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NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Sigurd Fluge Petterson, Marius Berg, Knut-Magnus Brautaset ,Hedda Gunnarsson Øyan

Sustainable Energy Systems For Sounder USV

Bachelor's thesis in Ingeniørfag, Fornybar Energi
Supervisor: Jacob Joseph Lamb
Co-supervisor: Pauline Zimmermann
May 2022

Kongsberg Maritime

NTNU
Norwegian University of
Science and Technology

KONGSBERG

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Sustainable Energy Systems For Sounder USV

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Rapporten frigitt etter ☐

Preface

This Bachelor thesis is written by four students at the Norwegian University of Science and Technology in Trondheim. The report finalises the students bachelor program at Renewable Energy Engineering at the Department of Energy and Process Engineering. It is written in the course FENT2900 Bachelor Thesis Renewable Energy, and is worth 20 credits. The assignment is written for Kongsberg Maritime in collaboration with Stian Michael Kristoffersen and Axel Albin Inge Relefors at Kongsberg Maritime AS.

The report analyses different propulsion systems for the Sounder USV produced by Kongsberg Maritime, and aims to suggest a more sustainable energy system. The group has received hand-on experience with conducting research and performing calculations concerning emissions, endurance, and costs.

We would like to thank our supervisors, Head of production, Stian Michael Kristoffersen, and Energy Specialist, Axel Albin Inge Relefors, for providing us with the informative discussions, necessary information and general counselling. We would also like to thank Thomas Petterson for giving us the opportunity to visit Kongsberg Maritime AS to observe the facilities.

Our internal supervisors, Jacob Joseph Lamb and Pauline Zimmermann, have also been helpful during the process of writing this BSc thesis. They have given us general help, guidance and thorough feedback throughout the project.

Trondheim, 20 may 2022

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Abstract

The world is facing a challenge regarding greenhouse gas emissions. An overhaul of energy-demanding sectors is needed to reduce emissions. Today, the marine sector emits 900 million tonnes of GHG each year, as most vessels still use carbon-based propulsion systems. Research is being conducted to change propulsion systems in the marine sector to more sustainable systems, either by a complete overhaul of the systems or by utilizing existing technology.

Currently, Kongsberg Maritimes Sounder USV uses a traditional diesel engine for propulsion. However, to reduce GHG emissions, Kongsberg considers alternatives to the current propulsion system.

The bachelor thesis aims to suggest a new propulsion system for the Sounder USV. Four different systems will be evaluated based on four different levels: endurance, feasibility, and technology readiness level, emissions, and cost. The primary goal is to suggest possible solutions for the vessel and highlight future solutions for a more sustainable energy system.

The first evaluated system utilized biofuels such as hydrotreated vegetable oil (HVO), fatty acid methyl esters (FAME), compressed biogas (CBG), and liquified biogas (LBG). The second system examined a fuel cell technology in relation to hydrogen use, where grey, blue and green hydrogen were evaluated. The third system utilized ammonia, considered by many to be the future of maritime propulsion. The last evaluated system was a hybrid system, combining a traditional internal combustion engine (ICE) with an energy storage system (ESS).

A case study was devised to determine an appropriate system. This accounted for endurance, costs, and emissions related to both investments required for the propulsion systems, as well as the daily fuel for one day of propulsion. A longer time period was also considered, evaluating the systems after 1000 days of propulsion.

After conducting the case study, the recommended propulsion system was the HVO biofuel system. Even though this system is more expensive than the conventional diesel system, its greenhouse gas savings (GHG) requires only 160 days of propulsion before the system will contribute to a decrease in emissions compared to the current system. The other biofuel solutions either lacked endurance or had a high price. Hydrogen and ammonia could be viable systems in the future but lacks infrastructure and TRL to be considered a present alternative. The hybrid systems had both high costs and emissions, especially related to the propulsion parts needed. Newfound technology might make some of the assumptions and premises in the report outdated with new research forthcoming. As a result, today's recommended propulsion system may not be the best solution in 10 years.

Sammendrag

Verden står ovenfor en utfordring relatert til klimagass utslipp. Flere energikrevende sektorer er nødt til å redusere sitt utslipp. Per i dag, er 900 millioner tonn klimagassutslipp tilknyttet den maritime sektoren, da flere fartøy fortsatt bruker karbonbaserte fremdriftssystemer. Forskning er satt i gang for å endre dagenes fremdriftssystemer i den maritime sektoren, til mer bærekraftige systemer, enten ved å endre hele systemet, eller ved å utnytte allerede etablert teknologi.

Kongsberg Maritimes Sounder USV bruker en tradisjonell dieselmotor for fremdrift. Kongsberg vurderer nå alternative fremdriftssystemer for å redusere klimagassutslipp.

Bacheloroppgaven har som mål å legge frem fire forskjellige bærekraftige fremdriftssystemer for Sounder USV og videre sammenligne disse systemene basert på: kostnad, utslipp, tilgjengelighet, rekkevidde og teknologiens modenhet. Oppgavens hovedmål er å legge frem mulige fremdriftsløsninger for fartøyet, og å belyse fremtidige løsninger for et mer bærekraftige energisystem.

Det første evaluerte systemet baseres på biodrivstoff i form av bioetanol (ED95), hydrotreated vegetabilsk olje (HVO), komprimert biogass (CBG), væskebasert biogass (LBG) og fettsyremetylestere (FAME). Det andre systemet tok for seg brenselcelle teknologi brukt for hydrogen, hvor grått, blått og grønt hydrogen ble evaluert. Det tredje systemet utnyttet ammoniakk som drivstoff, som for øvrig er ansett som fremtidens drivstoff innenfor marin sektor. Det siste systemet omhandler et hybridsystem basert på en tradisjonell forbrenningsmotor (ICE) med et energilagringssystem (ESS).

En casebasert undersøkelse ble tatt i bruk for å kunne velge det rette systemet. Denne undersøkelsen tok for seg kostnad og utslipp relatert til både nødvendig investering for fremdriftssystemet, i tillegg til drivstoffbruken per dag. En lenger periode med fremtid ble også vurdert, ved å evaluere systemene etter 1000 dager med fremdrift.

Det anbefalte systemet etter undersøkelsen var fremdriftssystemet basert på biodrivstoffet HVO. På tross av høyere kostnader enn et standard diesel system så gjør utslippsreduksjonen opp for dette ved at det er spart utslipp etter bare 160 dager med fremdrift, sammenlignet med Sounderens nåværende system. De andre biodrivstoffene hadde enten dårligere rekkevidde eller høy pris. Hydrogen og ammoniakk kan være gunstige alternativer i fremtiden, men mangel på både infrastruktur og teknologiens modenhet gjør at disse ikke blir evaluert som mulige løsninger per dags dato. Hybridsystemet hadde både høye kostnader og utslipp, spesielt tilknyttet systemets komponenter. Nyutviklet teknologi kan gjøre noen av antagelsene og premissene for denne rapporten utdatert. Som kan resultere i at den beste løsningen i dag, kanskje ikke er den beste løsningen om 10 år.

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List of Abbreviations

Acronym	**Explanation**
AEC	Alkaline electrolysis cell
AF	Animal fats
AFC	Alkaline fuel cell
BTL	Biomass to liquids
BOG	Boil of gas
B100	100 % biodiesel
CCS	Carbon capturage and storage
CBG	Compressed biogas
CI engine	Compression-ignition engine
CNG	Compressed Natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
ED95	Ethanol diesel, 95 % ethanol and 5 % diesel
ESS	Energy storage system
EU	European Union
EV	Electrical vehicle
FAME	Fatty acid methyl ester
GHG	Greenhouse gas
GWP	Global warming potential
HVO	Hydrotreated vegetable oil
H_2	Hydrogen
ICE	Internal combustion engine
IMO	International Maritime Organization
KOH	Potassium hydroxide
LBG	Liquified biogas
LCA	Lifecycle analysis
LMO	Lithium Manganese Oxide
LNG	Liquified Natural gas
Li-ion	Lithium-ion
MBF	Maritime Battery Forum
MEA	Membrane electrode assembly
MGO	Marine gas oil
NaOH	Sodium hydroxide
NG	Natural Gas
NMC	Lithium Nickel Manganese Cobalt Oxide
NOx	Nitrogen oxides9o
PEM	Proton exchange membrane
PFSA	Perlfluorsulfonic acid
PM	Particulate Matter
RME	Rapeseed methane ester
PPM	Parts per million
rpm	Revolutions per minute
SI engine	Spark-ignition engine
SOEC	Solid oxide electrolysis cell
TRL	Technology readiness level
TtW	Tank-to-wheel
UCO	Used Cooking Oil
USV	Unmannned surface vehicle
WtT	Well-to-tank
WtW	Well-to-Wheel

List of Terms

Term	**Explanation**
Air separation unit	A plant that splits air into nitrogen and oxygen.
Ambient temperature	The air temperature of any object or environment where equipment is stored.
Ammonia	Compound of nitrogen and hydrogen.
Anaerobic digestion	A process where microorganisms break down organic material.
Anhydrous	Substance which is free from water.
Anode	Electrode where oxidation occurs.
Argon	Atom with atom number 18.
Atom	The smallest particle of a chemical element that can exist.
Bioenergy	Form of renewable energy that is derived from recently living organic materials.
Blue Hydrogen	Fossil fuel based hydrogen with CCS.
Bohr model	Planetary model of an atom.
Boiling point	Temperature at which a liquid boils and turns to vapor.
Bulk carrier	Cargo ship carrying non-liquid cargo.
Carbon	Atom with atom number 6.
Carbon-manganese	Carbon steels containing between 1.2-1.8 % manganese.
Catalyst	Substance that increases the rate of a reaction without itself being consumed
Cathode	Electrode where reduction occurs.
Cetane number	Indicator of the ignitibility of fuels.
Charge gradient	Gradient of electrochemical potential.
Chlorophyll	Pigment that gives plants their green color.
Combustion chamber	Enclosed space in which combustion takes place.
Combustion promoter	Substance which enhance ignition.
Composite	Product which is produced from two or more constituent materials.
Compression-ignition engine	Ignition in an internal-combustion engine in which the necessary high temperature is produced by compressing air in the cylinder.
CO_2-eq	Measurment used to compare the warming potential for different greenhouse gases.
Crank angle	Position of an engines crankshaft in relation to the piston.
Crankshaft	Shaft driven by a crank mechanism.
Corrosion	Oksidation of metalls.
Cryogenic	Behaviour and production of materials at low temperatures.
Density	Mass per unit volume.
Drop-in-fuel	Fuels that can be directly used whiteout major system changes.
Dual-fuel combustion system	A strategy to use a mixture of two fuels with different auto-ignition temperatures.
Efficiency	The state or quality of being efficient.
Electric current	Stream of charged particles moving through an electrical conductor.

Electric current	Stream of charged particles moving through an electrical conductor.
Electrolysis	The process of passing an electric current through a substance to provoke a reaction.
Electron	Negatively charged subatomic particle.
Emission	Something that has been emitted—released or discharged.
Energy	The capacity for doing work.
Energy carrier	A transmitter of energy.
Energy density	The amount of energy stored in a given substance, system or given region of space per volume.
Esterification	Equilibrium reaction of acids and alcohols to form esters.
Feedstock	Raw material to supply or fuel a machine or industrial process.
Fermentation	Chemical breakdown of a substance by bacteria, yeasts, or other microorganisms.
Flame speed	The measured rate of expansion of the flame front in a combustion reaction.
Flammability Range	The minimum and maximum concentrations at which a given vaporous substance is produced by compressing air in the cylinder.
Fuel cell	Cell converting chemical energy to electrical energy
Force	Strength or energy as an attribute of physical action or movement.
Gasification	Conversion of biomass or fossil fuels to gasses.
Greenhouse gas	A gas that contributes to the greenhouse effect by absorbing infrared radiation.
Green Hydrogen	Hydrogen produced by electrolysis using electricity from renewable sources.
Grey Hydrogen	Hydrogen based on fossil fuels.
Hydrocarbons	Compound of hydrogen and carbon, such as any of those which are the chief components of petroleum and natural gas.
Hydrogen	Atom with atom number 1.
Hydro power	Power generated by water.
Internal Combustion Engine	An engine which generates motive power by the burning of petrol, oil, or other fuel with air inside the engine, the hot gases produced being used to drive a piston or do other work as they expand.
Ion	An atom or molecule with a net electric charge due to the loss or gain of one or more electrons
Methane	Compound of carbon and hydrogen.
Molecule	A group of atoms bonded together, representing the smallest fundamental unit of a chemical compound that can take part in a chemical reaction.
Nickle-steel	Steel consisting of up to 5 % of nickle.
Nitrogen	Atom with atom number 7.
Paris Agreement	Legally binding international treaty on climate change.
Photosynthesis	Chemical reaction creating oxygen and glucose from carbon dioxide, energy, and water.

Power	Amount of energy transferred or converted per unit time.
Pressure	Force per unit area.
Proton	Positively charged subatomic particle.
Oxidation	Loss of electrons during a reaction.
Redox Reaction	Reaction including an oxidation and a reduction.
Reduction	Gain of eletrcons during a reaction
Renewable energy	Energy from a source that is not depleted when used.
State of charge	Indication of the remaining energy available in the battery
Steam reforming	A method for producing syngas (hydrogen and carbon monoxide) by reaction of hydrocarbons with water.
Spark-ignition engine	An engine where the combustion process of the air-fuel mixture is ignited by a spark from a spark plug.
Torque	Force that cause rotation.
Transesterification	Group exhanging in an ester.
Vessel	Ship or boat.
Viscosity	State of being thick, sticky, and semi-fluid in consistency, due to internal friction.
Water shift reaction	The reaction of carbon monoxide and water vapor to form carbon dioxide and hydrogen.

1 Introduction

An unmanned surface vehicle (USV) is a self controlled multi-purpose system which can ensure high performance for hydroacoustic applications. Kongsbergs Sounder USV can be used in fishery, mapping of marine ground and research. In 2020 Kongsberg Maritime won the OSJ - offshore support journal - Subsea Innovation Award for their Sounder. The Sounder currently uses a Steyr diesel engine.

USVs are automated, unmanned marine vessels that allow for automated research and surveillance of water bodies. However, majority of these vessels use diesel for propulsion, and contribute to carbon emissions. Alternative propulsion systems may allow such vessels to have a lower impact on the environment. By implementing different energy sources into USVs, along with the required infrastructure, the carbon emissions of USVs would be significantly reduced. This project will investigate possibilities for a more sustainable propulsion system for USVs.

1.1 Background

The world faces a climate crisis due to our society's pursuit of wealth and resources. Especially during the last century, the excessive use of fossil fuels has led to high emissions of greenhouse gases (GHG), increasing the average temperature, consequently melting glaciers which results in a rise in the sea level. Additionally, climate change could result in famine, as crops will be affected by drought, extinction of endangered species, and reduced biodiversity, affecting the food chain. This dramatic increase in GHG emissions also triggers extreme weather, resulting in an uneven and unpredictable climate. To reduce the emissions, the world is forced to provide solutions to fossil-based systems which would not affect the environment in a negative manner. This problem is universal but would affect developing countries more, as their infrastructure and social protection usually lack the required demands to handle a potential crisis.

In order to reduce GHG emissions, several incentives have been suggested, aiming to hold the respective countries accountable for their emissions. The Paris agreement is an international treaty on climate change, aiming to limit global warming below 2°C, but preferably below 1.5°C. The main points from the agreement are mentioned below [1]:

- Keep the global warming temperature below 2°C, preferably under 1.5°C.
- Peak global emission as soon as possible
- Report to each other and the public through a robust transparency and accountability system
- Enhance support to developing countries, from rich countries, to deal with impacts of climate change

At the moment, more than 900 million tonnes of CO_2 are emitted each year globally due to the marine/shipping sector. The current trajectory indicates a growing emission outlet, culminating in about 1.3 billion tonnes globally each year in 2050 if no changes are implemented. Figure 1 shows five potential pathways for the shipping industry, one for the current trajectory, one for the 2008 baseline, one for the International Maritime Organizations (IMO) GHG strategy, and two related to the Paris agreement well below 2°C and 1.5°C, respectively. Amongst the different scenarios, it is important to look at the cumulative emissions between 2018 and 2050. The yellow line, indicating IMOs strategy, will have released 21 billion tonnes by 2050, twice of what is indicated with the zero by 2040 scenario, releasing 9.3 billion tonnes in the same period. Rapid change is therefore necessary, possibly saving billions of tons of emission [2].

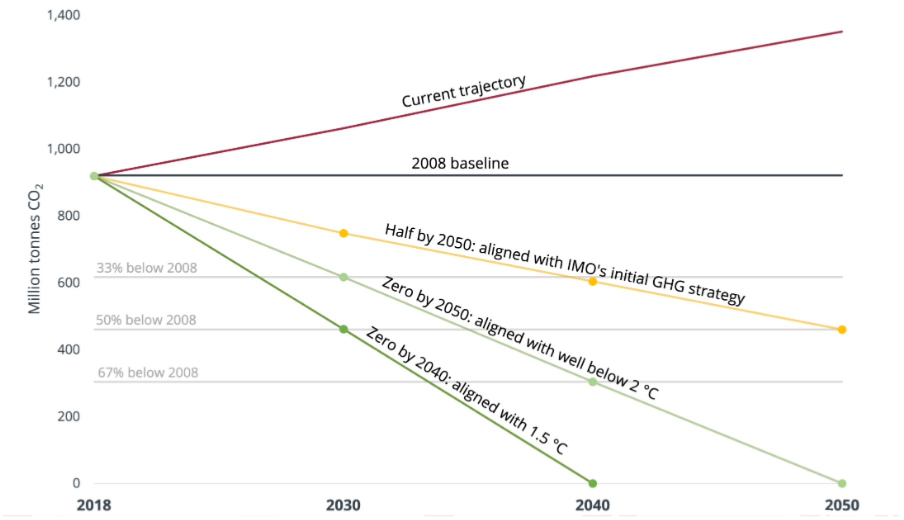


Figure 1: Current trajectory of emissions in the maritime sector[2].

In 2018 ICCT, the international council on clean transport, reported on behalf of the European Union that 29 % of GHG emissions in the EU originated from the transport sector. From Figure 2 the Marine sector contributed a total of 4 %, a small fraction compared to road-based transportation involving cars, vans, trucks, and busses [3].

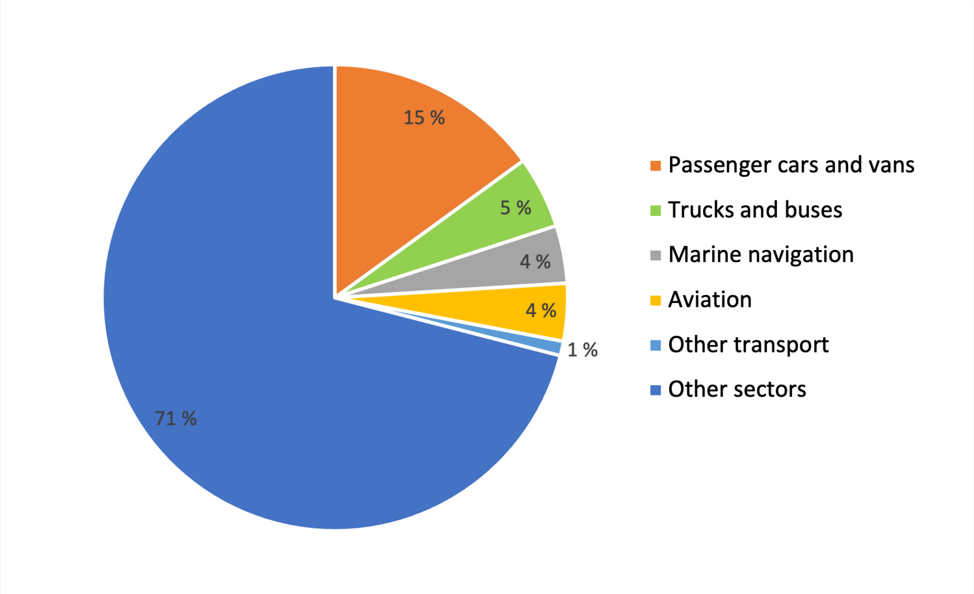


Figure 2: GHG emissions in the EU [3].

Even though the automotive transport sector contributes to the most significant part of emissions related to the transport sector, the technology development in this area has led to a rapid increase in electric vehicles and hybrid vehicles, utilizing energy storage systems known as ESS technology. However, this development is still lacking in most parts of the marine sector.

In 2019, Norway was responsible for 52.2 million tonnes of CO_2 equivalents. The transport sector, in general, was accountable for 31.7 % of the total emissions, where road traffic contributed 17.4 %, and other transport contributed the remaining 14.3 %. Figure 3 shows the percentage-wise contribution from each sector [4].

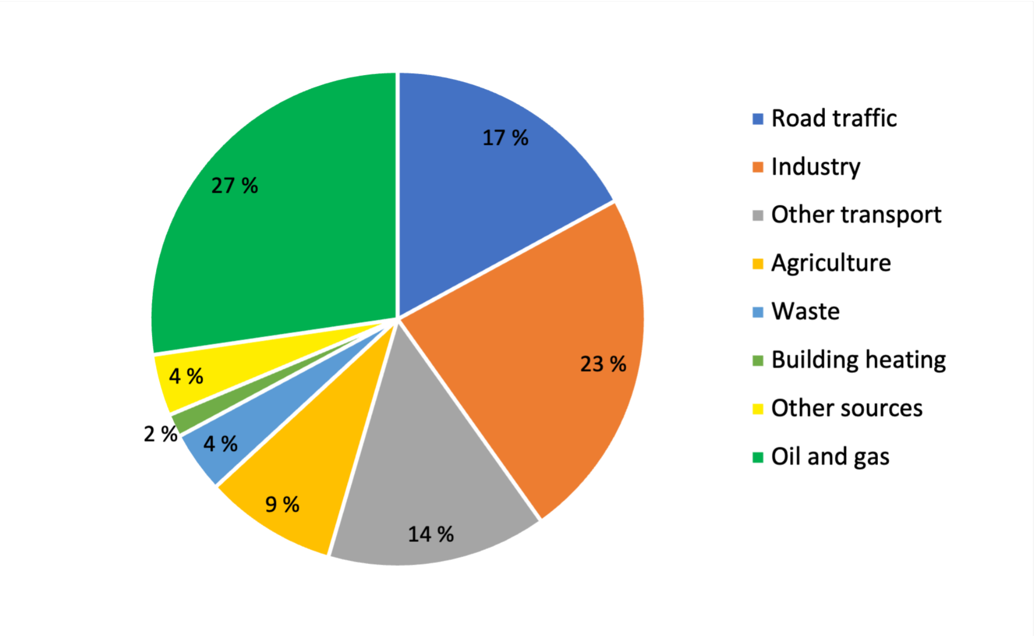


Figure 3: Overview of the emission contributors in Norway 2019 [4].

1.2 Purpose of the thesis

Kongsberg Maritime is world-leading in maritime technology, with an international reputation for quality expertise. The Sounder USV is an awardwinning surface vessel with multiple applications within seabed research by using sonars and other technological instruments. Currently, the Sounder USV uses a mechanical propulsion system, utilizing a traditional diesel motor. Kongsberg Maritime are investigating the opportunities for a more environmentally friendly propulsion system, reducing GHG emission, while at the same time providing an acceptable endurance. The main goal for the thesis is to provide alternative propulsion systems which may be considered as viable options on par with the existing propulsion system.

As the group was given free rein when approaching the task, multiple propulsion systems were considered at first. Through internal and external consulting, it was decided that four main propulsion systems were to be addressed. As the report is written on order from Kongsberg Maritime, it is important to include their wishes towards the groups approach to the report. Kongsberg Maritime emphasized the opportunities of other propulsion systems, rather than the limitations. Hence, the technological maturity of the four different propulsion systems may vary to some extent.

1.3 Limitations

This thesis will mainly focus on the current design of the Sounder USV. The weight and size shall preferably be kept in the same region as of status quo. Only the most important parts of the propulsion system will be presented, which means the auxiliary room of the Sounder will mostly be neglected. In terms of geographical use, the Sounder is a flexible vessel, but it is desirable to look at the opportunities the Sounder will have in the Nordic countries, especially around the coastline of Norway.

2 Methodology

The first approach to the report involves gathering information and data from Konsgberg Maritime, in order to optimise the potential propulsion systems. The different propulsion systems will be evaluated based on following parameters; endurance, feasibility and technology readiness level, emissions, and cost. All of the listed parameters are important, but emission and durability are evaluated as the most important parameters, which will be accounted for when reviewing the different systems. Emission savings is highlighted, as the need for GHG savings is related to the ongoing climate crisis, whereas propulsion is highlighted in order to remain competitive in the USV market.

