternative fuels, the relevant industry was contacted. Due to sensitive information, only estimations could be given, and then only under the condition of anonymity. It was stated that it could be assumed that methanol and biodiesel could run on the current diesel system, with the same efficiency curves, etc., and that this would provide relevant results for comparison. [13]

Based on the power demand of the ship, a rough estimate of an ammonia power system was given. This is shown in Table 12. Like the assumption that biodiesel and methanol could run on the currently installed engine, it could be assumed that this system could use LNG with the same efficiency curve and power output as ammonia. The component parameters gathered from the industry used in this report serve as placeholders, as the information given is censored for anonymity.[13]

Table 12: Ammonia and LNG power system

Component	Power [kW]
Ammonia/LNG main engine	2280
Ammonia/LNG auxiliary generator	1700
Ammonia/LNG auxiliary generator	1700

4.2.2 Systems

The systems simulated have different components and energy carriers serving as base parameters for calculations. Baseline assumptions made for all the systems are shown below.

- Uniform loads (no fluctuations in power demand)
- No ramp-up times
- One process at a time
- No self-discharge
- No losses to electrokinetics.

System 1 will be used as a reference system, representing the configuration used today. It follows the parameters of Table 6. Following the same assumptions, system efficiency, and parameters are the systems for methanol and biodiesel where the behavior is similar to the diesel system.

System 2 replaces the diesel-driven components with a Corvus Pelican Fuel Cell System and hydrogen storage tanks. The installed power of the PEMFC is 4.08 MW and the hydrogen is stored at 250 bar. Assumptions for the hydrogen system are the same as for the diesel system.

System 3 uses the same installed fuel cell capacity, but with the addition of a battery pack with an installed capacity of 3.941 MWh, capable of discharge and charge up to 0.5 C. The battery alleviates the PEMFC whenever the load goes over 1.885 MW, i.e. shaving the peak loads so that the PEMFC never has to deliver more than 1.885 MW. The baseline assumptions apply here as well, while it is also assumed that the battery works ideally with no losses to discharge or charge. It is also assumed that with the added battery, the load at port stay is covered by shore power as the vessel can connect to the grid.

The "ammonia system" and "LNG system", works similarly to system 2 with the exception of installed components, which are given in Table 12 The engine used for ammonia and LNG has an installed power of 2.28 MW. There are also two auxiliary generators of 1.7 MW to deliver the desired power. Using the same working principle as in the hybrid system, the generator supplies the necessary power to meet power demands in the case where the engine does not have enough power. The efficiency of the generator and engine is assumed to be the same.

Methanol and biodiesel were informed to work identically to System 1 by industry sources. Thus the only varying parameters for calculation are the specific energy and volumetric energy density. [13]

4.2.3 Trip

In order to have a representative trip, the historical time distribution shown in Table 5 was used as a baseline. The timeline chosen for the simulation was 48 hours, with a percentage load distribution identical to the historical data. For instance, the ships spend 22% of the year in port, which corresponds to roughly 10, 5 hours of the 48-hour simulation. The full process distribution minute by minute is given in Appendix A, and the load through time is visualized in Figure 25.

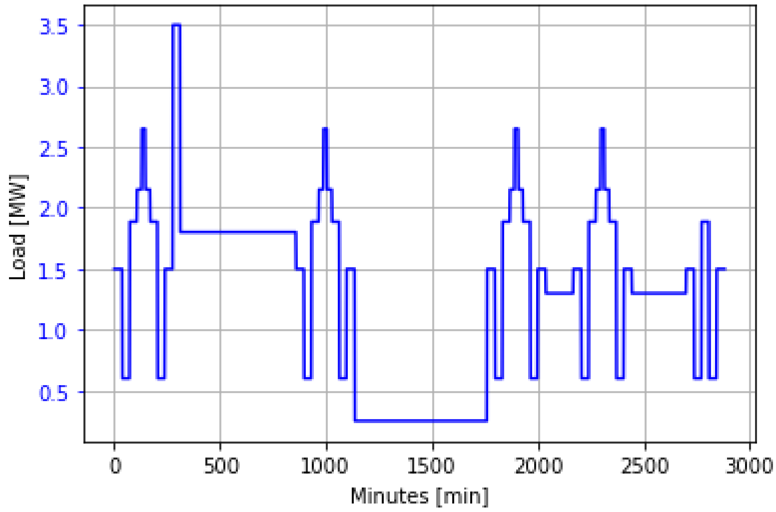


Figure 25: The load distribution throughout the 48 simulated hours.

In the simulated trip, delousing, and transportation of fish were carried out on separate days, with a port stay in between. The four identical peaks with their belonging dips illustrate the loads related to sailing, where each sail starts with maneuvering and slow steam, then increases the speed up to 12 knots, before slowing down to maneuvering again.

After the first sail, delousing is carried out for nearly 10 hours. The peak load illustrates the process of heating large amounts of water for thermal delousing, while the rest of the delousing load is related to mechanical work in pumps etc. When the delousing is finished, the ship sails back to port.

After the port stay, the ship loads fish between two identical sails, before unloading. Per Table 5, the unloading/delivering takes more than twice the time. The last sail of the simulation does not exceed 10 knots and has a shorter duration than the other sails.

4.3 Calculations

This section covers the necessary formulae and techniques for calculations made in the report. The formulae cover parameters of interest within energy demand, emissions, and storage.

4.3.1 Power and energy demand

Given a continuous function representing power applied at any given time, $P(t)$, one can calculate the total energy required over a given time period by integrating with respect to time as shown in equation 2.

$$E = \int_{t_{start}}^{t_{end}} P(t)\ dt \tag{2}$$

In the above equation, E is the total energy required, and P is the applied power. When using discrete datasets, the energy required is calculated more accurately using equation 3.

$$E = \sum_i P_i \cdot t_i \tag{3}$$

By replacing the power P with any flux, e.g. mass flow of hydrogen or volume flow of diesel, the total volume or mass consumed is obtained.

4.3.2 Storage calculations

The packing factor is a measurement of how much of a total volume is effectively utilized for its purpose. The packing factor P_f can be calculated using equation 4.

$$P_f = \frac{V_e}{V_t} \tag{4}$$

V_e is the efficient volume of the storage tank, and V_t is the total volume, e.g. the volume of a cylinder, using the outer diameter and length.

The storage pressure is $250bar$ by the recommendation of industrial partners. The hydrogen tank with the highest packing factor is then used to calculate the number of tanks and the amount of hydrogen storage that meets the dimensions of the existing diesel tank.

From data retrieved from industry the capacity of hydrogen was calculated. The number used is represented in Table 13.

Table 13: Number used for calculating storage capacities

Hydrogen per cylinder	kg	189
Cylinders per container 40"	n	6
Hydrogen per container 40"	kg	1134

The storage volume for systems not containing hydrogen is assumed to be the original measurements of 210 m^3.

4.3.3 Mass consumption

Based on the required power delivered from the fuel cell, it is possible to calculate the hydrogen mass flow by using equation 5, given below. P is the power delivered from the fuel cell, η is the efficiency of the system, and LHV is the lower heating value of mediums passed through the system.

$$\dot{m}_{H_2} = \frac{P}{\eta \ LHV} \tag{5}$$

The diesel consumption was calculated differently than the PEMFC consumption rates. Having received the statistical data shown in Table 5, the consumption rate was calculated using the volume consumed per year and the hours where the process was conducted per year. This yields the expression shown in equation 6.

$$\dot{V} = \frac{Litres \ per \ year}{Hours \ per \ year} = \frac{V}{t} \tag{6}$$

The exact efficiency curve of the Corvus Pelican fuel cell is confidential information, and for this thesis, a placeholder is used. The approximation is based on data points derived from an efficiency curve for a 100kW fuel cell [151]. By utilizing polynomial regression on the data points, the efficiency curve shown in Figure 26 was obtained.

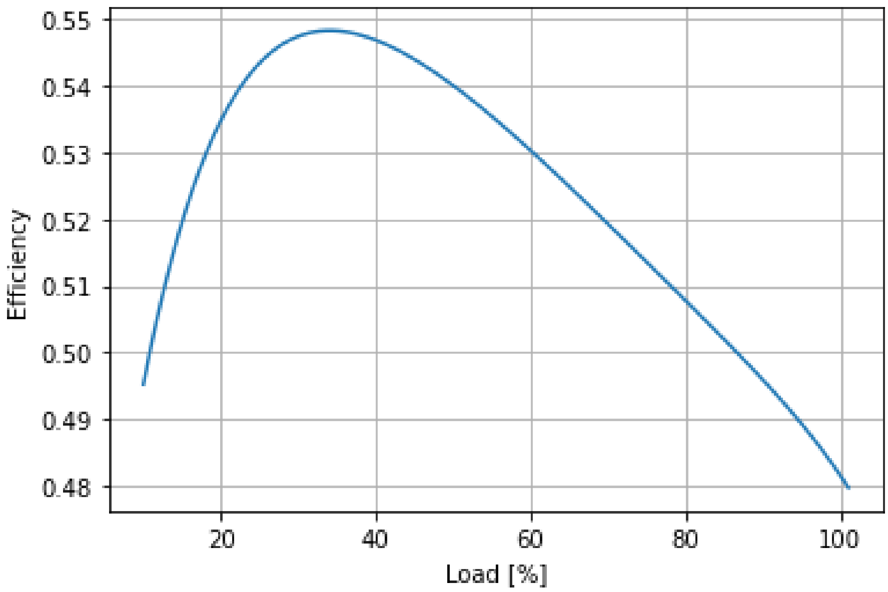


Figure 26: FC efficiency as a function of load

The efficiency curve for the ammonia/LNG engine was made through iterative methods and data from an anonymous partner, resulting in the efficiency curve presented in Figure 27. [13]

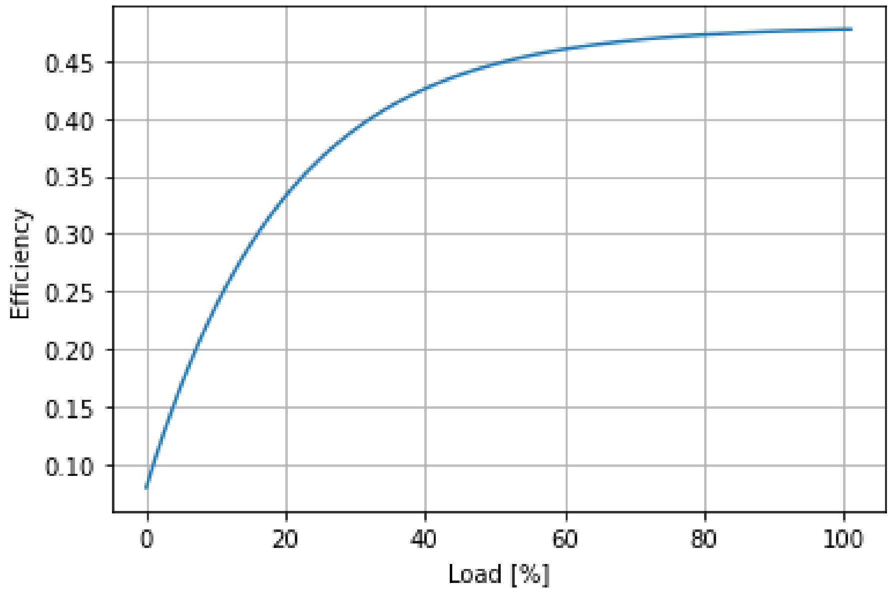


Figure 27: Efficiency curve for the ammonia and LNG system.

4.3.4 Linearization and interpolation.

A lot of the estimates in this report are based on linear trends. It is mostly used as a tool for estimating values in the future, such as increase or decrease in cost. In general, the formula presented in equation 7 has been used.

$$y = y_1 + \frac{y_2 - y_1}{x_2 - x_1} \cdot (x_i - x_1) \tag{7}$$

4.3.5 Emissions

To calculate emissions related to the combustion of different fuels, the emission factor per ton of fuel was used. The different emission factors are given in Table 14. With the consumed mass of each fuel known, multiplying this with the emission factors yields the respective emissions.

Table 14: Emission factors for different fuels.

Emission factor	CO2 [kg/ton]	NOx [kg/ton]	SOx [kg/ton]	CH4 [kg/ton]	Source
MGO	3206	54.88	2.15	0.05	[61]
LNG	2750	8.28	0.03	8.27	[61]
Biodiesel	3206[a]	54.88[a]	0.5	0.05[a]	[24]
Ammonia	N/A	N/A	N/A	N/A	[100]
Methanol	107	0.62	0	0	[103]

[a] Values for biodiesel are assumed to be almost the same as MGO as sources say they vary.[24]

To make a comparable system for GHG. CO_2e are calculated using the values given in Table 15. [35]

Table 15: CO_2e-table

Greenhouse gas	CO_2e per kg substance
NOx	298
SOx	22 800
CH4	25

4.3.6 Economics

As an essential part of the feasibility study, the economic impact is important. Comparing different carbon reductive systems, based on the lowering of emissions per NOK, enables the selection of the energy system that gives the most environmental benefits based on economic investment. While calculating the monetary aspects of this report, expenses associated with infrastructure have been excluded. Calculations and visualizations were made in Excel.

The investment cost regarding the installation of energy systems onboard is dependent on several factors. The investment cost is based on data gathered from different industry partners. As the investment cost is generally greater when utilizing low-emission systems, it is possible to get subsidies from the government. Enova is currently subsidizing up to 80% of the extra investment cost, up to 300 MNOK, of hydrogen vessels [53]. Due to the uncertainty in installation cost, the only costs included in the investment cost are the cost of the individual parts, e.g. batteries and engines.

The price of each component utilized in the energy systems is censored due to it being sensitive information given by an anonymous source.

Table 16: Component costs

	Price	Source
Main Generator(Diesel)	[redacted]/unit	[redacted]
Auxiliary Generator(Diesel)	[redacted]/unit	[redacted]
PEMFC	[redacted]/unit	[redacted]
Battery	[redacted]/unit	[redacted]
Converter	[redacted]/unit	[redacted]
CH_2 tank	[redacted]/unit	[redacted]

The variable cost, related to the cost of fuel and tax emissions varies depending on the fuel use of the vessel. The price of hydrogen is highly dependent on the production method of hydrogen. Using electrolysis as a production method, the cost corresponds to the cost of electricity [53].

According to the ICIS report from Q4 2023, both green, blue, and grey hydrogen have seen a substantial decline in price since January 2023. At the end of December 2023, the production cost of electrolysis-based hydrogen dropped beneath 7 € per kg H2, whilst the production cost of SMR and ATR-based hydrogen dropped beneath 3 € per kg H_2 [149]. These prices are based on the cost of producing hydrogen in Europe. The chosen price of H_2 however is based on estimates retrieved from ENOVA, due to it being a Norwegian firm and the cost being in the range provided by ICIS.

When calculating the electricity price for the charging of the battery in the hybrid system, the price is based on the average price of electricity in Q4 2023 at $0.79 NOK/kWh$ [48]. For the $CO_2 - tax$ the values used are given by the Norwegian government and shown in Appendix B [58]. The other OPEX rates are presented in table 17.

Table 17: Fuel and emissions prices

	Price	Source
CO_2	Appendix B	[58]
NO_x	11,50 NOK/kg	[75]
H_2	61,3 NOK/kg	[82]
MGO	14,42 NOK/l	[106]
Electrical power	0,79 NOK/kWh	[48]

The rates for future financial changes are calculated from the rate shown in table 18.

Table 18: Financial rates

	Rate	Source
Inflation	2.0%	[23]
Interest	5%	[150][a]
H_2	$-3,2\%$	[92][b]
Li-ion battery	-5%	[130][b]
Fuel cell	-7.7%	[130][b]

[a] The policy rate was used indicatively
[b] A yearly average of the values from citation

To calculate cost per emitted CO_2e, equation 8 was used. The ratio indicates how profitable the system is in an environmental perspective.

$$\frac{\Delta Cost_{average}}{\Delta emission} \tag{8}$$

5 Results and discussion

In this chapter, the possibilities for a zero-emission system on a wellboat will be investigated through the results of the simulation. Challenges and solution proposals will be presented to inform about the opportunities and limitations regarding the emission reduction of wellboats.

5.1 The simulated trip

The information gained from the closer-examined trips explained in Section 4.1.2 highlighted the ships varying sailing and operational patterns. This complicated the matter of setting simulation boundaries, as it would be challenging to make it representative. A simulation over 48 hours based on the historical process distribution given in Table 5 was chosen, as this ensures that the different processes are correctly weighted. The seasonal differences mentioned in Section 2.1 related to the production cycle are not taken into account.

Although the 48 simulated hours overall do not correspond with any of the examined trips, several aspects coincided well. The sailing distance on the first 24 hours can be estimated between 70-80 NM depending on assumed speeds for maneuvering and slow steam, which is representative of the median value shown in Table 9. Similar values were seen for the last 24 hours.

Operational information for time spent at fish farms is a more prominent point of uncertainty, as Marine Traffic gave no information about the matter, and the hours at fish farms varied greatly. How well the simulation represents the delousing and/or transportation of fish is unclear. However, considering that the onboard equipment can delouse 200 tonnes of fish per hour and each pen is assumed to hold 400-500 tonnes of fish, a simulation containing nine hours of delousing corresponds with a full delousing of four pens [128, 85].

In conclusion, a simulation aiming to identify a wellboat's power and energy demand should be more comprehensive. For this to be simulated, the data in Table 5 is insufficient and data on a minute-to-minute basis would be preferable. However, the chosen 48-hour simulation gives a general insight into the energy and power demand, further enabling a discussion about potential alternatives to fossil fuels.

5.2 Power demand

The power demand is crucial when deciding the capacity of the installed equipment, as the onboard energy system must be able to deliver the required load for all operations. The highest power demand aboard is 3.5 MW. In this section, the load profile of the simulated trip will be given and measures to reduce high loads are discussed. The chosen installed capacity for the alternative energy systems will be presented and compared to each other and the reference system.

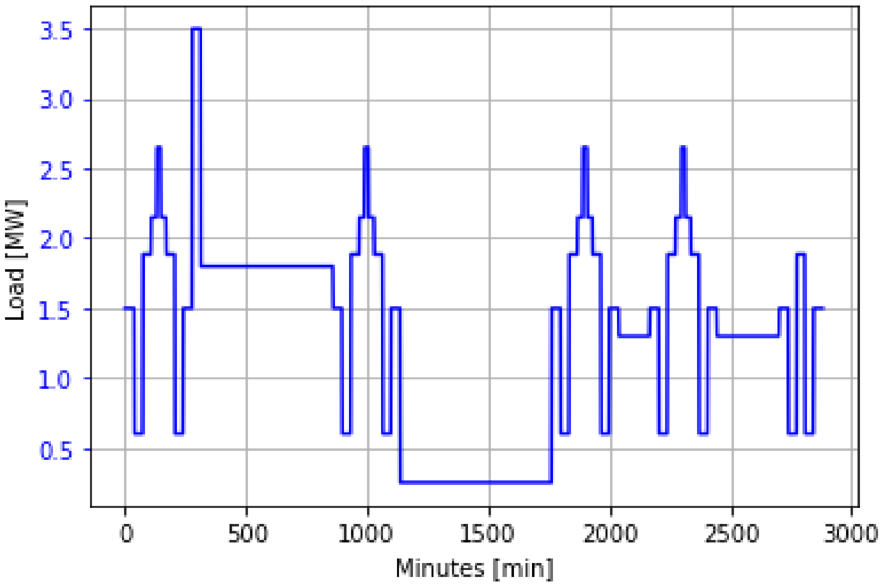


Figure 28: Load distribution through 48 hours.

5.2.1 System 1

To meet the power demand shown in figure 28 the reference system utilizes a combination of a main engine and two auxiliary generators running on diesel, which is given in Table 6. Several power sources enable the ship to operate even if one or more of the power sources fails, achieving redundancy in the system.

5.2.2 System 2

For the hydrogen-based systems, it is assumed that the Corvus Energy Pelican Fuel Cell system would be utilized. In terms of power demand, the PEMFC system's main issue was its significantly lowered life expectancy at high loads. System 2 is most efficient at roughly 34% load, as shown in Figure 26, and should ideally run below approximately 50% load due to the drop in life expectancy.

The PEMFC system consists of multiple packs of 340 kW which is assumed to operate independently for load distribution. To meet the required peak load of 3.5 MW, system 2 would need a minimum of 11 packs. With the independent operation of cell packs, a design surpassing the maximum load by a good margin does not have a problem of low efficiencies at small loads. In other words, the system is more flexible and efficient the bigger it is. An installed system with six of these packs is shown in Figure 29

Figure 29: A 2 MW fuel cell system illustration from Corvus. [39]

However, the cost and size of the system increase with the installed power. The gain in efficiency is not necessarily big enough to compensate for the extra cost, and volume required. The difference in efficiency at 34% and 50% load is less than 1%, thus designing for a continuously ideal load is arguably wasteful.