2.1 Endurance

In order to provide an efficient propulsion system, it is important to utilize the different fuel sources in an effective way to provide long endurance. The consumption levels varies with different speed and weather fluctuations. It is therefore essential to compare systems at the same speed. The current optimal speed range for the Sounder USV is 4-8 knots. In the case study, 4 knots will be used as a basis for endurance calculations.

2.2 Emissions

The methodology for emissions calculations will mainly be based upon different environmental impact methods. The two most prominent methods to measure environmental impact are life cycle analysis (LCA) and well-to-wheel (WtW) calculations.

LCA is an assessment of the environmental impact that goes into making a product; all the way from vehicle manufacturing to vehicle recycling. WtW is an application of LCA, assessing a smaller part, accounting for emissions attached to energy production and vehicle use, illustrated in Figure 4. A WtW analysis does not account for emissions related to vehicle production and vehicle recycling, differing from a LCA.

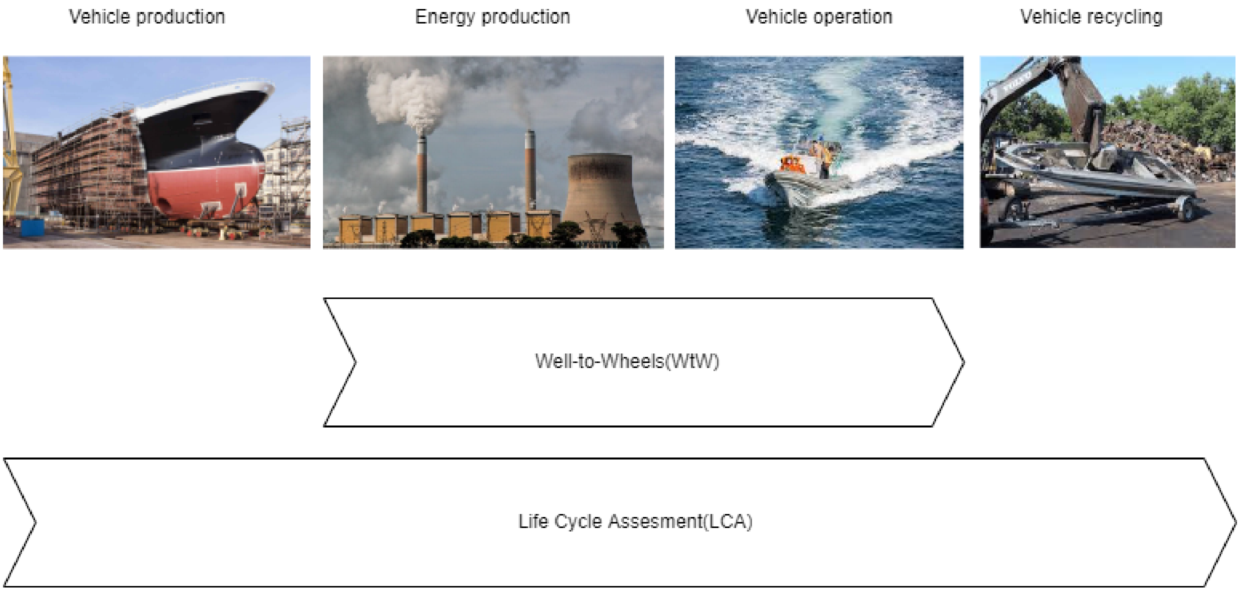


Figure 4: Comparison of LCA and WtW.

This report will use a WtW analysis when accounting for emissions related to the different propulsion systems, as an LCA is considered too comprehensive and unnecessary due to time limitations.

2.3 Cost

The economical analysis will mostly focus on expenses related to the propulsion systems, such as costs of engine, ESS and fuel. The cost of fuel will be presented per day of propulsion. The values will be obtained from various sources to add depth to the economical calculations.

2.4 Feasibility and Technology Readiness Level

In terms of feasibility, both infrastructure and commercially availability will be addressed in the assessment of each system. Whenever future infrastructure is addressed, reliable sources are used to back statements. Technology Readiness Level (TRL) is a method used to classify the technical maturity of a certain technology. The levels range from 1-9 as illustrated in Figure 5, with 1 indicating basic principles observed and reported, whereas 9 accounts for the most mature and proven technology. In order for the Sounder USV to utilize a propulsion system today, the TRL must be 9.

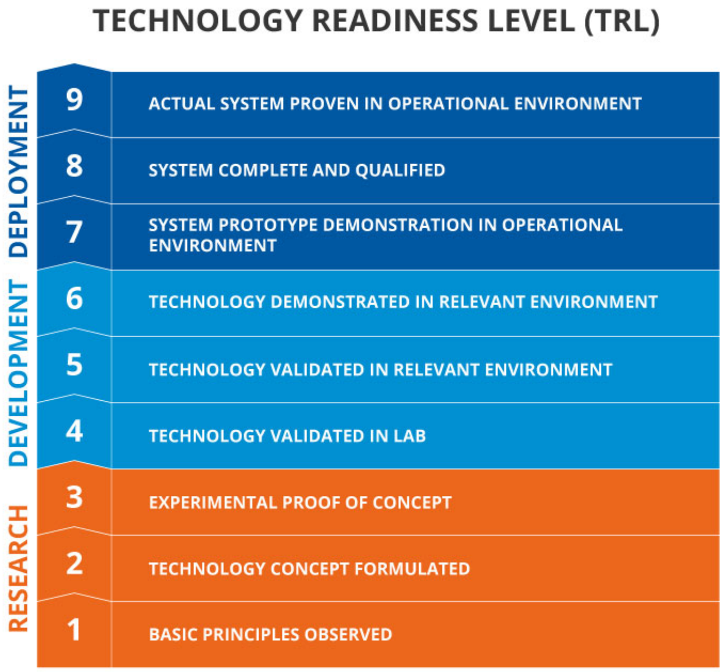


Figure 5: Description of the 9 levels of TRL [5].

3 Sounder - Unmanned surface vehicle

An unmanned surface vehicle system is a self controlled multi-purpose system which can ensure high performance for hydroacoustic applications. Kongsbergs Sounder USV can be used in hydroacoustic mapping, positioning, communication, and oceanographic research. The vessel is designed for optimal performance of its hydrostatic sensors and system.

Figure 6: Sounder USV. Photo credit Kongsberg [6].

In terms of performance and efficiency the Sounder has a well developed propulsion system. However, other fuel sources and propulsion systems may provide GHG and energy savings. The Sounder USV is powered by a Steyr 145 bhp diesel engine. The Sounders effective propulsion system and design can ensure safe sailing for up to 20 days at 4 knots [7].

The hull of the Sounder USV can be divided into two main compartments; the engine room and the payload room, visually illustrated in Figure 7. The internal combustion engine (ICE), the exhaust system, the power distribution cabinet and the rudder control are all located in the engine room, which will be the main focus for this project. The payload compartment holds the moonpool, the K-MATE rack mount, the payload rack mount, batteries, PLC system and power management system. Table 1 contains the technical specifications of the Sounder USV.

Table 1: Technical specifications of the Sounder USV [7].

Length	8 m
Beam	2,2 m
Mast down/up	2,3 m/4,4 m
Draft	0,7 m
Weight	4200 kg
Engine	145 bhp Steyr diesel engine with fixed propeller
Speed	13 knot max
Payload power	> 4 kW at 4 knots

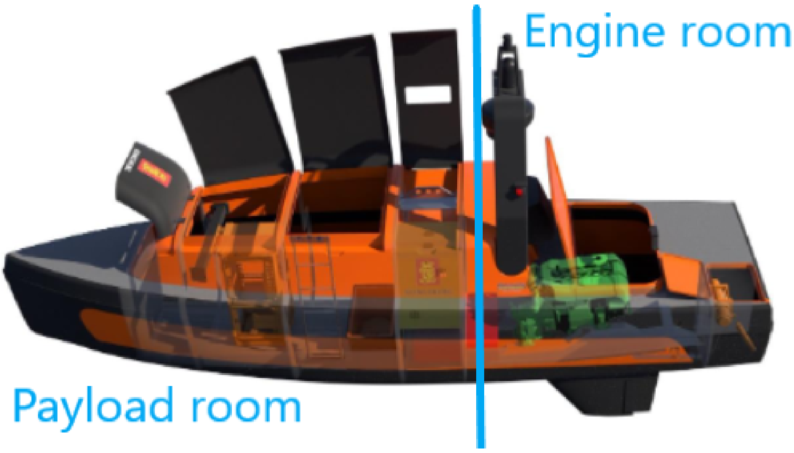


Figure 7: Sounder USV, divided into payload room and engine room.

3.1 Energy Utilization and Endurance

The Sounders endurance and durability is one of its stronger sides. High endurance allows the Sounder to cover big underwater areas and gather much information. Less time used on fuelling the vehicle is another aspect of the advantages following a solid endurance. Time used fuelling, is time better spent researching when it comes to sea mapping. Figure 8 is received from Kongsberg, showing how endurance will vary with different speeds. The figure includes tests for 400 L fuel tank and 800 L fuel tank. Measurements are derived from a mean of two runs east and west. Note that the speed is the speed through water, therefore endurance will be affected by the weather conditions during operation.

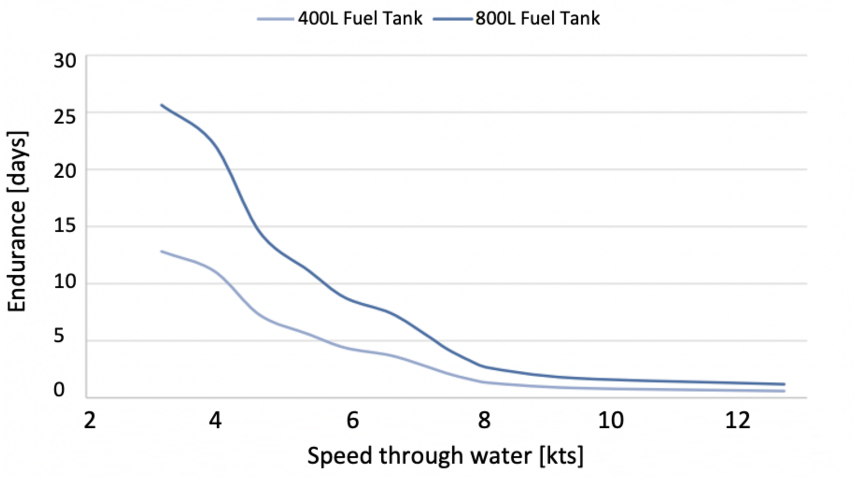


Figure 8: Endurance of Sounder USV based on speed through water.

The specifications of the Steyr diesel engine is shown in Figure 9. The red line illustrates the engine power output, the blue line shows the torque, the dotted black line the propeller power output, the light green dotted line the fuel consumption related to the propeller output and the green line the specific fuel consumption. All these numbers are derived from tests from Steyr and are not related to Kongsberg in any form.

At about 3200 rpm the propeller curve and the engine power output intersects. Before this rpm level, there is an energy difference between the engine power output and the propeller output. At about 2250 RPM the propeller output is about 46 kW whereas the engine power output is about 106 kW, resulting in a difference of 60 kW. This gap is what the engine manages to produce at the certain RPM level, but

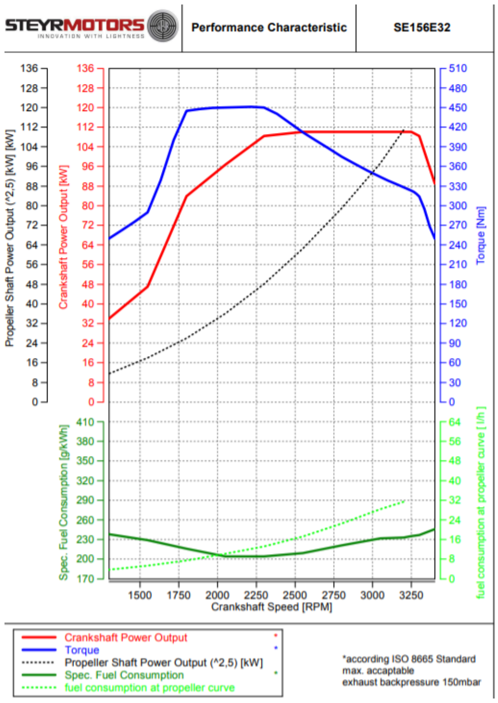
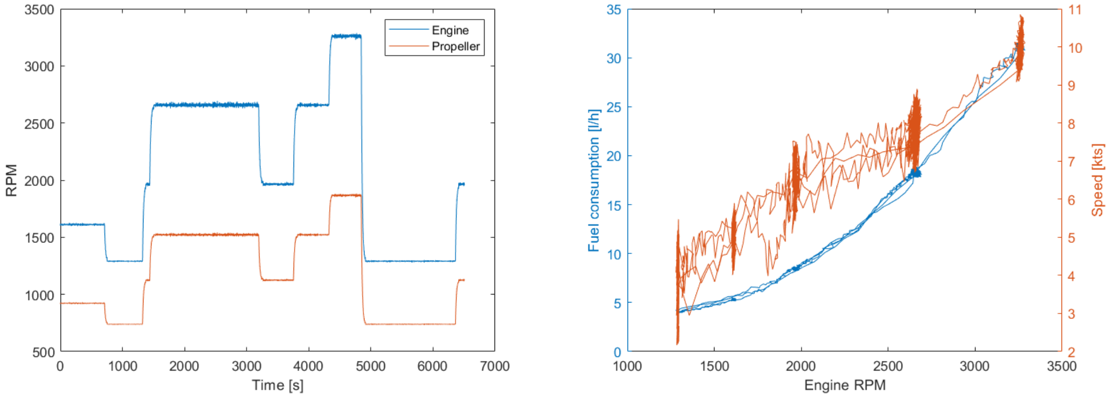


Figure 9: Power curve from Steyr

since the propeller only manages to utilize 46 kW, the engine will adjust the amount of fuel injected into the engine.

Another test performed by Kongsberg illustrates how rougher conditions will affect the performance characteristics of the Sounder USV. Figure 10 shows a graphical illustration of data obtained from the test. The first Figure 10a shows two different rpm values, one for the engine and one for the propeller. The gear ratio, 1.76:1, is obtained by dividing the engine rpm by the propeller rpm. Figure 10b shows how fuel consumption and speed varies with rpm. An interesting note is that the fuel consumption curve from the test matches the light green dotted fuel consumption curve in Figure 9.



(a) Engine and propeller rpm levels during the test.

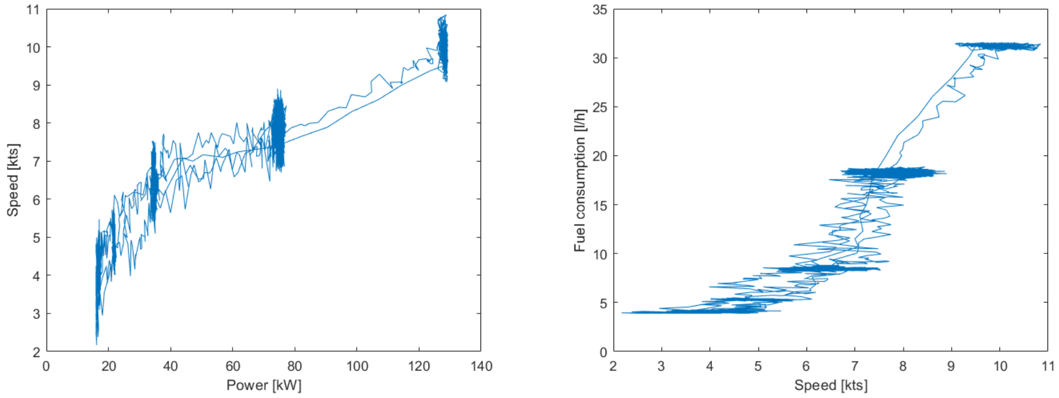
(b) Fuel consumption and speed plotted vs engine rpm.

Figure 10: Data obtained from the test

From the speed graph in 10b five dense rpm areas are identified, one running at 1300 rpm, one at 1650 rpm, one at 2000 rpm, one at 2600 rpm and the last at 3250 rpm. These areas are also located in Figure 11a and Figure 11b. Compared to Figure 8 the fuel consumption obtained from the test, approximately 4 L/h and illustrated in Figure 11b, is much higher than the initial values. As Kongsberg claim an endurance of 20 days at 4 knots for the 800 L tank, this equals a fuel consumption of

$$800\ \text{L}/(20\text{days} * 24\text{h}/\text{day}) = 1.667\text{L}/\text{h} \tag{1}$$

Which is about 41 % of the value received from the test in rough conditions.



(a) Speed plotted over power.

(b) Fuel consumption plotted over speed.

Figure 11: Results from test of Sounder USV under rough conditions.

3.2 Emissions

An exact calculation of WtW emissions for the Sounder USV is complex and hard to find. Therefore, this section will estimate the emissions for a general mechanical propulsion system fuelled by diesel. Other emissions related to the USV during production will not be accounted for, as a result of the limitations in this article.

For the mechanical system, emissions will be related to the combustion engine, as well as the fuel usage. An overview of emissions related to the mechanical system is illustrated in Table 2. The emissions related to the production of the engine is low compared to emissions related to the fuel usage. These calculations display the Well-to-Wheel (WtW) emissions.

Production		
Component	Emission factor per kg engine[g co2-eq/kg]	reference
Combustion engine	5.4	[8]
Fuel use		
Fuel	Emission factor [g CO2-eq/MJ]	Reference
Diesel	88,6	[9]

Table 2: Emissions regarding the mechanical propulsion system.

When comparing WtT and TtW, most of the emissions are related to TtW , accounting for 100 CO_2-eq/MJ of the total 115 CO_2-eq/MJ, roughly 87 % of the total emissions.

3.3 Cost of Diesel Propulsion

For economical calculations regarding the propulsion system of the Sounder, the diesel engine and the specific price of the fuel is taken account for. An exact price for the ICE in the Sounder USV is hard to estimate. Additional economical contracts between Kongsberg and manufacturers may provide further uncertainties towards the price estimations. However, an open market price for a similar Steyr engine was used, decreasing for quantities over a certain amount[10]. It is likely that Kongsberg could have access to lower prices than this as well, but this will be the case of every propulsion system and would be hard to account for.

The price for diesel tend to fluctuate, therefore the estimations is based on average values over a longer period. All the economical calculations for the propulsion system for the Sounder is displayed in Table 3.

Component/fuel	**Cost**	**Unit**	**Reference**
Diesel engine	93 140	NOK/piece	[11]
Diesel	19.9	NOK/L	[12]

Table 3: Cost of propulsion system Sounder USV

3.4 Feasibility and Technology Readiness Level

Diesel is a mature and reliable technology with an established infrastructure, the TRL is 9.

Fuel from fossil fuels is well established and has been around for years. Hence, the feasibility in terms of infrastructure is well developed. This includes diesel fuel, which the Sounder uses. The majority of vessels run on diesel, and fuelling stations can be found all around.

4 Biofuel Technology

This section will introduce biofuel technologies and its contribution to the decarbonization of the transportation sector. The section will mainly focus on the biofuels: Hydrotreated vegetable oil (HVO), Fatty Acid Methyl Ester (FAME), Ethanol diesel (ED95), Compressed biogas (CBG) and Liquified biogas (LBG).

Biomass is the oldest form of energy utilized by humans. The primary use has not changed much over the years, as it is still used in direct combustion for heating purposes. There are numerous different biomasses today, used for different purposes as heating, power, electricity and as a transpiration fuel. Utilizing biofuel as a transportation fuel will not only contribute solving the global warming, but also contribute to handling waste [13].

Bioenergy is considered an ideal choice as a transition energy source. Biofuels are a substitute for fossil fuels and can contribute to lowering emissions of greenhouse gas (GHG) [14]. Bioenergy is energy from the sunlight stored as chemical energy. Even though biomass has promising potential, the utilisation is still limited.

4.1 Formation of Biomass

Biomass can be formed through photosynthesis, a process where plants use H_2O, sunlight and CO_2 to create O_2 and energy in the form of glucose. Plants contain a structure of cells called chloroplasts, which enables photosynthesis and converts light to chemical energy [15]. Figure 12 illustrates the chemical reaction of photosynthesis. H_2O reacts with CO_2, and forms $C_6H_12O_6$, water vapor and O_2. [16].

Sunlight is critical for biomass formation through photosynthesis. Plants have light-harvesting pigments, where chlorophyll traps solar energy. This creates a charge gradient across the chloroplast membrane providing energy for a chemical synthesis[17].

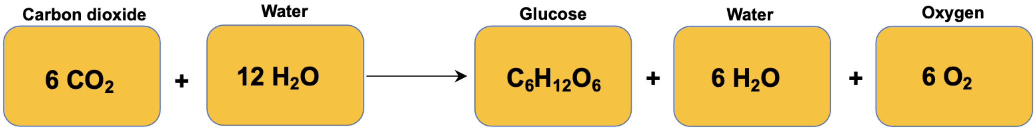


Figure 12: Photosynthesis [15]

4.2 Biomass Feedstocks

A feedstock is a renewable, biological material used directly as a fuel or converted to another form of fuel or energy product [18]. Biomass contains stored chemical energy in the form of glucose and can be divided into starch-, sugar- lipid-, lignocellulose-, or algae- based feedstocks [17].

Starch-based feedstocks are usually corn, sweet potato, sugarcane, and cassava. These feedstocks are used for food and energy production and have a high potential for biofuel production, primarily as bioethanol. The energy content of the feedstock depends on the geographical harvest location [19] [17]. Sugar-based feedstocks are also used for bioethanol production, which are feedstocks produced from sweet sorghum, sugarcane, and sugarbeet.

Feedstocks used for liquid fuel production are lipid-based, such as palm oil, soybean oil, corn oil, and canola oil. Biodiesel from these feedstocks can also be made from waste and byproducts, like used cooking oil (UCO) and residual animal fats.

Lignocellulosic-based feedstock comes from organic matter from plant origins such as, crop residues, dedicated energy crops, and forest biomass. Lignocellulosic biofuel production utilizes existing land, which does not compete with food production[17].

Algaes are a group of plant organisms in seawater, freshwater, and marine water. An algae-based feedstock is divided into three subgroups: cyanobacteria, microalgae, and macroalgae. The formation of algae occurs only if the right CO_2 concentration, temperature, pH, salinity, and nutrients are available. On average, microalgae contain 40-60 % lipid content. Algae cultivation, harvesting, drying, and lipid extraction are necessary to convert algae to biodiesel [20].

4.3 Generations of Biofuel

Biofuels are divided into four generations based on the type of feedstock used to produce the biofuel [21]. First generation biofuel is often referred to as conventional biofuel, while second and third generations are advanced biofuels [22]. In Figure 13 the three main biofuel generations, and their respective feedstocks are presented.

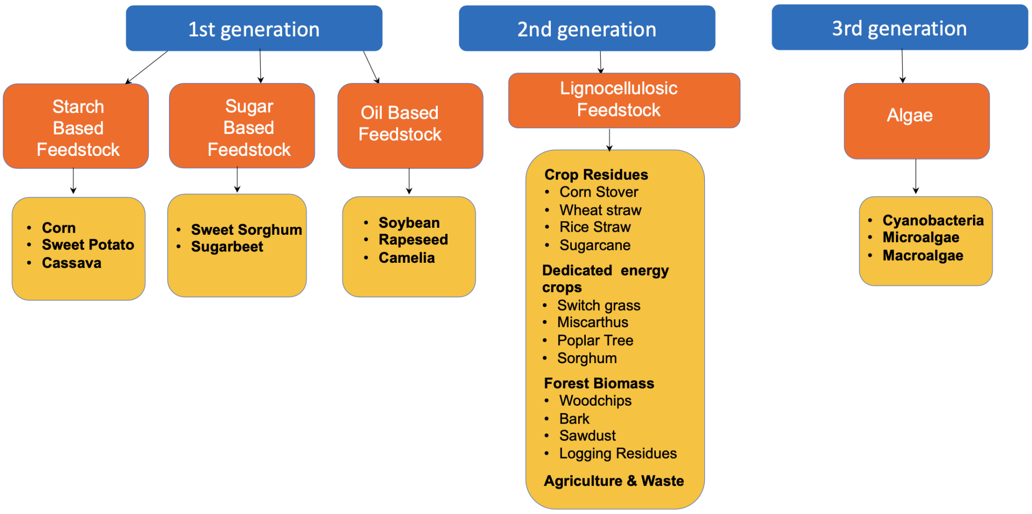


Figure 13: Generations of biomass feedstocks, divided in first, second and third generation [17]

4.3.1 First-generation

First-generation biofuel is a food-related source with high contents of starch, sugar, and oil. The most common feedstocks are corn, wheat, and sugar. It is a limited feedstock as it requires large areas to grow, which also could be used as food crops. This has resulted in an ethical discussion regarding the usage of first-generation feedstocks [23].

4.3.2 Second-generation

Biofuels from second-generations come from feedstocks with high content of lignocellulose, such as forest biomass, dedicated energy crops, waste, and crop residues. These feedstocks are sustainable, as they do not compete with the food industry. It has high costs of conversion and requires large amounts of water and land when produced [23].

4.3.3 Third-generation

Third-generation biofuels are biofuels with high yield derived from algae. These feedstocks are also considered sustainable, as they do not affect land or food production. Third-generation feedstocks have advanced technology for production which is still under development. Nevertheless, it is a feedstock emerging and will play a prominent role in the coming years [17] [23].

4.3.4 Fourth-generation

Biofuels produced from synthetic biology technologies are classified as fourth-generation biofuels. The technology is still in the research and development phase [24]. Therefore, this report will not include fourth-generation feedstocks for biofuel production.

4.4 Conversion of Biomass

Biomass needs to be converted to produce energy either thermochemically, biochemically/biologically, or mechanically. Biofuel can be produced from various feedstocks, depending on the desired end product. Furthermore, biomass can be converted to energy in the form of heat, gas, or liquid fuel [25]. This section will present the production of biodiesel, bioethanol, and biogas.

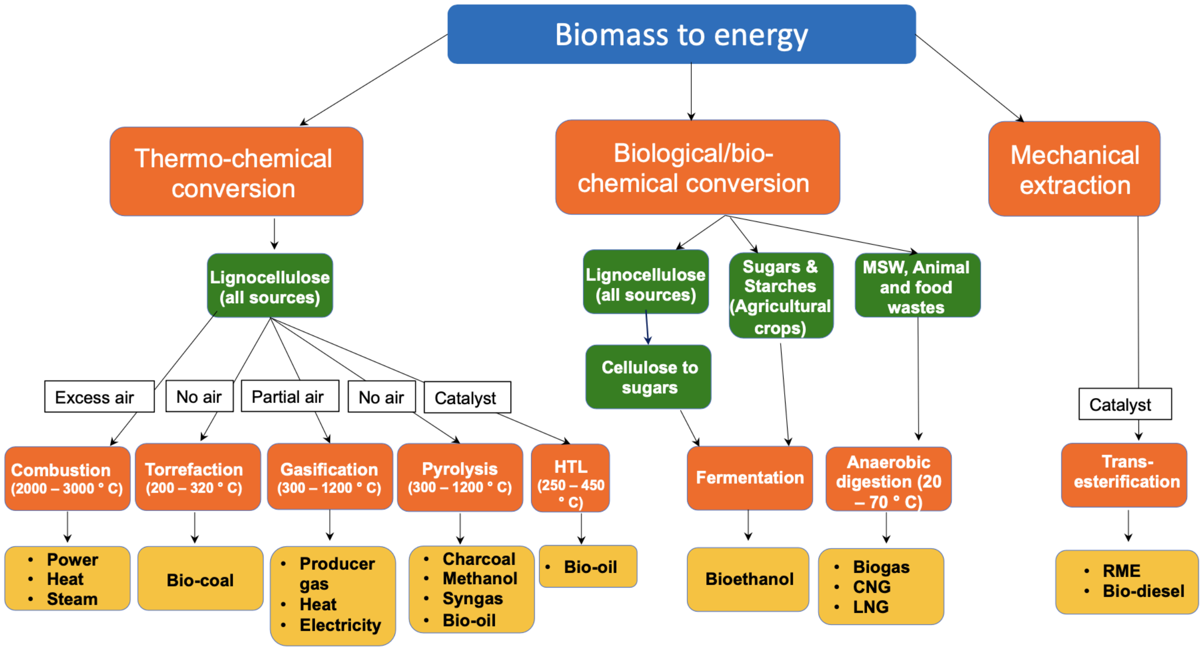


Figure 14: Biomass to Energy.

4.4.1 Biodiesel Production

This section will present biodiesel production of Hydrotreated Vegetable Oil (HVO), Fatty Acid Methyl Esters (FAME), and biomass to liquids (BTL).

Biodiesel is commercially developed as a transportation fuel, either as HVO or FAME. It is an environmentally friendly substitute for fossil diesel. Both HVO and FAME come from organic biomass, but are produced differently [26]. Biodiesel is either produced through esterification or transesterification, both using lipid-based feedstocks [17].

The most common feedstocks used to produce biodiesel in Europe and Norway are presented in Figure 15 and 16 [27] [28]. This report will further examine feedstocks such as rapeseed, sunflower, used cooking oil (UCO), algae, and residual animal fat, due to their availability and potential for biodiesel production. Palm oil will not be considered for biodiesel production due to its contribution of deforestation.

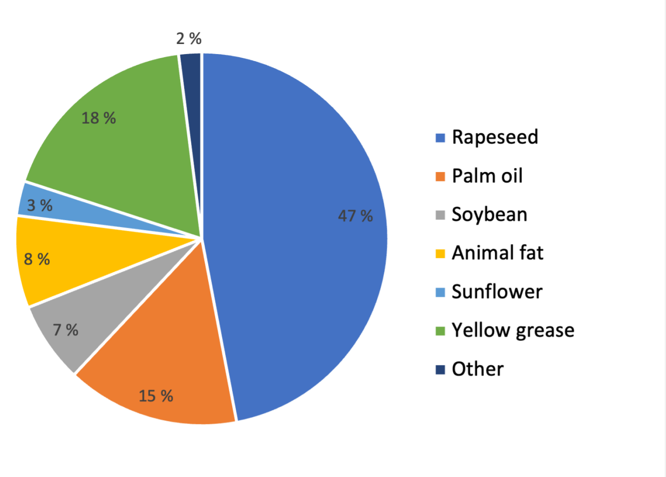


Figure 15: Feedstocks used for biodiesel production in the EU, 2017. Data modified from: [27].

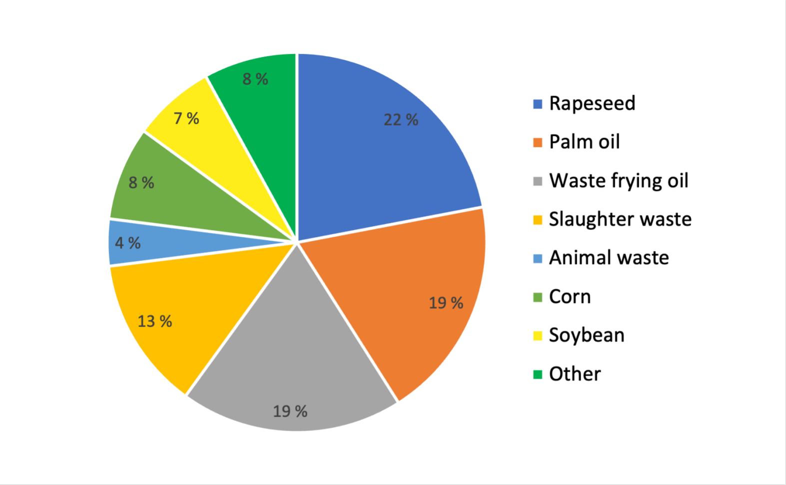


Figure 16: Feedstocks used for biodiesel production in Norway, 2018. Data modified from: [28].

4.4.1.1 Hydrotreated Vegetable Oil (HVO)

Hydrotreated vegetable oil (HVO) is a renewable diesel option produced by mixing H_2 and vegetable oil. The mix has excellent properties and can be a drop-in-fuel in most CI engines with minor modifications. It can either be used in pure form or mixed with conventional diesel, which is beneficial for the industry as it does not require an energy system overhaul.

Animal fats and vegetable oil contain triglyceride, an ester consisting of fatty acids, which are organic acids with long paraffinic backbones and glycerol. In Figure 17 an example of a triglyceride is presented.

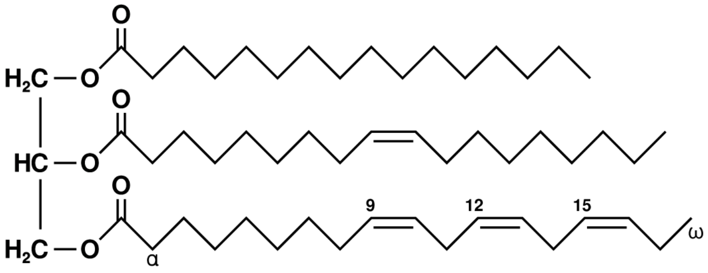


Figure 17: Chemical structure of triglyceride [29].

A paraffinic backbone is a long chain of hydrocarbons in a C_{15}-C_{18} range. When producing HVO, hydrogen is added to triglyceride. All the oxygen and smaller amounts of sulfur and nitrogen are removed by complete hydrogenation. A byproduct of HVO production is paraffin, which is a good fuel, usually isomerized for optimal preferences [13].

4.4.1.2 Fatty Acid Methyl Esters (FAME)

Fatty Acid Methyl Esters (FAME) is biodiesel produced from lipid-based feedstocks. In the transesterification process, a glyceride reacts with an alcohol in the presence of a catalyst, producing a mixture of alcohol and fatty acid esters [30]. The catalyst can either be a strong base or acid. When using triglycerides in the production phase, the byproduct is glycerol. Glycerol is unfortunately not valuable compared to paraffin. Figure 18 shows the reaction in the transesterification process. [13]

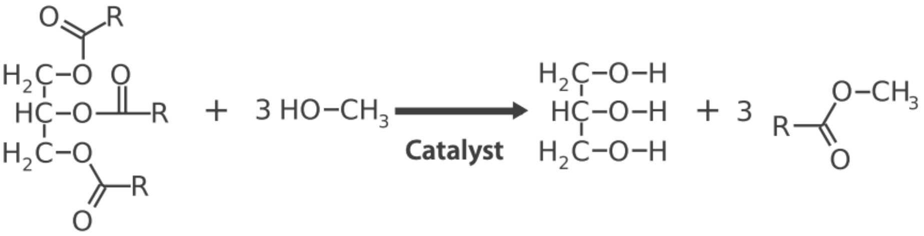


Figure 18: Transesterification reaction [30].

4.4.1.3 Biomass to Liquids (BTL)

Through gasification and the Fischer-Tropsch synthesis, biomass can be converted into a liquid. In gasification, the chemical energy in carbon is converted into chemical and thermal energy with the help of oxygen or steam, converting biomass to synthetic gas. To produce a liquid biofuel, the Fischer-Tropsch synthesis purifies and refines the synthetic gas, creating a liquid. As this technology is still under development, it will not be considered a potential biofuel production path in this report.

4.4.2 Bioethanol Production

Bioethanol is a renewable biofuel commonly referred to as ED95, a mixture of 95 % ethanol and 5 % diesel, and is produced through fermentation of lignocellulosic, sugar- or starch-based feedstocks [31]. First-generation bioethanol is produced from first-generation feedstocks, such as sugary- or starch-based crops. Second generation bioethanol is produced from lignocellulosic feedstocks. Using sugary crops is beneficial, as it only requires a one-step bio-conversion to bioethanol. When using either starch-based or lignocellulosic feedstocks, it needs to be converted to sugar, then bioethanol. Figure 19 shows the most common feedstocks used in Europe to produce bioethanol.

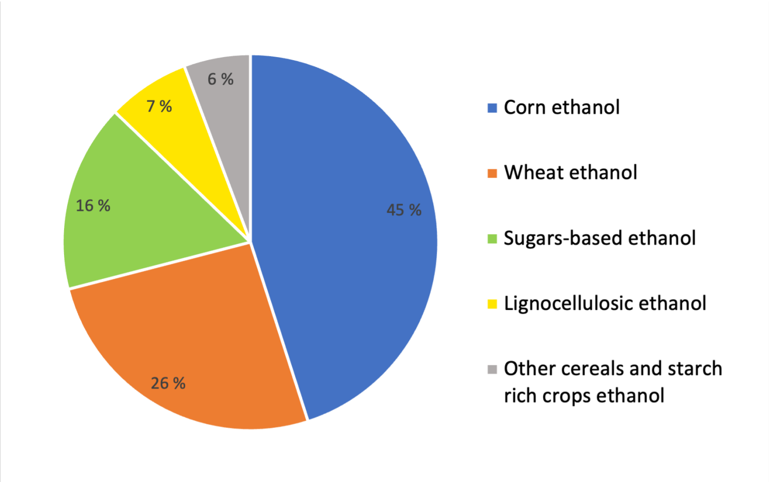


Figure 19: Ethanol Feedstock Production In Europe in 2020 [32].

Bioethanol can be produced from for example sweet sorghum through sugar-based biorefinery. In this process, sorghum is first harvested and cleaned. Once it is cleaned, the sorghum is crushed to extract the juice, which contains a large amount of glucose. Furthermore, the juice is filtered, and the sugar content is adjusted. The inoculation is performed when the filtration is done, which means that the juice is induced with yeast. At last, the juice is converted into glucose, before the glucose is converted into ethanol, as shown in the chemical reactions, 2 and 3. These chemical reactions demonstrate that one mole of glucose generates four moles of ethanol. The final step involves distillation of ethanol to purify the desired concentration of ethanol [17].

$$C_{12}H_{22}O_{11} + H_2O = 2C_6H_{12}O_6 \tag{2}$$

$$2C_6H_{12}O_6 = 4C_2H_5OH + 4CO_2 \tag{3}$$

4.4.3 Biogas Production

Biogas can be used as a transport fuel, either in Liquefied biogas (LBG) or Compressed biogas (CBG). Biogas mainly consists of CH_4, CO_2, and other trace gases such as H_2S [33]. The primary energy contributor to biogas is CH_4, a highly energetic gas. The amount of biogas produced from an anaerobic digestion depends on the type of feedstock and technology used.

Biogas is produced through anaerobic digestion, a biochemical conversion pathway. The process is an oxygen free process and occurs spontaneously in nature. First, organic biomass is converted into simple substances such as carbohydrate fats and proteins. Further, these compounds are degraded to the final products, mainly CO_2 and CH_4. The mixture is typically heated to 20-70 °C. This process can be divided into four steps; hydrolysis, acideogensis, acendogenesis, and methanogenesis [17] [34].

Hydrolysis is the degradation of biomass into simple sugars with hydrolytic bacteria. The resulting products are further converted to acids, through acideogensis. In the next step, another group of bacteria converts the acids, into different acetates, called acendogenesis. The products from the acendogenesis process are degraded into biogas, in the final step, called methanogenesis. The chemical reactions that take place in the four steps in anaerobic digestion are shown in Table 4.

Table 4: The chemical reactions that takes place during Anaerobic Digestion [34].

Steps in Anaerobic Digestion	**Chemical Reaction**
Step 1	$C_6H_{10}O_4 + 2H_2O = C_6H_{12}O_6 + H_2$
Step 2	$C_6H_{12}O_6 = 2CH_3CH_2OH + 2CO_2$ $C_6H_{12}O_6 + 2H_2 = 2CH_3CH_2COOH + 2H_2O$
Step 3	$2CH_3CH_2COOH + 2H_2O = CH_3COOH + CO_2 + 3H_2$
Step 4	$2CH_3CH_2OH + CO_2 = 2CH_3COOH + CH_4$ $CH_3COOH + CO_2 = 2CH_4 + 2CO_2$ $CH_3OH + H_2 = CH_4 + H_2O$ $CO_2 + 4H_2 = 2CH_4 + 2H_2O$

4.5 Energy utilization and Propulsion System

This section will briefly introduce the energy utilisation of biofuels and how the different biofuels are used in propulsion systems. Table 5 presents the energy density, spesific energy density and the engine efficiency regarding the various biofuels.

Table 5: Properties biofuel.

Biofuel	**Energy Density [MJ/kg]**	**Spesific Energy Density [MJ/L]**	**Efficiency[%]**	**Reference**
Diesel	43	36	40	[35] [35]
FAME	37	33	40	[35] [35]
HVO	44	34	40	[35] [35]
ED95	27	21	38	[35] [36]
LBG	50	21	35	[37] [38]
CBG	50	9	35	[37] [38]

4.5.1 Fatty Acid Methyl Esters (FAME) and Hydrotreated Vegetable Oil (HVO)

HVO works as a drop-in fuel for conventional diesel, in contrast to FAME. Few adjustments are needed before HVO can fully replace diesel [39]. The cetane number of HVO is very high compared to diesel, and as a result, minor adjustments are needed in a diesel engine to balance the fuel ignition in the cycle [40]. HVO has better temperature tolerance compared to FAME, and can also operate in temperatures down to -20 °C. Therefore, HVO is well suited for locations with a cold climate, such as Norway [41].

FAME and HVO work in an ICE. Figure 20 shows an illustration of a proposed system. The tank contains either HVO or FAME, which is further fed to the combustion engine. The biofuel is ignited through compression, and the engine produces mechanical energy. Additionally, the rpm created is slowed down by a gearbox and delivers mechanical work into the propeller [8].

4.5.2 Ethanol Diesel (ED95)

An ED95 tank needs to be around 58 % larger than a standard diesel tank to store the same amount of energy. ED95 and diesel are different in both their physical and flow properties. ED95 has lower energy

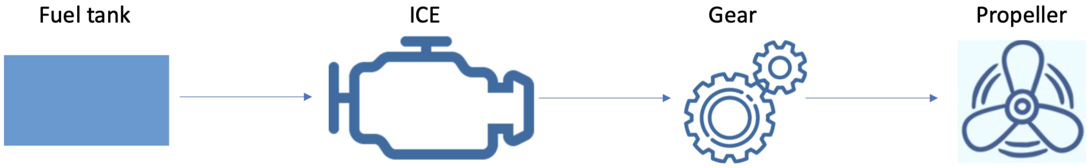


Figure 20: The propulsion system of biodiesel [8].

content, density, viscosity, and cetane number than diesel. From a fuel perspective, ED95 still needs further development, especially when it comes to combustion quality and lubrication properties [42] [33].

Bioethanol can be used in an ICE [43]. It can be stored in a diesel tank but requires adjustments to the engine. Unlike HVO, ED95 cannot be used as a drop-in fuel for marine diesel engines today. Using bioethanol as a marine fuel requires further engine development, as the suggested TRL of the ED95 engines are 6 [44]. However, if the marine engine technology for ED95 matures, ED95 can be a sustainable biofuel for the marine sector in the future.

4.5.3 Compressed biogas (CBG) and Liquified biogas (LBG)

In order to use biogas as fuel, the methane content must be 95 % [45]. LBG and CBG have approximately the same properties as liquefied natural gas (LNG) and compressed natural gas (CNG) [33] [46]. Both LBG and CBG have a higher energy density compared to diesel, while the volumetric energy density is lower, especially for CBG, which is 75 % lower than diesel. Biomethane is usually used in a modified SI engine, but the engine technology is still under development [47].

CBG is used in an ICE, and the system consists of a gas tank, engine, gearbox, and mechanical driveline [43]. The SI engine used for CBG is the same for CNG. LBG is also used in an SI-engine but requires a dual LBG engine [44]. Since biogas can handle very high compression, it is more suited for a modified SI-engine compared to a CI engine [48].

4.6 Biofuel Storage

The different biofuels require different methods of storing. This section will briefly introduce how the different biofuels are stored.

4.6.1 Fatty Acid Methyl Esters (FAME) Hydrotreated Vegetable Oil (HVO)

FAME should not be stored for more than six months due to oxidation and microbial growth, which will lead to a lack in fuel quality. Corrosion and softening of the fuel storage materials can occur when stored over time [49] [50] [35]. HVO can be stored for up to 10 years, and needs less maintenance compared to FAME. Biodiesel can be stored in a diesel tank with minor adjustments [51]. Asplan Viak's LCA of express boat propulsion systems suggested using a composite fuel tank for HVO and FAME. Therefore, this report assumes that FAME and HVO is stored in a composite fuel tank [8].

4.6.2 Ethanol Diesel (ED95)

ED95 requires larger fuel tanks than diesel due to ethanol's low volumetric energy density, resulting in more fuel use per km than fossil diesel. ED95 can be stored in a similar tank as biodiesel, a composite fuel tank [52].

4.6.3 Compressed biogas (CBG) and Liquified biogas (LBG)

CBG and LBG are produced and stored differently. CBG must be stored around 200-300 bar, while LBG is liquefied at -162 degrees. LBG requires less space due to its volumetric energy density and is more suitable as a longer-distance transportation fuel. LBG is stored in a cryogenic fuel tank [39], whereas CBG is stored in a thick composite fuel tank. Biogas is highly flammable and has low volumetric energy density. As a result, CBG tanks are placed on top of the vehicle, due to safety reasons. [53].

4.7 Emissions

This section will present the emissions for HVO, FAME, CBG, LBG, and ED95. To calculate GHG emissions, various studies were considered. Due to lack of comprehensive WtW analyses, both a WtT and TtW were used. By studying the total emissions from these two, a WtW analysis was attained [54].

4.7.1 Fatty Acid Methyl Esters (FAME) and Hydrotreated vegetable oil (HVO)

Biodiesel produces less GHG emissions than fossil diesel in a TtW perspective, except for NOx emissions. NOx emissions increase with the use of biodiesel in the engine,as shown in Figure 21. The reason why the NOx emissions increase with the use of biodiesel is due to differences in mechanical properties and a higher viscosity compared to regular diesel. This contributes to a change in fuel injection, resulting in a higher temperature in the combustion chamber, consequently increasing the NOx emissions [55] [56].

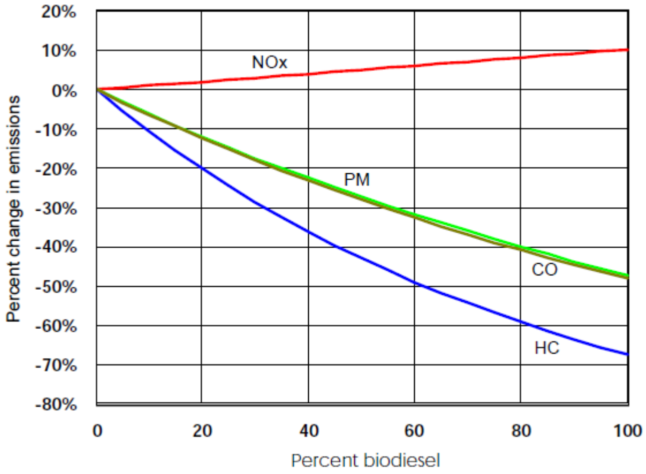


Figure 21: Emissions from biodiesel when used in an engine [57]

Figure 22 presents the WtW analysis for biodiesel. The analysis shows that HVO from UCO has the lowest emissions amongst the feedstocks for biodiesel. According to the WtW analysis, HVO emits between 13 to 39 g CO_2-eq/MJ. With the use of HVO, a reduction in climate footprint by 36-91 %, compared to fossil based fuel, can be achieved. The extensive range is caused by the dependency on the feedstock and production process [58].

The GHG emissions from HVO and FAME are compared using production data from sunflower and rapeseed. Utlizing rapeseed for FAME production, increases its resistance to cold weather [59]. In addition, the WtW emissions of algae fat is presented due to its potential as a biofuel [60]. The emissions for algae, UCO and residual animal fat are based on different studies than for the other feedstocks [61]. The report stated that the GHG emissions for microalgae to biodiesel are 28.5 g CO_2-eq/MJ [60].

UCO and residual animal fat were included due to their potential and availability in Norway. Based on findings from the research report, Residual animal fat and fish for biodiesel production - Potentials in Norway [62], GHG emissions for biodiesel from residual animal fat as fish waste are 20 % of conventional diesel emissions. Using fish oil as a feedstock can reduce emissions by around 80 % [62]. This was used to conduct further the WtW analysis of residual animal fat and fish oil.

However, the feedstocks algae and residual animal fat will not be further examined, as the studies failed to state the production method for the WtW emissions from the feedstocks. Due to this uncertainty, these emissions will not be applied for FAME or HVO. However, both algae and residual animal fat have great potential to be used as feedstocks for biodiesel production.