As shown in both Table 5 and Figure 28, the load was 1.885 MW or less more than 90% of the time. When including the load for 11 knots sails, only 3% of the loads are above 2.150 MW. With 3.740 MW installed capacity (11 packs), the fuel cells will experience a load of 50.4% or less for the most frequent operations. Even though this is acceptable, this option provides no redundancy for the highest load, and if one pack should fail or need maintenance, delousing could not be carried out. However, in the case of an emergency, the wellboat is still capable of propulsion.

With 12 fuel cell packs, every operation could be conducted even with one pack out of operation, and one would obtain a higher efficiency 40% of the time, compared to 11 packs. The higher efficiency would lower the hydrogen consumption, but according to simulations, the gain was negligible. Based on this, the reason for installing redundant fuel cell packs would be to extend the life expectancy of the fuel cells. The increase in life expectancy compared with fewer packs, is unknown and would require further investigation. Based on this, an installed capacity of 4.080 MW (12 packs) was chosen as a compromise between price, size, and safety margin. Based on the dimensions shown in Table 10, and Figure 24, the fuel cell and electrical engine would not exceed the area or volume used by the existing engine and generators, given in Table 6.

As depicted in section 2.5 there are several examples of large ships with PEMFC installed, such as the Torghatten project and the recently launched Feadship 821 [86]. These projects indicate that PEMFC systems are viable for large, power demanding ships and that the system size chosen for the wellboat is technologically possible. SOFC could be utilized in large marine vessels if the technology improves aspects such as slow kinetics. The higher life expectancy and efficiency could then be a major factor for the feasibility of fuel cell systems.

5.2.3 System 3

As fuel cells prefer stable loads, hybrid systems are convenient. A hybrid system including PEMFC and a lithium-ion battery pack was simulated, with the main purpose of the battery pack being peak shaving to reduce the high loads on the fuel cells. Assuming the same fuel cell system with an installed power of 4.08 MW, and a battery pack handling any load above 1.885 MW, the load distribution for the simulated trip would be as shown in Figure 30. The peak loads experienced by the fuel cell are significantly reduced by the introduction of the battery.

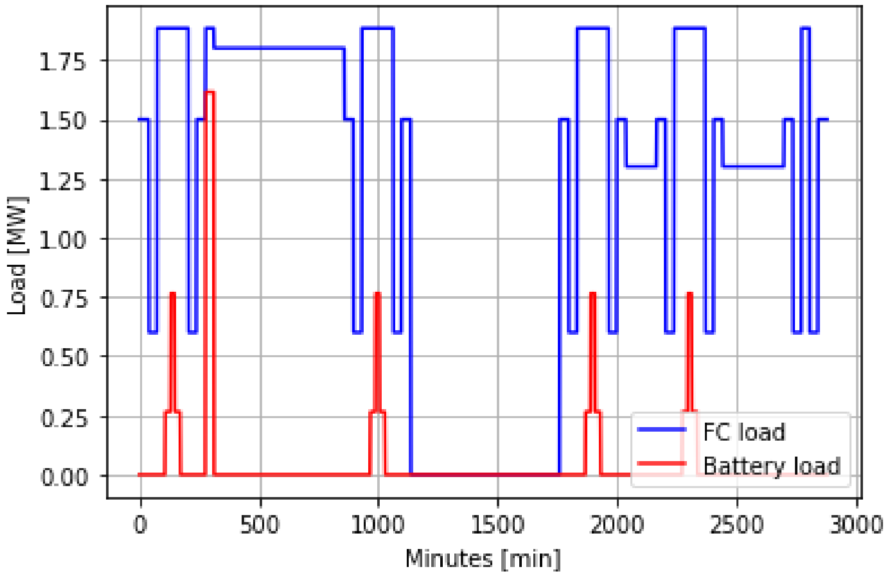


Figure 30: Hybrid system load distribution

Similar to fuel cells, battery packs have a high degree of modularity. Due to the nominal C-rate of 0.5 for discharge [41], the installed battery capacity must be at least 3.23 MWh to meet the peak battery load of 1.615 MW. The full system parameters for the battery pack will be presented in Section 5.3.3. A battery pack is shown in Figure 31.

There are more configurations available for the battery. A smaller battery with a larger C-rate could be utilized to deliver the same power as the pack already discussed. A battery with e.g. 1.17 MW installed capacity, and a C-rate of 3 could deliver the necessary power as the previous one, when used at 100% load. An interesting alternative could be the Corvus Orca ESS, which is the worlds most installed marine battery energy storage system. [40]

Figure 31: A Corvus Dolphin battery pack. [51]

5.2.4 Other systems

None of the other systems were simulated with batteries, and the load distribution were therefore the same as for System 1.

Biodiesel can run in almost identical ICEs as diesel [168]. Thus, a similar setup of one main engine with an axial generator and two auxiliary generators was assumed for this system, with equal installed power. Based on the efficiency curves provided by the industry, shown in Figure 27, the fuel economy favored higher loads [13]. The possibility of retrofitted diesel engines provides methanol with a large variety of options, and meeting different loads are not an issue. An example of a diesel engine retrofitted to run on methanol is shown in Figure 32. Furthermore, pure methanol engines are in development noe kilde.

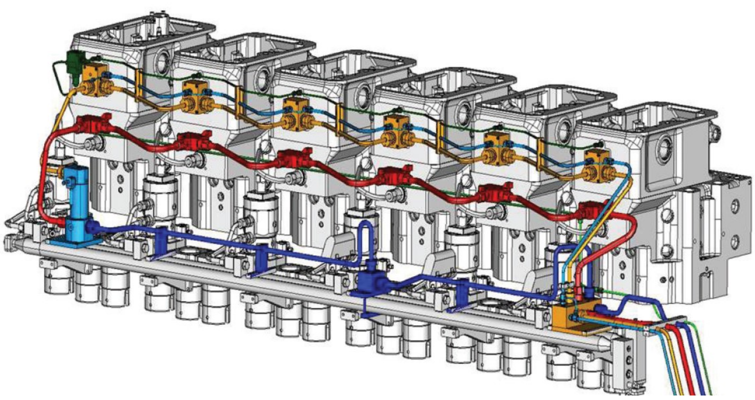


Figure 32: A diesel engine retrofitted for methanol use. [152]

The power system for LNG is given in Section 4.2.1. The main engine of 2.28 MW is substantially smaller than that of System 1. This leads to a higher probability of a scenario where two generators must be operated to deliver the necessary power, as opposed to system 1, where fewer processes require an auxiliary generator. As ICEs for NH_3 have just recently entered the commercial market, with several being in the testing phase [66], the range of possible power installations is more limited compared to less immature technologies.

5.2.5 Potential power reduction

The load distribution is shown in Figure 28. Preheating the water for delousing has the highest load of 3.5 MW, while the rest of the delousing operation has a power demand of 1.885 MW. As delousing is done 30% of the year, reducing these loads could be beneficial.

The peak load is related to thermal energy, which is gained through a diesel burner as of today, while the rest of the delousing load is related to equipment such as pumps [17]. A Sintef project examining ways to reduce the use of burners on cruise ships highlights the use of heat pumps and excess heat from the engine to provide thermal energy. Thermal energy storage through phase change materials (PCMs) is also examined to store heat for port stays. Although cruise ships vary greatly from wellboats, the project could have transferable input, and its results, as well as conclusions, should be further investigated. [64]

Delousing operations are carried out at the fish farms, and the majority of these are connected to shore power [4]. By further connecting shore power from the feeding barge to the ship, the required power output of the onboard energy system could be reduced. The challenges related to electrifying feeding barges were mainly concluded to stem from cost, and the local grid being unable to deliver $500 - 700\ kW$ [3, 109]. Recommendations to extend the shore power to the pens only mentioned up to 200 kW [3], which is only a fraction of what delousing requires. To provide the necessary power, the feeding barges would require more power from land, which might not be possible [109].

For future delousing operations, alternative methods may have very different load profiles. Neither freshwater nor mechanical delousing requires a high load from the boiler. As salmon would still have to be transported from the sea through similar delousing equipment, the 1.885 MW load could be representative of the operational load of these alternative delousing methods, although this would have to be investigated further.

With freshwater delousing becoming more common [29, 129, 88], different operational issues become present as freshwater is required. This must be stored in onboard tanks and depots either at the fish farms or on land. Another option is to produce it through reverse osmosis [88].Ronja Strom is a large wellboat utilizing reverse osmosis equipment delivered from Norwater [114]. A Norwater reverse osmosis system on a ship is shown in Figure 33, and some of their systems can produce 150 m^3/day, requiring less than 50 kW [124]. Considering that Ronja Strom is producing 700 m^3/day [114], this could create a significant reduction in power demand related to delousing operations, although with an increased base load.

Figure 33: Reverse osmosis system on board a ship. [124]

Aside from potential changes in delousing methods, the trend of the industry moving towards more specialized ships will result in the operational profile for future wellboats being significantly altered. One example is the assumption that wellboats will have a higher interval of port stays. The total effect of this trend is unknown but should be kept in mind nonetheless. [88]

Excluding the delousing preparation, sailing at high speeds is the most power-demanding operation, especially at 11-12 knots. Based on the load distribution shown in Figure 25, it is evident that lower sailing speeds reduce power demand. This complies with certain observations that one of the quickest ways to reduce CO_2-emissions from shipping is to lower the sailing speed [24].

Wellboats are a part of the industry's preparedness plans in cases of disease outbreaks or similar instances and must be able to respond quickly in cases where fish farms require immediate attention [88]. Limiting the potential sailing speed to obtain a lower required installed capacity may not be a viable option, but reducing speeds when possible will contribute to lower energy demand and emissions.

The base load of the ship contributes greatly to the ship's total load, as shown in Table 5, and was reported to include hotel loads for the crew and equipment such as cranes and pumps. The possible solutions presented by Sintef to reduce the use of boilers. [64]. Living quarters require certain temperatures, as well as hot water for showers, etc. The ship was reported not to utilize the exhaust heat from the currently installed diesel engine, even though it is commonly adopted in newer ships due to its power, energy, and cost-reducing benefits [95]. The utilization of heat pumps on board assumed not installed. Installing this is an effective method to reduce hotel loads [64].

The base load is significantly lower during slow steam and port stays. No explanation has been given regarding the low base load during slow steam compared to manoeuvring or 10-knot sailing, and despite its odd nature, the data given was assumed correct. In port, shore power can potentially cover the load. Using shore power reduces the time other power-generating equipment is running, and it can be assumed that maintenance and fuel costs will be reduced. Even if shore power is not accessible in every port the ship docks, it is potentially economically beneficial. Especially with financial support from Enova covering up to 40% of the cost. [1]

Based on the ship's current operating profile, certain measures to lower loads seem viable. Shore power has the potential to contribute to a limited extent during operations at fish farms, and cover the entire load at port. Energy efficiency installations can further lower the load related to heating, and potentially reduce the peak load. For future wellboats, the greatest opportunity to lower peak loads thus seems related to structural changes in the industry, either by changing delousing methods or by outsourcing the process to specialized ships.

5.3 Energy demand and storage

The total energy demand from the simulations is given in Figure 34. As the load profiles for each system are identical, the difference in energy consumed serves as a measurement of the different system efficiencies.

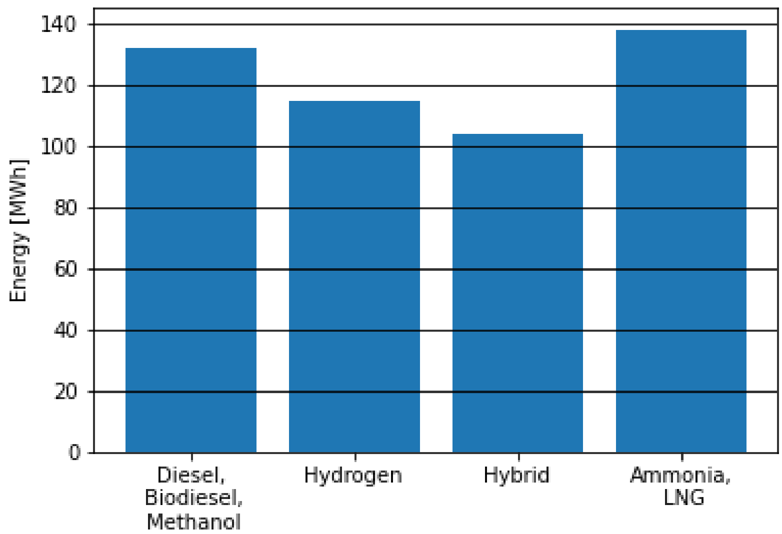


Figure 34: Energy consumed from onboard storage system.

The simulated trips gave fuel consumptions shown in Table 19. The total storage capacity, along with the used capacity during the simulated trip are shown in Table 19.

Table 19: Fuel usage for the simulated trip

Systems	Fuel usage kg/simulated trip	Total storage capacity[a]	Used capacity [%]
System 1	11 121.52 kg	179 550 kg	6.16 %
System 2	3 447.68 kg	6 500 kg	53.03 %
System 3	3 117.24 kg	6500 kg	47.96 %
NH_3	26808.17 kg	153 300 kg	17.49 %
LNG	10 259.92 kg	108 000 kg	9.50 %
Biodiesel	12 592.69 kg	184 800 kg	6.81 %
Methanol	23 866.97 kg	166 320 kg	14.35 %

[a] The effective storage volume for section 4.3.2

5.3.1 System 1

The total energy required for System 1 was 132.22 MWh, consuming 12 932 L of diesel. With a total of 210 m^3 storage capacity, this equals roughly 6% of the storage volume. The ship could then operate as in the simulation for more than four weeks without bunkering. This resembles the real operational patterns where bunkering happens once every three weeks. Assuming that the real operational pattern is similar, this shows that a safety margin of 25% fuel capacity is practised.

5.3.2 System 2

The energy demand of System 2 was 114.92 MWh. The amount of CH_2 needed for this amount is 3447 kg. The CH_2 can be stored either as shown in Moen's work vessel in Figure 4, or in different container solutions as shown in Figure 35

Figure 35: A 40 ft containerized CH_2-storage solution. [72]

Storage above the deck seems preferred [68, 159] to ensure proper ventilation, but this requires free space. For a pure H_2-based energy system, the need for a diesel exhaust pipe is eliminated, and this space, marked with "1" in Figure 36, could be used for H_2 storage. For the ship examined in this thesis, it was estimated that four 40 ft containers could be installed on deck if the diesel exhaust pipe were removed. This alone would enable the ship to store roughly 4500 kg of CH_2 based on the estimations from the industry shown in Table 13. [12]

The possibility of containerized storage would be highly dependent on the removal of the exhaust pipe. While FPS Waal completely removed its diesel system, MF Hydra operates with a diesel backup system, and Torghatten is planning to have one [104, 159]. Given the role of wellboats as a part of the aquaculture industry's preparedness plans [88], a backup system along with the main system will still be likely as alternative systems continue to develop. Backup systems could contain other storage mediums such as batteries or more redundancy in the original system.

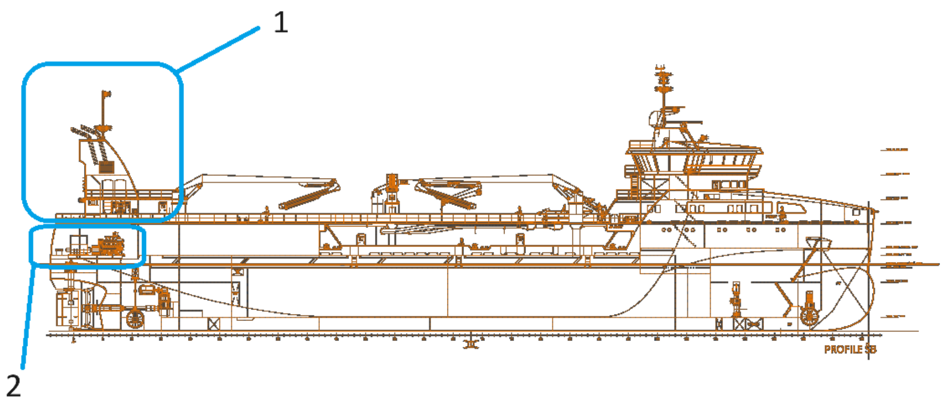


Figure 36: Suggestion for alternative storage placement where 1 is space for the container, and 2 is the engine room. [118]

To further improve the ship's range, it could be possible to add internal tanks to accommodate CH_2. The diesel tanks could contain smaller Type IV tanks, but the topography of the tank would dictate the effective storage space. Due to safety reasons, a portion of the tank volume must be allocated to ventilation- or inert gas systems. Encompassing this, the packing factor used for the internal tank was estimated to be 66 %. For the examined ship, its 210 m^3 of storage could thus store approximately 2000 kg of CH_2. Given the previous assumption of container-based storage, the total CH_2 capacity increases to 6500 kg. Considering the consumption of nearly 3500 kg, this would enable the ship to operate just below four days before bunkering, which is highly impractical compared to System 1.

For the relatively low pressure at 250 $bars$, cheaper tank types can be considered as opposed to Type IV, but a compromise between weight, price, and required strength would need to be evaluated on an individual basis. For instance, does FPS Waal use Type II tanks [38], while the working boat from Moen Marin uses Type IV tanks [49].

5.3.3 System 3

Implementing the aforementioned battery pack increased the overall system efficiency, and reduced the hydrogen consumption compared to System 1 by nearly 10%, to 3117.24 kg. As the hydrogen storage system is assumed to be equal to that of System 2, the consumed hydrogen is 47.96% of the total CH_2 storage capacity. System 3 used the least energy of any system. This is partly due to the battery allowing the PEMFC to run more at beneficial loads, as well as port stay being covered by shore power. Furthermore, the hybrid solution is beneficial for the fuel cell's life expectancy, although to an unknown degree.[15]

As detailed in Section 5.2.3, a 3.23 MWh battery capacity was required to meet the highest load. However, the chosen system has a capacity of 3.941 MWh which allows the battery to stay between the recommended 80% and 10% SoC [30]. Furthermore, a larger battery pack adds more flexibility to the system.

A battery package of this size would require 16.02 m^2, excluding wiring and supporting components, and a total volume of 31.65 m^3 [41]. As the reference system components use roughly 40 m^2 based on the data in Table 6, the area required for System 3 would demand a larger area. However, the possibility to store batteries in different locations on board is possible, as done on FPS Waal [38].

The maximum fuel cell load before activating the battery could be lowered to increase the energy delivered by the battery and reduce hydrogen consumption. Due to the significantly lower price of electricity compared to hydrogen, this could be economically beneficial. However, the battery

SoC is more likely to drop below 10% or completely discharge, leading to the fuel cells operating without peak shaving.

The ratio between energy stored in hydrogen versus batteries in currently operating vessels varies. In Moen's work vessel, the ratio is close to 17 [49], and in MF Hydra the ratio is close to 140 [104, 105]. With the chosen parameters in System 3, the energy stored in hydrogen is roughly 65 times the amount stored in the battery.

5.3.4 Other alternatives

Based on the assumption of a storage volume equal to 210 m^3, the other alternatives represent other advantages and disadvantages in terms of energy demand.

Biodiesel can, due to its similar characteristics to diesel, be stored in the same tanks. Biodiesel has a slightly higher density, and as shown in Table 19, and more weight can be stored in the same tanks. However, its lower LHV compared to diesel still results in higher fuel consumption, both in kg and percentage of the stored fuel used.

Running on biodiesel increased the used capacity by 10.6% compared to System 1, based on Table 19. Although this is less optimal than System 1, it still allows the ship to obtain an operational pattern similar to today, compared to System 2 and 3's need for bunkering several times a week. Furthermore, biodiesel does not require extra safety measures similar to System 1, and is commonly regarded as an easily handled fuel. Its option to be gradually phased in as a mixture with diesel further lowers the implementation threshold.

Like biodiesel, methanol can also be stored in conventional diesel storage tanks due to its properties at ambient temperature and pressure [141, 24]. However, due to its lower density, less methanol is stored compared to diesel. Furthermore, despite assumed identical efficiency curves, the significantly lower LHV of methanol results in the fuel consumption being 14.35% of the total capacity in the simulation. This is more than twice the amount of both System 1 and biodiesel and indicates that a ship using methanol fuel would need approximately twice the bunkering intervals compared to a diesel system. For a new methanol ship aiming to maintain the same operational pattern, substantially larger storage tanks would be necessary.

Due to NH_3's toxic and corrosive nature, as well as the need for storage at either $-33°C$ at 1 bar, or 18 bar at ambient temperature, the existing storage tanks could not be directly used. Extra safety measures and insulation would impact the storage volume, and decrease the effective storage in the current ship. However, it is for the sake of comparison assumed that the ship could store 210 m^3 of NH_3. Even with this effective storage, NH_3's relatively low density leads to less amounts of energy stored.

The NH_3 and LNG system uses the highest amount of energy, due to its low efficiency, as shown in Figure 34. For the simulated trip, the NH_3 system uses 17.5% of its storage capacity. While this would allow the ship to operate nearly three times as long as the hydrogen-based systems, it would have to bunker three times as often as System 1.