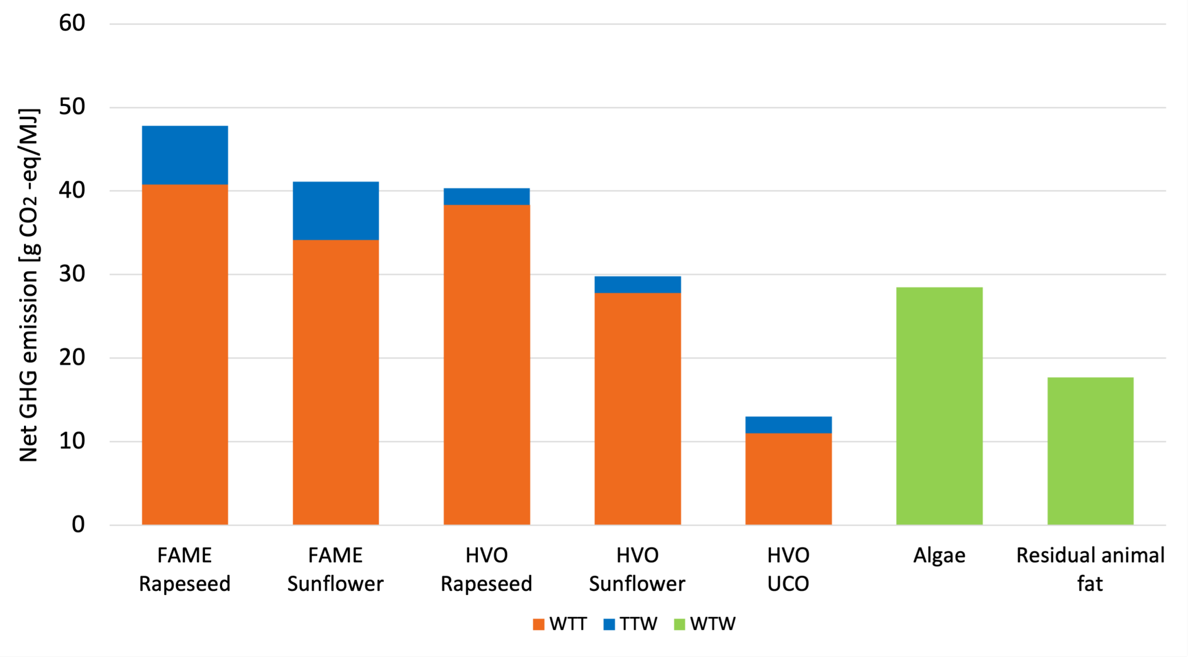


Figure 22: Well-to-wheel analysis of biodiesel. Data presented in Appendix A. [9, 62, 61, 63, 64, 65].

Biodiesel is used in an ICE, and stored in a composite fuel tank. According to Asplan Viaks' research report, the emission factor for a composite storage tank is 21 kg CO_2-eq /kg. Therefore, the system's emissions will vary with the tanks size and quantity. The diesel engine used in this report has an emission factor of 5.4 kg CO_2-eq/kg [8].

4.7.2 Ethanol Diesel [ED95]

In 2020 79.2 % of the bioethanol produced was used as a biofuel, ED95. It is an environmental friendly transportation fuel that emits 75.5 % less GHG than petrol [32]. The WtW emissions related to bioethanol are presented in Figure 23. Bioethanol from sugarcane has lower GHG emissions than bioethanol from wheat.

ED95 utilizes the same storage system as HVO and FAME, a composite storage fuel tank with an emission factor of 21 kg CO_2 -eq/kg [8]. Also, it is assumed to use the same CI engine.

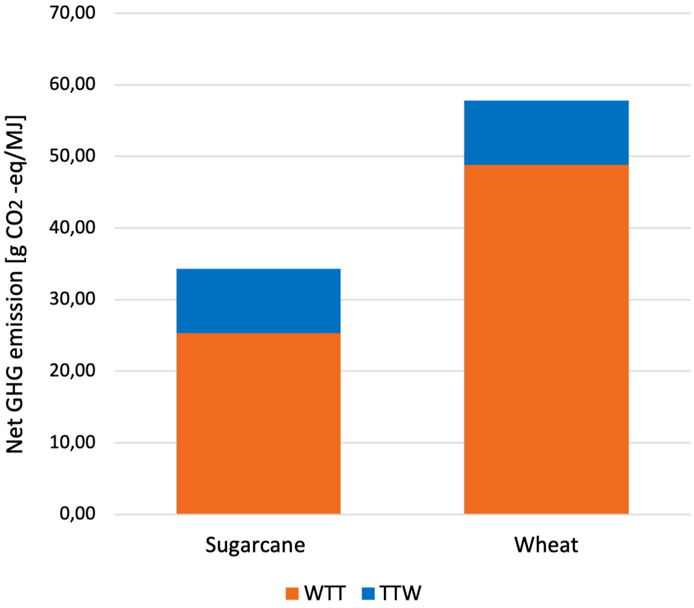


Figure 23: Bioethanol Well-to-wheel analysis. Data presented in Appendix A. [9, 64, 63].

4.7.3 Compressed biogas (CBG) and Liquified biogas (LBG)

Utilizing biogas in the transport sector can reduce GHG emissions by 80 % compared to fossil fuels. It is also the third fastest growing renewable energy source in the world [66]. Biogas comes from feedstocks that continuously grow and is therefore considered a renewable source.

Biogas has low NOx emissions compared to fossil diesel. A gas engine using LBG will also contribute to reducing SOx emissions [66]. Combustion of LBG releases water and CO_2. However, since it is a biodegradable material, the CO_2 would have been emitted by natural means [67] [66].

Figure 24 present the WtW emissons for LBG and CBG produced from waste, cow manure, wheat and logging residues. Figure 24 shows that cow manure has very low emissions. Agriculture emits large amounts of CH_4, therefore, using cow manure for biogas production is beneficial. All the feedstocks used in the analysis are second-generation feedstocks, which is why the GHG emissions are so low.

According to Asplan Viak's research report, CBG is stored in a composite storage tank and LNG is stored in a cryogenic fuel tank. A cryogenic fuel tank has an emission factor of 17 kg CO_2-eq/ kg, whereas a composite storage fuel tank has an emission factor of 21 kg CO_2-eq/kg. Even though the emission factor for the cryogenic fuel tank is lower compared to the composite storage tank, the production emission will be higher because the cryogenic tank is heavier [8]. Biogas must use a modifed SI-engine, which is asumed to have same production emissions as for the CI engine, 5.4 kg CO_2-eq/kg.

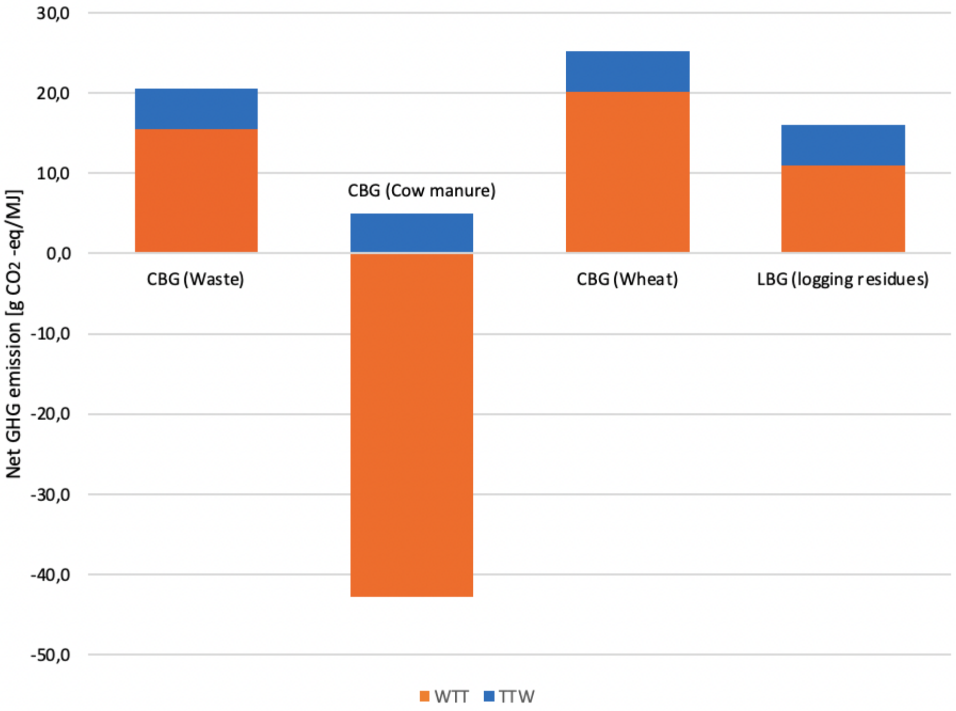


Figure 24: Biogas well-to-wheel analysis. Data presented in Appendix A. [9, 64, 63].

4.8 Cost of Biofuel Propulsion

This section will present the estimated price for biofuels between 2019 and 2030. Furthermore the costs of the systems used for the various biofuels are presented. In addition, the data used is based on a price analysis conducted by Argus Consulting for the Norwegian Environment Agency [68] [69].

4.8.1 Fuel costs

Figure 25 shows the price estimated for LNG, LBG, HVO, and MGO (marine gas oil) in the maritime sector. The price for advanced HVO is expected to grow due to increase in demand and limited supply. The biogas prices are rough estimates as it is still under development. The price estimations for biogas, from the Norwegian Environment Agency, are received from biogas suppliers in Norway. LBG (low) represents the price evaluation of LBG used for the maritime sector. It is lower than LBG for road transportation because it is assumed it will use already existing infrastructure for LNG. [68]

In Figure 26 the price estimations for diesel, advanced and conventional HVO and FAME are presented. In 2030, advanced HVO, the most expensive biofuel, is estimated to be 90 % more expensive than conventional diesel.

The price for conventional bioethanol in 2030 is expected to be 18 % higher than gasoline, whereas the price for advanced bioethanol is expected to be 60 % higher than gasoline. [69].

The taxes correlated to diesel, biodiesel, bioethanol, gasoline, and biogas are presented in Table 6. These taxes were not considered when estimating the prices in the figure above. However, the taxes cannot directly correlate to a maritime transportation fuel as the taxes represents road charge and CO_2 tax for road transportation. In order to simplify the calculations, taxes from road transportation are included in the fuel prices.

Table 7 shows the fuel prices for April 2022 for the different transportation fuels, including taxes. The

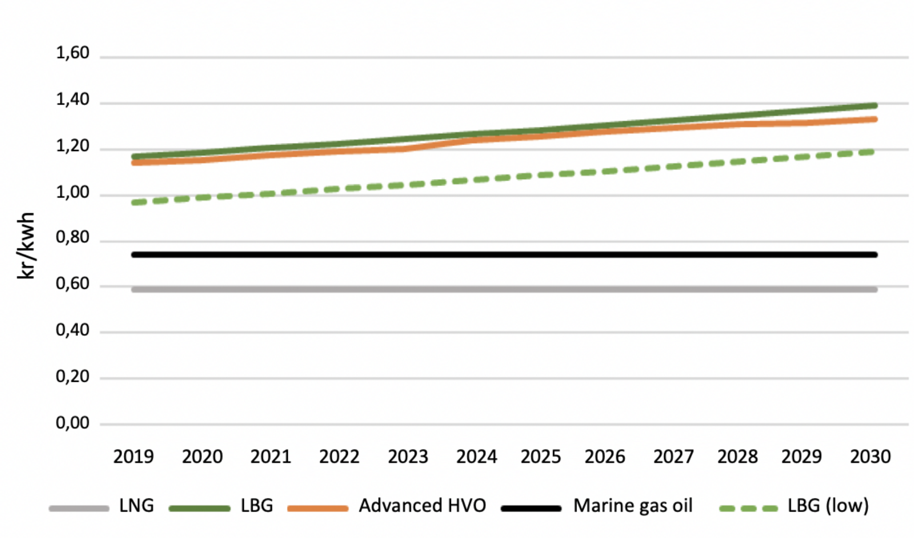


Figure 25: Price estimations for maritime sector [68].

prices for diesel, gasoline, B100 (100 % biodiesel), and HVO are from Circle K [12]. The price for ED95 is estimated to be roughly the same as ED85 (Ethanol diesel- 85 % ethanol and 15 % diesel) due to lack of priceinformation [70]. The current LBG and CBG costs are gathered from the prices Gasum currently delivers [71]. Also, the fuel prices presented in Table 7 show that the data collected from the Norwegian Environment Agency in 2019 is different from expected. Hence, the 2022 fuel prices were much higher than expected.

Table 6: Taxes, such as Road- and CO_2 charge.

Fuel	Tax price [NOK/L]	Reference
Diesel	5.57	[72]
Gasoline	6.73	[72]
Biodiesel	3.09	[73]
Bioethanol (ED95)	2.02	[73]
Biogas	0	[74]

Table 7: Prices in april 2022 for the different fuels (Taxes included) [53].

Fuel	Price [NOK/L]	Reference
Diesel	19.9	[12]
Gasoline	21.7	[12]
FAME (Biodiesel B100)	31.9	[12]
HVO	33.8	[12]
ED95	17.8	[70]
LBG	20.1	[71]
CBG	17.5	[71]

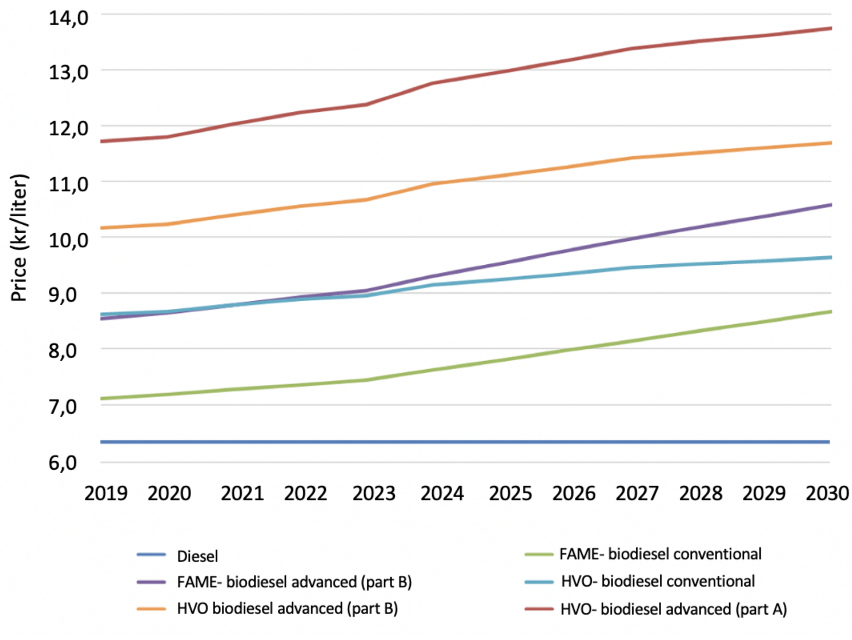


Figure 26: Price estimate for biodiesel (without taxes). Analyses from Norwegian Environment Agency (NEA), conducted by Argus Media [69].

4.8.2 System costs

The system costs include the fuel tanks and the engine used for the system. HVO, FAME, ED95, and CBG are stored in a composite fuel tank and LBG in a cryogenic storage tank. The cost per kilogram is presented in Table 22.

HVO and FAME utilize a CI engine with an estimated price of 93 140 NOK. CBG and LBG will also use the price of a CI engine, even though the system uses a modified engines. This may lead to some uncertainties, however, for simplicity, potential price differences are neglected.

Table 8: Costs of storage tanks.

Storage type	Cost [kr/kg]	Reference
Composite fuel tank	96.6	[75]
Cryogenic tank	9.5	[75]

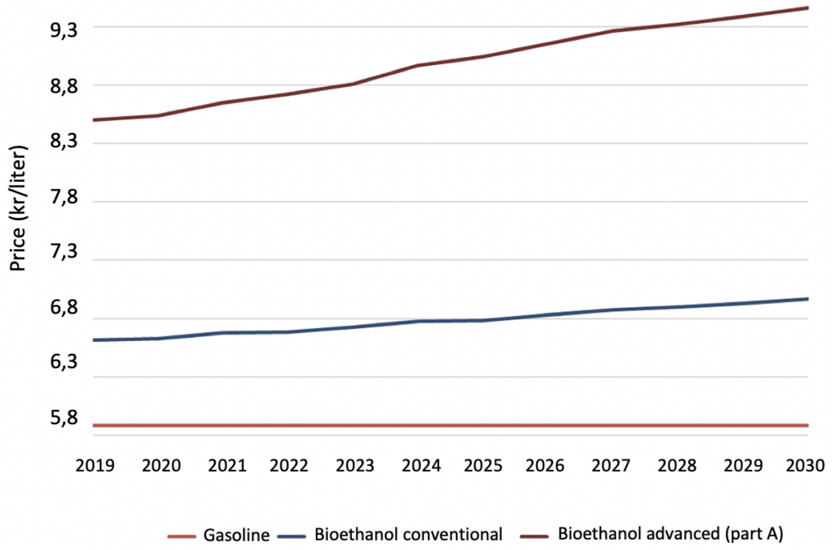


Figure 27: Price estimate for bioethanol (without taxes). Analyses from NEA, conducted by Argus Media [69].

4.9 Feasibility and Technology Readiness Level

Due to the current development and status within the transportation sector, the feasibility of FAME, HVO, LBG, CBG, and ED95 will be addressed in this section.

The consumption of bioenergy has varied over the last decade, mainly due to electrification, taxes and government standards tied to liquid biofuels. From 2017 through 2018, the usage of liquid biomass was reduced due to outphasing of palm oil used in biofuel production [22].

Currently, large amounts of industrial waste are exported from Norway. New ongoing industrial projects, presented in Table 9, will produce biofuel from the industrial waste. These four projects have a total investment of 14 billion NOK and will meet half the expected demand for biofuels in Norway in 2050 [69].

Table 9: Upcoming producers of advanced biofuel [69].

Location and Producer	Feedstock	Volume/ year [million litre]	Start up	Sort of biofuel
St1 Follum	Industrial waste	50	2023	Bioethanol + (Biogas and biocoal)
Silva Green fuel, Tofte	Industrial waste	100-150	2024/2025	drop in diesel, (diesel and jetfuel)
Biozin, Åmli	Industrial waste	120	2023	drop in diesel, (diesel and jetfuel)
Quantafuel, Østlandet	Industrial waste	10	Unkown	Bio-jetfuel

The availability of biofuels heavily depends on the available feedstocks. In theory, all organic material can be directly used for biofuel production, however, not all feedstocks are easily accessible in every part of the world. Thus, the main concern is pollution tied to transportation. Therefore, it is preferable to choose local biomass to reduce GHG emissions.

The TRL is dependent on feedstocks, but for this evaluation only industrial availability affects the TRL.

The biofuel technologies HVO, FAME, CBG and LBG evaluated are well developed and have a TRL level of 9, except for ED95, which has a TRL level of 7 in the maritime sector [76].

4.9.1 Fatty Acid Methyl Esters (FAME)

FAME is used as a blend for transportation fuels, accounting for up to 7 % in conventional diesel used in Norway. Fully replacing FAME with conventional diesel is challenging, due to limitations in storing, and sensitivity to cold temperatures. [49].

In 2019 11 million liters of FAME were produced in the EU, distributed over 187 biorefineres [77] [78]. Sweden have two main production facilities for rapeseed oil methyl ester (RME); Perstorp located in Stenungsund with a production capacity of 150 000 m^3 and Ecobransle in Karlshamn with a production capacity of 40 000 m^3 [79]. At the moment, Norway has one facility producing FAME, Perstorp located in Fredrikstad producing around 115 million liters yearly.

4.9.2 Hydrotreated vegetable oil (HVO)

In 2018, Circle K announced that they would offer milesBio HVO100, an advanced biofuel, for some fuel stations. Currently, HVO100 (100 % HVO) is available at seven stations around Norway; five in the Oslo area, one in Bergen and one in Trondheim. These stations are currently used for automobile vehicles, proving that the HVO100 infrastructure is developing [80].

There are no HVO production facilities located in Norway. In Europe there are three big producers, Neste oil in Finland, Preem in Sweden, and ENI in Italy. Both Finland and Sweden are neighbouring countries to Norway, and therefore, pollution tied to transportation of fuel will be small [13]. Sweden has several HVO plants, and two of the facilities, Preem and St1, produces 450 000 tonnes yearly [77].

There is a high incentive for Norwegian HVO production due to two favorable industrial oils for hydrotreatment: fish oil and rapeseed oil. Norway is one of the largest exporters of fish and can easily utilize fish oil or fish waste for biodiesel production. In 2018, Norway produced over 4 million tons of fish [81]. Usually, 1/3 of the fish goes to waste, resulting in 1.3 million tons of fish waste in 2018 [82].

4.9.3 Ethanol Diesel (ED95)

The largest producers of bioethanol are North- and South America. In 2020, bioethanol facilities in Europe produced roughly 8190 million liters [83]. In 2018, the transportation industry in Sweden had a bioethanol consumption of 131.5 ktoe [84]. Bioethanol is yet to play a significant role in the transportation sector in Norway.

The production facility Borregård in Sarpsborg, Norway, produces 20 million liters of bioethanol from forest waste per year, whereas 20 % of this is used as fuel. Three production facilities of advanced bioethanol in Sweden are SEKAB, St1 and Domsjö fabriker, which combined produce 23 160 tonnes yearly [85]. Bioethanol is still not an available fuel for the marine sector, due to engine technology [44].

4.9.4 Compressed biogas (CBG) and Liquified biogas (LBG)

In 2017 Europe produced 196 TWh biogas, whereas only 1.75 TWh were used for transportation [68]. Biogas has an accessible infrastructure available for Norway. There are 40 methane filling stations in Norway, primarily located around Oslo, the South-west, and in Trondheim. Only three of the stations offer LBG. [86].

Skogn Biokraft in Trondheim, shown in Figure 28, is one of the most extensive biogas facilities globally, producing LBG from fish residues. Two other production facilities in Norway are Nes in Romerriket that produce LBG from food waste, and EGE in Oslo that produces CBG from sewage waste. Sweden produces large amounts of LBG and CBG. In 2018, Sweden had 280 biogas production facilities, producing 2.1 TWh biogas. In 2019, 64 % of the produced biogas were upgraded to biomethane and used as a transportation fuel.

Figure 28: Skogn Biokraft facility in Trondheim. Photo credit Intrafish [87]

4.10 Summary

HVO is an excellent substitute for diesel today due to its properties and the that it can go directly into a diesel engine with just small adjustments. However, it has the highest prices of all the fuels. On the other hand, FAME has similar properties to diesel. Also, it has lower pricing and is more accessible in Scandinavia than HVO. Thus, FAME is not well suited to cold climates, an issue known for cold winters in Norway.

CBG and LBG have competitive pricing. However, the fuels require a more significant amount of refill due to their lower specific energy density and become more expensive in the total picture. Thus, the technologies are accessible in Scandinavia and are a technology that can be a direct substitute for LNG and CNG. However, the storage tanks with CBG and LBG must be placed on top of the boat due to safety reasons. This can therefore be a challenge to have enough space.

Bioethanol has a TRL level of 7, and is still developing as a maritime fuel due to its engine technology. Therefore, ED95 will not be considered further in the case study.

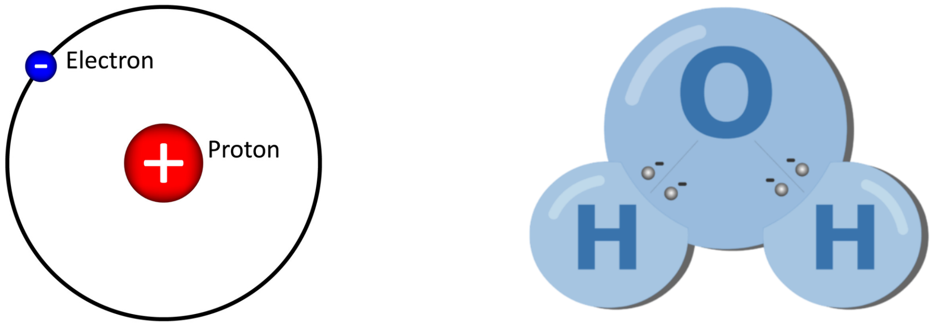
5 Hydrogen

The following section describes hydrogen as an energy carrier, as well as its technical and chemical characteristics for production, fuel cell technology, and storage. Furthermore, the feasibility, emission, energy utilization, and economic aspects will be addressed.

5.1 Hydrogen Properties

Hydrogen is the first and lightest element in the periodic table. In addition, hydrogen is also the most common element in the universe, with an estimated mass fraction of 75 % [88]. The hydrogen atom consists of an electron and one proton. Figure 29a shows the Bohr model of hydrogen.

Although it is a common element, hydrogen is rarely found in its pure form. Instead, hydrogen on earth is found in chemically bonded molecules. Hence, a separation of a hydrogen-consisting molecule is required to use hydrogen directly as an energy carrier. Until 1960, hydrogen's characteristics as an energy carrier were unknown, mostly recognized as an element of the water molecule [89]. Today, hydrogen is heavily researched and, by many, considered an essential energy carrier in the future. Figure 29b shows how hydrogen connects to oxygen in the water molecule.



(a) Hydrogen atom.

(b) Water molecule.

Figure 29: Hydrogen atom and the water molecule [90] [91].

Hydrogen is characterized by a high energy density but a low volumetric energy density. Due to its low boiling point, hydrogen is usually found in gas form. In order to exist as a liquid, hydrogen must be cooled below -259.14 C°. Table 10 shows hydrogen's characteristics as an energy carrier.

Table 10: Characteristics of the hydrogen molecule.