Similar to NH_3, LNG storage tanks require extra equipment due to the low storage temperature of $-162°C$. With an even lower volumetric density than NH_3, 210 m^3 of effective storage would only enable the ship to store 70% of the mass. However, due to LNG's relatively high LHV, LNGs fuel use is less than 40% of the NH_3 system. When compared to System 1, the increase in fuel consumption is roughly 50%.

With storage temperatures at $-253°C$, liquid hydrogen is challenging to store. Its low density of 70.8 g/L only yields 14 868 kg hydrogen if 210 m^3 of effective storage is assumed. As the liquid hydrogen would use the power system from either System 2 or 3, 3 117.24 or 3 447.68 kg of hydrogen would be consumed. In that case, liquid hydrogen storage would enable the ship to sail $8 - 10$ days without bunkering.

Although this is substantially better than bunkering intervals for compressed hydrogen, the actual storage volume including tanks and supporting system would make a ship with this system larger.

Furthermore, this does not include boil-off losses which could be up to 3.5% per day, as mentioned in Section 2.4.5.

Due to the extensive safety and insulation measures, it would require up to ten times the volume to store as much energy as diesel [86]. Despite this, it is used on MF Hydra and Project 821, with 91 m^3 and 92 m^3 storage respectively. Project 821's storage system is shown in Figure 37. [105, 86]

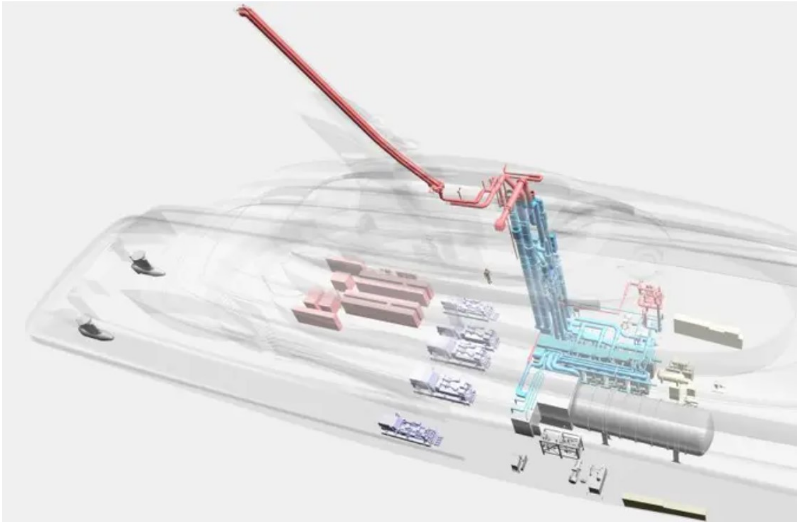


Figure 37: Schematic of Project 821's hydrogen storage system. [86]

5.4 Emissions

The driving force behind investigating fuel alternatives for wellboats in the aquaculture industry is a reduction of GHG emissions. Any industry using fossil fuels has problems regarding their emission, and solving these problems is of paramount significance [117]. The emissions from the 48-hour simulated trip is presented in Table 20. An important note is that these are only the emissions directly related to the trip. Emissions related to other parts of the fuel's life cycle are not included in the table but will be discussed.

Table 20: Direct emissions from the simulated trip

SYSTEM	CO_2 [kg]	NO_x[kg]	CH_4 [kg]	SO_x [kg]	CO_2e [kg]
System 1	36 900.00	631.64	0.58	24.75	789 443.22
System 2	0	0	0	0	0
System 3	0	0	0	0	0
NH_3	N/A	N/A	N/A	N/A	N/A
Methanol	32 844.00	190.40	0	0	67 349.6
LNG	28 215.00	84.95	84.90	0.31	62 720.6
Biodiesel	36 900.00	631.64	0.63	6.3	368784.47

System 1 represents the current status in terms of emissions. The CO_2 emissions from the simulation accumulated to nearly 37 *tons* of CO_2 over 48 hours. Including 631.6 kg NO_x and 24.75 kg SO_x, the total emissions are the highest of any system.

Table 20 shows a reduction in SO_x for biodiesel. For the other emission from MGO however, the uncertainties are of such significance that they are assumed the same. As mentioned in Section 2.4.2 it can be categorized as sustainable under the right circumstances, implying that the emissions in Table 20 do not contribute to global warming. As this is not always the case, the fuel has gained critisism. Europe's biodiesel demand has increased due to policies aiming for more sustainable fuel sources, but due to unsustainable farming requiring extensive land use, there are indications that the total emissions have increased due to this [26]. Aside from emissions, this can have a negative impact on food reliability and deforestation [26].

Using hydrogen as a fuel in PEMFC has the benefit of zero GHG emissions, thus all emissions are set to zero in Table 20. The same applies to the hybrid system, as the batteries have no exhaust gases. While this is beneficial for the local environment in which the ship sails, hydrogen also requires sustainable production to be considered environmentally friendly. The International Energy Agency estimates the global emissions from hydrogen production to be between $12-13.6\ kg\ CO_2e/kg\ H_2$ [74]. If these values for hydrogen production are used for the simulated trip, the total emissions would be between 41 and 47 tonnes of CO_2e.

Even for hydrogen made from renewable energy sources, the area and materials required are high due to the low system efficiency shown in Figure 14. Conflicts of area that have been observed with wind farms can indicate that extended use of land for renewable power production might be a challenge [146].

As NH_3 does not contain carbon or sulphur, CO_2, CH_4 and SO_x-emissions are neglected [63]. However, when combusting NH_3 NO_x-emissions may occur. As these emissions have a CO_2e of 298 kg [35], the engine technology needs to be optimized to minimize the GHG emissions. As NH_3 engines have recently been released to the market, calculating the exact emissions is difficult [100]. Nonetheless, engine technology providers expect the emissions to be equal or less than those of conventional fuels [100].

An IMO report stated that the emissions of NO_x is 0.4 g/MJ, as well as 69 g/MJ of CO_2, which is used for the calculations in Table 20 [103]. Similar to biodiesel, methanol can be produced as a carbon-neutral fuel, which leads to CO_2-emissions not contributing to global warming [103]. Most of today's methanol is produced through natural gas synthesis, but it can also be made using natural gas.

LNG is becoming more common as an energy supply within marine shipping and has been called an "enabler of transition" for the maritime industry [24]. The technology is mature and proven to function well within the industry. It is also estimated that GHG emissions can be reduced by 23% [46]. However, a life cycle analysis for LNG indicates a maximum of 15% reduction in GHG can be obtained in a 100-year perspective, and an increase of 4% in a 20-year perspective. These best-case scenarios only apply for a certain engine type which accounted for 12% of the ships in service or ordered for 2020. For other crafts, GHG emissions increased up to 70% in the 20-year perspective when transitioning from MGO to LNG [131]. Given the urgent nature of reducing emissions, and varying results regarding environmental impact, this raises a series of questions related to LNG's suitability as an alternative fuel.

5.5 Logistics and infrastructure

A critical criterion for implementing alternative fuels onboard wellboats is developed infrastructure. Historically the framework surrounding diesel has been solid. Due to its applicable nature, diesel is widely utilized in almost all heavy-duty machinery. As a consequence of this, the availability, handling, and cost of diesel have been advantageous as opposed to most other energy carriers. Therefore the problems in transitioning from diesel to greener alternatives are linked to the competition against such an energy-dense, mature, and proven technology. Production and density of fueling sites, along with fueling time, are major problems within the infrastructural situation shown in Figure 38.

One of the main challenges for implementing alternative fuels is related to supply and demand. Due to the few hydrogen-fueled vessels in operation, there are no major distribution networks, production sites, and end clientele within the Norwegian hydrogen market. Requiring major investments without the demand to support them involves a big risk for investors.

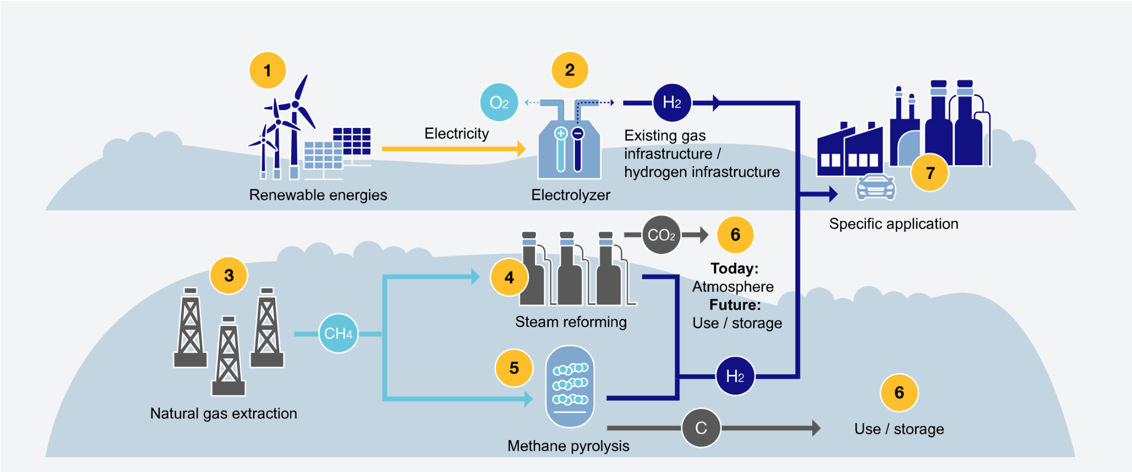


Figure 38: A concept of hydrogen infrastructure [161].

5.5.1 Production of hydrogen

A problem regarding the production of hydrogen is the energy-inefficient production process with electrolysis, contributing to a high cost for green hydrogen [77]. For other production methods, e.g. steam reformation, emissions are an issue. As a transitory solution, producing hydrogen using more efficient procedures that emit GHG while the market grows, can help the establishment of a bigger customer base, which could further motivate a bigger investment in green hydrogen [132].

Despite the production challenges, both Moen‘s work vessel and the Torghatten projects will use locally produced hydrogen [68], as opposed to MF Hydra who gets liquid hydrogen delivered from Germany through trucks [91]. The Torghatten project will require between $6 - 10$ tonnes of hydrogen per day and has signed a 15-year contract with GreenH, to ensure local production [65]. Byproducts of hydrogen production include heat, which can be used for district heating, and oxygen which is of high interest to the aquaculture industry. Furthermore, such a large local production can act as an enabler for other local industries to implement hydrogen as an energy carrier [65].

5.5.2 Production of alternative fuels

As mentioned in section 2.6 NH_3 is a highly traded substance and more than 120 ports around the world can handle it [63]. Due to an increase in demand from the shipping industry, two green NH_3 production plants will be opened in Norway in 2026 and 2027, in Mongstad and Korgen [43]. As with green hydrogen, this requires major investments, along with a high supply of power. The production site at Korgen is the biggest one, with a daily production capacity of 600 tonnes of NH_3, requiring 2 TWh of electricity annually. 14

Methanol produced using synthesis gas, also requires hydrogen, as explained in section 2.4.7. The production of methanol naturally suffers in many of the same areas as hydrogen. The advantage of methanol is that the fuel in itself is more viable for heavy-duty machinery compared to hydrogen, further warranting the production of it. Although it is not necessarily entirely green, the production and use of methanol could reduce emissions by huge amounts compared to continuing the use of diesel. Methanol also represents a flexible option in transitory production methods. Having the choice of utilizing grey, blue or green methanol allows for an easier transitory period rather than committing without safety measures.[6]

Biodiesel production has its main difficulties regarding the production method. Production requires biological mass, preferably waste or byproducts as described in section 2.4.2. Reports from Transport & Environment have indicated that biofuels have higher emissions than fossil fuels. However, this is highly dependent on the mass used in production, for example, oils from palm and soy have a large impact regarding land use. [160]

Regardless of the fuel chosen, the production method is an essential part of ensuring a total low emission impact. Making use of the products, such as oxygen and heat, is also a significant benefit. Choosing a fuel that has enough supply, locally, is a big advantage and should be taken into consideration for each case. Nevertheless, individual supply deals is probably a requirement for a ship with this big of a demand.

5.5.3 Distribution

The feasibility of a hydrogen supply chain in Germany was deemed satisfactory by a report considering a case study by Almansoori and Betancourt-Torcat [10, 125]. It concluded that the distribution was possible due to the 20 existing hydrogen production sites, as well as the governmental decarbonization goal. Norway does not have the infrastructure required to distribute enough hydrogen to meet the energy demands of the maritime sector [34] as of now, and the investments demanded to fulfill the distribution chain shown in Figure 39 would be tremendous [125].

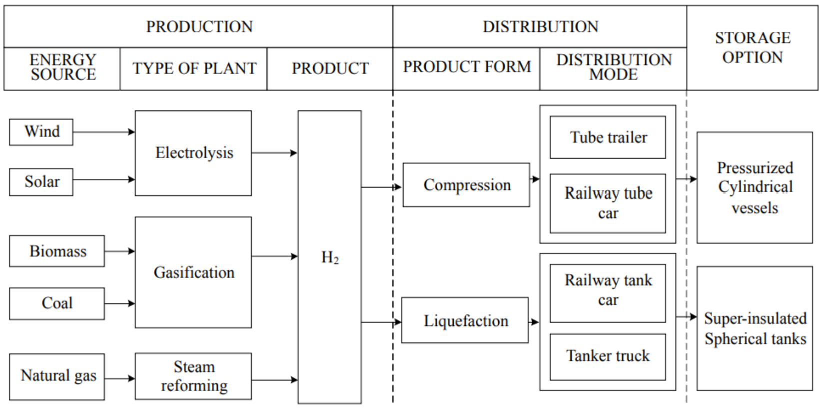


Figure 39: Hydrogen supply/distribution chain.[125]

As for H_2, NH_3- and methanol infrastructure are lacking in Norway. Transportation from the production site to the bunkering site is a necessity. This could be solved in different manners, by utilizing transportation by trucks or ships. The fuel could either be transferred into an onshore tank or be fueled directly from ship to ship or by truck to ship. As of today, methanol is produced in large quantities by Equinor, from natural gas, at Tjeldbergodden. From the production site, it is mainly transported by boat to the rest of Europe [136]. If the demand for methanol grew in marine applications along the Norwegian coast, similar solutions may be viable.

5.5.4 Fuel accessibility

Having the fuel readily available is essential for the operation of every ship. As of the writing of this thesis, diesel bunkering stations are developed, while alternative fuels lack availability.

Increasing the amount of fuel stations for biodiesel would require minor adjustments. Being liquid at ambient pressure and temperature, handling biodiesel is relatively easy. Given the easy conversion between diesel and biodiesel, the development of infrastructure would be small.

Mentioned in section 5.5.1, a possible solution to the low density of hydrogen fueling stations is through own production.

As the wellboat used $3.1 - 3.5$ tonnes of hydrogen over the simulated 48 hours, a similar deal to the ones of Moen and Torghatten could secure the supply of hydrogen for the wellboat. However, the operational pattern of a ferry differs greatly from the wellboat and local agreements of this nature may limit the geographical working area. While a ferry and a working boat travel between the same locations every day, a wellboats operation varies significantly more. Thus having a local deal could result in loss of contracts due to the limitation in available bunkering ports along the coast.

To help facilitate the investment in a local production plant, cooperation between several fish farming companies would be beneficial to increase the number of possible end-users. As many of the fish farms are located close to each other, having a production site in close proximity would enable different types of boats in the industry, to become hydrogen-fueled. Nevertheless, if a wellboat uses hydrogen, longer contracts with the fish farms located close to the production site may be a necessity to initiate the investment. With the shipping industry expanding into the hydrogen market, the production site could help grow and accelerate the transition locally.

As described in Section 2.5 there are several ships operating on methanol. Among them is the ferry Stena Germanica [148]. Stena Line chose methanol over LNG due to the lower cost of retrofitting along with the fuel being easily accessible at the specific local port [33]. The fueling practice has evolved since Stena's launch in 2015, and Stena Germanica became the first non-tanker vessel that performed ship-to-ship fueling in January 2023 [147]. This makes it even more accessible as methanol is often transported by boat, as described in section 5.5.3.

Yara and Azane Fuel Solutions are currently developing the world's first bunkering terminal for NH_3 use. This will contain 1000 m^3 of NH_3, located in Florø, and enable ships to bunker with green NH_3. The barge is depicted in Figure 40. By facilitating bunkering stations, the motivation for retrofitting and constructing NH_3 vessels will increase. [170, 145]

Figure 40: Illustration of the projected bunkering barge. [171]

LNG has several bunkering terminals along the coast of Norway. However, the density of the terminals is not necessarily high enough to supply a wellboats operating pattern but can be a viable solution in some special cases.

5.5.5 Fueling duration

Depending on the individual fueling site, diesel fueling varies massively. The wellboat used for the reference system has a fueling speed ranging from 20 $m^3/h - 100\ m^3/h$ [14] in its main ports. It is assumed that bio-diesel fuels at approximately the same rate.

In the case of how one would bunker hydrogen, there are two main methods. The tanks could be refilled like a conventional wellboat or by swapping the on-deck containers. Utilizing a traditional refueling system, the need for onsite storing of hydrogen arises. The stored hydrogen could be transported from a production site to the boat, either by truck or another ship [101]. The different scenarios are depicted in Figure 41.

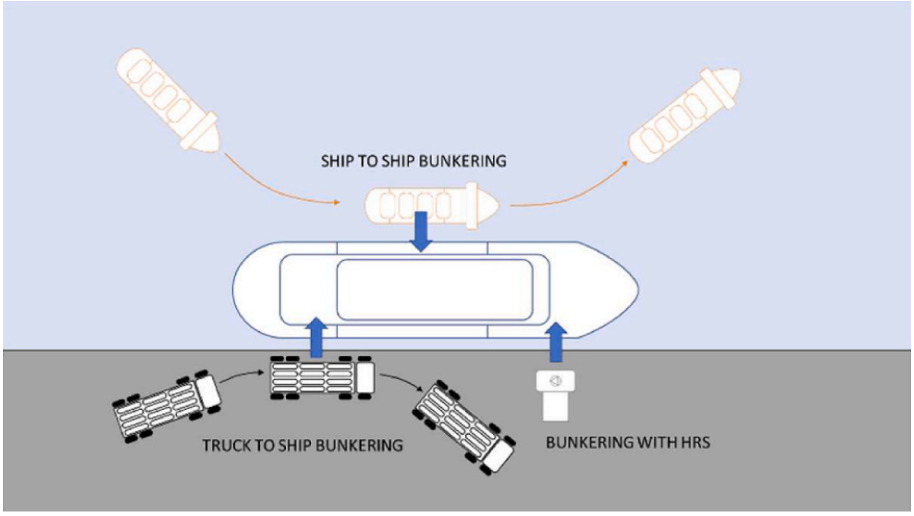


Figure 41: Different hydrogen fueling solutions. [101]

As explained in section 2.6 the maximum fueling rate is currently 216 kg/h, with estimations reaching 480 kg/h - 1 $tonn/h$. Bunkering in a shorter period will make the wellboat's operating pattern more flexible. Table 21 shows the fueling time, based on the different fueling rates of 216 and 480 kg/h, both for a full tank and refueling the consumed hydrogen in the simulation. For compressed hydrogen, at 216 kg/h, the bunkering time required to bunker the entirety of the used hydrogen in the simulated 48 hours, is between 15 and 16 hours. This estimation does not include connection and inspection. For the simulated trip, the wellboat is at port for 10.4 hours and during this period it could be possible to bunker. Nevertheless, the frequency of bunkering has to be significantly higher than for the reference system due to the lower storage capacity explained in section 5.3.2

Table 21: Hydrogen fueling time

Fuel [kg]	Time used (216 kg/h) [h]	Time used (8kg/h) [h]
6500,00	30,09	13,54
3447,68	15,96	7,18
3117,24	14,43	6,49

Swapping has the potential to be more time efficient, however, there are several considerations regarding the safety and logistics of this operation. During the loading and unloading of the tanks, an accidental drop of the tank could result in loss of lives, along with major material damage. As the fuel tank connections also utilize nitrogen and/or vacuum as a safety measure [12], it would be challenging to acquire this state after the swapping. Regardless it is a proven concept and is used by the FPS WAAL cargo boat in the Netherlands [31]. Safety routines and protocols have been developed to ensure the safety of the operations. These include the use of clean break couplings to ensure no air or dirt enters the tank, and the lifting operation being handled by a crane with four lifting points. Such a crane could have one point failing and still not drop the cargo. [19]

Looking into the batteries, the charging time would be dependent on power from shore-based power. In the simulation it is assumed a charger at 1.9705 MW resulted in a charging time of 1.4 hours from 10% SoC to 80% SoC. As the port stay in the simulation is 10.4 hours, and the median is 5.5 hours it is possible to have a lower C-rate at charging to possibly extend the life expectancy of the battery. New fish farms are being developed with shore-based power available. Using this the battery could be charged directly at the cages. In this event the battery would be able to shave the peaks for longer, reducing the energy demand from the PEMFC.

LNG has the possibility to bunker up to 2000 m^3/h, when bunkering using port to ship, however this decreases drastically to only 50 m^3/h when utilizing truck to ship [139]. Nevertheless, bunkering truck to ship can be done on-demand, making it possible to order LNG to a specific port.

According to a report from DNV, NH_3 could achieve a fueling speed of 200 m^3/h when bunkering a passenger ship, with ship-to-ship bunkering [54]. The report found that the risk was not acceptable when evaluating shore to ship, due to the major consequences of a potential leak. The risk was deemed acceptable for ship to ship, as the NH_3 is stored in a refrigerated tank, as opposed to a heated one, causing smaller gas clouds and a shorter leakage duration. [54]

Regardless of the fuel utilized, a comprehensive risk analysis would be essential in deciding fueling solutions. New safety protocols need to be developed and implemented, as done in the case of FPS WAAL [38]. As fueling duration affects the ship's operational profile and flexibility, finding fast and safe solutions is essential if zero carbon or reductive fuels are going to become the norm.

5.6 Economics

It is evident that the transition to green systems is costly. The technology revolving around green energy carriers involves new costs connected to the fuel itself, replacement, and maintenance. However, subsidies and support from governmental organs exist to help realize greener alternatives. In the case of e.g. biofuels, there are no CO_2 fees [143].

Finding information regarding costs related to methanol, NH_3, and LNG systems proved to be a difficult task. Further research was done to gather prices of NH_3, methanol, and LNG generators. The data found for these energy carriers was not representative, and the industry was not willing to share prices. Thus, these fuels were not included.

The only clear thing was that of other alternative fuels, only NH_3 was supported through Enova.

5.6.1 Investment cost

The total cost to build a wellboat was approximately 300 – 400 MNOK in 2022, due to variations in material costs and inflation [22]. Therefore, the economic calculations are primarily done for the energy systems. This includes generators, fuel cells, batteries, and storage tanks. All the prices for each system are shown in Table 22.

Table 22: Investment costs excluding engineering costs based on table 16

Equipment	**Diesel**	**Hydrogen**	**Hybrid**
Main generator [NOK]	[redacted]	N/A	N/A
Essential generator [NOK]	[redacted]	N/A	N/A
PEM [NOK]	N/A	[redacted] [a] / [redacted] [b]	[redacted] [a] / [redacted] [b]
Battery [NOK]	N/A	N/A	[redacted] [a] / [redacted] [b]
Converter [NOK]	N/A	N/A	[redacted]
Tanks [NOK]	N/A [c]	[redacted]	[redacted]
Total [NOK]	[redacted]	[redacted]	[redacted]

[a] The initial investment cost does not include changing the equipment.
[b] Investment cost inclusive component replacement expenses.
[c] Assumed to be designed in the hull of the ship and therefore included in the engineering costs.

The reference system contains one main generator and 2 auxiliary generators, with prices of approximately [redacted] NOK/unit and [redacted] NOK/unit respectively [16]. This leads to a total cost of [redacted] NOK.

The fuel cells and tank solutions for both System 2 and 3 use the same design. The cost is approximately [redacted] NOK for the fuel cells and [redacted] NOK for the hydrogen tanks. The price for the hydrogen tanks carries a high degree of uncertainty. Through conversations with industry personnel, the issues regarding the price estimates were discussed. Regulations for hydrogen, used as fuel in the maritime sector, are not yet defined and each system needs to be approved individually. This leads to additional costs and a high degree of unpredictability. Future clarifications in regulations and standardized components would contribute to reductions in prices.

For System 3 an additional cost of approximately [redacted]NOK was added for the batteries. Systems 2 and 3 have initial investment costs of [redacted]NOK and [redacted]NOK respectively. The lifespan for a fuel cell is approximately 5 years, while it is 10 years for a battery. However, the life expectancy of the fuel cell in Systems 2 and 3 may differ due to the installed battery.

The cost of fuel cells is expected to drop to a far bigger extent, than that of batteries. Exchanging the PEMFC in 20 years will cost approximately [redacted], compared to a battery with a replacement cost of [redacted].

With a life expectancy of 25 years for the ship, the fuel cells need to be changed 4 times and the battery 2 times. Including these expenses in the investment costs results in an increase of approximately [redacted]NOK and [redacted]NOK for the fuel cell and battery. This results in a total investment cost of [redacted]NOK and [redacted]NOK respectively.

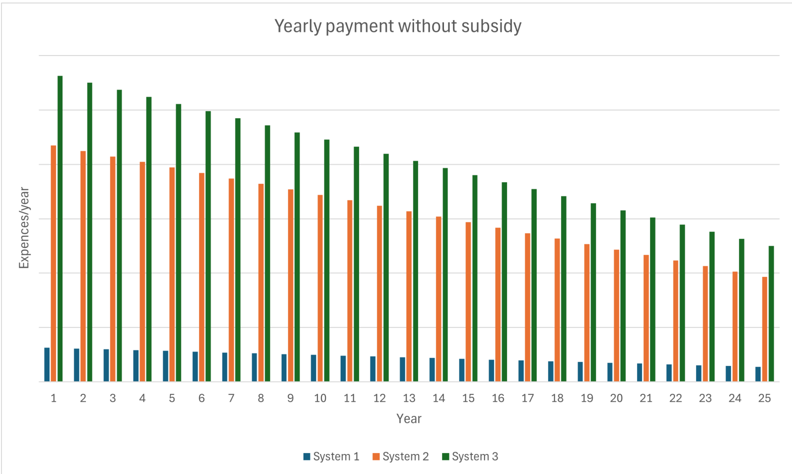


Figure 42: Down payment of loan with 5% interest without financial support

Assuming an interest of 5% and the entire investment cost financed through loans, the down payment over 25 years is as shown in figure 42. Although Systems 2 and 3 bring a significant increase to the investment costs some of them can be covered by financial support from organizations such as ENOVA. Figure 43 shows the down payment adjusted for financial support based on the boundaries of the subsidy scheme, as explained in section 4.3.6.

Compared with the reference system, the yearly down payment for Systems 2 and 3 with financial support, becomes 13.7% and 57.3% higher than System 1. This illustrates the importance and necessity of the subsidies if System 2 and 3 should be deemed as a viable option. Financial support is assumed to be necessary to make carbon-neutral fuels more viable. However, calculations for fuels, excluding hydrogen, were not included due to the lack of economic data surrounding these fuels, and the only alternative fuel valid for ENOVA financial support is NH_3. Nevertheless, the costs associated with these systems are expected to decrease in the near future.

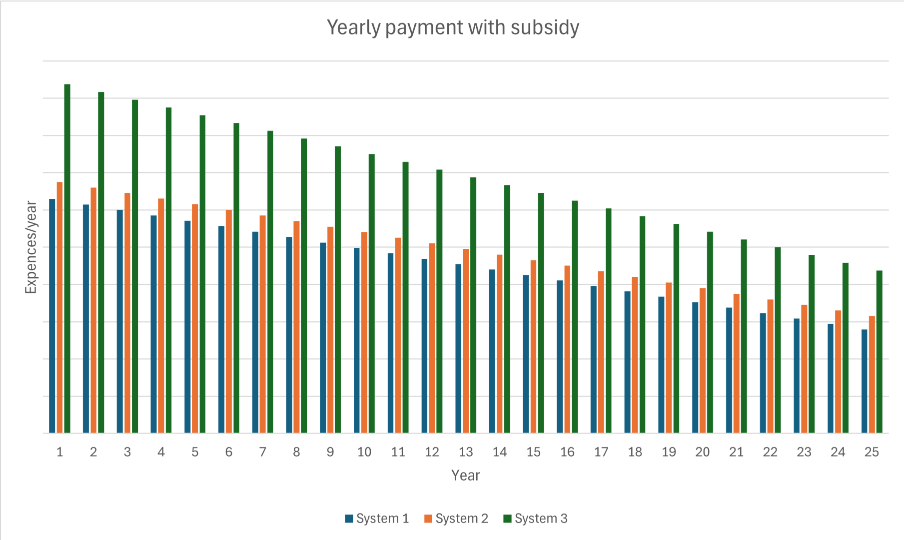


Figure 43: Down payment of loan with 5% interest with financial support

5.6.2 Variable cost

The calculations executed for the variable cost of the different systems only consist of fuel and emission taxes. With climate action strongly discouraging fossilized fuels, the diesel system shows an estimated increase of 2% in fuel costs as well as an increase in CO_2 taxes from appendix B. The yearly fuel expenses are shown in figure 44. Although the operational cost of the diesel system is expected to grow, the total cost over the 25 years, including investment cost, is still cheaper than the hydrogen system. However, when taking the possible subsidies into account, the total costs of Systems 2 and 3 are less expensive. This is due to the increase in $CO_2 - taxes$ over time.

The operational cost of System 3 reduces the expenses affiliated with fuel by an average of 8.11% over 25 years compared to System 2. The reduction is a result of the system efficiency increasing along with the installation of a battery.

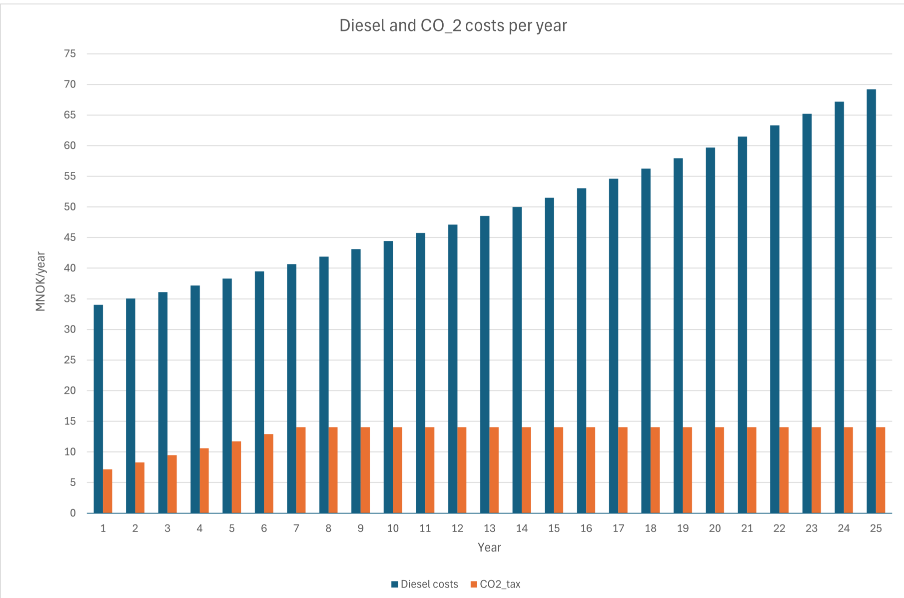


Figure 44: Diesel system fuel and emission cost.

Contrary to MGO, the price for hydrogen is predicted to decrease over time[92, 7], as production lines increase. As a result of this, the yearly fuel costs for the PEMFC system decrease significantly as shown in figure 45. The price utilized for these calculations was $61.3 NOK/kg$ from Section 4.3.6. With such a price, the operational costs for cases 1 and 2 seem viable.

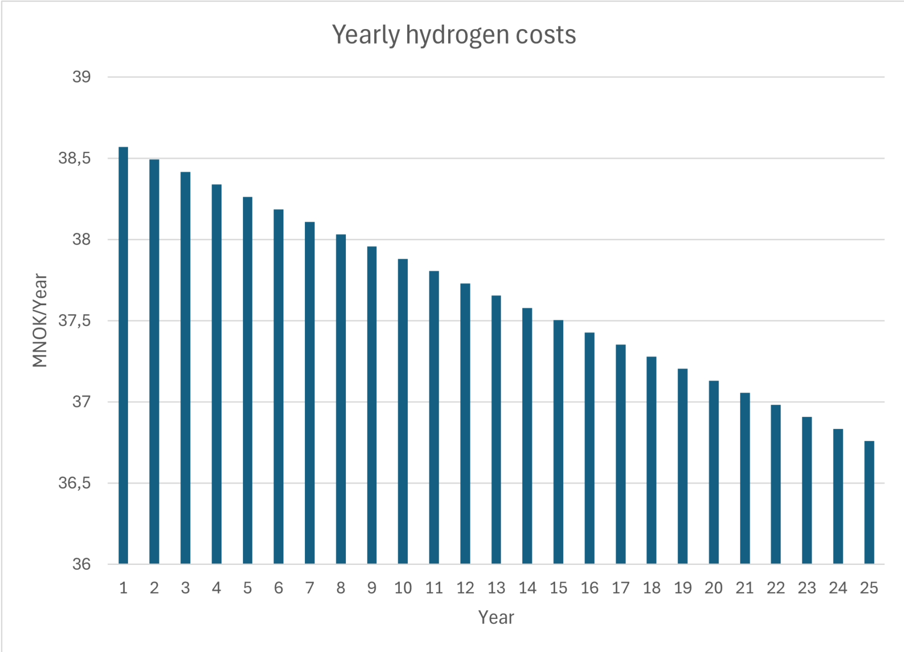


Figure 45: Hydrogen system fuel cost

System 3 has an equivalent reduction in yearly fuel expenses as System 2. The annual cost is represented in figure 46.

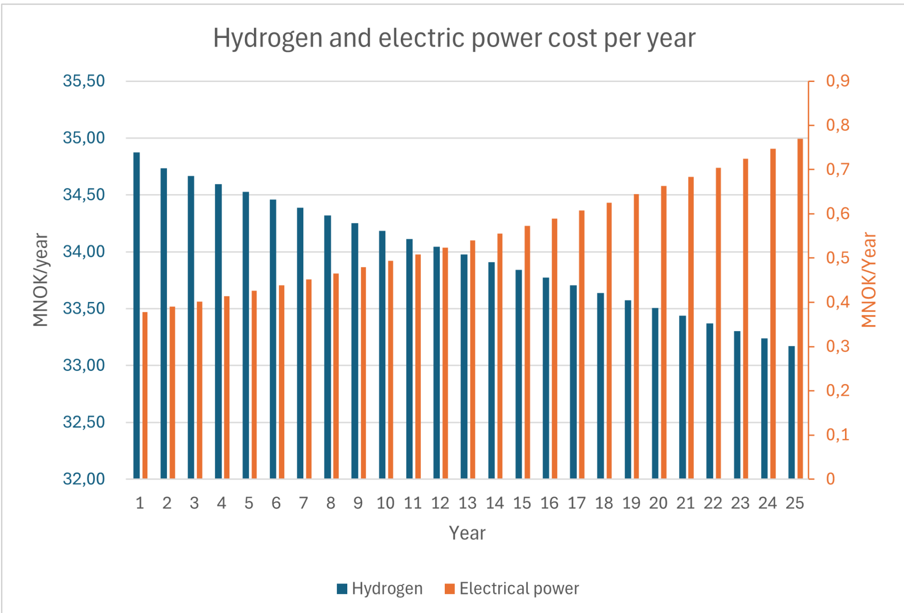


Figure 46: Hybrid system fuel and electrical power cost.

When comparing the three systems' annual fuel costs the hydrogen-based systems get cheaper each year. With similar costs at the beginning of the life cycle as shown in figure 47. In the later span of the life cycle, this price difference is expected to increase.

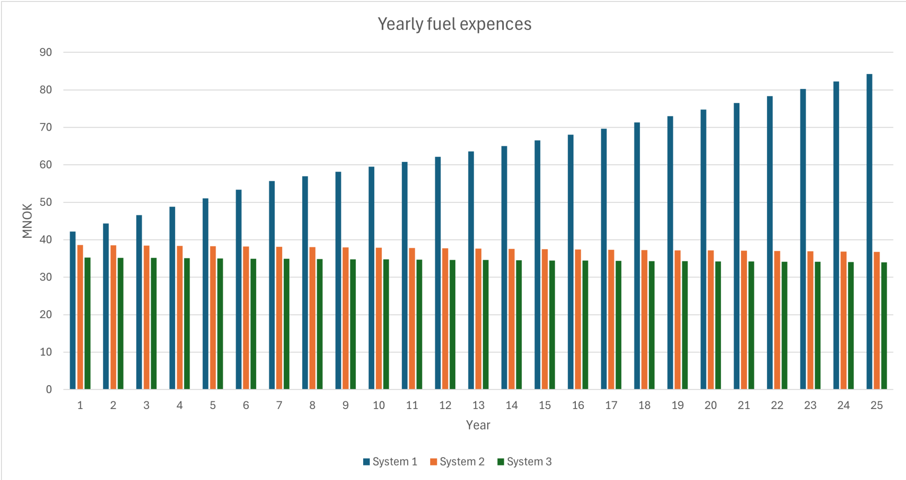


Figure 47: Fuel expenses for each system.

The yearly fuel and emission costs plus annual down payments are shown in Figure 48 and 49, with and without subsidy respectively. When comparing System 2 and 3 to the reference system, without subsidy, the fossil system is cheaper for the first 7 years. However, with the maximum subsidy from Enova, both hydrogen cases have lower costs.

[redacted]

Figure 48: Annual sum of OPEX and CAPEX with subsidy

[redacted]

Figure 49: Annual sum of OPEX and CAPEX without subsidy.

In summary, the fuel cost alone is more profitable with both the hydrogen and the hybrid system. In the future as CO_2 tax continues to rise, as well as the cost of green alternatives decrease, the profitability will continue to be more in favor of carbon reductive energy carriers. This is however in terms of fuel costs alone, without considering the added maintenance, and support systems that follow.

5.6.3 Emission and costs

The price of reducing GHG varies from system to system. The relationship between expenses and emissions cut is a vital ratio to give an indication of environmental impact in correlation to profit.

Table 23 presents the difference between average expenses for the fossil fuel-based system and the carbon reductive system. The calculation is divided in year 7. The results shows that both of the CH^2-based systems are more expensive for the first 7 year and less expensive after.

Table 23: Average cost difference without subsidy

	Year 1-7	**Year 7-25**
System 1 vs System 2	[redacted]NOK	[redacted]NOK
System 1 vs System 3	[redacted]NOK	[redacted]NOK

In table 24, the average price per CO_2e is shown. The first 7 years, the cost to reduce emission becomes [redacted]NOK/kg and [redacted]NOK/kg for system 2 and 3 respectively.

Table 24: Cost per kg emitted CO_2e without subsidy

	Year 1-7	**Year 7-25**
System 1 vs System 2	[redacted]NOK/kg	[redacted]NOK/kg
System 1 vs System 3	[redacted]NOK/kg	[redacted]NOK/kg

5.7 Sources of error

During the project assumptions and shortcomings in information lead to inaccurate but necessary alternative solutions. Amounting to possibly unrealistic, and misrepresenting outcomes.

Component interface

For the different systems simulated, components are analyzed from different companies and manufacturers. The calculations do not address the significance of how the different components work together. The interface of these technologies could contribute to losses which are not included in the results of this report.

System efficiencies

In this report it is assumed that the system efficiency of diesel, biodiesel, and methanol are the same, therefore making LHV the only variable of difference between them. The energy consumption for these are also based purely on empirical data, not through efficiency curves and the applied loads. Similarly, the NH_3 and LNG system use the same efficiency curve which gives an equal system efficiency. In reality, the efficiency would vary from system to system due to fuel characteristics such as viscosity, ignition temperature, etc.

The fuel cell efficiency curve used for calculating mass flow is only an approximation and serves as a placeholder for the actual efficiency values. The real operational characteristics at different loads are classified due to the information being sensitive to the industry contact. The methods used would not be altered directly in any way if the efficiency curve changed, only the output values. Although choices such as the installed capacity of the fuel cell could have been influenced.

Battery discharging and charging

In the python script it is assumed that the load applied to the battery is uniform (without fluctuations) and that the battery runs at ideal conditions. The discharge rate of the battery might therefore be inaccurate at a small scale. In the same way, losses connected to electrokinetics and self-discharge are also neglected due to the scope of this project. In other words, the battery works in an ideal fashion during computations.

Randomness within trips

Unlike cruises and ferries, wellboats are susceptible to random operation patterns, and certain trips will require substantially more energy than others. On the other hand, the ship could have weeks with low-load operations. The simulation does not account for these trips, which could impact the results both ways. The risk of dimensioning the power system wrong is thus present, which in turn affects the energy consumption and system price.

Diesel consumption values

Mainly deducted from values given by an anonymous industry contact, the consumption traits of the wellboat can suffer from inaccurate documentation. Another obstacle concerning the values provided from the fuel consumption arises when converting to hydrogen or battery solutions. Assumptions regarding how the system works in practice can also result in a skewed outcome regarding the consumption of fuel and total energy required.

Economy

Projections of future fuel cell costs are hard to find, although they are comparable to LIB in the sense that they are relevant as green alternatives in the future. Operating under the assumption that fuel cells will decrease in cost similarly to batteries, the estimation of fuel costs was made with a projection for batteries. The source showed a decline in price by 77% in 10 years (from 2010 to 2020) [130]. This assumption might be a long reach as PEMFC and batteries utilize different materials, production processes, etc.

While calculating the cost of the different systems, expenses affiliated with manual labor such as installing the components, project management, and so forth have been excluded. The uncertainty connected to these parameters makes it nearly impossible to give a reasonable price estimate.

The subsidies granted from ENOVA is not guaranteed to be handed out. Receiving 80% of the added value is a price won in a competition and the range of coverage can vary greatly.