Energy density [MJ/kg]	**Volumetric energy density** [MJ/L]	**Boiling temperature** C°	**Reference**
120	0.01	-259.14	[92]

5.2 Production of Hydrogen

Almost all organic compounds include hydrogen in their molecules. Multiple pathways exist to produce pure hydrogen. The three main categories of hydrogen production are; steam reforming or gasification, steam reforming with carbon capture and storage, and electrolysis. These pathways produce pure hydrogen, distinguished by their emissions and divided into colors. This section explains the three production types. In Figure 30 the different production paths for hydrogen are displayed.

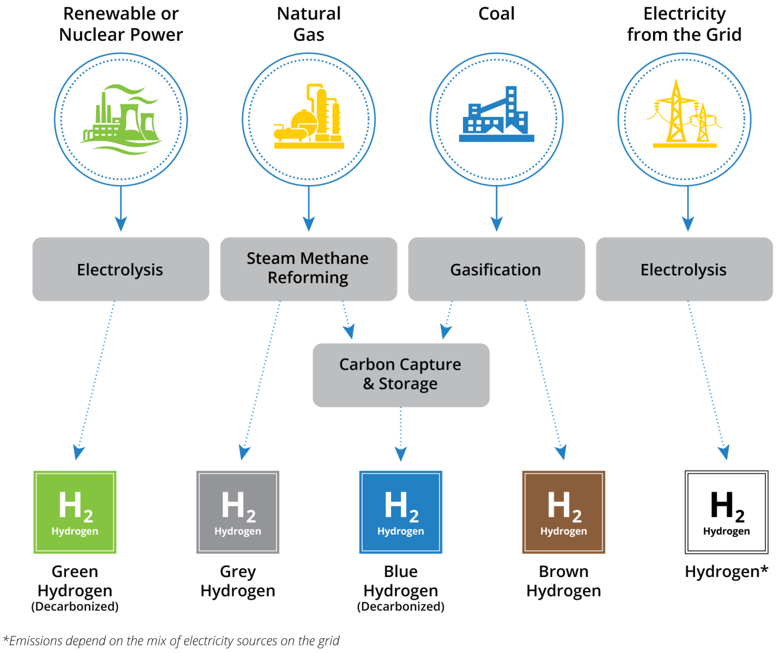


Figure 30: Hydrogen production types [90].

5.2.1 Steam Reforming - Grey Hydrogen

Currently, 96 % of all produced hydrogen is qualified as grey. The production of grey hydrogen emits more GHG emissions than blue and green hydrogen. Grey hydrogen has similarities with blue hydrogen, as the energy used in the gasification or steam reforming process also originates from fossil fuels. However, grey hydrogen does not capture and store the emissions. Therefore, this production process emits more emissions than blue and green hydrogen production. Grey hydrogen is the most common variation of hydrogen because of the low cost and the accessibility of fossil fuels. Figure 31 illustrates the production process for grey hydrogen.

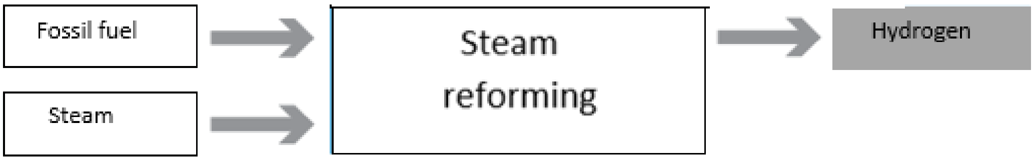


Figure 31: Production of grey hydrogen [93].

Steam reforming is the most used way of producing grey hydrogen. This process uses steam from water to produce hydrogen and CO_2 from hydrocarbons. The steam reforming method consists of four processes [94]:

1. Methane and water reacts to create carbon mono oxide, carbondioxide and hydrogen

$$\mathrm{CH_4 + H_2O \longrightarrow CO + 3H_2}$$

$$\mathrm{CH_4 + 2H_2O \longrightarrow CO_2 + 4H_2}$$

2. Carbon monoxide reacts with water and creates carbon dioxide and hydrogen

$$\mathrm{CO + H_2O \longrightarrow CO_2 + H_2}$$

3. Carbon dioxide removal
4. Remaining carbon dioxide and carbon monoxide is reformed to methane

5.2.2 Steam Reforming with Carbon Capture and Storage - Blue Hydrogen

Blue hydrogen originates from fossil fuels containing hydrocarbons. As for grey hydrogen production, CH_4 is steam reformed and creates hydrogen and CO_2. However, blue hydrogen is considered an environmentally friendly way of producing hydrogen. The CO_2 is captured and stored during hydrogen separation from fossil fuels. These emissions are stored underwater. Theoretically, 90 % of the GHG emissions are captured during this production process. However, estimations show that far less than 90 % are captured using currently available technology. As with green hydrogen, the production of blue hydrogen is expensive. Furthermore, the technology for storing and transporting emissions has to develop further before steam methane reforming is the preferred way of hydrogen production. Figure 32 illustrates the steam reforming process of blue hydrogen [95].

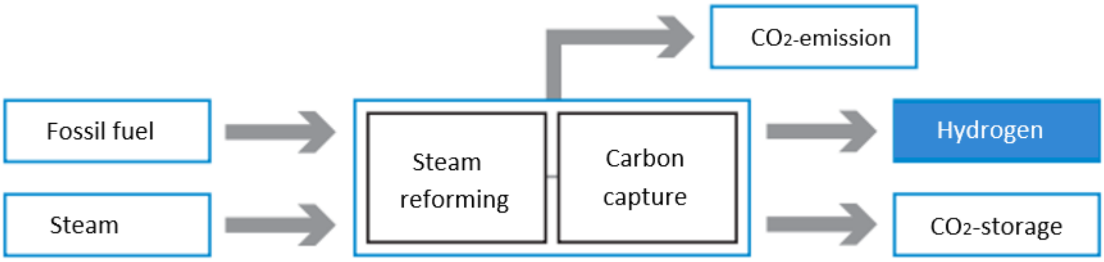


Figure 32: Production of blue hydrogen [93].

Carbon capture and storage (CCS) is essential in blue hydrogen production. With access to natural gas and 20 years of research and experience regarding CO_2 managing, does Norway have an opportunity to capitalize on these advantages and develop CCS projects. Longship is a project developed to capture, transport, and storage of CO_2, launched by the Norwegian government in 2020. Two CCS projects are currently fully or partially financially supported by the Longship project. In Breivik, capture of CO_2 at the Norcem cement factory and capture of CO_2 at the waste-to-energy plant Fortum Oslo Varme in Oslo are the supported projects [96]. Figure 33 illustrate the sequence of events in the project.

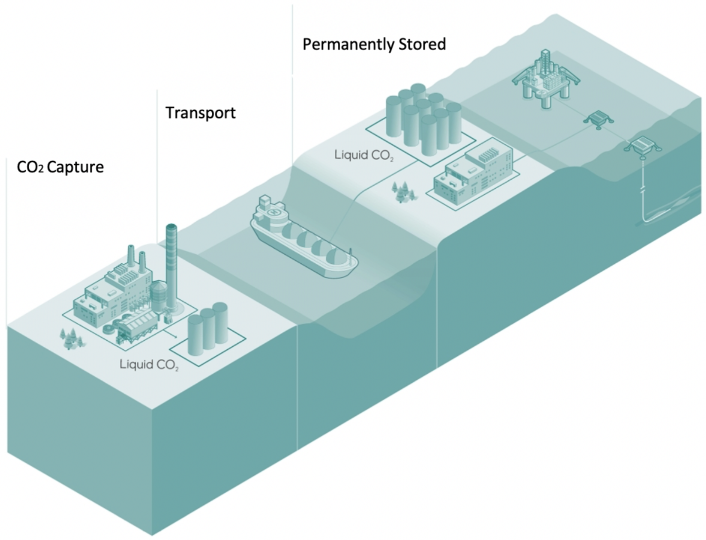


Figure 33: The longship project. Picture credit Northern Lights Project [96].

5.2.3 Electrolysis - Green Hydrogen

Electrolysis uses electrical energy to decompose molecules into different components. The process is a redox reaction, where both an oxidation and a reduction occur. This process separates hydrogen and oxygen from the water molecules. The system consists of an electric current connected with two electrodes. The electrodes consist of a positively charged anode and a negatively charged cathode. This process emits zero GHG emissions, but the required electrical input may result in GHG emission, dependent on its origin. For example, if the electrical input originates from renewable energy, the hydrogen is considered green, whereas electrical input from electricity based on fossil energy results in white hydrogen. In this report, white hydrogen will not be further discussed, as the environmental impacts are less beneficial than green hydrogen. Figure 34 illustrates the electrolysis process for green hydrogen.

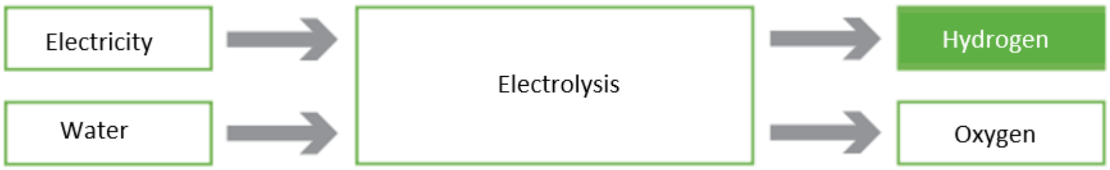


Figure 34: Production of green hydrogen [93].

As of today, the disadvantage with green hydrogen production is the inefficiency and high cost. Furthermore, renewable sources of energy may not be available due to topographical restrictions. Therefore, hydrogen production for green hydrogen is strongly dependent on the prevalence of electricity from renewable energy.

Hydrogen from Seawater

Hydrogen can also be produced by electrolysis using seawater. However, the chlorine gas reaction at the anode promotes corrosion, induced by the chlorine ions, which is undesirable. This type of hydrogen production is still at a reserach level [97], and will therefore not be further discussed in the report. However, seawater may be an excellent alternative for electrolyzing in the future.

Proton Exchange Membrane Electrolysis

Different electrolyzer cells may be used in hydrogen production. The proton exchange membrane electrolysis cell (PEM) is considered the most efficient and safe way of producing hydrogen from water [97]. As displayed in Figure 35 the PEM electrolyzer forms a membrane electrode assembly (MEA), which contains two electrodes, one positive and one negative. The proton-conducting polymer electrolyte membrane separates the electrodes, and allows for transportation of protons. The electrolyte typically consists of a thin polymer, such as perlfluorsulfonic acid (PFSA) polymers [75].

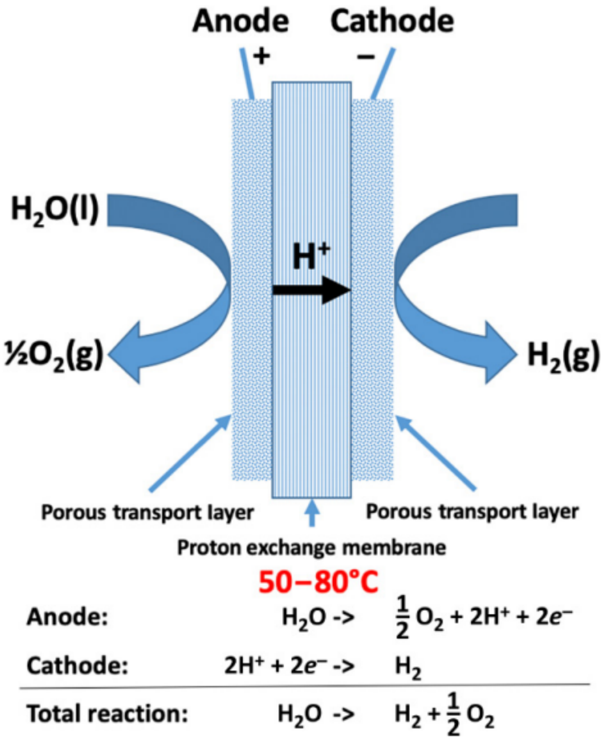
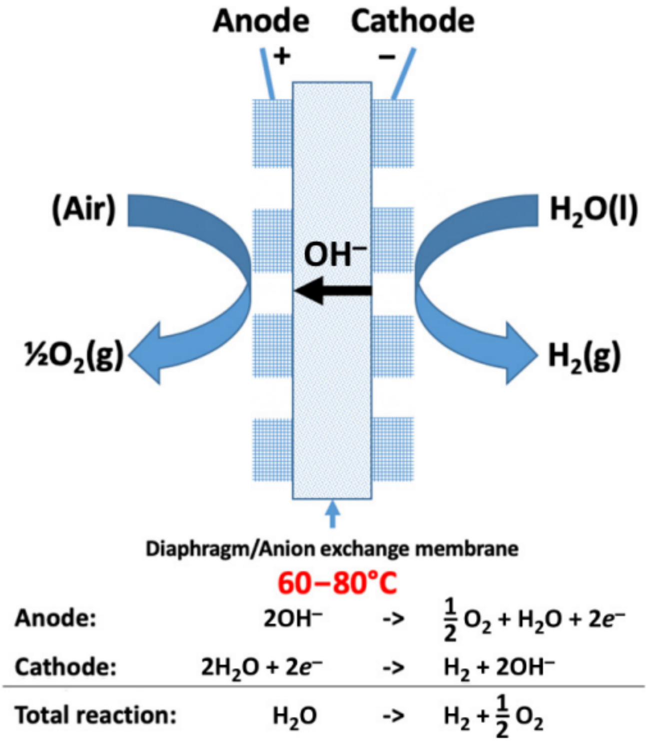


Figure 35: Schematic of a proton exchange membrane electrolysis cell [97].

Figure 35 displays the cell reaction of the PEM electrolyzer. The PEM electrolysis can operate at high current densities while maintaining high efficiency. In the PEM electrolyzer, high purity water is required, resulting in high purity of the produced gases. The PEM cell also has a high dynamic range, beneficial in relation to renewable energy sources due to to the intermittent nature of renewable energy sources. The disadvantages with the PEM cell are related to high capital costs, its need for high-quality water, and not yet applicable for larger-scale system [97]. The current state of the PEM electrolyzer can be described as an early phase of commercialization [75].

Alkaline Electrolysis Cell

The alkaline electrolysis cell (AEC) is the electrolyzer cell with the highest technological maturity. The main difference between the AEC and the PEM appears in the cell assembly and the reactions in the cell. In the AEC cell, two metallic electrodes are placed in a liquid electrolyte solution consisting of Potassium hydroxide (KOH) and Sodium hydroxide (NaOH). To achieve maximum electrical conductivity, the liquid electrolyte should have a combined NaOH and KOH mass concentration of 40 % [97].



Anode:	$2OH^-$	->	$\frac{1}{2}O_2 + H_2O + 2e^-$
Cathode:	$2H_2O + 2e^-$	->	$H_2 + 2OH^-$
Total reaction:	H_2O	->	$H_2 + \frac{1}{2}O_2$

Figure 36: Schematic figure of an Alkaline electrolysis cell [97].

As illustrated in Figure 36, water is reduced at the cathode, producing hydrogen. The negative OH^- ion is transported through the membrane and produces oxygen when reacting with air. AEC is cheap compared to the investment costs of the other electrolyzer cells. Larger systems based on AEC already exists. Furrthermore purification of water is not required [97].

Compared to PEM, AEC will produce hydrogen of lower quality. Studies show that purity of the gas decrease when operating pressure increases. Another problem that might occur because of high pressure, is the risk of gasmixing. The electrodes in the AEC are often coated with a layer of porous nickel produced by the leaching of zinc from the Raney nickel. For a long time, asbestos was used for this application. However, because of its toxicity and ability to cause lung cancer, a large number of different solutions were implemented to replace the asbestos [97]. A practical disadvantage for the alkaline cell is the weight. The PEM is more attractive if the required application is weight dependent and of small scale, as the Sounder USV.

Solide Oxide Electrolysis Cell

The solid oxide electrolysis cell (SOEC) is the newest way of separating hydrogen from water. The SOEC requires a high operating temperature, between 600-900 C°. Furthermore, in the SOEC, the solid electrolyte and cell separator consist of oxide-ion-conducting ceramics.

Figure 37 is a schematic display of the SOEC. The figure shows both the reactions at the anode and cathode and the ions moving through the membrane. The O_2^- ion passes through the membrane and reacts with air, creating oxygen molecules. A standard electrolyte used in this type of cell is zirconia coated with manganite [97]. These cells have increased in demand because of their ability to operate with high current densities and efficiency. Due to its high temperature the cell can be reversed and utilized as a fuel cell. The SOEC is the newest of the described cells and is therefore not commercially available [75]. In contrast to the PEM electrolyser, the SOEC have a low dynamic range, which is not beneficial in relation to renewable energy sources.

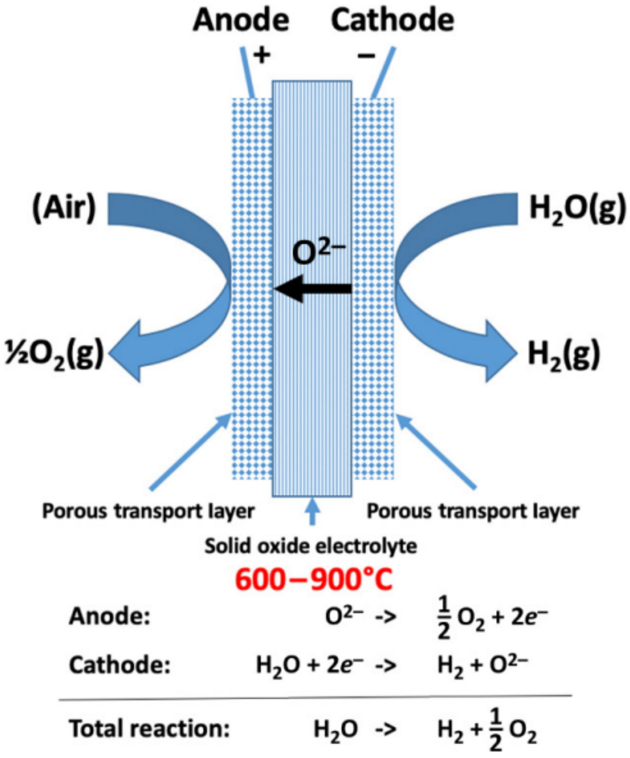


Figure 37: Schematic display of solid oxide electrolysis cell [97].

Losses During Green Hydrogen Production

A potential drawback for green hydrogen is the total efficiency of the production process. The losses occur because green hydrogen requires multiple processes. As efficiency propagates, the added steps also reduce the total efficiency of the whole energy conversion process. Therefore, when looking at a WtT efficiency analysis, the efficiency of electrolyzed hydrogen is significantly lower than the process for batteries, illustrated in Figure 38.

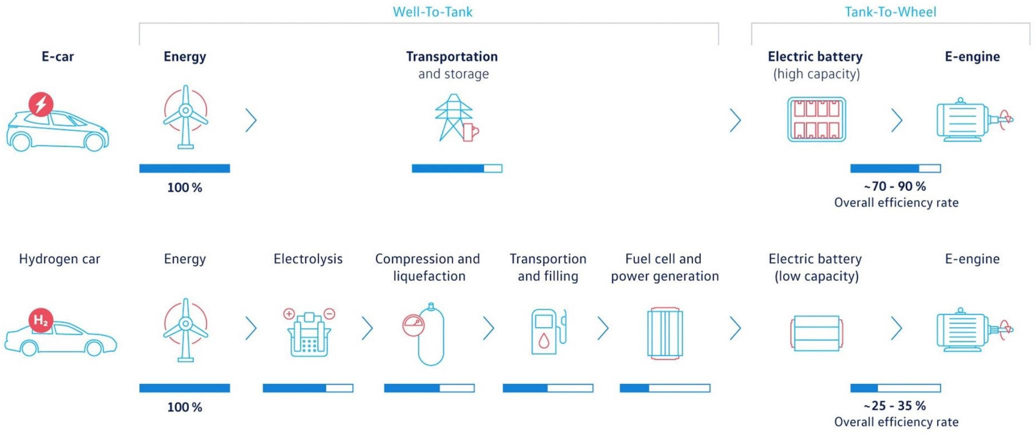


Figure 38: Losses during hydrogen losses compared to electricity [98].

5.3 Hydrogen Storage

Hydrogen can be stored in various ways. This section will focus on the storage systems based on liquefaction, compression, and metal absorption. The main differences between these types of energy storage are the state of hydrogen and the volumetric energy density, which indicates the amount of energy stored per unit volume. In Table 11 the variation of hydrogen specific energy density is displayed.

Table 11: Hydrogen energy density.

Hydrogen type	Energy density [MJ/L]	Reference
Pure gas	0.01	[92]
Compressed at 70 MPa	4.5	[92]
Liquid	8.5	[92]
Metal hydride	15	[75]

The most common storage system for standard propulsion systems is compression or liquefaction. The liquified storage has the highest volumetric energy density out of these two. However, the low temperature to keep hydrogen liquefied increases the storage complexity, cost, and weight. Therefore, liquefied storage is rarely beneficial for small propulsion systems. Hydrogen stored as non-pressurized gas takes up too much space, and the energy density is too low. Pressurized hydrogen at around 70 MPa or 700 bar is the most common storage system for a marine vessel like the Sounder USV.

Pressurized H_2 Storage

Pressurized hydrogen storage is done in many ways. Conventional pressure bottles can hold up to 500 bar and are cheap and easily accessible. For storage types that can handle higher pressure, the carbon fiber composite can hold up to 1000 bar. Higher pressure will increase the volumetric energy density, which is preferred if storage space is an issue. The industry normally acquires storage tanks that can hold 700-800 bar [99]. The advantages of the pressurized storage are the simple technology and the fast filling and release. The energy required to pressurize the hydrogen, does not increase linearly in relation to pressure. Pressurizing hydrogen from 20-350 bar would require 1,05 kWh/kgH_2, while further compression to 700 bar demands 1,36 kWh/kgH_2 [97].

Pressurized hydrogen consists of four conventional types; fully metallic, steel with glass fiber composite overwrap, full composite wrap with metal liner, and fully composite. Figure 39 displays the different storage types for pressurized H_2.

Type I - Fully metallic The fully metallic hydrogen storage is the cheapest and most conventional type. However, it can not hold more than 500 bar. In addition, the fully metallic is heavy compared to the other pressurized hydrogen storage tanks. [99].

Type II - Steel with glass fiber composite overwrap Type II is pretty similar to type one in storage capacity based on pressure; type two consists of a 50/50 share of steel and composite. This results in a 60-70 % weight reduction compared to type I. As composite is characterized by high cost, type II is typically 50 % more expensive than fully metallic tanks [99].

Type III - Full composite wrap with metal liner and fully composite

Type III is fully composite with aluminium only for sealing purposes. This type of storage can safely hold up to 450 bar, but tests have shown possible problems regarding aging when the pressure reaches 700 bar. Type III is 50 % of the weight of type II and 15 % of type I. Cost-wise, type III is twice the price of type two and two and a half the cost of type I [99].

Type IV - Fully composite

Type IV has the highest volumetric energy density as it can handle the pressure of 1000 bar. Type IV uses high-density polyethylene as liner and, the composite consists of carbon fiber. In addition, type IV is the lightest of all the storage types, but also the most expensive.

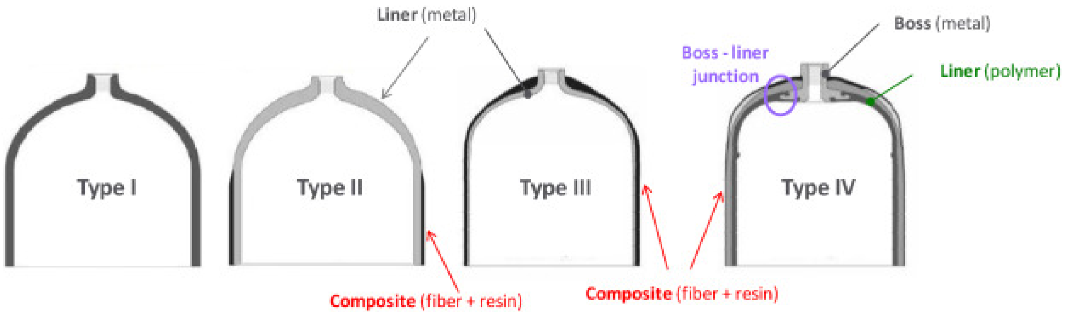


Figure 39: H2 pressurized storage types [99].

Cryogenic Storage

Cryogenic storage is used to store liquefied hydrogen. Because of hydrogen's low boiling temperature, isolation in the tank is essential. A temperature higher than -259.14 C°expands the hydrogen. Therefore the management of BOG, boil of gas, is vital. Cryogenic hydrogen storage provides a high volumetric density of 70 g/L, twice the energy density of a 700 bar pressurized tank. However, the complexity of the cryogenic system is more advanced, and more expensive than the pressurized system. In addition, 40 % of the energy can be lost in the liquefaction process. Cryogenic tanks are also associated with high weight. Because of the complexity, expensive tanks, and weight, this type of storage is typically acquired in large-scale systems.