The tax associated with NOx emissions is assumed to be constant contrary to the CO_2 emissions, based on the current tax value of "NOx-fondet" and its previous history. The assumption of a constant NOx tax is not necessarily applicable and can represent an uncertain factor in operational cost. The source informed that the NOx agreement is applicable to 2025 with the possible option of extension to 2027.[75]

Finding the cost of components, fuel, storage units, and so forth is based on conversations with relevant industries. It was frequently mentioned that to give an accurate estimate, factors outside the scope of this report would be necessary. This may have made the estimates given by industrial sources inaccurate and potentially misleading.[12, 13, 14, 15, 16]

Linearization of price estimates is useful for calculations, although when used to estimate values in a long time they tend to deviate from the real value. Factors such as future competitors, inflation, and more can both increase and decrease the cost of products.

5.8 Further work

During the writing of the thesis, topics outside the scope of the report, and with too little available information have been discovered. As the technology revolving around the green shift develops, potential studies investigating the aforementioned topics Would be interesting.

Life expectancy as a function of applied load

The life expectancy of various components investigated is a vague science. The effects of increasing load has not been tested to the extent to where it is an accurate estimate. An interesting research question could then be revolving around the life expectancy of these components as a function of load.

Emissions of NH_3

The process of mapping the emissions related to an NH_3 system proved to be a difficult task. The substance is notoriously known for its nitrogen content, which in turn could emit NOx. As NOx emissions are a far more volatile substance than CO_2.

Life cycle emissions

The scope of this report focuses mostly on the parameters and logistics aboard the boat. Throughout the report, technologies and fuels have been analyzed with the consequences in operation, but not with a focus on a more broad perspective such as the emissions during the production of fuels.

Areas for decarbonization

In this report, wellboats have been investigated as the main source of carbon reduction. As mentioned at the beginning of the report, the aquaculture industry spans far longer than just wellboats, and the potential for reducing emissions is in more sectors.

Economics

The marine industry is highly competitive and sensitive information regarding products is hard to find. Cost regarding components and retrofitting of vessels could be an interesting field to study to reveal a more accurate estimate of price points for alternative systems.

6 Conclusion

After reviewing the different systems, their various aspects, and their included solutions, some important findings have been made when comparing them to the current industry standard. The results indicate that as of now, the zero-emission systems need more support to become viable.

Today, diesel engines and generators are used to meet the power demand aboard most wellboats. Changing to an electric alternative presents minimal trouble in terms of installed power as long as the power-generating component, e.g. PEMFC, battery, or alternative engine, fits the boat in terms of volume. Various power configurations have different advantages and disadvantages. The hybrid configuration proved to be a more flexible and efficient system, indicating that the addition of batteries make a major difference in system performance.

As a consequence of the systems respective energy densities, the storage required to cover the energy demand varies. For System 2 and 3, the energy stored using the same volume as System 1 resulted in a used capacity of 53.03% and 47.96%. In both cases, the boat would be required to refuel every two or three days whereas a diesel system refuels every 19th day. If the goal is not to compromise existing practice and productivity too much, this would not be considered feasible at all.

Ammonia and LNG had a used capacity of 17.49% and 9.50%, and along with biodiesel and methanol, bunkering would be required at a much lower interval compared to for hydrogen. The bunkering intervals for these indicate that they are much more realistic choices in terms of alternative fuels.

It is clear that the standard of today is not sustainable from an environmental perspective. To maintain the production levels, a transitory solution comprised of fuels with a moderate energy density and emission profile seems to be a likely alternative while completely green alternatives continue to develop. The incentives to lower emissions are becoming more apparent as GHG emissions are being taxed to a bigger extent.

All the liquid fuels presented could be viable alternatives despite their emissions, until the market and solutions surrounding H_2 develop. Another alternative is to stick with H_2-based fuels, compromising the practice. The latter could be profitable as the price and infrastructure surrounding H_2 is expected to improve.

Diesel infrastructure is mature and accessible. Transitioning into H_2-based systems would require a huge push in infrastructural support to reason for the change. Charging sites and cheaper production would have to be established alongside an easy way to refuel H_2. The decentralized areas where many wellboat operate, along with their varying sailing patterns complicates the infrastructure matter.

Batteries on the other hand are becoming easier to implement as charging does not require such a complex process as with H_2. The cost is also improving as improvements within the battery industry are continuously being made. As shore power continues to be the cheapest energy available, installing a battery can also prove to be profitable in the long run.

All the alternative systems represent a higher cost. Mainly due to costly production and/or related costs due to infrastructural problems such as transport. As of today, subsidiaries and funding for the green shift exist, but not to the degree where green alternatives are profitable at the time of investment, but after some years time.

In a pespective regarding emissions saved per expense, System 2 was the most economically viable solution to reduce emissions.

Bibliography

[1] *6 gode grunner til å bruke landstrøm.* en-US. URL: https://www.enova.no/bedrift/sjotransport/maritimt-tema/landstrom/gode-grunner-til-a-bruke-landstrom/ (visited on 16/05/2024).

[2] *90% av havnene med mest utslipp har fått landstrøm med Enovastøtte - nå tar markedet over — Enova.* no. URL: https://kommunikasjon.ntb.no/pressemelding/17968638/90percent-av-havnene-med-mest-utslipp-har-fatt-landstrom-med-enovastotte-na-tar-markedet-over?publisherId=17848299 (visited on 11/05/2024).

[3] ABB and Bellona. *Helelektrisk havbruk Hvordan oppnå nullutslipp innen 2030?* Tech. rep. ABB/Bellona, 2021. URL: https://new.abb.com/docs/librariesprovider50/media/9akk107992a3675-helelektrisk-havbruk_hvordan-oppn%C3%A5-nullutslipp-innen-2030---sider.pdf?sfvrsn=c4716d0b_2.

[4] Bellona ABB. *Grønt skifte i havbruk Laks på landstrøm kan kutte 300 000 tonn CO2.* 2018. URL: https://new.abb.com/docs/librariesprovider50/media/abb---bellona---gr%C3%B8nt-skift-i-havbruk-med-laks-p%C3%A5-landstr%C3%B8m.pdf?sfvrsn=38238a14_4 (visited on 16/05/2024).

[5] *About.* en-US. Sept. 2018. URL: https://flagships.eu/about/ (visited on 10/05/2024).

[6] ABS. *Methanol Value Chain.* URL: https://ww2.eagle.org/en/Products-and-Services/sustainability/methanol-value-chain.html#tabs-cf2bbead8d-item-be94587da7-tab (visited on 18/05/2024).

[7] *Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies.* en-US. URL: https://theicct.org/publication/accounting-for-well-to-wake-carbon-dioxide-equivalent-emissions-in-maritime-transportation-climate-policies/ (visited on 22/05/2024).

[8] *ACEL Connect.* URL: https://www.acel.no/blogg/acel-connect-skal-gi-sikrere-fergestrom (visited on 27/03/2024).

[9] . *Akvakultur.* URL: https://portal.fiskeridir.no/portal/apps/webappviewer/index.html?id=87d862c458774397a8466b148e3dd147 (visited on 20/03/2024).

[10] A. Almansoori and A. Betancourt-Torcat. 'Design of optimization model for a hydrogen supply chain under emission constraints - A case study of Germany'. In: *Energy* 111 (Sept. 2016), pp. 414–429. ISSN: 0360-5442. DOI: 10.1016/j.energy.2016.05.123. URL: https://www.sciencedirect.com/science/article/pii/S0360544216307514 (visited on 15/05/2024).

[11] *Ane Maersk, the world's first large green methanol-enabled vessel, makes her first call in Dubai at DP World, Jebel Ali.* en. Aug. 2024. URL: https://www.maersk.com/news/articles/2024/05/08/ane-maersk-makes-her-first-call-in-dubai-at-dp-world (visited on 10/05/2024).

[12] Anonymous person 1. *Conversation.* Personal communication. Name kept anonymously by request. 2024.

[13] Anonymous person 2. *Conversation.* Personal communication. Name kept anonymously by request. 2024.

[14] Anonymous person 3. *Conversation.* Personal communication. Name kept anonymously by request. 2024.

[15] Anonymous person 4. *Conversation.* Personal communication. Name kept anonymously by request. 2024.

[16] Anonymous person 5. *Conversation.* Personal communication. Name kept anonymously by request. 2024.

[17] Anonymous person 6. *Conversation.* Personal communication. Name kept anonymously by request. 2024.

[18] Stakeholder AS. 'Kartlegging av utslipp fra fiskeri og havbruk i Norge'. no. In: (June 2022), p. 61. URL: https://zerokyst.no/wp-content/uploads/2022/08/Rapport-endelig-ZeroKyst-juni-2022.pdf (visited on 08/02/2024).

[19] Future Proof Shipping B.V. *ADN Safety Commitee Retrofit of FPS Waal with H2 fuel cell power generation system*. Tech. rep. Jan. 2023. URL: https://unece.org/sites/default/files/2023-06/WP.15-AC.2-42-inf4e.pdf (visited on 09/05/2023).

[20] Skyla Baily. *Effect of Fast-Charging on Lithium-Ion Battery Performance*. en. Section: Materials Article. Jan. 2022. URL: https://www.azom.com/article.aspx?ArticleID=21260 (visited on 15/02/2024).

[21] H. Barthelemy, M. Weber and F. Barbier. 'Hydrogen storage: Recent improvements and industrial perspectives'. In: *International Journal of Hydrogen Energy*. Special issue on The 6th International Conference on Hydrogen Safety (ICHS 2015), 19-21 October 2015, Yokohama, Japan 42.11 (Mar. 2017), pp. 7254–7262. ISSN: 0360-3199. DOI: 10.1016/j.ijhydene.2016.03.178. URL: https://www.sciencedirect.com/science/article/pii/S0360319916305559 (visited on 25/04/2024).

[22] Aslak Berge. *Sølvtrans skal bygge brønnbåter for over 4 mrd. kroner, men prissjokk på stål setter fokus på finansiering*. nb-NO. Mar. 2022. URL: https://ilaks.no/solvtrans-skal-bygge-bronnbater-for-over-4-mrd-kroner-men-prissjokk-pa-stal-setter-fokus-pa-finansiering/ (visited on 15/05/2024).

[23] *Bestemmelse om pengepolitikken - Lovdata*. URL: https://lovdata.no/dokument/LTI/forskrift/2019-12-13-1775 (visited on 19/05/2024).

[24] Levent Bilgili. 'A systematic review on the acceptance of alternative marine fuels'. In: *Renewable and Sustainable Energy Reviews* 182 (Aug. 2023), p. 113367. ISSN: 1364-0321. DOI: 10.1016/j.rser.2023.113367. URL: https://www.sciencedirect.com/science/article/pii/S1364032123002241 (visited on 09/05/2024).

[25] *Biodrivstoff i Norge - Miljødirektoratet*. URL: https://www.miljodirektoratet.no/ansvarsomrader/klima/transport/biodrivstoff/ (visited on 20/05/2024).

[26] *Biofuels: An obstacle to real climate solutions - Transport &...* en. Feb. 2024. URL: https://www.transportenvironment.org/articles/biofuels-an-obstacle-to-real-climate-solutions (visited on 20/05/2024).

[27] britannica. *Diesel engine - Fuel Injection, Efficiency, Emissions — Britannica*. en. Apr. 2024. URL: https://www.britannica.com/technology/diesel-engine (visited on 21/05/2024).

[28] *brønnbåt*. no. Aug. 2023. URL: https://snl.no/br%C3%B8nnb%C3%A5t (visited on 14/02/2024).

[29] *Bruk av legemidler i fiskeoppdrett i 2023*. no. Mar. 2024. URL: https://www.fhi.no/he/legemiddelbruk/fisk/bruk-av-legemidler-i-fiskeoppdrett/ (visited on 03/04/2024).

[30] Odne Stokke Burheim. *Engineering Energy Storage*. en. Google-Books-ID: 2uUlDwAAQBAJ. Academic Press, July 2017. ISBN: 978-0-12-814101-4.

[31] Abhinand Chandrasekar and Milinko Godjevac. *Hydrogen Refuelling Solutions for the H2 Barge 1 and FPS Waal*. Tech. rep. June 2023, p. 7. URL: https://futureproofshipping.com/wp-content/uploads/2023/06/ZEM-Ports-NS_Paper2_forPublishing-29-06-2023.pdf (visited on 09/05/2023).

[32] *Charging – Marine vessel charging systems*. en. URL: https://www.wartsila.com/marine/products/ship-electrification-solutions/shore-power/charging (visited on 15/05/2024).

[33] Christos Chryssakis, Dnv Gl and Christos Chryssakis. 'The authors would like to thank all those who contributed with their comments: Toril Grimstad Osberg, Rolf Skjong, Fenna van de Merwe, Johan Vedeler, Bjørn Johan Vartdal, Eirik Nyhus, Per Holmvang.' en. In: (Mar. 2015).

[34] Cicero. 2021. URL: https://pub.cicero.oslo.no/cicero-xmlui/bitstream/handle/11250/2755909/Rapport%202020%2004%20-%20web.pdf?sequence=1&isAllowed=y (visited on 15/05/2024).

[35] ClimateChangeConnection. *CO2 equivalents*. June 2020. URL: https://climatechangeconnection.org/emissions/co2-equivalents/ (visited on 22/05/2024).

[36] Bryan Comer and Liudmila Osipova. *Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies*. Tech. rep. INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION, 2021. URL: https://theicct.org/wp-content/uploads/2021/06/Well-to-wake-co2-mar2021-2.pdf.

[37] European comission. *Recommendations on energy storage*. en. URL: https://energy.ec.europa.eu/topics/research-and-technology/energy-storage/recommendations-energy-storage_en (visited on 15/02/2024).

[38] ADN Safety Commitee. *Retrofit of FPS Waal with H2 fuel cell power generation system*. Rapport. Future Proof Shipping, 2023. URL: https://unece.org/sites/default/files/2023-06/WP.15-AC.2-42-inf4e.pdf.

[39] Corvus. *Marine Fuel Cell Systems*. en-US. URL: https://corvusenergy.com/products/fuel-cell-systems/ (visited on 04/05/2024).

[40] Corvus. *Orca ESS*. 2024. URL: https://corvusenergy.com/products/energy-storage-solutions/corvus-orca-energy/ (visited on 22/05/2024).

[41] *Corvus Dolphin Energy NxtGen ESS*. en-US. URL: https://corvusenergy.com/products/energy-storage-solutions/corvus-dolphin-energy/ (visited on 19/05/2024).

[42] Xiaoti Cui, Søren Knudsen Kær and Mads Pagh Nielsen. 'Energy analysis and surrogate modeling for the green methanol production under dynamic operating conditions'. In: *Fuel* 307 (Jan. 2022), p. 121924. ISSN: 0016-2361. DOI: 10.1016/j.fuel.2021.121924. URL: https://www.sciencedirect.com/science/article/pii/S0016236121018019 (visited on 11/05/2024).

[43] Kjersti Dalfest. *Fuella vil bygge grønt ammoniakkanlegg i Nordland (2 TWh) — Montel News - English*. Apr. 2022. URL: https://montelnews.com/no/news/1314562/fuella-vil-bygge-grnt-ammoniakkanlegg-i-nordland (visited on 19/05/2024).

[44] Karolis Dambrauskas et al. *Energies — Free Full-Text — A Method for Efficiency Determination of Permanent Magnet Synchronous Motor*. URL: https://www.mdpi.com/1996-1073/13/4/1004 (visited on 03/04/2024).

[45] *Det norske hydrogenlandskapet kartlagt*. no. URL: https://www.hydrogen.no/aktuelt/nyheter/det-norske-hydrogenlandskapet-er-kartlagt (visited on 26/03/2024).

[46] dnv.com. *Why LNG as fuel*. en. URL: https://www.dnv.com/maritime/insights/topics/lng-as-marine-fuel/ (visited on 14/05/2024).

[47] electronicoffice electronicoffice electronicoffice. *What is the recommended SOC range for maintaining optimal battery health in electric vehicles? - Electronic Office Systems*. en-US. Section: Uncategorized Archives. Oct. 2023. URL: https://www.electronicofficesystems.com/2023/10/11/what-is-the-recommended-soc-range-for-maintaining-optimal-battery-health-in-electric-vehicles/ (visited on 10/04/2024).

[48] *Elektrisitetspriser*. nb. URL: https://www.ssb.no/energi-og-industri/energi/statistikk/elektrisitetspriser (visited on 01/03/2024).

[49] Lars Ivar Elvertro. *Pilot-E - verdens første hydrogendrevne arbeidsfartøy*. nb-NO. Feb. 2024. URL: https://www.moenmarin.no/pilot-e-verdens-forste-hydrogendrevne-arbeidsfartoy/ (visited on 14/05/2024).

[50] Corvus Energy. *Corvus awarded battery supply for the world's largest Battery Electric Ship*. en-US. Aug. 2023. URL: https://corvusenergy.com/corvus-awarded-battery-supply-for-the-worlds-largest-battery-electric-ship/ (visited on 11/05/2024).

[51] Corvus Energy. *Corvus Energy awarded contract with NOV for ESS delivery to offshore drilling rig*. en-US. Nov. 2020. URL: https://corvusenergy.com/corvus-energy-awarded-contract-with-nov-for-ess-delivery-to-offshore-drilling-rig/ (visited on 18/05/2024).

[52] *Enova*. en-US. URL: https://enova.cust.avento.no/landstrom/kart/ (visited on 11/05/2024).

[53] Enova. *Hydrogen i fartøy - Enova*. nb-NO. URL: https://www.enova.no/bedrift/sjotransport/hydrogen-i-fartoy/ (visited on 23/04/2024).

[54] Ksenia Zakariyya et.Al. 'AMMONIA BUNKERING OF PASSENGER VESSEL - CONCEPT QUANTITATIVE RISK ASSESSMENT'. In: (2021). URL: https://grontskipsfartsprogram.no/wp-content/uploads/2021/07/Ammonia-bunkering-of-passenger-vessel-Concept-quantitative-risk-assessment.pdf.

[55] fassmer.de. *34m Work Boat*. en-US. URL: https://www.fassmer.de/en/shipbuilding/products/multi-purpose-vessels/34m-work-boat (visited on 14/05/2024).

[56] Feadship. *Feadship ushers in the fuel-cell era with the launch of 118.80-metre...* en. Apr. 2024. URL: https://www.feadship.nl/press/feadship-ushers-in-the-fuel-cell-era-with-the-launch-of-118-80-metre-project-821 (visited on 09/05/2024).

[57] *Ferry Charger*. URL: https://www.ferrycharger.com/en/ferry-charger (visited on 27/03/2024).

[58] Finansdepartementet. *Karbonprisbaner for bruk i samfunnsøkonomiske analyser i 2024*. nb-NO. Innhold. Publisher: regjeringen.no. Dec. 2023. URL: https://www.regjeringen.no/no/tema/okonomi-og-budsjett/statlig-okonomistyring/karbonprisbaner-for-bruk-i-samfunnsokonomiske-analyser-i-2024/id3020031/ (visited on 18/05/2024).

[59] fiskerforum.com. *Aas Mek awards contract for wellboat pumps - FiskerForum*. Section: Aquaculture. Jan. 2020. URL: https://fiskerforum.com/aas-mek-awards-contract-for-wellboat-pumps/ (visited on 14/05/2024).

[60] Nærings-og fiskeridepartementet. *Melder Norge på europeisk batterisatsing*. nb-NO. Pressemelding. Publisher: regjeringen.no. Mar. 2023. URL: https://www.regjeringen.no/no/aktuelt/melder-norge-pa-europeisk-batterisatsing/id2966796/ (visited on 15/02/2024).

[61] *Fourth IMO GHG Study 2020*. EN. Rapport. 2018. URL: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf.

[62] Mikael Hansen Furberg. 'Sammenlikning av mekanisk og termisk avlusing: Klekkesuksess og larveutvikling fra eggstrenger med vurdering av smittepotensial hos lakselus (Lepeophtheirus salmonis)'. nob. Accepted: 2022-07-09T17:22:36Z. MA thesis. NTNU, 2022. URL: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/3004413 (visited on 31/01/2024).

[63] Cecilia Gabrielii. *Ammonia: From cleaning product to maritime fuel*. en-GB. Feb. 2023. URL: https://blog.sintef.com/sintefenergy/ammonia-from-cleaning-product-to-maritime-fuel/ (visited on 12/05/2024).

[64] Cecilia Gabrielii. *Thermal storage and heat pumps: a step towards zero-emission cruise ships*. en-GB. Nov. 2021. URL: https://blog.sintef.com/sintefenergy/thermal-storage-and-heat-pumps-a-step-towards-zero-emission-cruise-ships/ (visited on 16/05/2024).

[65] GreenH. *Torghatten Nord og GreenH har signert avtale om leveranse av hydrogen*. nb-NO. Aug. 2023. URL: https://greenh.no/torghatten-nord-og-greenh-har-signert-avtale-om-leveranse-av-hydrogen/ (visited on 16/05/2024).

[66] *Groundbreaking First Ammonia Engine Test Completed*. en. URL: https://www.man-es.com/company/press-releases/press-details/2023/07/13/groundbreaking-first-ammonia-engine-test-completed (visited on 19/05/2024).

[67] Marius Guttormsen. *Norsk verft skal bygge verdens største hydrogenferger*. nb-NO. Section: dk. Apr. 2024. URL: https://www.nrk.no/nordland/norsk-verft-skal-bygge-verdens-storste-hydrogenferger-1.16848858 (visited on 09/05/2024).

[68] Torkil Marsdal Hanssen. *MOEN bygger verdens første hydrogendrevne arbeidsbåt*. nb-NO. June 2022. URL: https://moen.no/2022/06/moen-bygger-verdens-forste-hydrogendrevne-arbeidsbat-for-havbruk/ (visited on 10/05/2024).

[69] NY state department of health. *The Facts About Ammonia*. URL: https://www.health.ny.gov/environmental/emergency/chemical_terrorism/ammonia_general.htm (visited on 22/02/2024).

[70] Trygve Holtebekk, Bjørn Pedersen and Geir Martin Haarberg. *brenselcelle*. no. Feb. 2024. URL: https://snl.no/brenselcelle (visited on 18/05/2024).

[71] Kjetil Malkenes Hovland. *Bygger hydrogenskip i Norge*. nb. Apr. 2024. URL: https://e24.no/i/Ey45QA (visited on 09/05/2024).

[72] *Hydrogen Storage Tank, Gas Transport 40ft Hydrogen Tank High Pressure Hydrogen Gas Cylinder TPED Certificated High Pressure Package Structure For Transportation, Hydrogen Storage Tank for sale, Hydrogen Storage Tank price*. en. URL: https://www.heatingstoragetank.com/sale-14818557-gas-transport-40ft-hydrogen-tank-high-pressure-hydrogen-gas-cylinder-tped-certificated-high-pressure.html (visited on 21/05/2024).

[73] *HyFuel*. en-US. URL: https://www.oceanhywaycluster.no/projectlist/h2-production-fjord-base (visited on 26/03/2024).

[74] IEA. *Global hydrogen production CO2 emissions and average emissions intensity in the Net Zero Scenario*. en-GB. Oct. 2023. URL: https://www.iea.org/energy-system/low-emission-fuels/hydrogen (visited on 02/05/2024).

[75] *Innbetalingssatser*. no. URL: https://www.noxfondet.no/artikler/innbetalingssatser/ (visited on 03/04/2024).

[76] *Introduction to NH3 Fuel*. en-US. URL: https://nh3fuelassociation.org/introduction/ (visited on 09/05/2024).

[77] Yuki Ishimoto et al. 'Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers'. In: *International Journal of Hydrogen Energy* 45.58 (Nov. 2020), pp. 32865–32883. ISSN: 0360-3199. DOI: 10.1016/j.ijhydene.2020.09.017. URL: https://www.sciencedirect.com/science/article/pii/S036031992033384X (visited on 15/05/2024).

[78] *Kart over alternative drivstoff for sjøfarten - Kystverket*. URL: https://lavutslipp.kystverket.no/ (visited on 11/05/2024).

[79] Tammy Klein. *Methanol: A Future-Proof Fuel*. URL: https://www.methanol.org/wp-content/uploads/2020/03/Future-Fuel-Strategies-Methanol-Automotive-Fuel-Primer.pdf (visited on 08/05/2024).

[80] *Klima og miljø*. nb-NO. URL: https://www.salmar.no/baerekraft/klima-og-miljo/ (visited on 15/02/2024).

[81] Marius Knutsen. *World´s first: MF Hydra sails on liquid hydrogen*. en-GB. Mar. 2023. URL: https://maritimecleantech.no/2023/03/31/worlds-first-mf-hydra-sails-on-liquid-hydrogen/ (visited on 08/05/2024).

[82] *Kostnader for hydrogenproduksjon fra kraft i Norge*. Rapport. Enova, 2023. URL: https://www.enova.no/download?objectPath=upload_images/F0C522B2B9BC4A95A96677229E8EEC96.pdf&filename=Kostnader%20for%20hydrogenproduksjon%20fra%20kraft%20i%20Norge_Enova%202023.pdf.

[83] D P and Nagrath Kothari. *Electric machines*. Vol. 5. McGraw Hill, 2018. URL: https://www.amazon.com/Electric-Machines-Kothari/dp/935260640X.

[84] Justin Laddusaw et al. 'Combining a Fuel Cell and Ultracapacitor Bank to Power a Vertical Take-Off and Landing Unmanned Aerial System'. In: Aug. 2020. DOI: 10.1115/POWER2020-16560.

[85] laks.no. *Laks er viktig — Fra fjord til bord*. no. URL: https://laks.no/lakseproduksjon/ (visited on 16/05/2024).

[86] *Launch of Feadship 821 Superyacht with Liquid Hydrogen Storage and Fuel Cells*. May 2024. URL: https://hyexsafety.com/news/launch-of-feadship-821-superyacht-with-liquid-hydrogen-storage-and-fuel-cells/ (visited on 09/05/2024).

[87] Max Lin. *Methanol at pole position for Jan alternative fuel ship orders: DNV*. en. Feb. 2024. URL: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/shipping/020224-methanol-at-pole-position-for-jan-alternative-fuel-ship-orders-dnv (visited on 10/05/2024).

[88] Eivind Lona. *Nullutslipps havbruksfartøy - utredning av fartøystyper og relevant teknologi*. https://static1.squarespace.com/static/5d1c6c223c9d400001e2f407/t/6194c9cc38f289714cf6ae95/1637140942992/Nullutslipps+havbruksfartoy+-+utredning+av+fartoystyper+og+relevant+teknologi.pdf. 2021.

[89] Dana Lowell, Haifeng Wang and Nic Lutsey. *Assessment of the fuel cycle impact of liquefied natural gas as used in international shipping*. Rapport. The International Council on Clean Transportation, 2013. URL: https://theicct.org/sites/default/files/publications/ICCTwhitepaper_MarineLNG_130513.pdf.

[90] *M/S «AMPERE»*. nb-NO. Section: båtomtaler. Nov. 2014. URL: https://www.skipsrevyen.no/ms-ampere/1101941 (visited on 15/05/2024).

[91] *Må importere hydrogen til verdens første hydrogenferge — Kystens Næringsliv — Vi skaper kysten sammen!* URL: https://www.kystens.no/nyheter/ma-importere-hydrogen-til-verdens-forste-hydrogenferge/2-1-1600827 (visited on 25/04/2024).

[92] Wood Mackenzie. *Green hydrogen costs to fall by up to 64% by 2040 — Wood Mackenzie.* en. Aug. 2020. URL: https://www.woodmac.com/press-releases/green-hydrogen-costs-to-fall-by-up-to-64-by-2040/ (visited on 19/05/2024).

[93] *Maersk names first vessel of its large methanol-enabled fleet "Ane Maersk".* en. Jan. 2024. URL: https://www.maersk.com/news/articles/2024/01/26/maersk-names-first-vessel-of-its-large-methanol-enabled-fleet-ane-maersk (visited on 10/05/2024).

[94] Sofoklis S. Makridis. June 2016. URL: https://arxiv.org/pdf/1702.06015 (visited on 21/05/2024).

[95] *Marine.* en-US. URL: https://www.methanol.org/marine/ (visited on 19/05/2024).

[96] *MarineTraffic: Global Ship Tracking Intelligence — AIS Marine Traffic.* en. URL: https://www.marinetraffic.com/en/ais/home/centerx:-12.0/centery:25.0/zoom:4 (visited on 20/05/2024).

[97] *Maritim transport status.* no. URL: https://2022.enova.no/artikkel/maritim-transport-status (visited on 11/05/2024).

[98] Carlos Marques. *MARINE METHANOL Future-Proof Shipping Fuel.* Rapport. Methanol Institute, 2020. URL: https://www.methanol.org/wp-content/uploads/2023/05/Marine_Methanol_Report_Methanol_Institute_May_2023.pdf.

[99] Conor Martin et al. 'Demonstration of swirl-controlled 3D-printed mesoscale burner array using gaseous hydrocarbon fuels'. In: Jan. 2017. DOI: 10.2514/6.2017-1778.

[100] Mærsk Mckinney. *Managing emissions from ammonia-fueled vessels.* Mar. 2023. URL: https://cms.zerocarbonshipping.com/media/uploads/documents/Ammonia-emissions-reduction-position-paper_v4.pdf.

[101] Daniele Melideo and Umberto Desideri. 'The use of hydrogen as alternative fuel for ship propulsion: A case study of full and partial retrofitting of roll-on/roll-off vessels for short distance routes'. In: *International Journal of Hydrogen Energy* 50 (Jan. 2024), pp. 1045–1055. ISSN: 0360-3199. DOI: 10.1016/j.ijhydene.2023.10.142. URL: https://www.sciencedirect.com/science/article/pii/S0360319923052503 (visited on 08/05/2024).

[102] *Methanol as fuel heads for the mainstream in shipping.* en. URL: https://www.dnv.com/expert-story/maritime-impact/Methanol-as-fuel-heads-for-the-mainstream-in-shipping/ (visited on 15/05/2024).

[103] *METHANOL AS MARINE FUEL: ENVIRONMENTAL BENEFITS, TECHNOLOGY READINESS, AND ECONOMIC FEASIBLITY.* Rapport. IMO, 2016. URL: https://greenvoyage2050.imo.org/wp-content/uploads/2021/01/METHANOL-AS-MARINE-FUEL-ENVIRONMENTAL-BENEFITS-TECHNOLOGY-READINESS-AND-ECONOMIC-FEASIBLITY.pdf.

[104] *MF ≪Hydra≫.* nb-NO. Section: båtomtaler. Oct. 2021. URL: https://www.skipsrevyen.no/mf-hydra/1094069 (visited on 08/05/2024).

[105] *MF Ampere.* en-US. URL: https://corvusenergy.com/projects/mf-ampere/ (visited on 15/05/2024).

[106] Minol. 2024. URL: https://www.minol.no/getfile.php/1321758-1713165978/Internett/Filer/Prisliste%20uke%2016-2024.pdf.

[107] Bård Misund. *fiskeoppdrett.* no. Aug. 2023. URL: https://snl.no/fiskeoppdrett (visited on 26/01/2024).

[108] MIT. *The Future of Energy Storage.* en. May 2022. URL: https://energy.mit.edu/research/future-of-energy-storage/ (visited on 15/02/2024).

[109] Sofie Møller. 'Reduction of CO2 Emissions in the Salmon Farming Industry: The Potential for Energy Efficiency Measures and Electrification'. eng. Accepted: 2019-10-26T14:03:44Z. MA thesis. NTNU, 2019. URL: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2624655 (visited on 24/01/2024).

[110] Ramin Moradi and Katrina M. Groth. 'Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis'. In: *International Journal of Hydrogen Energy* 44.23 (May 2019), pp. 12254–12269. ISSN: 0360-3199. DOI: 10.1016/j.ijhydene.2019.03.041. URL: https://www.sciencedirect.com/science/article/pii/S0360319919309656 (visited on 25/04/2024).

[111] Thea Mørk. 'Energiomlegging av oppdrettsanlegg i Finnmark'. nob. Accepted: 2020-08-20T12:14:18Z Journal Abbreviation: Electrification of fish farms in Finnmark Publication Title: 76. MA thesis. Norwegian University of Life Sciences, Ås, 2020. URL: https://nmbu.brage.unit.no/nmbu-xmlui/handle/11250/2673213 (visited on 25/01/2024).

[112] Mowi. *Salmon Farming Industry Handbook 2019*. https://mowi.com/it/wp-content/uploads/sites/16/2020/06/Mowi-Salmon-Farming-Industry-Handbook-2020.pdf. 2020.

[113] *MS «Bjørg Pauline»*. nb-NO. Section: båtomtaler. Apr. 2021. URL: https://www.skipsrevyen.no/ms-bjorg-pauline/1094327 (visited on 10/05/2024).

[114] *MS «Ronja Storm»*. nb-NO. Section: båtomtaler. Dec. 2019. URL: https://www.skipsrevyen.no/ms-ronja-storm/1096248 (visited on 16/05/2024).

[115] mship.no. *Siemens electric motor Type 1RN4 560-6HM90-Z*. en-us. URL: https://mship.no/electric-motors/944-siemens-electric-motor-type-1rn4-560-6hm90-z.html (visited on 08/05/2024).

[116] Moritz Müller et al. 'Comparison of green ammonia and green hydrogen pathways in terms of energy efficiency'. In: *Fuel* 357 (Feb. 2024), p. 129843. ISSN: 0016-2361. DOI: 10.1016/j.fuel.2023.129843. URL: https://www.sciencedirect.com/science/article/pii/S0016236123024572 (visited on 10/05/2024).

[117] United Nations. *Causes and Effects of Climate Change*. en. Publisher: United Nations. URL: https://www.un.org/en/climatechange/science/causes-effects-climate-change (visited on 06/05/2024).

[118] Vera Navis. *Structural and Systems Detail Design for Wellboat "Ronja Explorer"*. en-GB. Oct. 2019. URL: https://veranavis.com/structural-and-systems-detail-design-for-wellboat-ronja-explorer/ (visited on 08/05/2024).

[119] Statistics Netherlands. *NOx co2 equivalent*. en-GB. webpagina. Last Modified: 0001-01-01T00:00:00+00:00. URL: https://www.cbs.nl/en-gb/news/2019/37/greenhouse-gas-emissions-down/co2-equivalent (visited on 06/05/2024).

[120] Nils Røkke. *Blue hydrogen: the real bridge between fossil fuels and renewable energy*. en. Feb. 2023. URL: https://www.sintef.no/en/latest-news/2023/blue-hydrogen-the-real-bridge-between-fossil-fuels-and-renewable-energy/ (visited on 02/05/2024).

[121] Andrea Arntzen Nistad et al. *Potensialet for reduserte klimagassutslipp og omstilling til lavutslippsamfunnet for norsk oppdrettsnæring*. Rapport. Asplan Viak, 2021. URL: https://7649011.fs1.hubspotusercontent-eu1.net/hubfs/7649011/Rapport%20-%20Energi%20og%20klimakartlegging%20havbruk%20-%20Av%20Asplan%20Viak%20og%20SINTEF%20Ocean.pdf.

[122] NOx-fondet. *What is NOx?* en. URL: https://www.noxfondet.no/en/articles/what-is-nox/ (visited on 06/05/2024).

[123] NRK. *Eksplosjon ved hydrogenstasjon*. nb-NO. Section: nyheter. June 2019. URL: https://www.nrk.no/nyheter/eksplosjon-ved-hydrogenstasjon-1.14582944 (visited on 22/02/2024).

[124] *NWS-Series*. en-US. URL: https://norwater.no/services/nws-series/ (visited on 16/05/2024).

[125] Anton Ochoa Bique and Edwin Zondervan. 'An outlook towards hydrogen supply chain networks in 2050 — Design of novel fuel infrastructures in Germany'. In: *Chemical Engineering Research and Design* 134 (June 2018), pp. 90–103. ISSN: 0263-8762. DOI: 10.1016/j.cherd.2018.03.037. URL: https://www.sciencedirect.com/science/article/pii/S0263876218301643 (visited on 15/05/2024).

[126] Bureau Veritas Marine & Offshore. *Methanol as fuel — Bureau Veritas Marine & Offshore*. en. URL: https://marine-offshore.bureauveritas.com/inside-look-methanol-fuel (visited on 22/05/2024).

[127] Oiltanking. *Marine Gasoil (MGO)*. en-US. URL: https://www.oiltanking.com/en/news-info/glossary/marine-gasoil-mgo.html (visited on 21/05/2024).

[128] *Optilice*. URL: https://optimar.no/optilice?gad_source=1&gclid=CjwKCAjw_LOwBhBFEiwAmSEQAVUaVNMOEnun0lYtGigbQcNdiBzIB47zj9cGATiDCLDm_p1kskokSxoCgO4QAvD_BwE (visited on 03/04/2024).

[129] *Optimising delousing strategies: developing best practice recommendations for maximal efficacy and positive welfare*. en. URL: https://www.hi.no/en/hi/nettrapporter/rapport-fra-havforskningen-en-2023-29 (visited on 03/04/2024).

[130] Sina Orangi et al. 'Historical and prospective lithium-ion battery cost trajectories from a bottom-up production modeling perspective'. In: *Journal of Energy Storage* 76 (2024), p. 109800. ISSN: 2352-152X. DOI: https://doi.org/10.1016/j.est.2023.109800. URL: https://www.sciencedirect.com/science/article/pii/S2352152X23031985.

[131] Nikita Pavlenko et al. *The climate implications of using LNG as a marine fuel*. Rapport. INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION, 2020. URL: https://cms.zerocarbonshipping.com/media/uploads/documents/Ammonia-emissions-reduction-position-paper_v4.pdf.

[132] extension Pennstate. *Unraveling the Hydrogen Rainbow: Green, Blue, and Gray Hydrogen Production*. en. URL: https://extension.psu.edu/unraveling-the-hydrogen-rainbow-green-blue-and-gray-hydrogen-production (visited on 06/05/2024).

[133] Konstantin Räuchle et al. 'Methanol for Renewable Energy Storage and Utilization'. en. In: *Energy Technology* 4.1 (2016). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ente.201500322, pp. 193–200. ISSN: 2194-4296. DOI: 10.1002/ente.201500322. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/ente.201500322 (visited on 11/05/2024).

[134] *Renewable Methanol*. en-US. URL: https://www.methanol.org/renewable/ (visited on 06/05/2024).

[135] Researchgate. *Figure 1. The working principle of PEMFC*. en. URL: https://www.researchgate.net/figure/The-working-principle-of-PEMFC_fig1_334222897 (visited on 15/02/2024).

[136] *Ressurser – Tjeldbergodden Utvikling*. nb-NO. URL: https://www.tbu.no/ressurser/ (visited on 18/05/2024).

[137] *Risikorapport norsk fiskeoppdrett 2022 - risikovurdering*. no. URL: https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-2022-12 (visited on 15/02/2024).

[138] Tyto Robotics. *AC vs DC vs BLDC Motor Efficiency Comparison*. en. URL: https://www.tytorobotics.com/blogs/articles/ac-vs-dc-motor-efficiency (visited on 03/04/2024).

[139] Giovanni Satta et al. 'LNG Bunkering Technologies in Ports: An Empirical Application of the SWOT Analysis'. In: *KMI International Journal of Maritime Affairs and Fisheries* 13.1 (2021). Publisher: Korea Maritime Institute, pp. 1–21. ISSN: 2799-4376, 2005-9795. DOI: 10.54007/ijmaf.2021.13.1.1. URL: http://www.kmij.org/archive/view_article?pid=ijmaf-13-1-1 (visited on 16/05/2024).

[140] Kendra Seymour. *LNG Bunkering in U.S. Ports: Change is Coming*. en-US. Dec. 2018. URL: https://stillwaterassociates.com/lng-bunkering-in-u-s-ports-change-is-coming/ (visited on 12/05/2024).

[141] *Simplifies storage and distribution – Glocal Green*. en-US. URL: https://glocalgreen.com/en/simplifies-storage-and-distribution/ (visited on 18/05/2024).

[142] Norges Sjømatråd. *Nøkkeltall*. URL: https://nokkeltall.seafood.no/ (visited on 26/01/2024).

[143] Skatteetaten. *Avgift på mineralske produkter*. no. URL: https://www.skatteetaten.no/bedrift-og-organisasjon/avgifter/saravgifter/om/mineralske-produkter/ (visited on 14/05/2024).

[144] Redaksjon Skipsrevyen. *HAV Design valgt til å utvikle ammoniakkdrevet brønnbåt*. nb-NO. Section: nyheter. Dec. 2023. URL: https://www.skipsrevyen.no/alternativt-drivstoff-ammoniakk-hav-design/hav-design-valgt-til-a-utvikle-ammoniakkdrevet-bronnbat/1599264 (visited on 10/05/2024).

[145] Redaksjon Skipsrevyen. *Storinvestering i norsk ammoniakk-startup*. nb-NO. Section: nyheter. Oct. 2023. URL: https://www.skipsrevyen.no/ammoniakk-yara/storinvestering-i-norsk-ammoniakk-startup/1584767 (visited on 20/05/2024).

[146] Susann Funderud Skogvang. *Fosen-saken*. no. Mar. 2024. URL: https://snl.no/Fosen-saken (visited on 19/05/2024).

[147] *STENA GERMANICA first non-tanker vessel in the world to be ship-to-ship bunkered with methanol, STENA GERMANICA first non-tanker vessel in the world to be ship-to-ship bunkered with methanol*. en. Jan. 2023. URL: https://www.shippax.com/en/news/stena-germanica-first-non-tanker-vessel-in-the-world-to-be-ship-to-ship-bunkered-with-methanol-.aspx (visited on 18/05/2024).

[148] *Stena Germanica RoPax Ferry*. en-US. Mar. 2015. URL: https://www.ship-technology.com/projects/stena-germanica-ropax-ferry/ (visited on 10/05/2024).