Metal Hydride Storage

Metal hydride storage of hydrogen is based on chemical absorption of hydrogen into a metal. This type of storage has a high volumetric density, typically in the region 70 - 150 g/L, potentially twice of cryogenic hydrogen storage. Disadvantages for this technology are high costs, sluggish reaction kinetics and heavy tanks. This makes the hydride metal storage non-beneficial if the application is dependent on weight, cost, or quick energy release [100].

Metal Organic Framework Storage

Metal organic framework storage has many similarities with metal hydride storage , but for metal organic storage, the hydrogen is adsorbed, instead of absorbed into the metal. The metal must be a microporous material, which has high porosity. This type of storage has about the same energy density as liquified hydrogen, at 70 g/L. One of the advantages for this type of hydrogen storage, is the large surface area, as the metal does not require much energy to adsorb the hydrogen. In addition, the energy release reaction happens fast, in contrast to the metal hydride storage. The disadvantages of organic storage may be related to the low energy density, the heavy tanks, and the energy required to maintain a low temperature in combination with high pressure. As a result, this type of storage is beneficial if used in an application where the energy is extracted fast, and weight is less of a concern [101].

Table 12: Hydrogen storage types [99] [100] [101].

Type of storage	**Volumetric energy density gH2/L**	**Disadvantage**	**Advantage**
Pressurized	0,3-55	o Low energy density	o Cheap o Simple energy o Fast filling/releasing
Cryogenic	70	o Requires much energy o Complex	o High energy density
Metal hydride	70-150	o High weight and cost o Slow reaction	o High energy density
Metal organnic framework	70	o Weight o Require low temp and high pressure	o Fast kinetics o Low required energy

Table 12 displays an overview of the different storage types. For the Sounder USV, a relatively small vessel, pressurized hydrogen storage will be beneficial due to its cheap technology, low weight, fast filling and energy release. However, cryogenic hydrogen storage may also be viable option, and will therefore be considered in the report.

5.4 Energy Utilization and Propulsion System

The propulsion system required for hydrogen energy utilization consists of four components; a fuel tank, fuel cell, electric motor, and a propeller. In addition, the fuel cell requires access to air. Figure 40 shows a simple illustration of the system. Hydrogen and air are fuelled into a fuel cell, converting chemical energy into electrical energy. Next, the electrical energy goes to an electric motor, and the motor transforms electrical power into mechanical power. At last, this mechanical power powers the propeller, which causes the propulsion.

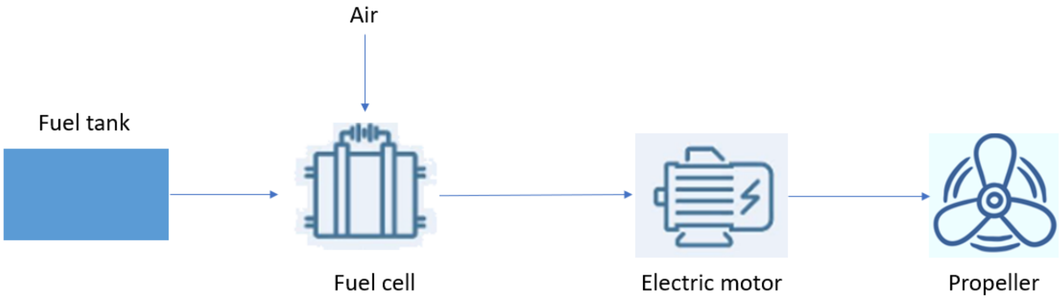


Figure 40: Propulsion system based on hydrogen.

As hydrogen is an energy carrier and not an energy producer, the energy must be subtracted from the molecule, through fuel cells. This section will discuss three different fuel cells: proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), and solid oxide fuel cell (SOFC). In table 13, the main attributes of the fuel cells can be found.

The efficiency for the different fuel cells in table 13 is about 60% [102]. For the Sounder USV, the most beneficial fuel cell is the PEMFC. AFC is concidered to heavy, whereas the high required temperature of SOFC would require more energy compared to the PEMFC. However, all three fuel cells will be addressed to illustrate how fuel cell properties will affect the system.

Table 13: Different fuel cells [102].

Fuel cell	**Common electrolyte**	**Operating temperature**	**Advantages**	**Challenges**
PEM	Perfluorosulfonic acid	<120°	o Low corrosion o Few electrolyte problems o Low temperature o Quick start-up	o Expensive o Sensitive to fuel impurities
Alkaline	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°	o Low cost o Low temperature o Quick start up	o Sensitive to CO_2 in fuel - and air o Heavy o Electrolyte managment o Electrolyte conductivity
SOFC	Yttria stabilized zirconia	500-1000°	o High efficiency o Fuel flexibility o Solide electrolyte	o High temperature o High corrosion o Some breakedown of - cell components o Long start-up Limited numbers - of shutdown

The estimated power density for the PEMFC is 1.6 kW / kg [103]. A fuel cell used in the Apollo space program, was used in order to estimate the power density for an AFC. The AFC delivered 1.5 kW and had a weight of 113 kg [104], which resulted in a power density less than one percent of the PEMFC power density. The SOFC has the highest power density of 2.5 kW/kg [105].

In order to utilize the electric energy from the fuel cell an electric motor is needed as it to transforms electrical energy into mechanical energy. The power density of the electrical motor is 5.8 kW/ kg [103]. Table 14 shows the power density for the fuel cells, as well as the electric engine.

Table 14: Weight of fuel cells and electric engine.

Component	**Power density [kW/kg]**	**Reference**
PEMFC	1.6	[103]
AFC	0.0132	[104]
SOFC	2.5	[105]
Electric motor	5.8	[103]

Fuel Cell Basics

Fuel cells are located in hydrogen propulsion systems, utilizing the energy carried in the stored hydrogen tanks. The hydrogen fuel cell may remind of the discharge of a battery. However, in contrast with batteries, the fuel cell must be continuously fueled by an energy source. Whereas the electrolyser uses energy and water to produce hydrogen and oxygen, the hydrogen fuel cell operates as a reversed electrolyser, creating energy and water, from oksygen and hydrogen

Overall the hydrogen fuel cell uses hydrogen and oxygen to produce energy and water. The chemical reaction of the system is illustrated in equation 4.

$$2H_2 + O_2 = 2H_2O + \text{Energy} \tag{4}$$

Equation 4 shows that the products for the fuel cell reaction is water and heat. The hydrogen fuel cell can be traced back to 1839. However, solid installation were not made before 1940, furthermore commercially available in the following years. As a result, the technological use of fuel cells is relatively new and still under development [106].

5.4.1 Proton Exchange Membrane Fuel Cell

The PEMFC is the most attractive fuel cell for the Sounder USV because of its low weight and high power density. Figure 41 shows a schematic representation of a PEMFC. The components in the fuel cell are the same as the electrolyzer and will therefore not be further explained.

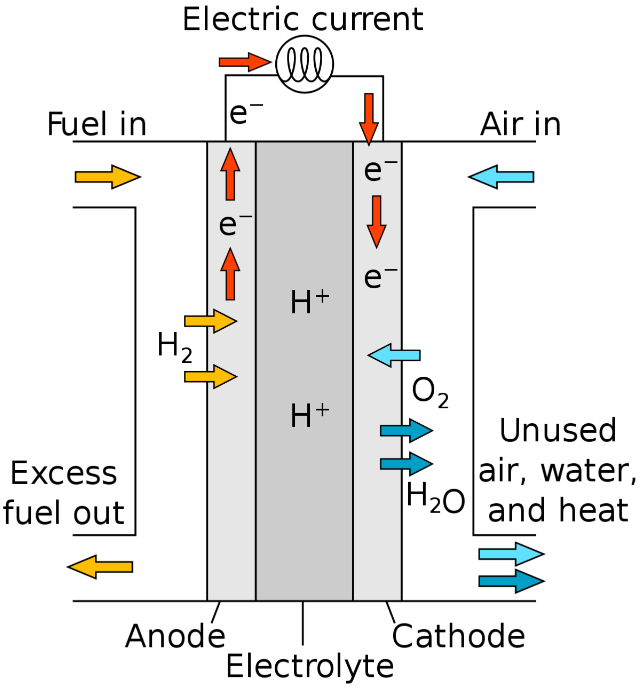


Figure 41: Schematic PEM fuel cell [107].

The hydrogen oxidation happens at the anode, where electrons are extracted. The positive hydrogen ions flows through the membrane while the electrons travel in an external circuit creating an electric current. At the cathode, the positive hydrogen ions reacts with air and creates water molecules. The PEMFC has the advantage of extracting excess fuel for later use.

5.4.2 Alkaline Fuel Cell

The AFC is the oldest fuel cell technology. Figure 42 shows a schematic representation of the fuel cell. Hydrogen is oxidated at the anode and oxygen is reduced at the cathode by the released electrons from the hydrogen. As a result, OH^- ions is transported through the electrolyte, which creates water at the anode. In contrast to the PEMFC, AFC does not save excess fuel.

The alkaline fuel cell is cheaper compared to PEMFC, as the fuel cell may use cheap materials like nickel and nickel oxide electrodes. However, AFC requires pure oxygen and hydrogen to prevent the production of solidified alkaline carbonates in the electrolyte, which is undesirable as the AFC operates with a circulating electrolyte. This need for pure oxygen makes the alkaline fuel cell less appealing for use in transportation [104].

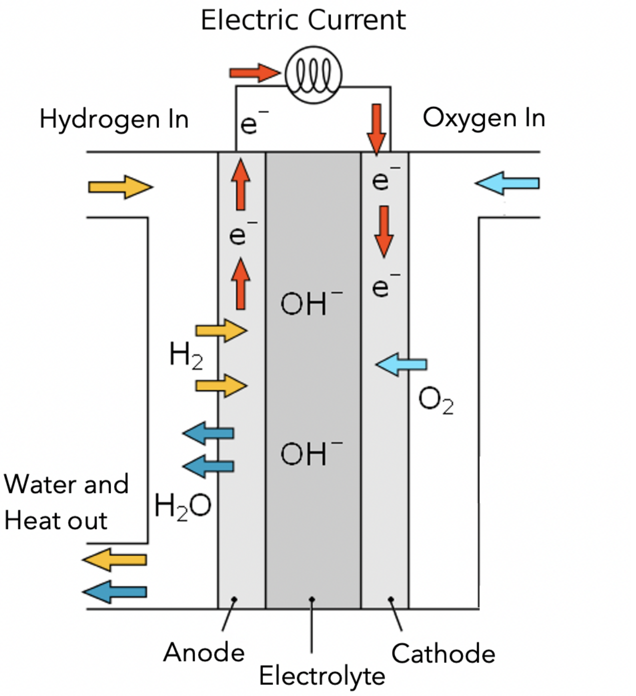


Figure 42: Schematic figure of an alkaline fuel cell, inspired by: [108].

5.4.3 Solide Oxide Fuel Cell

The solid oxide fuel cell (SOFC) is the most pristine of the three addressed fuel cells. Both excess fuel and air are released during the use of SOFC. Figure 43 shows a schematic explanation of the SOFC. As with PEMF and AFC, hydrogen is oxidated at the anode, whereas oksygen is reduced at the cathode. For the SOFC, O^{-2} moves through the electrolyte, producing water and energy.

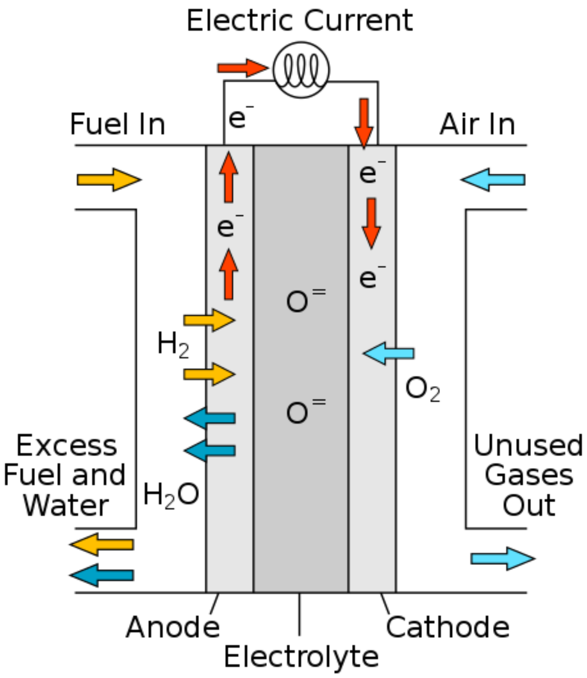


Figure 43: Schematic figure of a solide oxide fuel cell [109].

The SOFC can utilize various fuels as natural gas, ammonia, methanol, petroleum and hydrogen. This advantage have caused great interest in SOFC, due to its flexibility. However, the technology for SOFC is expensive and requires high temperatures to operate [110].

5.5 Emissions

If hydrogen is produced locally, with no transportation, and with the use of renewable energy in the electrolysis process, there is no GHG emissions related to the production of hydrogen. However, this approach is expensive and may come with significant losses. Therefore, this section will consider the three different hydrogen categories; grey, blue and green.

5.5.1 Fuel Production

All estimations in the following sections are based on a study done by the European Commission Joint Research Centre, Institute for Energy [63]. This is a WtW analysis for grey, blue and green hydrogen. The emission estimations accounts for hydrogen compressed to 880 bar.

When producing blue hydrogen based on carbon capture, local production is rarely an option. This is because carbon capture requires full decarbonization, somewhere geographically suited for storage of emissions. As the study used for the emission estimations covered many different scenarios, one scenario accounting for hydrogen production from natural gas was used. The study explains the process as "Here hydrogen is produced by steam reforming of natural gas (pipeline 4000 km) in a central plant from where it is distributed through a local pipeline network (50 km average distance) before compression to 88 MPa at the refuelling station" - [63]. As this scenario is related to large scale production, carbon capture is accounted for. Hydrogen production from natural gas is highly relevant in Norway because of large access of natural gas. The emission estimations for hydrogen is illustrated in Table 15. Hydrogen emissions without carbon capture are considered grey, whereas emissions with carbon capture are considered blue.

Table 15: Emission for hydrogen based on natural gas.

With or without carbon capture	**Net GHG emitted g CO_2-eq/MJ**	**Reference**
Without Carbon Capture	98.8	[63]
With Carbon Capture	37.8	[63]

Coal is often utilized in hydrogen production. The following estimations are based on the gasification of hard coal with an EU-mix origin. The case also estimates that the average transportation distance for a local pipeline is 50km. These emissions are illustrated in Table 16, considering emissions with and without carbon capture.

Table 16: Emissions for hydrogen based on hard coal.

With or without carbon capture	**Net GHG emitted g CO_2-eq/MJ**	**Reference**
Without carbon capture	234.4	[63]
With carbon capture	52.7	[63]

For green hydrogen, the only emissions come from hydrogen compression. The scenario in the study rsuggested no emissions for transportation of green hydrogen as the hydrogen is produced locally. For the compression, an EU-electricity mix has been used, whereas electricity from windenergy were used for the electrolysis. Table 17 shows the emission for green hydrogen.

Table 17: Emission for electrolyzed hydrogen.

Hydrogen production	Net GHG emitted g CO_2-eq/MJ	Reference
Electrolyzed water fueled with wind energy	9.1	[63]

A comparison of the emissions are presented in Figure 44.

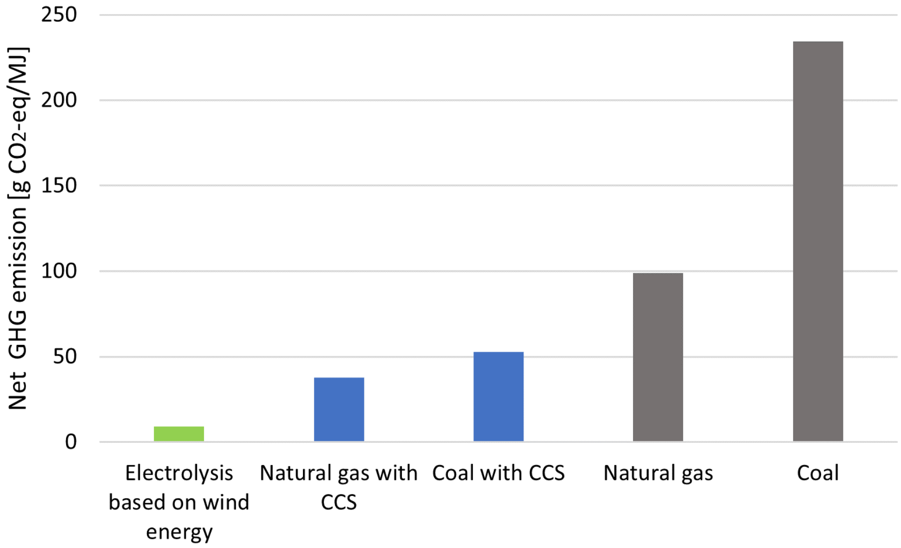


Figure 44: Emission for different hydrogen.

Hydrogen compression and liquification

The scenarios above only considered compressed hydrogen for storing. In comparison, liquefaction of hydrogen requires more energy, which results in more emissions compared to compressed hydrogen. Table 18 shows the estimated emissions for the hydrogen conversions.

Table 18: Emissions regarding physical conversion of hydrogen.

Electricity origin	Compression [g CO_2eq/MJ]	Liquification [g CO_2eq/MJ]	Reference
EU-mix	9.1	38.4	[63]

5.5.2 System Production

This section will display the emissions for production of a standard PEMFC. Emissions related to PEMFC are well documented, and as the difference in construction of the FCs are small, potential emission differences between the FCs are neglected.

The calculations for the emission estimations are gathered from a Jornual about cleaner production, written by Lorenzo Usai [111]. Here, a life cycle assessment of fuel cell systems for light-duty vehicles is conducted. These calculations include production of the fuel cell stack, hydrogen tanks, and fuel cell auxiliaries. The journal suggested that the most prominent contributers are the production of hydrogen tanks, fuel cell auxiliaries, and catalysts. The total cumulative emissions can be found in Appendix B 102.

The study by Usai showed that almost 40 % of the total GHG emissions are related to the production of storage tanks. These estimations are based on a tank capable of pressure up to 700 bar. Another significant contributor to the emissions, is the catalyst, responsible for 24 % of the total emission. The auxiliaries of the fuel cell contributed with 17% of the total emissions.

The majority of the emissions for the production of hydrogen tanks are related to the production of carbon fiber. According to Usais estimations, 36 % of the total emissions of the fuel cell system is related to the carbon fiber. In the production of 60 kg carbon fiber, which is required in a standard 80 kW fuel cell [111], 2.5 GWh of electricity and 7.3 GJ in heat is needed in the production phase. Standard EU-mix-based electricity and natural gas for heating were used in the calculations done by the study.

For the catalyst layer, most of the emissions are related to the electricity used to mine platinum. The remaining contributor to the catalyst's emissions comes from the preparation of the catalyst powder.

The last significant emission contributor is related to production of fuel cell auxiliaries. These include managing air, fuel, heat, water, and the electronics in the fuel cell. The production emissions is a result of the carbon intensive components [111].

The study suggested that the production of an 80 kW fuel cell system for vehicles, results in 5 tonnes of CO_2-eq. This system could contain up to 5 kg of hydrogen gas. To obtain a general emission calculation, the emissions displayed in Figure 102 have been used and divided by the component's respective kW or weight. It is assumed that emissions are linear with regards to weight and power. As a result, calculations that include these numbers should be considered somewhat uncertain, but is still regarded as the most accurate way of estimating emissions. The production emissions for the fuel cell system is illustrated in Table 19.

Table 19: Cradle-to-gate fuel cell components.

Component	**Size in study**	**Emission in study** tons CO_2-eq	**General production emission factor** [kg CO_2-eq/kW]	**Reference**
PEMFC	80kW	2.2	27,5	[111]
Composite fuel tanks	105 kg	2	19	[111]
Auxiliaries	80 kW	0.8	10	[111]

The composite fuel tank emissions in the estimations does not vary much from the fuel tank presented in the biofuel section. The composite fuel tank in the biofuel section emitted 21 kg CO_2 -eq/kg [8], whereas the fuel tank used in the fuel cell system emits 19 kg CO_2 -eq/kg .As the results were in the same region, 21 kg CO_2 -eq/kg will also be used for the fuel cell emission calculations, to provide consistency throughout the case study.

The emissions regarding fuel cell system production are estimated to be reduced by 25-70 % as the technology improves [111].

The production of the electric engine, needed for transforming electrical energy into mechanical energy, has emissions of 7.1 kg CO_2-eq/kg [8] when produced.

5.6 Cost of hydrogen propulsion

When estimating the cost of hydrogen and its utilization, several parameters must be accounted for. Costs related to the production of the components are not relevant, only the price of the final products applied in the propulsion system. This simplification is done to show the cost of investing and utilizing a new hydrogen system.

5.6.1 Fuel Cost

Hydrogen requires energy to be produced, either through electricity or natural gas. The energy source affect the will the cost of hydrogen production. Hence, as the electricity and natural gas prices changes over time, the hydrogen prices may be adjusted accordingly. As grey, blue and green hydrogen uses different energy sources, their price will differ. Grey and blue is dependent on the natural gas price, whereas green is dependent on the price for renewable electricity. Despite these variations, the European Commission's July 2020 hydrogen strategy estimated some prices for these different hydrogen types, displayed in Table 20.

Table 20: The cost of different hydrogen types.

Hydrogen type	Cost [kr/kg]	Reference
Grey	14.48	[112]
Blue	19.3	[112]
Green	24-53	[112]

In the price estimations for blue and grey hydrogen, CO_2-taxes were not evaluated. Because of uncertainties to these cost estimates, the prices where cross referenced with estimations by Max Åhman at the University of Lund [113], as well as calculations done SP global [114]. The price estimations by Max Åhman and SP global did not differ a lot from the calculations done by the EU commission. As a result, the calculations are considered trustworthy. The calculations done by Åhman is displayed in figure 45.

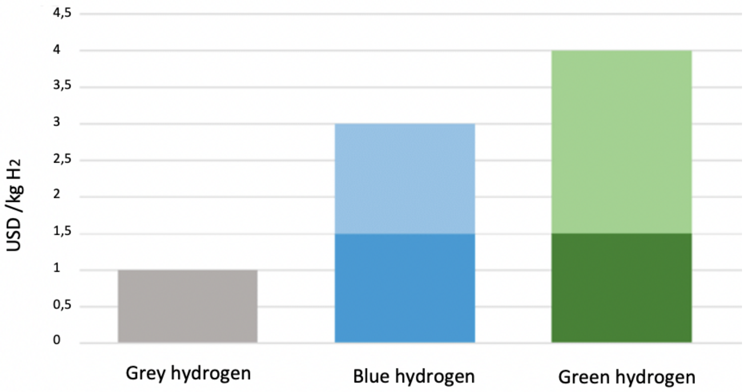


Figure 45: The price estimates for grey, blue and green hydrogen in 2018 and future. Figure from Max Åhman [113].

Figure 45 shows the prices for hydrogen in 2018, as well as Åhmans estimations future prices. The European comission has also predicted the future hydrogen prices, suggesting a 50 % price drop within 2030. In addition, larger areas with access to renewable energy will provide cheaper green hydrogen, which may compete with fossil fuel prices by 2030 [112]. These assumptions are backed by SP Global. The estimated price development is displayed in Figure 46.

The calculations done by SP Global in Figure 46 also shows the variety of prices regarding hydrogen. However, Figure 46 shows that the price variety is expected to be reduced over time.

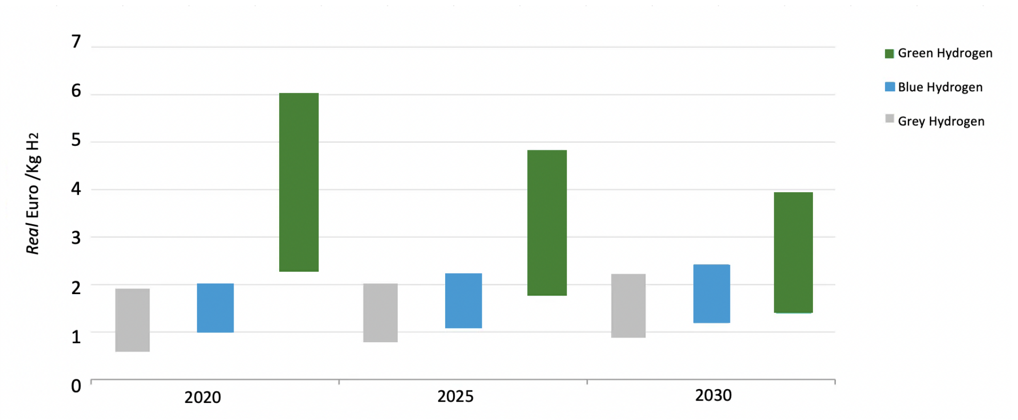


Figure 46: The price estimates for grey, blue and green hydrogen in from 2020, 2025 and 2030. Modified from: [114].

5.6.2 System Cost

The production costs for the three different fuel cells, PEM, AFC and SOFC are presented in Table 21.

Surprisingly, prices for fuel cells were hard to come by. On the other hand, prices for electrolyzers were estimated by various sources. As fuel cells and electrolyzers are very similar, it was estimated that the price for a fuel cell, would equal the price of the electrolyzer. The average of three estimated prices were used for all fuel cells. The calculations, as well as the price of an el motor, are presented in Table 21.

Table 21: Prices for different fuel cells.

Type of fuel cell	Cost of investment	Maintenance cost % of investment cost per year	Reference
Alkaline	12 062 [NOK/kW]	3	[75]
PEM	20 265 [NOK/kW]	4	[75]
SOEC	> 19 300 [NOK/kW]	2	[75]
El motor	3 611 NOK/kW	-	[115]

Estimations for fuel storage included the cost of a composite pressurized fuel tank and a cryogenic fuel tank. The prices were located in the same study as the prices for the electrolyzers, providing consistency within the estimations. The price of the storage tanks accounts for the average prices from three different studies. Table 22 shows the estimated cost for the composite fuel tank and the cryogenic fuel tank.

Table 22: The cost of different hydrogen storages.

Storage type	Cost [kr/kg]	Reference
Composite fuel tank	96.6	[75]
Cryogenic tank	9.5	[75]

The compressed tank has a much higher cost per kilogram because it contains composite material needed to handle high pressure. The cryogenic storage must be well isolated and is therefore usually heavier compared to the composite fuel tank. Based on the weight difference, the cryogenic tank will often surpass the compressed tank in total price, despite the cost per kg being 10 times cheaper.

5.7 Feasibility and Technology Readiness Level

In June 2020, The Norwegian Government launched its hydrogen strategy, a proposed expansion of hydrogen infrastructure. The report envisions large-scale production and usage of hydrogen within the next 30 years. In 2025 five bunkering stations are expected to become operative, resulting in accessible hydrogen for the marine sector [116] [117].

Large-scale hydrogen production is possible with current technology. However, investments from companies such as Enova and Innovation Norway are essential for the growth of the hydrogen market. Currently, 15 different hydrogen projects have received one million NOK each from Enova, contributing to the development of green hydrogen in the maritime sector [118].

In 2021, Enova provided 38 million NOK to Norled for the production of a hydrogen ferry [119]. The ferry is called HIDLE and will operate 100 % on liquid hydrogen, used at Finnøysambandet in Rogaland. The hydrogen ferry shown in Figure 47 is the world's first operating liquid hydrogen ferry. In addition to H_2, the ferry has installed a large battery package and is expected to utilize hydrogen 50.1 % of the time [120] [121].

Figure 47: Norled hydrogen ferry HYDRA, at Hjelmeland in Rogaland. Photo credit Norled [122].

Renewable energy sources account for 98 % of the electricity produced in Norway [123]. Furthermore, Norway has a continental shelf well suited for CO_2 storage. Long Ship is an ongoing CCS project that will decarbonize industrial projects, such as Norcems cement factory and Fortum Oslo Varme's waste facility. The Northern Lights project is part of the long ship project, but is responsible for transporting and storing the CO_2 on the Norwegian continental shelf. The project will contribute to the development of blue Hydrogen in Norway as it develops the CCS infrastructure [96].

Hydrogen infrastructure is still developing, with 20 hydrogen fuelling stations combined in Norway, Denmark, Sweden, and Iceland. The green flags in Figure 48a show operating hydrogen fuelling stations in Scandinavia, whereas only four hydrogen stations are located in Norway. One of the operating stations in Trondheim is run by ASKO, producing 300 kg of hydrogen daily to fuel their trucks. The yellow flags in Figure 48b show planned hydrogen fuelling stations. According to h2stations.org both Norway and Sweden have two planned hydrogen stations, whereas Denmark has four, expected to operate within a few years. Due to the expected growth of hydrogen energy in the future, it is plausible to believe that the infrastructure will grow in the coming years [93] [124].

(a) Hydrogen stations in operation [124]

(b) Planned Hydrogen stations [124]

Shell performed a study in 2017 to address the market maturity for hydrogen. The results of this study is shown in figure 49. Fuel cells using hydrogen has in many years been used in space ships and therefore resulting in a TRL of 9. The other hydrogen applications place somewhere between 5 and 9. Hydrogen in the maritime sector is located between the TRLs 5 and 6, suggesting that it is approved at pilot scale, but not ready for commercial use. However, this can vary in different ways due to varieties within the maritime sector. For instance hydrogen ferries is already tested in Norway [125]. Furthermore, Shell suggests that commercial hydrogen in the maritime sector will be available within 2030, resulting in a TRL of 8-9. Cars may struggle to reach a TRL level this high, as they are more dependent on the infrastructure and development of fuelling stations.

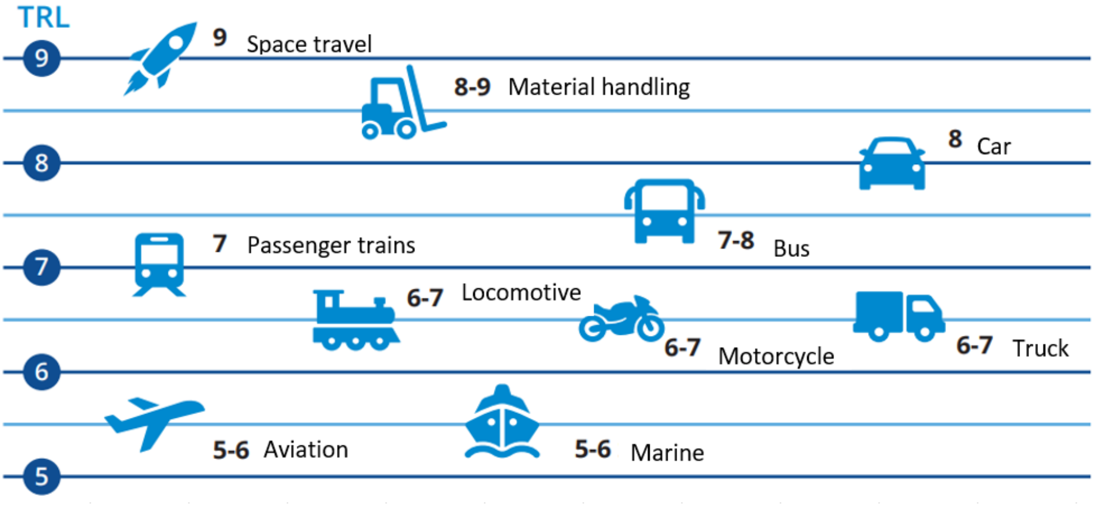


Figure 49: Hydrogen TRL levels for different applications [125].

6 Ammonia

Over the last few years, ammonia has received attention as a fuel in the marine sector. This section will look at how ammonia can be utilized for a more sustainable energy system [126].

6.1 Ammonia Properties

Ammonia is a molecule consisting of three hydrogen atoms and one nitrogen atom, shown in Figure 50. Ammonia is a colorless gas under ambient conditions with a lower density than air at 0.73 kg/m^3.

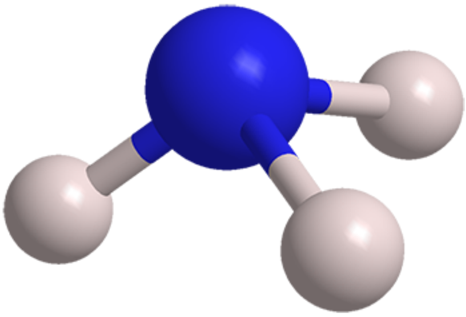


Figure 50: Chemical structure of ammonia [127].

The boiling point for ammonia is -33 °C, but at a moderate pressure of 8.6 bar, it is possible to store it in liquid form at 20 °C. One of the main reasons ammonia has received recognition as a potential fuel may be related to the difficulties of pure hydrogen. The boiling point for pure hydrogen is -253 °C which provides a significant challenge for storing. Therefore, ammonia is considered a more convenient zero-carbon fuel under the right conditions. Even though hydrogen has a much higher energy density, 120 GJ/t, than ammonia, 18.6 GJ/t, the density of the fuel require less volume to store the same amount energy. This is highly significant as it solves one of the most complex challenges for hydrogen, volumetric storage. Since ammonia consists of three hydrogen atoms, research is being conducted for ammonia use in fuel cells, and as a hydrogen energy carrier. It can also be used directly in standard ICE's which is the primary reason for its recognition. Ammonias low cetane number may cause ignition problems, therefore, using it in conjunction with a traditional fossil-fuel is optimal. With zero emission from combustion, it can play a significant role in the transition to the predicted hydrogen-economy. [126] [128]

6.2 Production of Ammonia

For this report, ammonia produced from renewable electricity is labeled green ammonia, ammonia produced from carbon sources with carbon capture is labeled blue ammonia, and ammonia produced from carbon sources like coal or natural gas is labeled brown ammonia, illustrated in Figure 51. Most ammonia is produced through a Haber-Bosch process which combines nitrogen gas and hydrogen gas at high pressures and elevated temperatures [129]. In the method, nitrogen in the air reacts with hydrogen in the following reaction: .

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3$$

The reaction often occurs at about 400-500 °C and at 300 bar.

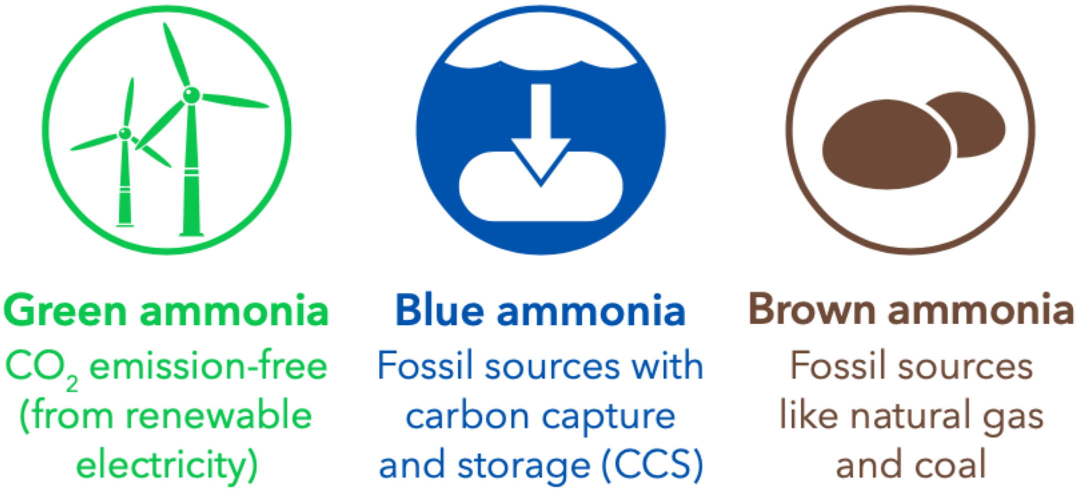


Figure 51: Illustration of different production pathways for Ammonia [126].

6.2.1 Brown Ammonia

Brown Ammonia production, the most common production pathway, uses fossil fuel as raw material for hydrogen production. When producing brown ammonia, hydrocarbons are converted by a primary steam reformer followed by a secondary reformer which adds air. The product from this process is mainly a mixture of CO, hydrogen, and nitrogen. Furthermore, a water gas shift reaction converts CO and H_2O to CO_2 and hydrogen. The CO_2 and CO are then removed in several steps. The result is nitrogen and hydrogen in a 1:3 ratio, with a bit of argon and CH_4. To further create ammonia in a Haber-Bosch process, the mixture is compressed to about 300 bar and 400-500 °C in an iron-based catalyst. The ammonia is then removed through condensation [126]. Figure 52 illustrates the production process of brown ammonia. Natural gas is mainly used because of its high methane content, but as a result, large quantities of carbon dioxide is formed during hydrogen production. To reduce emissions, the production of ammonia with carbon capture technology has been heavily researched in later years, called blue ammonia.

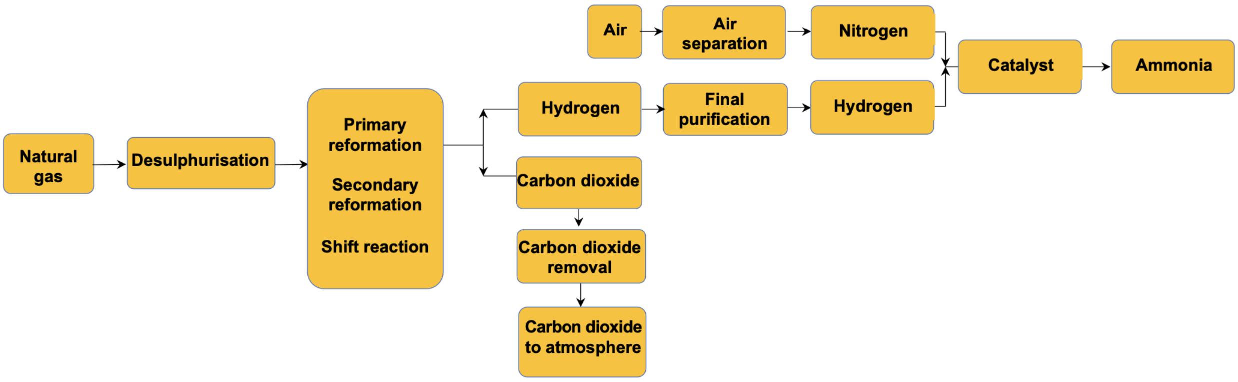


Figure 52: Schematic of brown ammonia production [130].

6.2.2 Blue Ammonia

Blue Ammonia aims to reduce the emissions in hydrogen production by capturing the released CO_2. This is an effective process, with mature technology, and can reduce the total emissions by up to 90%.

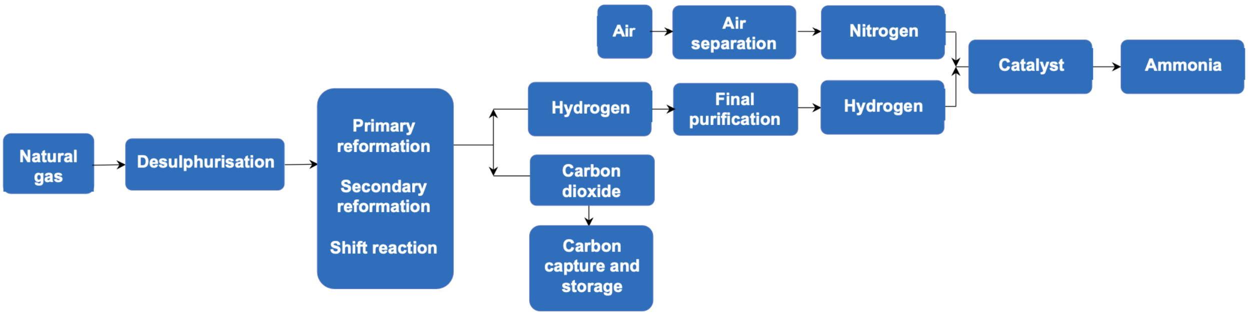


Figure 53: Schematic of blue ammonia production [130].

The production process of brown and blue ammonia is very similar. The main difference occurs after the water gas shift reaction, where CO and water is converted to hydrogen and carbon dioxide. This can be seen from Figure 53. In large-scale production factories, there are CO_2 storage sites in the vicinity, where the carbon dioxide can be stored indefinitely, or until it is transported to another storage site. Producing ammonia with carbon capture leads to an increased cost. An interesting comparison is the cost and emission of green and blue ammonia. If the CO_2 has to be transported by ship, there will be both cost and emissions tied to the whole process. Therefore it is crucial that for any blue ammonia plant, there has to be a CO_2 storage site in the vicinity, or else the cost of transport will reach closer to the cost of producing ammonia through renewables [130].

6.2.3 Green Ammonia

The most frequent method of producing hydrogen through water electrolysis is by the PEM method, shown in Figure 54. The quantities available for production are limited, and therefore there is still ongoing research to develop large-scale green ammonia production. The production of hydrogen gas, the primary feedstock for green ammonia production, forms the basis of the decarbonization of all ammonia production processes [130]. Nitrogen is obtained from the air through an air separation unit. In parts of the world where renewable energy is available, the cost has decreased in the last ten years.

The reason brown ammonia is more widespread than green ammonia is simply because of efficiencies and pricing. Green ammonia production has been tested in Rjukan, Norway, through hydropower. However, it was not competitive compared to other production pathways like natural gas [126]. Brown ammonia requires large amounts of energy. However, electricity is more expensive than natural gas, therefore, green ammonia is more expensive than brown ammonia. The most cost-efficient way of reducing emissions today is to integrate CCS in the production phase [130]. In order for green ammonia to compete with brown ammonia, it will require additional government taxes on fossil sources, as well as improved production efficiency. Researchers are also intensively researching the improvement of alternative ammonia production processes.

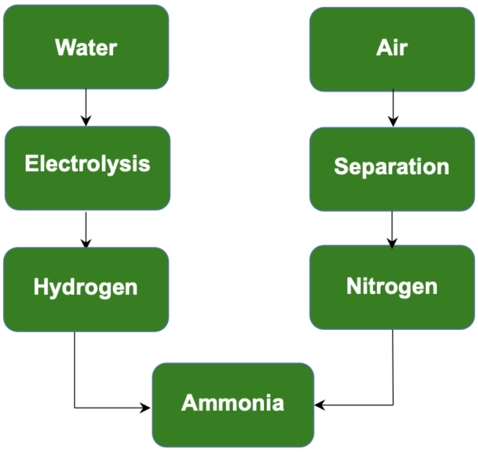


Figure 54: Scheme of green ammonia production [130].

6.3 Energy Utilization and Propulsion System

There are several ways to utilize the energy contents of Ammonia. The biggest challenge for hydrogen, especially in the marine sector, is that it requires five times as much volume to store, compared to traditional fossil fuels. Not only does it require extensive storage systems and dedicated fuel supply systems for containment, it also needs to be stored cryogenically. Compared to hydrogen, ammonia storage is more suitable due to its liquefaction temperature and energy density [131].

6.3.1 Ammonia in Fuel Cells

Ammonia can be used in fuel cells and SOFC's have been identified as best suited. There are currently no such fuel cells operating, but in 2023 ShipFC are launching an off-shore vessel running on a 2 MW SOFC solely on ammonia [132]. A possible way to utilize ammonia for fuel purposes is by using ammonia as an energy carrier for PEMFCs by cracking the ammonia into hydrogen. Once cracked, the hydrogen can be used in fuel cells to produce electrical power. Cracking requires extensive and complex equipment to be stored on-board. PEM fuel cells are also highly sensitive to ammonia impurities, therefore SOFC is the preferred fuel cell [126]. The disadvantages of SOFC have been briefly discussed in the hydrogen section.

6.3.2 Ammonia in ICE

ICEs are preferred for ammonia as they are robust, power-dense, and cost-efficient. The best-suited engines for ammonia are low-speed engines, due to its low flame speed and narrow flammability range, 15 % -28 %. Flame speed is defined as the rate of expansion of the flame front in combustion. The flammability range is the minimum and maximum concentrations at which a vaporous substance will ignite or combust when in contact with air [133]. The main challenge when using ammonia in an ICE is its poor compression- and spark ignition. An alternative is to use ammonia in a dual-fuel combustion system. The combustion promoter can be gasoline, diesel, hydrogen, LPG or ethanol. Biodiesel can also work as combustion promoter, but this is still at research level. Hydrogen as a combustion promoter, is not as widespread and would require storage of hydrogen on the boat, or complex cracking equipment. Big cryogenic tanks are not only expensive, but also usually emit a lot of CO_2, in the production phase. Since gasoline, diesel, and belonging engines, are available everywhere, they are more reliable.

Ammonia can enter the engine either by air in gas form through the air intake, or injected into the cyl-

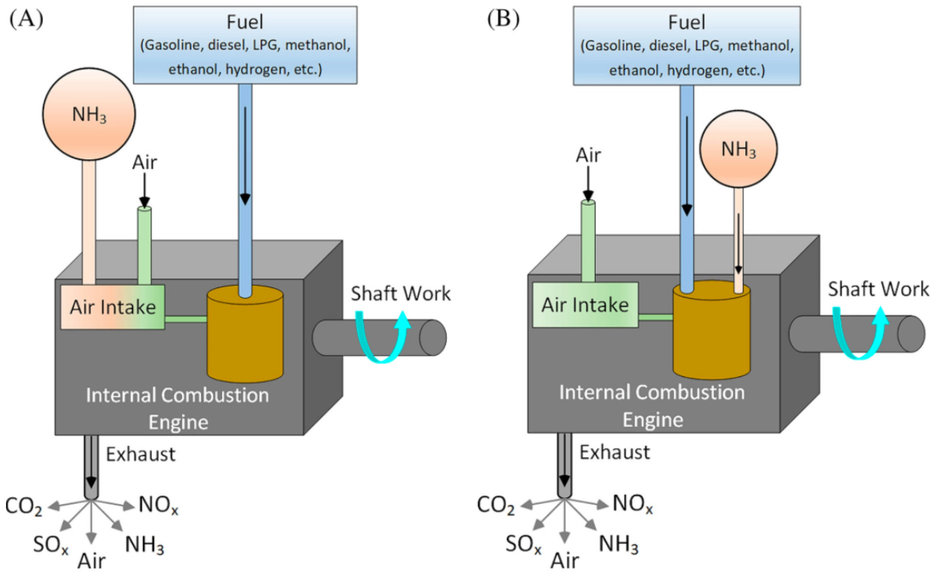


Figure 55: Illustration of how ammonia can enter the engine [134].

inder in its liquid form, shown in Figure 55. This is very practical as it does not require major additional modifications to already existing engines. In order to enhance combustion to increase power output, one can integrate a supercharger into the engine [135] [136]. Ammonia can either be introduced via direct- or port-injection. In direct-injection, the fuel is sprayed directly onto the spark-plug to ignite, whereas in port-injection the fuel is injected into the cylinder [137] [136].

Studies show that when using ammonia in an SI-engine, in conjunction with gasoline, it is preferable to have an engine that can run purely on gasoline, as ammonia in idle operation is inconvenient. Furthermore, ammonia and gasoline can achieve almost the same energy as pure gasoline operation. In higher speed engines, less ammonia can be utilized [136].

Various studies have been performed to achieve successful combustion in CI engines using ammonia. The optimal mixture of ammonia and diesel was found to be 40-60 % diesel energy, where the fuel efficiency, NOx emission and ignition temperature were optimal. As expected, CO_2 emissions were lower, as more ammonia was used, however, the ammonia slip also increased [136].

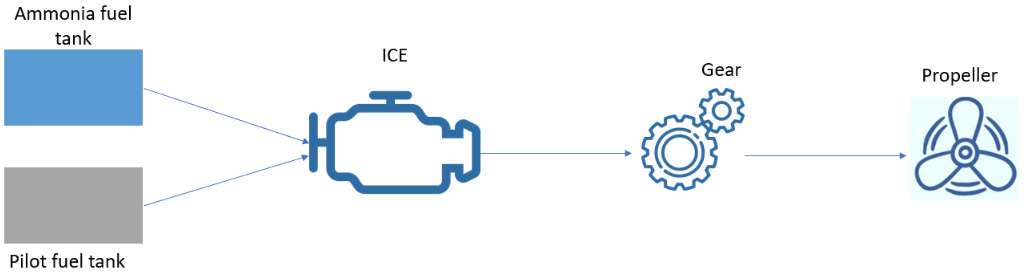


Figure 56: Ammonia propulsion system.

The preferable conditions for ammonia usage in ICEs are high compression ratios, low speeds and high loads, due to its low flame speed [136]. Figure 56 illustrates a proposed ICE system for ammonia.

The report will focus on ammonia in dual-fuel combustion with diesel as combustion promoter as the Sounder USV already uses diesel, illustrated in Figure 56. A 60 % and 80 % ammonia as substitute fuel will be adressed [126].

6.4 Ammonia storage

Ammonia is highly toxic, and other considerations for handling gas releases will be needed if ammonia is used for propulsion. One of the most significant risks has been identified as the risk of unburnt ammonia in the engine due to its low flammability range. Due to the high toxicity of ammonia, exposure must be limited for safety reasons. In low concentrations ammonia is irritating to the eyes, lungs, and skin. In high concentrations or direct contact, it is fatal. Nevertheless, ammonia has been handled in cargo for a long time, and it is feasible to believe that this is avoidable [131]. For the case study it is assumed that ammonia is stored in a cryogenic tank. [126]

6.5 Emissions

This section will highlight the emissions from NG and green ammonia if transported and produced with grids powered by fossil sources. It will also cover the production emissions from motor and storage tank.