[149] Jake Stones. *ICIS QUARTERLY EUROPEAN HYDROGEN MARKETS UPDATE: Q4 2023*. en-US. June 2024. URL: https://www.icis.com/explore/resources/news/2024/02/06/10969378/icis-quarterly-european-hydrogen-markets-update-q4-2023 (visited on 07/05/2024).

[150] *Styringsrenten*. nb. URL: https://www.norges-bank.no/tema/pengepolitikk/Styringsrenten/ (visited on 19/05/2024).

[151] *Sustainability — Free Full-Text — Research on Energy Management Method of Fuel Cell/Supercapacitor Hybrid Trams Based on Optimal Hydrogen Consumption*. URL: https://www.mdpi.com/2071-1050/15/14/11234 (visited on 25/04/2024).

[152] sustainableships. *The State of Methanol as Marine Fuel 2023*. en-US. URL: https://www.sustainable-ships.org/stories/2023/methanol-marine-fuel (visited on 13/05/2024).

[153] Linquip Team. *Efficiency of Induction Motor: Calculation & Equation — Linquip*. en-US. Section: Efficiency Calculation. Sept. 2021. URL: https://www.linquip.com/blog/efficiency-of-induction-motor/ (visited on 03/04/2024).

[154] *The difference between green hydrogen and blue hydrogen*. en-US. URL: https://www.petrofac.com/media/stories-and-opinion/the-difference-between-green-hydrogen-and-blue-hydrogen/ (visited on 02/05/2024).

[155] *The Norwegian Hydrogen Landscape*. no. URL: https://www.hydrogen.no/faktabank/det-norske-hydrogenlandskapet (visited on 20/04/2024).

[156] *The race is on to build the world's first ammonia-powered ship*. en. Nov. 2022. URL: https://www.canarymedia.com/articles/sea-transport/the-race-is-on-to-build-the-worlds-first-ammonia-powered-ship (visited on 10/05/2024).

[157] *The world's first clean ammonia-powered container ship — Yara International*. en. Nov. 2023. URL: https://www.yara.com/corporate-releases/the-worlds-first-clean-ammonia-powered-container-ship/ (visited on 10/05/2024).

[158] *Thermolicer®*. nb-NO. URL: https://scaleaq.no/produkt/thermolicer/ (visited on 21/05/2024).

[159] *Torghatten Nord and GreenH have entered into a hydrogen delivery agreement*. en. URL: https://torghatten.no/en/about/news/fad37310-62a2-4e86-aec9-0e2cf4006c3f__i18n_en/torghatten-nord-and-greenh-have-entered-into-a-hydrogen-delivery-agreement (visited on 09/05/2024).

[160] Transport. *Biofuels*. en. Feb. 2024. URL: https://www.transportenvironment.org/topics/energy/biofuels (visited on 19/05/2024).

[161] tuev.de. *Hydrogen as an energy source — TÜV NORD*. en. URL: https://www.tuev-nord.de/en/company/energy/hydrogen/ (visited on 08/05/2024).

[162] UNSW. *Seven things you need to know about lithium-ion battery safety*. en. URL: https://www.unsw.edu.au/newsroom/news/2023/03/seven-things-you-need-to-know-about-lithium-ion-battery-safety (visited on 22/02/2024).

[163] USenergyInformation. *Use of diesel - U.S. Energy Information Administration (EIA)*. URL: https://www.eia.gov/energyexplained/diesel-fuel/use-of-diesel.php (visited on 15/02/2024).

[164] Muhammad R. Usman. 'Hydrogen storage methods: Review and current status'. In: *Renewable and Sustainable Energy Reviews* 167 (Oct. 2022), p. 112743. ISSN: 1364-0321. DOI: 10.1016/j.rser.2022.112743. URL: https://www.sciencedirect.com/science/article/pii/S1364032122006311 (visited on 25/04/2024).

[165] *Vellykket test av første hydrogenstasjon for den maritime sektoren*. no. URL: https://www.hydrogen.no/aktuelt/nyheter/vellykket-test-av-forste-hydrogenstasjon-for-den-maritime-sektoren (visited on 26/03/2024).

[166] Volvo. *Fuel use - how low can you go?* en. URL: https://www.volvoce.com/global/en/news-and-events/news-and-stories/2018/fuel-use-how-low-can-you-go/ (visited on 03/04/2024).

[167] Xiaoyu Wang, Jianzhong Zhu and Minfang Han. 'Industrial Development Status and Prospects of the Marine Fuel Cell: A Review'. en. In: *Journal of Marine Science and Engineering* 11.2 (Feb. 2023). Number: 2 Publisher: Multidisciplinary Digital Publishing Institute, p. 238. ISSN: 2077-1312. DOI: 10.3390/jmse11020238. URL: https://www.mdpi.com/2077-1312/11/2/238 (visited on 18/05/2024).

[168] Dennis Wiesenborn, Michael Rosendahl and Jason Webster. 'Vern Hofman, Extension agricultural engineer'. en. In: (Jan. 2006), p. 8. URL: https://library.ndsu.edu/ir/bitstream/handle/10365/5114/ae1305.pdf?sequence=1 (visited on 19/05/2024).

[169] Mengyao Yang and Jasmine Siu Lee Lam. 'Operational and economic evaluation of ammonia bunkering – Bunkering supply chain perspective'. In: *Transportation Research Part D: Transport and Environment* 117 (Apr. 2023), p. 103666. ISSN: 1361-9209. DOI: 10.1016/j.trd.2023.103666. URL: https://www.sciencedirect.com/science/article/pii/S1361920923000639 (visited on 12/05/2024).

[170] *Yara Clean Ammonia and Azane granted safety permit to build world's first low emission ammonia bunkering terminal — Yara International*. en. Mar. 2024. URL: https://www.yara.com/corporate-releases/yara-clean-ammonia-and-azane-granted-safety-permit-to-build-worlds-first-low-emission-ammonia-bunkering-terminal/ (visited on 18/05/2024).

[171] *Yara International and Azane Fuel Solutions to launch world's first carbon-free bunkering network, delivering green ammonia fuel to the shipping industry — Yara International*. en. Apr. 2022. URL: https://www.yara.com/news-and-media/news/archive/news-2022/yara-international-and-azane-fuel-solutions-to-launch-worlds-first-carbon-free-bunkering-network-delivering-green-ammonia-fuel-to-the-shipping-industry/ (visited on 20/05/2024).

Appendix

A

Python script used for calculations. The script is modular for the hybrid system, as well as ammonia/LNG. To get the results for LNG and ammonia the LHV has to be changed to the respective value. The script runs with the hydrogen system as default. To activate the battery one must change the variable ”Batteryswitch” to True.

```
"""
Script used for calculating parameters of diesel/biodiesel/methanol,
hybrid, hydrogen and LNG/Ammonia system.

"""

#packages
import numpy as np
import matplotlib.pyplot as plt



"""
Functions and base variables
"""

#Expression for efficiency as a function of load
def etafunc(loadinpercent):
    return -1.4579e-12 * loadinpercent**6 + 5.5857e-10 * loadinpercent**5
- 9.1261e-08 * loadinpercent**4 + 8.2835e-06 * loadinpercent**3 -
4.4912e-04 * loadinpercent**2 + 1.2831e-02 * loadinpercent + 4.0441e-01


#Computes massflow of hydrogen as a function of load and installed power
[kg/min]
def mdotfunc(loadindecimals,installedP): #NB fcpower i MW
    LHV=120 #LHV hydrogen
    return
((loadindecimals)*installedP/(etafunc(loadindecimals*100)*LHV))*60


#Accumulates values over time
def accumulate_array(arr):




    accumulated = []
    total = 0
    for num in arr:
        total += num
        accumulated.append(total)
    return accumulated

#load varying from 10 to 100% NB!!!!!!!!!!!!!!!!!
#This needs 400 interval points so that the efficiency regression is
legitimate.
load = np.linspace(10,100,400)



"""
Hydrogen parameters and consumption
"""

#installed power
installedpower = 4.08 #Installed power of fuel cell. Given in MW.
```

```
#Efficiency as a function of load#
eta = etafunc(load)

#massflow as a function of load at 4.08MW installed capacity
mdot4_08mw = mdotfunc(load/100,installedpower)

#Batteryswitch True = activated battery, False = not activated battery
batterySwitch = False



#loads for each process in MW
loads = {
        'transit12':2.65,
        'transit11':2.15,
        'transit10':1.885,
        'slowsteam':0.6,
        'manouvering':1.5,
        'delousing':1.8,
        'delousingheating':3.5,
        'loading':1.3,
        'unloading':1.3,
        'portstay': 0.25
        }


#Maximum load before the battery kicks in.
maxload = 1.885 #loads['transit10'] 1.885

#turns off portstay if battery is active and correcting FC loads due to
alleviation from battery
if batterySwitch == True:
    loads['portstay'] = 0
if batterySwitch == True and loads['transit12']>maxload:
    loads['transit12']=maxload
if batterySwitch == True and loads['transit11']>maxload:
    loads['transit11']=maxload
if batterySwitch == True and loads['transit10']>maxload:
    loads['transit10']=maxload
if batterySwitch == True and loads['slowsteam']>maxload:
    loads['slowsteam']=maxload
if batterySwitch == True and loads['manouvering']>maxload:
    loads['manouvering']=maxload
if batterySwitch == True and loads['delousing']>maxload:
    loads['delousing']=maxload
if batterySwitch == True and loads['delousingheating']>maxload:
    loads['delousingheating']=maxload
if batterySwitch == True and loads['loading']>maxload:
    loads['loading']=maxload
if batterySwitch == True and loads['unloading']>maxload:
    loads['unloading']=maxload


#Hydrogen consumption per minute for each process
H2con = {

'transit12':mdotfunc((loads['transit12']/installedpower),installedpower),
```

```
'transit11':mdotfunc((loads['transit11']/installedpower),installedpower),

'transit10':mdotfunc(loads['transit10']/installedpower,installedpower),

'slowsteam':mdotfunc(loads['slowsteam']/installedpower,installedpower),

'manouvering':mdotfunc(loads['manouvering']/installedpower,installedpower
),

'delousing':mdotfunc(loads['delousing']/installedpower,installedpower),

'delousingheating':mdotfunc(loads['delousingheating']/installedpower,inst
alledpower),
    'loading':mdotfunc(loads['loading']/installedpower,installedpower),

'unloading':mdotfunc(loads['unloading']/installedpower,installedpower),
    'portstay':mdotfunc(loads['portstay']/installedpower,installedpower)
    }



#Efficiency for each process
etaprocess = {
    'transit12':etafunc((loads['transit12']/installedpower)*100),
    'transit11':etafunc((loads['transit11']/installedpower)*100),
    'transit10':etafunc((loads['transit10']/installedpower)*100),
    'slowsteam':etafunc((loads['slowsteam']/installedpower)*100),
    'manouvering':etafunc((loads['manouvering']/installedpower)*100),
    'delousing':etafunc((loads['delousing']/installedpower)*100),

'delousingheating':etafunc((loads['delousingheating']/installedpower)*100
),
    'loading':etafunc((loads['loading']/installedpower)*100),
    'unloading':etafunc((loads['unloading']/installedpower)*100),
    'portstay':etafunc((loads['portstay']/installedpower)*100)
    }

#How much each processload is compared to installed power
processLoadPercent = {
    'transit12':loads['transit12']/installedpower,
    'transit11':loads['transit11']/installedpower,
    'transit10':loads['transit10']/installedpower,
    'slowsteam':loads['slowsteam']/installedpower,
    'manouvering':loads['manouvering']/installedpower,
    'delousing':loads['delousing']/installedpower,
    'delousingheating':loads['delousingheating']/installedpower,
    'loading':loads['loading']/installedpower,
    'unloading':loads['unloading']/installedpower,
    'portstay':loads['portstay']/installedpower
    }



#Liter diesel consumed per minute [L/min]
fuelC = {'transit12':568/60, #9.67
         'transit11':477/60, #7.95
```

```
        'transit10':418/60, #6.97
        'slowsteam':133/60, #2.217
        'manouvering':333/60, #5.55
        'delousing':367/60, #6.117
        'delousingheating':556/60, #9.27
        'loading':289/60, #4.817
        'unloading':289/60, #4.817
        'portstay':25/60} #0.417"

"""
Total time and zero-vectors for formatting of trip
"""
n = 48*60
minutes = np.array([i for i in range(n+1)])


transit12,transit11,transit10,slowsteam =
np.zeros(n+1),np.zeros(n+1),np.zeros(n+1),np.zeros(n+1)
manouvering,delousing,delousingheating =
np.zeros(n+1),np.zeros(n+1),np.zeros(n+1)
loading,unloading,portstay = np.zeros(n+1),np.zeros(n+1),np.zeros(n+1)
totalfuelc = np.zeros(n+1)



"""
Time distributions with hydrogenconsumptions
"""

manouvering[0:38] = H2con['manouvering']
slowsteam[38:73] = H2con['slowsteam']
transit10[73:107] = H2con['transit10']
transit11[107:130] = H2con['transit11']
transit12[130:147] = H2con['transit12']
transit11[147:170] = H2con['transit11']
transit10[170:205] = H2con['transit10']
slowsteam[205:239] = H2con['slowsteam']
manouvering[239:277] = H2con['manouvering']


delousingheating[277:312] = H2con['delousingheating']
delousing[312:858] = H2con['delousing']


manouvering[858:896] = H2con['manouvering']
slowsteam[896:931] = H2con['slowsteam']


transit10[931:966] = H2con['transit10']
transit11[966:988] = H2con['transit11']
transit12[988:1005] = H2con['transit12']
transit11[1005:1028] = H2con['transit11']
transit10[1028:1063] = H2con['transit10']
slowsteam[1063:1097] = H2con['slowsteam']
manouvering[1097:1136] = H2con['manouvering']

portstay[1136:1760] = H2con['portstay']
```

```
manouvering[1760:1798] = H2con['manouvering']
slowsteam[1798:1833] = H2con['slowsteam']

transit10[1833:1868] = H2con['transit10']
transit11[1868:1890] = H2con['transit11']
transit12[1890:1908] = H2con['transit12']
transit11[1908:1930] = H2con['transit11']
transit10[1930:1965] = H2con['transit10']
slowsteam[1965:1999] = H2con['slowsteam']
manouvering[1999:2038] = H2con['manouvering']

loading[2038:2166] = H2con['loading']
manouvering[2166:2204] = H2con['manouvering']
slowsteam[2204:2239] = H2con['slowsteam']

transit10[2239:2273] = H2con['transit10']
transit11[2273:2296] = H2con['transit11']
transit12[2296:2313] = H2con['transit12']
transit11[2313:2336] = H2con['transit11']
transit10[2336:2370] = H2con['transit10']
slowsteam[2370:2405] = H2con['slowsteam']
manouvering[2405:2443] = H2con['manouvering']

unloading[2443:2700] = H2con['unloading']

manouvering[2700:2738] = H2con['manouvering']
slowsteam[2738:2773] = H2con['slowsteam']
transit10[2773:2807] = H2con['transit10']
slowsteam[2807:2842] = H2con['slowsteam']
manouvering[2842:2880] = H2con['manouvering']

#Vector for hydrogen consumption per minute through time
totalH2consumption = transit12 + transit11 + transit10 + slowsteam +
manouvering + delousing + delousingheating + loading + unloading +
portstay


#Accumulated hydrogen through time
accumH2 = {
         'transit12':accumulate_array(transit12),
         'transit11':accumulate_array(transit11),
         'transit10':accumulate_array(transit10),
         'slowsteam':accumulate_array(slowsteam),
         'manouvering':accumulate_array(manouvering),
         'delousing':accumulate_array(delousing),
         'delousingheating':accumulate_array(delousingheating),
         'loading':accumulate_array(loading),
         'unloading':accumulate_array(unloading),
         'portstay':accumulate_array(portstay),
         'total':accumulate_array(totalH2consumption),
         }



#total H2 consumed for each process
```

```
H2mass = {
    'transit12': sum(transit12),
    'transit11':sum(transit11),
    'Transit 10 knots':sum(transit10),
    'Slowsteam':sum(slowsteam),
    'Manouvering':sum(manouvering),
    'Mechanical delousing':sum(delousing),
    'Thermal delousing':sum(delousingheating),
    'Loading':sum(loading),
    'Unloading':sum(unloading),
    'Portstay':sum(portstay),
    'Total':sum(totalH2consumption)
    }




#Loads for each process in MW, non-alleviated values are necessary for
the battery for loop.
loads = {
        'transit12':2.65,
        'transit11':2.15,
        'transit10':1.885,
        'slowsteam':0.6,
        'manouvering':1.5,
        'delousing':1.8,
        'delousingheating':3.5,
        'loading':1.3,
        'unloading':1.3,
        'portstay': 0.25
        }

if batterySwitch == True:
    loads['portstay'] = 0




"""
Time distributions with load
"""
manouvering[0:38] = loads['manouvering']
slowsteam[38:73] = loads['slowsteam']
transit10[73:107] = loads['transit10']
transit11[107:130] = loads['transit11']
transit12[130:147] = loads['transit12']
transit11[147:170] = loads['transit11']
transit10[170:205] = loads['transit10']
slowsteam[205:239] = loads['slowsteam']
manouvering[239:277] = loads['manouvering']


delousingheating[277:312] = loads['delousingheating']
delousing[312:858] = loads['delousing']
```

```
manouvering[858:896] = loads['manouvering']
slowsteam[896:931] = loads['slowsteam']


transit10[931:966] = loads['transit10']
transit11[966:988] = loads['transit11']
transit12[988:1005] = loads['transit12']
transit11[1005:1028] = loads['transit11']
transit10[1028:1063] = loads['transit10']
slowsteam[1063:1097] = loads['slowsteam']
manouvering[1097:1136] = loads['manouvering']

portstay[1136:1760] = loads['portstay']

manouvering[1760:1798] = loads['manouvering']
slowsteam[1798:1833] = loads['slowsteam']

transit10[1833:1868] = loads['transit10']
transit11[1868:1890] = loads['transit11']
transit12[1890:1908] = loads['transit12']
transit11[1908:1930] = loads['transit11']
transit10[1930:1965] = loads['transit10']
slowsteam[1965:1999] = loads['slowsteam']
manouvering[1999:2038] = loads['manouvering']

loading[2038:2166] = loads['loading']
manouvering[2166:2204] = loads['manouvering']
slowsteam[2204:2239] = loads['slowsteam']

transit10[2239:2273] = loads['transit10']
transit11[2273:2296] = loads['transit11']
transit12[2296:2313] = loads['transit12']
transit11[2313:2336] = loads['transit11']
transit10[2336:2370] = loads['transit10']
slowsteam[2370:2405] = loads['slowsteam']
manouvering[2405:2443] = loads['manouvering']

unloading[2443:2700] = loads['unloading']

manouvering[2700:2738] = loads['manouvering']
slowsteam[2738:2773] = loads['slowsteam']
transit10[2773:2807] = loads['transit10']
slowsteam[2807:2842] = loads['slowsteam']
manouvering[2842:2881] = loads['manouvering']

totalloads = transit12 + transit11 + transit10 + slowsteam + manouvering
+ delousing + delousingheating + loading + unloading + portstay




#Installed capacity (fixed value) MWh
installedCap = 3.941 #3.941

#Capacity vector for the installed battery (varies with time)
batteryCapacity = np.ones(n+1)*installedCap*0.8 #MWh 0.8 is because of
the limiting SoC being 80% to not damage the battery.
```

```
#charge rate
c_rate = 0.5

#efficiency at discharge and charge
batteryefficiency = 0.9

#Maximum load before the battery kicks in.
#maxload = 1.885 #loads['transit10'] 1.885

FCload = totalloads.copy()

batteryLoad = np.zeros(len(FCload)) #Empty array made for editing in the
for loop

dischargearr = np.zeros(len(FCload)) #Empty array made for accumulating
energy delivered by battery.

#Reduces fuel cell load to max load permitted and runs battery at the
same time using its capacity.
if batterySwitch == True:
    for i in range(len(FCload)):

        if FCload[i] > maxload and batteryCapacity[i] > installedCap*0.1:
#Criteria for discharge.
            batteryCapacity[i:] -= (FCload[i]-maxload)/60  #Discharges
the battery with the difference of peakload-maxload

            dischargearr[i:] += (FCload[i]-maxload)/60 #Accumulates the
energy delivered by the battery

            FCload[i] = (maxload)     #Sets the fuelcell load to the
maximum load specified

            batteryLoad[i] = totalloads[i]-maxload #Sets the battery load
to the difference in load alleviated


        elif FCload[i] == loads['portstay'] and batteryCapacity[i] <
installedCap*0.8: #Criterias for charging
            batteryCapacity[i:] += installedCap*(c_rate/60) #Updates the
capacity of the battery


        else:
            pass



def etafuncNH3(loadinpercent):
    return (48-40*np.exp((-loadinpercent*0.05)))/100

LHV = 18.6 #change to the heating value of chosen fuel (ammonia or lng).

def mdotfunc(loadindecimals,installedP): #NB fcpower i MW
    LHV = 18.6 #LHV pressurized ammonia 18.6 or use LHV for LNG 48.6
    return
((loadindecimals)*installedP/(etafuncNH3(loadindecimals*100)*LHV))*60
```

```
#Accumulates values over time
def accumulate_array(arr):
    accumulated = []
    total = 0
    for num in arr:
        total += num
        accumulated.append(total)
    return accumulated


load = np.linspace(0,101,400)


"""
Total time and zero-vectors for formatting of trip
"""
n = 48*60
minutes = np.array([i for i in range(n+1)])


transit12,transit11,transit10,slowsteam =
np.zeros(n+1),np.zeros(n+1),np.zeros(n+1),np.zeros(n+1)
manouvering,delousing,delousingheating =
np.zeros(n+1),np.zeros(n+1),np.zeros(n+1)
loading,unloading,portstay = np.zeros(n+1),np.zeros(n+1),np.zeros(n+1)
totalfuelc = np.zeros(n+1)

enginemaxpower = 2.28 #MW
generatormaxpower = 1.70 #MW

loads = {
        'transit12':2.65,
        'transit11':2.15,
        'transit10':1.885,
        'slowsteam':0.6,
        'manouvering':1.5,
        'delousing':1.8,
        'delousingheating':3.5,
        'loading':1.3,
        'unloading':1.3,
        'portstay': 0.25
        }

engineloads ={
        'transit12':2.65,
        'transit11':2.15,
        'transit10':1.885,
        'slowsteam':0.6,
        'manouvering':1.5,
        'delousing':1.8,
        'delousingheating':3.5,
        'loading':1.3,
        'unloading':1.3,
        'portstay': 0.25
        }

generatorloads = {
```

```
     'transit12':0,
     'transit11':0,
     'transit10':0,
     'slowsteam':0,
     'manouvering':0,
     'delousing':0,
     'delousingheating':0,
     'loading':0,
     'unloading':0,
     'portstay':0
     }


if engineloads['transit12'] > enginemaxpower:
    generatorloads['transit12'] = engineloads['transit12']-enginemaxpower
    engineloads['transit12'] = enginemaxpower
if engineloads['transit11'] > enginemaxpower:
    generatorloads['transit11'] = engineloads['transit11']-enginemaxpower
    engineloads['transit11'] = enginemaxpower
if engineloads['transit10'] > enginemaxpower:
    generatorloads['transit10'] = engineloads['transit10']-enginemaxpower
    engineloads['transit10'] = enginemaxpower
if engineloads['slowsteam'] > enginemaxpower:
    generatorloads['slowsteam'] = engineloads['slowsteam']-enginemaxpower
    engineloads['slowsteam'] = enginemaxpower
if engineloads['manouvering'] > enginemaxpower:
    generatorloads['manouvering'] = engineloads['manouvering']-
enginemaxpower
    engineloads['manouvering'] = enginemaxpower
if engineloads['delousing'] > enginemaxpower:
    generatorloads['delousing'] = engineloads['delousing']-enginemaxpower
    engineloads['delousing'] = enginemaxpower
if engineloads['delousingheating'] > enginemaxpower:
    generatorloads['delousingheating'] = engineloads['delousingheating']-
enginemaxpower
    engineloads['delousingheating'] = enginemaxpower
if engineloads['loading'] > enginemaxpower:
    generatorloads['loading'] = engineloads['loading']-enginemaxpower
    engineloads['loading'] = enginemaxpower
if engineloads['unloading'] > enginemaxpower:
    generatorloads['unloading'] = engineloads['unloading']-enginemaxpower
    engineloads['unloading'] = enginemaxpower
if engineloads['portstay'] > enginemaxpower:
    generatorloads['portstay'] = engineloads['portstay']-enginemaxpower
    engineloads['portstay'] = enginemaxpower


mdotengine = {

'transit12':mdotfunc((engineloads['transit12']/enginemaxpower),enginemaxp
ower),

'transit11':mdotfunc((engineloads['transit11']/enginemaxpower),enginemaxp
ower),

'transit10':mdotfunc(engineloads['transit10']/enginemaxpower,enginemaxpow
er),
```

```
'slowsteam':mdotfunc(engineloads['slowsteam']/enginemaxpower,enginemaxpow
er),

'manouvering':mdotfunc(engineloads['manouvering']/enginemaxpower,enginema
xpower),

'delousing':mdotfunc(engineloads['delousing']/enginemaxpower,enginemaxpow
er),

'delousingheating':mdotfunc(engineloads['delousingheating']/enginemaxpowe
r,enginemaxpower),

'loading':mdotfunc(engineloads['loading']/enginemaxpower,enginemaxpower),

'unloading':mdotfunc(engineloads['unloading']/enginemaxpower,enginemaxpow
er),

'portstay':mdotfunc(engineloads['portstay']/enginemaxpower,enginemaxpower
)
    }

mdotgenerator = {

'transit12':mdotfunc((generatorloads['transit12']/generatormaxpower),gene
ratormaxpower),

'transit11':mdotfunc((generatorloads['transit11']/generatormaxpower),gene
ratormaxpower),

'transit10':mdotfunc(generatorloads['transit10']/generatormaxpower,genera
tormaxpower),

'slowsteam':mdotfunc(generatorloads['slowsteam']/generatormaxpower,genera
tormaxpower),

'manouvering':mdotfunc(generatorloads['manouvering']/generatormaxpower,ge
neratormaxpower),

'delousing':mdotfunc(generatorloads['delousing']/generatormaxpower,genera
tormaxpower),

'delousingheating':mdotfunc(generatorloads['delousingheating']/generatorm
axpower,generatormaxpower),

'loading':mdotfunc(generatorloads['loading']/generatormaxpower,generatorm
axpower),

'unloading':mdotfunc(generatorloads['unloading']/generatormaxpower,genera
tormaxpower),

'portstay':mdotfunc(generatorloads['portstay']/generatormaxpower,generato
rmaxpower)
    }


mdottot = {
    'transit12':mdotengine['transit12']+mdotgenerator['transit12'],
```

```
    'transit11':mdotengine['transit11']+mdotgenerator['transit11'],
    'transit10':mdotengine['transit10']+mdotgenerator['transit10'],
    'slowsteam':mdotengine['slowsteam']+mdotgenerator['slowsteam'],
    'manouvering':mdotengine['manouvering']+mdotgenerator['manouvering'],
    'delousing':mdotengine['delousing']+mdotgenerator['delousing'],

'delousingheating':mdotengine['delousingheating']+mdotgenerator['delousin
gheating'],
    'loading':mdotengine['loading']+mdotgenerator['unloading'],
    'unloading':mdotengine['unloading']+mdotgenerator['unloading'],
    'portstay':mdotengine['portstay']+mdotgenerator['portstay'],
    }

manouvering[0:38] = mdottot['manouvering']
slowsteam[38:73] = mdottot['slowsteam']
transit10[73:107] = mdottot['transit10']
transit11[107:130] = mdottot['transit11']
transit12[130:147] = mdottot['transit12']
transit11[147:170] = mdottot['transit11']
transit10[170:205] = mdottot['transit10']
slowsteam[205:239] = mdottot['slowsteam']
manouvering[239:277] = mdottot['manouvering']


delousingheating[277:312] = mdottot['delousingheating']
delousing[312:858] = mdottot['delousing']


manouvering[858:896] = mdottot['manouvering']
slowsteam[896:931] = mdottot['slowsteam']


transit10[931:966] = mdottot['transit10']
transit11[966:988] = mdottot['transit11']
transit12[988:1005] = mdottot['transit12']
transit11[1005:1028] = mdottot['transit11']
transit10[1028:1063] = mdottot['transit10']
slowsteam[1063:1097] = mdottot['slowsteam']
manouvering[1097:1136] = mdottot['manouvering']

portstay[1136:1760] = mdottot['portstay']

manouvering[1760:1798] = mdottot['manouvering']
slowsteam[1798:1833] = mdottot['slowsteam']

transit10[1833:1868] = mdottot['transit10']
transit11[1868:1890] = mdottot['transit11']
transit12[1890:1908] = mdottot['transit12']
transit11[1908:1930] = mdottot['transit11']
transit10[1930:1965] = mdottot['transit10']
slowsteam[1965:1999] = mdottot['slowsteam']
manouvering[1999:2038] = mdottot['manouvering']

loading[2038:2166] = mdottot['loading']
manouvering[2166:2204] = mdottot['manouvering']
slowsteam[2204:2239] = mdottot['slowsteam']

transit10[2239:2273] = mdottot['transit10']
```

```
transit11[2273:2296] = mdottot['transit11']
transit12[2296:2313] = mdottot['transit12']
transit11[2313:2336] = mdottot['transit11']
transit10[2336:2370] = mdottot['transit10']
slowsteam[2370:2405] = mdottot['slowsteam']
manouvering[2405:2443] = mdottot['manouvering']

unloading[2443:2700] = mdottot['unloading']

manouvering[2700:2738] = mdottot['manouvering']
slowsteam[2738:2773] = mdottot['slowsteam']
transit10[2773:2807] = mdottot['transit10']
slowsteam[2807:2842] = mdottot['slowsteam']
manouvering[2842:2880] = mdottot['manouvering']

#Vector for hydrogen consumption per minute through time
totalNH3consumption = transit12 + transit11 + transit10 + slowsteam +
manouvering + delousing + delousingheating + loading + unloading +
portstay



accumNH3LNG = {
         'transit12':accumulate_array(transit12),
         'transit11':accumulate_array(transit11),
         'transit10':accumulate_array(transit10),
         'slowsteam':accumulate_array(slowsteam),
         'manouvering':accumulate_array(manouvering),
         'delousing':accumulate_array(delousing),
         'delousingheating':accumulate_array(delousingheating),
         'loading':accumulate_array(loading),
         'unloading':accumulate_array(unloading),
         'portstay':accumulate_array(portstay),
         'total':accumulate_array(totalNH3consumption),
         }
accumNH3LNGarr = np.array(accumNH3LNG['total'])*LHV/3600


NH3LNGmass = {
    'transit12': sum(transit12),
    'transit11':sum(transit11),
    'Transit 10 knots':sum(transit10),
    'Slowsteam':sum(slowsteam),
    'Manouvering':sum(manouvering),
    'Mechanical delousing':sum(delousing),
    'Thermal delousing':sum(delousingheating),
    'Loading':sum(loading),
    'Unloading':sum(unloading),
    'Portstay':sum(portstay),
    'Total':sum(totalNH3consumption)
    }

def kgco2(volumdiesel):
    return volumdiesel*2.67


def accumulate_array(arr):
```

```
    accumulated = []
    total = 0
    for num in arr:
        total += num
        accumulated.append(total)
    return accumulated



def NOxfunc(literdiesel):
    return literdiesel*0.89/1000*54.88 #0.85kg/l 44kg nox/tonndiesel

LHVdiesel = 42.8 #MJ/kg

#Diesel consumption rates
fuelC = {'transit12':568/60, #9.67
         'transit11':477/60, #7.95
         'transit10':418/60, #6.97
         'slowsteam':133/60, #2.217
         'manouvering':333/60, #5.55
         'delousing':367/60, #6.117
         'delousingheating':556/60, #9.27
         'loading':289/60, #4.817
         'unloading':289/60, #4.817
         'portstay':25/60} #0.417"




#Duration of the trip
n = 48*60
minutes = np.array([i for i in range(0,n+1)])



#Zero-vectors for formatting
transit12,transit11,transit10,slowsteam =
np.zeros(n+1),np.zeros(n+1),np.zeros(n+1),np.zeros(n+1)
manouvering,delousing,delousingheating =
np.zeros(n+1),np.zeros(n+1),np.zeros(n+1)
loading,unloading,portstay = np.zeros(n+1),np.zeros(n+1),np.zeros(n+1)
totalfuelc = np.zeros(n+1)

#Process loads in MW
loads ={
        'transit12':2.65,
        'transit11':2.15,
        'transit10':1.885,
        'slowsteam':0.6,
        'manouvering':1.5,
        'delousing':1.8,
        'delousingheating':3.5,
        'loading':1.3,
        'unloading':1.3,
        'portstay':0.25
        }

"""
```

```
Process distribution using diesel consumption rates
"""
manouvering[0:38] = fuelC['manouvering']
slowsteam[38:73] = fuelC['slowsteam']
transit10[73:107] = fuelC['transit10']
transit11[107:130] = fuelC['transit11']
transit12[130:147] = fuelC['transit12']
transit11[147:170] = fuelC['transit11']
transit10[170:205] = fuelC['transit10']
slowsteam[205:239] = fuelC['slowsteam']
manouvering[239:277] = fuelC['manouvering']


delousingheating[277:312] = fuelC['delousingheating']
delousing[312:858] = fuelC['delousing']


manouvering[858:896] = fuelC['manouvering']
slowsteam[896:931] = fuelC['slowsteam']


transit10[931:966] = fuelC['transit10']
transit11[966:988] = fuelC['transit11']
transit12[988:1005] = fuelC['transit12']
transit11[1005:1028] = fuelC['transit11']
transit10[1028:1063] = fuelC['transit10']
slowsteam[1063:1097] = fuelC['slowsteam']
manouvering[1097:1136] = fuelC['manouvering']

portstay[1136:1760] = fuelC['portstay']

manouvering[1760:1798] = fuelC['manouvering']
slowsteam[1798:1833] = fuelC['slowsteam']

transit10[1833:1868] = fuelC['transit10']
transit11[1868:1890] = fuelC['transit11']
transit12[1890:1908] = fuelC['transit12']
transit11[1908:1930] = fuelC['transit11']
transit10[1930:1965] = fuelC['transit10']
slowsteam[1965:1999] = fuelC['slowsteam']
manouvering[1999:2038] = fuelC['manouvering']

loading[2038:2166] = fuelC['loading']
manouvering[2166:2204] = fuelC['manouvering']
slowsteam[2204:2239] = fuelC['slowsteam']

transit10[2239:2273] = fuelC['transit10']
transit11[2273:2296] = fuelC['transit11']
transit12[2296:2313] = fuelC['transit12']
transit11[2313:2336] = fuelC['transit11']
transit10[2336:2370] = fuelC['transit10']
slowsteam[2370:2405] = fuelC['slowsteam']
manouvering[2405:2443] = fuelC['manouvering']

unloading[2443:2700] = fuelC['unloading']

manouvering[2700:2738] = fuelC['manouvering']
slowsteam[2738:2773] = fuelC['slowsteam']
```

```
transit10[2773:2807] = fuelC['transit10']
slowsteam[2807:2842] = fuelC['slowsteam']
manouvering[2842:2881] = fuelC['manouvering']

totalfuelconsumption = transit12 + transit11 + transit10 + slowsteam +
manouvering + delousing + delousingheating + loading + unloading +
portstay



#Accumulated diesel through time L
accum = {
         'transit12':accumulate_array(transit12),
         'transit11':accumulate_array(transit11),
         'transit10':accumulate_array(transit10),
         'slowsteam':accumulate_array(slowsteam),
         'manouvering':accumulate_array(manouvering),
         'delousing':accumulate_array(delousing),
         'delousingheating':accumulate_array(delousingheating),
         'loading':accumulate_array(loading),
         'unloading':accumulate_array(unloading),
         'portstay':accumulate_array(portstay),
         'total':accumulate_array(totalfuelconsumption),
         }

accumdieselarr = np.array(accum['total'])*0.86*LHVdiesel/3600 #GIVEN IN
ENERGY [MWh]

#Total dieselvolumes consumed by each process
dieselvolumes = {
    'transit12': sum(transit12),
    'transit11':sum(transit11),
    'Transit 10 knots':sum(transit10),
    'Slowsteam':sum(slowsteam),
    'Manouvering':sum(manouvering),
    'delousing':sum(delousing),
    'Thermal delousing':sum(delousingheating),
    'loading':sum(loading),
    'unloading':sum(unloading),
    'Portstay':sum(portstay),
    'Total':sum(totalfuelconsumption)
         }
```

B

År	(1) Kvotepliktig utslipp (unntatt luftfart og petroleum)	(2) Ikke-kvotepliktig utslipp	(3) Petroleum	(4) Luftfart	(5) Opptak og utslipp fra skog- og arealbruk
2023	798	952	1559	1447	798
2024	836	1135	1724	1611	836
2025	872	1317	1907	1796	872
2026	915	1500	2121	2016	915
2027	937	1682	2230	2230	937
2028	961	1865	2230	2230	961
2029	985	2047	2230	2230	985
2030	1010	2230	2230	2230	1010
2031	1065	2230	2230	2230	1065
2032	1123	2230	2230	2230	1123
2033	1185	2230	2230	2230	1185
2034	1249	2230	2230	2230	1249
2035	1318	2230	2230	2230	1318
2036	1390	2230	2230	2230	1390
2037	1466	2230	2230	2230	1466
2038	1546	2230	2230	2230	1546
2039	1631	2230	2230	2230	1631
2040	1720	2230	2230	2230	1720
2041	1743	2230	2230	2230	1743
2042	1766	2230	2230	2230	1766
2043	1789	2230	2230	2230	1789
2044	1812	2230	2230	2230	1812
2045	1836	2230	2230	2230	1836
2046	1860	2230	2230	2230	1860
2047	1885	2230	2230	2230	1885
2048	1909	2230	2230	2230	1909
2049	1935	2230	2230	2230	1935
2050	1960	2230	2230	2230	1960
2051	2038	2230	2230	2230	2038
2052	2120	2230	2230	2230	2120
2053	2205	2230	2230	2230	2205

kategori av utslipp

	Kategori utslipp	Pris første år	Pris frem til 2030	Pris 2031–2100
1	Kvotepliktige utslipp – med unntak av luftfart og petroleum	Gjennomsnittlig pris på EU ETS-kvoter siste måned før publisering av prisbane.	Bruke noterte forward-priser som i dag foreligger for de nærmeste årene, og deretter en fremskrevet videreføring av den forventede prisutviklingen. Omregnet til faste norske kroner.	Følger det internasjonale energibyråets «Announced Pledges Scenario» frem til 2050. For senere år øker prisen med kalkulasjonsrenten for samfunnsøkonomiske analyser.
2	Ikke-kvotepliktig utslipp	Den generelle satsen i CO_2-avgiften for mineralske produkter.	Gradvis økning til 2 000 kroner i 2030 (prisnivå 2020) (CO_2-avgift i 2030 som signalisert i Klimaplan 2021–2030.)	Det varslede nivået for 2030 holdes reelt uendret frem til langsiktige karbonpriser på kvotepliktig utslipp når samme nivå. Deretter prises ikke-kvotepliktige utslipp og kvotepliktige utslipp likt.
3	Petroleum	Kvotepris som i 1, med påslag for CO_2-avgiften for petroleum (opp til et tak på 2 000 kroner)	Utvikling i kvotepris som i 1, med påslag for gradvis økning av CO_2-avgiften for petroleum (opp til et tak på 2 000 kroner). (summen av kvotepris og CO_2-avgift for sektoren som signalisert i Klimaplan 2021–2030)	Som 2

4	Luftfart	Kvotepris som i 1, med påslag for CO_2-avgiften for luftfart (opp til et tak på 2 000 kroner)	Utvikling i kvotepris som i 1, med påslag for gradvis økning av CO_2-avgiften for luftfart (opp til et tak på 2 000 kroner). (summen av kvotepris og CO_2-avgift for sektoren som signalisert i Klimaplan 2021–2030)	Som 2
5	Opptak og utslipp i skog- og arealbruk	Som 1	Som 1	Som 1

Tabell 2. Priser som skal benyttes på klimagassutslipp i samfunnsøkonomiske analyser for utslipp i årene 2023–2100

Alle priser i norske kroner. Prisnivå 2023. Valutakurs 10,25 kroner/euro benyttet.

År	(1) Kvotepliktig utslipp (unntatt luftfart og petroleum)	(2) Ikke-kvotepliktig utslipp	(3) Petroleum	(4) Luftfart	(5) Opptak og utslipp fra skog- og arealbruk
2023	798	952	1559	1447	798
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2029	985	2047	2230	2230	985
2030	1010	2230	2230	2230	1010
2031	1065	2230	2230	2230	1065
2032	1123	2230	2230	2230	1123
2033	1185	2230	2230	2230	1185
2034	1249	2230	2230	2230	1249
2035	1318	2230	2230	2230	1318
2036	1390	2230	2230	2230	1390
2037	1466	2230	2230	2230	1466
2038	1546	2230	2230	2230	1546
2039	1631	2230	2230	2230	1631
2040	1720	2230	2230	2230	1720
2041	1743	2230	2230	2230	1743
2042	1766	2230	2230	2230	1766
2043	1789	2230	2230	2230	1789
2044	1812	2230	2230	2230	1812
2045	1836	2230	2230	2230	1836
2046	1860	2230	2230	2230	1860
2047	1885	2230	2230	2230	1885
2048	1909	2230	2230	2230	1909
2049	1935	2230	2230	2230	1935
2050	1960	2230	2230	2230	1960
2051	2038	2230	2230	2230	2038
2052	2120	2230	2230	2230	2120
2053	2205	2230	2230	2230	2205

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