In order for ammonia to be considered green, it must originate from 100 % renewable energy. This, however, is not a guarantee as in some countries they are either expensive or not available. When ammonia is produced purely from renewable sources, the production of ammonia will have emissions close to zero. Combustion of ammonia does not include any carbon, as shown in Equation 5, and as a result, all the emissions are connected to the production process.

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O \tag{5}$$

In many countries fossil fuels still powers some electrical grids. Germany, for example, has a grid emission of 0.45 tCO_2/MWh, which will correspond to a total emission of 4.5 tCO_2/tNH_3 [126]. Ammonia needs a combustion-promoter, typically conventional diesel or gasoline. These fuels have high emission rates both when combusting and when produced. Diesel has been assumed to have an emission factor of 0.0886 kg CO_2/MJ.

Earlier in this report, an emission overview of hydrogen was provided, and since the production of ammonia involves the same routes as the production of hydrogen, the emissions will be unaltered. Furthermore, ammonia production requires another step, the Haber Bosch process. This process requires electricity, and the only emissions related to the process, are the emissions from the grid. The comparison of emissions will include two electricity mixes, a Nordic and Norwegian mix. Brown ammonia has not been considered, because of its high emissions.

As ammonia is used in an ICE, the only other emissions tied to the WtW analysis of ammonia are the production of the motor, and the tank where ammonia is stored. Based on Asplan Viak's report, a cryogenic tank is assumed for ammonia storage, and the emission factor for this tank is 17,1 kg CO_2/kg. For the ICE, the emission factor is set to 5,4 kgCO_2-eq/kg. The best Haber-Bosch plant uses around 10 MWh to produce one tonne of ammonia. With this estimate, calculations using the emissions from blue and green hydrogen, and the electricity for the Haber-Bosch process have been presented in Table 23.

Table 23: Emissions from ammonia with different feedstocks and electricity .

NG with CCS from Norwegian mix [g kgCO_2-eq/MJ]	**NG with CCS from Nordic mix [kgCO_2-eq/MJ]**	**Green Ammonia from Norwegian mix [kg CO_2-eq/MJ]**	**Green Ammonia from Nordic mix [kg CO_2-eq/MJ]**	**Reference**
0,0491	0,0976	0,0204	0,0688	[92]

Figure 57 shows that using Nordic electricity mix has a significant impact on the total emission of ammonia. Therefore, using renewable energy throughout the whole production process is vital.

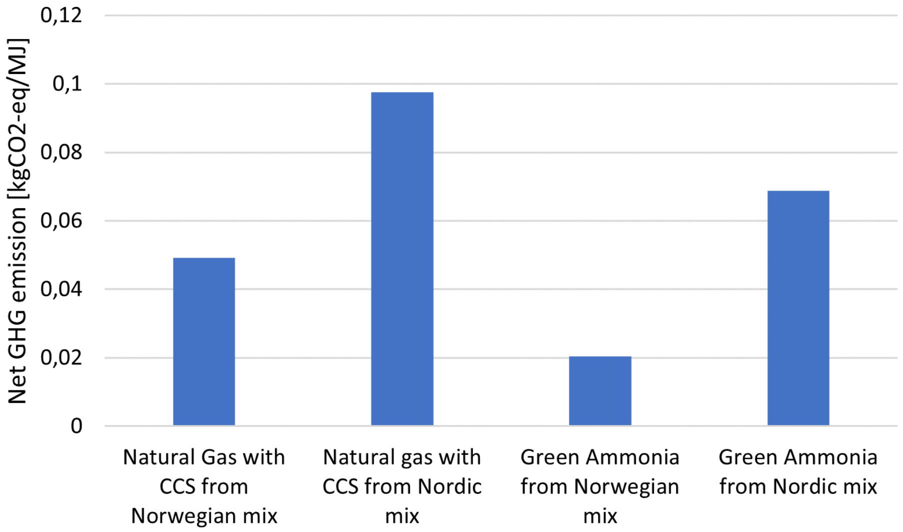


Figure 57: comparison of emissions from differnet production pathways.

Although there are zero carbon dioxide emissions in both the production and combustion of green ammonia, there are NOx emissions. This heavily depends on engine technology. However, as engine technology and the utilization of ammonia are not mature, more research will have to be conducted on the matter. It has been assumed that the NOx emissions will be at the same level as for MGO. [126] [131]

6.6 Cost of Ammonia Propulsion

The prices for ammonia are gathered from a report by DNV, on ammonia as a marine fuel. Figure 58 shows the price development of ammonia, in the last decade. The average price point for one tonne ammonia is 400 dollar/t if produced from NG and about 750 dollar/t from renewable energy. Conversion rates constantly fluctuate, but in Table 24 prices for ammonia are presented.

Table 24: Ammonia and Diesel prices.

Fuel	**Cost per tonne [dollar/t]**	**Cost per liter [NOK/L]**
Ammonia from NG	400	2,43
Ammonia from renewables	750	4,53

NG accounts for about 70 - 85 % of the production of ammonia, and therefore the price of NG heavily influences the price of ammonia. Ammonia from renewable energy is more expensive than using NG as feedstock for the production of ammonia. Obviously, this depends heavily on the price of electricity, but is still far from being competetive with ammonia from NG. IEA has indicated that with the reduction in price for renewable energy, green ammonia could become more competitive and reach a price of 450-700 dollar/t.

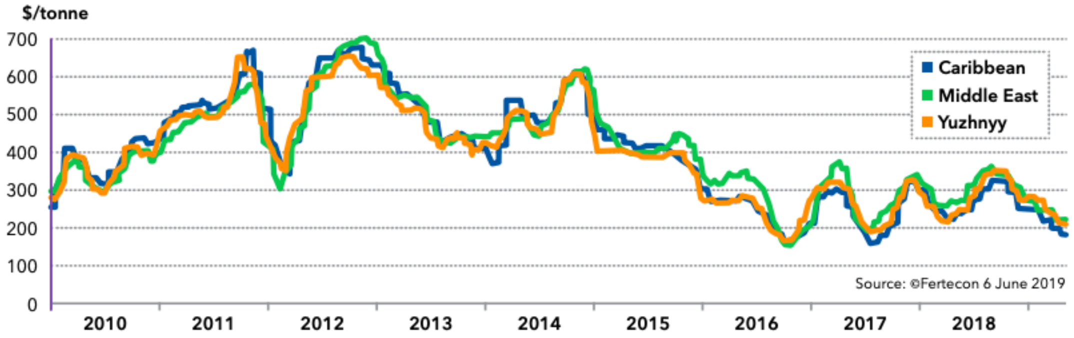


Figure 58: Ammoniaprices at the biggest trade centers for ammonia globally [126]

6.7 Feasibility and Technology Readiness Level

About 80 % of the ammonia available today is used for fertilizers, while the rest is being used in explosives, plastics, synthetic fibers and resings, refrigerants, and chemicals like nitric acid. In 2018 the global production of ammonia was 170 million tonnes, an increase of 383% from 2000, and the trend is only expected to grow. However, as ammonia production competes with the food industry, this might affect the availibity, possibly resulting in severe socio-economic ramifications. For ammonia to be competitive as a fuel, an expansion of the production capacity is required, preferably from renewable energy based on electrolysis, or hydrogen production from NG with CCS.

The primary producer of ammonia globally is China, accounting for roughly 31% of all ammonia produced. Figure 59 shows that India, USA and Russia are also big producers, producing 7,9%, 8,9% and 10%, respectively [126].

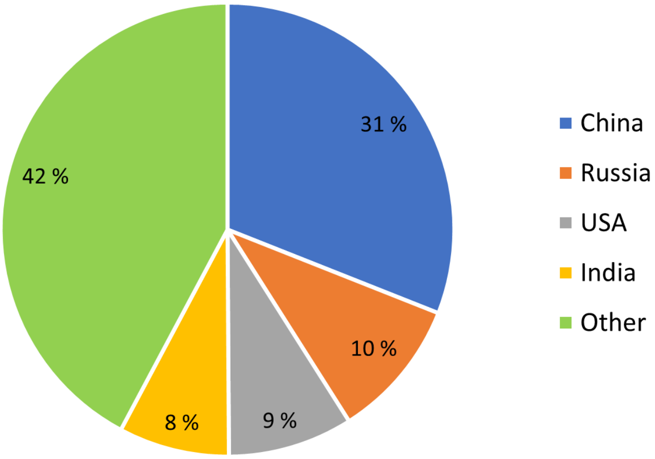


Figure 59: Primary producers of ammonia [126].

About 11% of all ammonia produced globally is traded. Whereas the US is the primary consumer of ammonia, the key exporters are Trinidad and Russia, with 4.6 and 3.6 million tonnes, respectively. Saudi Arabia, Algeria, Canada, and Indonesia export over 1 million tonnes per year. The main trade center for Ammonia is Yushnyy in the black sea.

There are currently no ships using ammonia as fuel, however this does not mean ammonia cannot contribute to decarbonization of ships. Ammonia is a so called electro fuel, meaning it can be produced through electrolysis followed by a Haber-Bosch synthesis, making it a sustainable fuel under the right conditions. Ammonia is toxic, but fatal consequences can be avoided with proper handling. Ammonia is currently more favorable than hydrogen as it takes less volume to store more energy. It can be straightforwardly used in ICE and low-pressure fuel tanks. The technology has been demonstrated with success in ICEs with pleasing results in conjunction with a pilot-fuel. Already in 1941, buses in Belgium used ammonia in conjunction with coal, as fuel [135]. MAN ES have constructed dual-fuel engines to be used for LPG. However, they have recently started developing two-stroke engines designed for ammonia, which is expected to be commercially available in 2023 [126]. Wärtsilä is also investing in research and development in four-stroke engines using ammonia in either diesel, dual-fuel or spark-ignition systems. Nevertheless, since investment in both research and development has been done, and products being predicted to be commercially available as early as 2023, the TRL level is between 7-8.

There are ongoing projects that will contribute to the development of ammonia in Norway. It is not a widespread technology in the maritime sector but has prominent potential, due to its high volumetric energy density. The availability and development of zero-emissions fuels is essential to decarbonize the marine sector.

At the moment, Enova are funding three ammonia projects in Norway; Yaras Clean Ammonia, The Barents blue plant, and Viridis Bulk Carriers [138].

Viridis Bulk Carriers have received 14 million NOK to develop a flexible bulk shipping network of ammonia fuelled ships. Figure 60 shows a picture of a Viridis vessel. The project is a step towards a zero-emission shipping industry and the development of ammonia.

Yara have received funding of 283 million NOK to electrify its ammonia facility in Porsgrunn. The facility will produce 500 000 tonnes/year, and will start supplying green ammonia products in 2030 [139] [140]. Horisont Energis Barents blue project is funded with 482 million NOK, aiming to produce green hydrogen in Finnmark, Norway[141] [142].

Figure 60: Viridis Bulk Carriers. Photo credit Viridis [143].

7 Hybrid

A hybrid propulsion system allows the vessel to combine the stability of traditional mechanical propulsion with innovative and modern devices such as batteries, fuel cells, and capacitors. Combining a fuelled power source with a stored power source makes the vessel both flexible and reliable at the same time. The main goal for a hybrid system is to optimize the ICE, and as a consequence, reduce the emissions as the engine is run in its preferred area due to max torque and high power. This approach for a marine propulsion system has already experienced large amounts of research and investment, therefore making it a feasible and renewable alternative to the existing mechanical system [144].

There are mainly three different ways to design a hybrid propulsion system; series hybrid system, parallel hybrid system and a parallel-series hybrid system.

The series hybrid system combines two energy systems in series and usually consists of a fuel tank, a generator/combustion engine, an energy storing device, an electric motor, and the propeller, as illustrated in Figure 61. There is no direct mechanical connection between the combustion engine and the propeller, subsequently dissociating the operating points of the propeller and the engine. By optimizing the operational range for the propeller and the engine, the system's overall efficiency is usually improved. This advantage would be more visible for larger ships than the Sounder USV, as more generators and energy storage devices would allow further optimization. Different energy sources could be designed to fit a wide range of optimal areas, running the most efficient system at any time. Due to volume and mass limitations, this will not be further discussed.

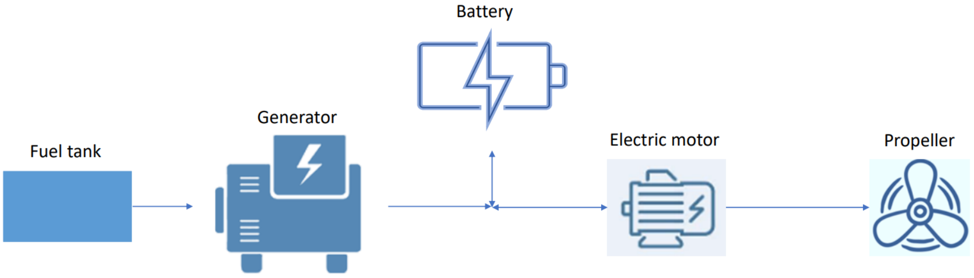


Figure 61: Series hybrid propulsion system.

For a parallel hybrid system, it is necessary with two motors, one for mechanical propulsion and one for electrical propulsion, as illustrated in Figure 62. The electrical motor is supplied by an energy storing system and is not directly connected to the mechanical side. The two systems can be used separately or simultaneously by using a gear system. Parallel hybrid systems are often designed to utilize one of the sides at a lower speed range, usually the electrical side, and then use the mechanical side for situations where high speed is favorable. Another option is to use both sides simultaneously, utilizing the electrical side as a boost system to provide extra power to the propeller. The parallel hybrid system is a flexible and viable system, and will be further used in the case study.

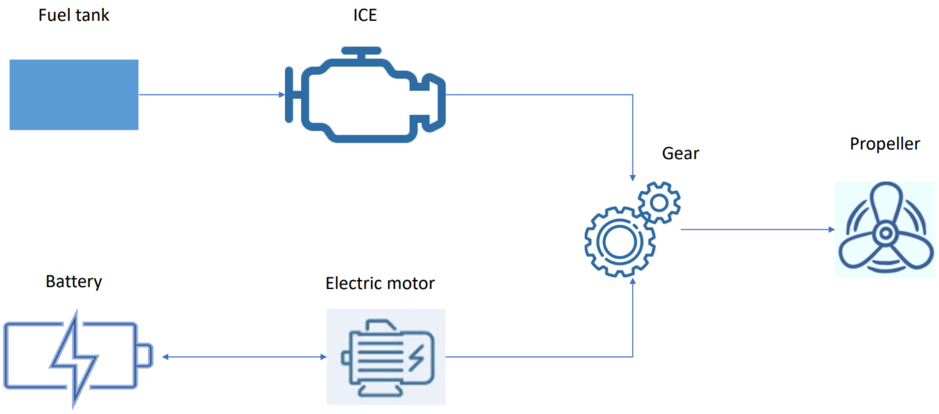


Figure 62: Parallel hybrid propulsion system.

The parallel-series hybrid system combines both of the two previous systems, but due to its complexity, it is not frequently used in the marine sector. A schematic design is provided in Figure 63 [145].

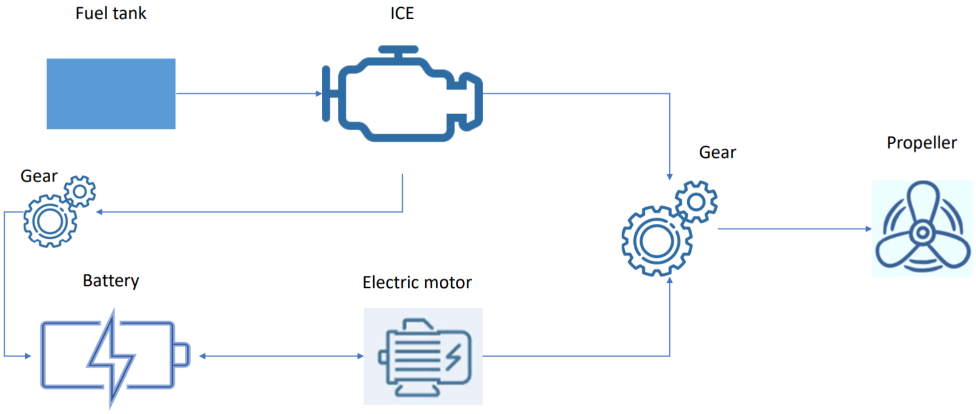


Figure 63: Parallel-series hybrid propulsion system.

7.1 Batteries

The energy storage system (ESS) is a crucial component in a hybrid propulsion system. The most common ESS used for marine applications is batteries. Compared to other ESS, batteries offer a relatively high energy density at an affordable price. A battery transforms chemical energy directly to electrical energy through an electrochemical oxidation-reduction reaction, known as a redox reaction. Oxidation/reduction is respectively the loss/gain of electrons during a reaction by an atom, ion, or a molecule. The structure form for batteries contains separators, which allow the transport of ionic charge carriers needed to close the circuit, electrodes and electrolytes. The oxidation happens on the anode, the negative pole, whereas the reduction happens on the cathode. The favourable battery type for the marine sector, or transportation sector in general, is the lithium-ion battery (Li-ion), as they are highly energetic, offer a high lifetime, and are commercially available. The development in recent years has also led to a price drop for Li-ion batteries, but for pure electric propulsion, the price is still considered high. In addition, Li-ion batteries have problems related to the degradation of the battery, the lack of a sufficient recycling system for large-scale batteries, safety issues, and thermal ageing [145] .

Li-ion batteries are secondary batteries capable of being used multiple times through recharging. This can occur as the chemical reactions in the battery are reversible; when discharging, the reactions go one way, providing power, whereas the reactions go the opposite direction when charging, thus providing power to the battery. During discharge, the positive lithium ions move from the negative electrode, through the electrolyte, to the positive electrode. The electrons will subsequently flow from the negative electrode to the positive electrode through a closed circuit, illustrated in Figure 64. The direction in which a positive charge move is considered the direction of the electrical current, hence moving in the opposite direction as the negative electrons [146] [147].

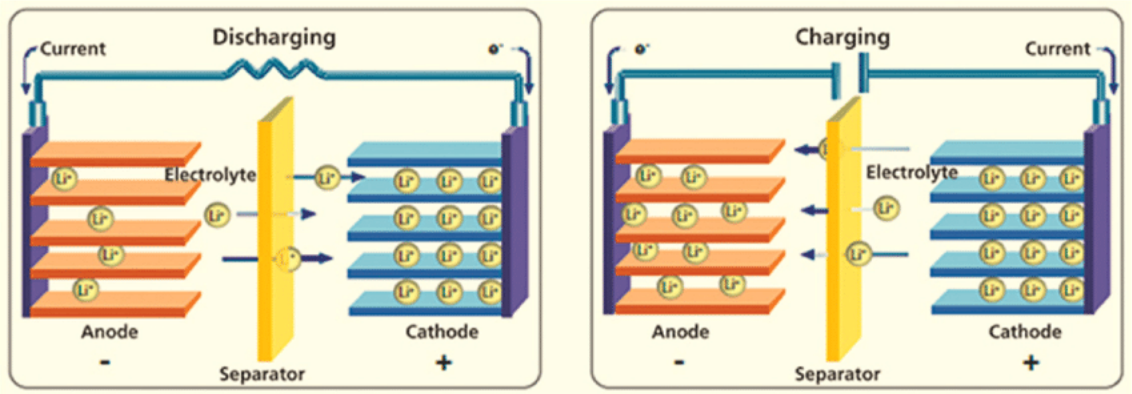


Figure 64: Illustration of discharging and charging for a Li-ion battery [146].

One could also consider using other ESS such as supercapacitors and flywheels, but as with batteries, these ESS also have their flaws. Table 25 justifies the choice of Li-ion batteries as the preferred ESS. The ultracapacitors' power density is superior to the other two choices, suited for situations where much power is needed over a short period, for example, in the acceleration phase. However, the ultracapacitors offer lower energy density and efficiency compared to the other two choices. As a result, ultracapacitors are not considered a viable option, primarily due to the low energy density. A flywheel might be the best option in terms of safety, and along with the superior life cycle and lifetime, it could be a viable option. However, as with ultracapacitors, the energy density does not meet the required demands to work as a propulsion alternative. Overall the characteristics of the Li-ion battery might be considered the best middle way, as it is a flexible system with acceptable characteristics. In the future, however, the development of the ultracapacitor could be a viable alternative, especially in a hybrid system, allowing for more efficient acceleration. At the same time, the battery development reaches new highs ever, with better energy density, contributing to a more extended range, which overall could have a better impact on an environmental scale [148].

Table 25: Comparison of different ESS [148]

Technology	**Energy density Wh/kg**	**Power density W/kg**	**Life cycles**	**Years lifetime**	**Overall efficiency %**
Li-ion	150-250	100-500	1000-20 000	5-10	90-98%
Ultra-capacitor	0.05-5	100 000	50 000	5-8	60-65
Flywheel	5-100	1000	20 000-100 000	15-20	93-95

A short summary of the different battery factors is illustrated in Table 26. The factors should be seen as indicators rather than absolute values as there may be some aspects that vary. The main factors worth looking into are the energy density and the power density, where energy is usually the limiting factor. The development of the different battery types suggests that the energy density increases the most compared to the power density, suggesting that this factor has been the main priority for battery development

The different battery efficiencies are mostly related to two reasons. The first reason is the induction of ohmic loss from the current flow. This loss relative to the reversible potential defines the efficiency, which means that when the potential increases, the efficiency also increases. The other factor is related to the geometric design of the batteries. Reducing the distance between the electrodes results in a higher efficiency. In modern Li-ion batteries, the distance can be as small as 20 μm.[149]

Table 26: Comparision of different batteries [149]

Capacity factor	**Lead Acid**	**Ni-Cd**	**Ni-MH**	**Zebra**	**Li-ion**
Energy/ Wh/kg	20-40	40-60	50-70	100-150	150-250
Power/ W/kg	5-200	10-150	10-100	150-250	100-500
Cycles/ 1000	1-5	1-3	1-3	1-2	1-20
Energy eff/ %	60-90	80	80	90	90-98
T-range/ °C	-10-50	-20-45	-20-45	90-250	-20-50
OCV/ V	2.05	1.2	1.6	2.6	3-4
SoC Window/ %	0-100	0-100	0-100		20-90
Relev. time frame	1940-	92-02	98-05	95-09	2005-
Application	o Car battery o Forklift o Golf cart	o Flashlight battery	o Laptop/ electronic batteries	o Continuous veichles	o EVs o Consumer electronics e.g Phonebatteries

A Ragone plot, illustrated in Figure 65, is a valuable tool for comparing different ESS. For this chart, the power density (W/kg) is plotted against the energy density (Wh/kg). Note that the vertical axis is logarithmic in Figure 65. Supercapacitors offer a significant amount of specific power, but the specific energy is low compared to the Li-ion batteries.

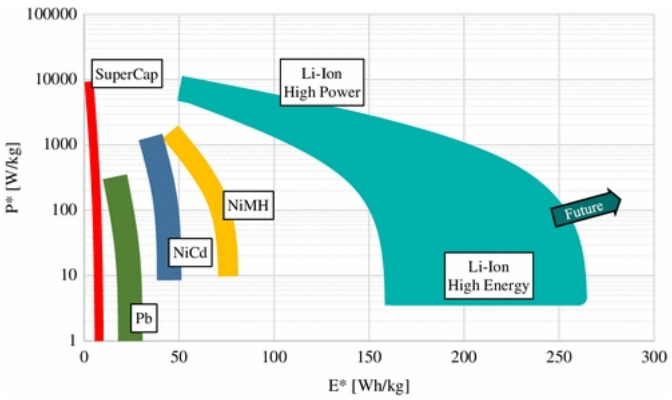


Figure 65: Ragone plot over ESS [150].

There are multiple alternatives within the Li-ion battery section due to different combinations of anode and cathode materials. The anode material has traditionally been based on some form of carbon particles, but newer batteries also utilize silicon or titania-based anode materials as the technology has developed. Most batteries tend to use manganese (Mn), nickel (Ni), cobalt (Co), or iron (Fe) as cathode material, as they are lighter metals with partially filled d-orbitals. All these different combinations of anode and cathode materials will result in distinct advantages and disadvantages. Figure 66 compares six different types of Li-ion batteries based on the following parameters; specific energy, specific power, safety, performance, life span, and cost. Specific energy is an indication of range for the vessel. Specific power illustrates how fast the vessel can extract the energy available, typical in the acceleration phase. Performance and life span reflect how the battery will behave in different conditions, its cycle life, and longevity. The last parameter cost accounts for all related costs for the battery. A large covered area in Figure 66 is desirable [151].

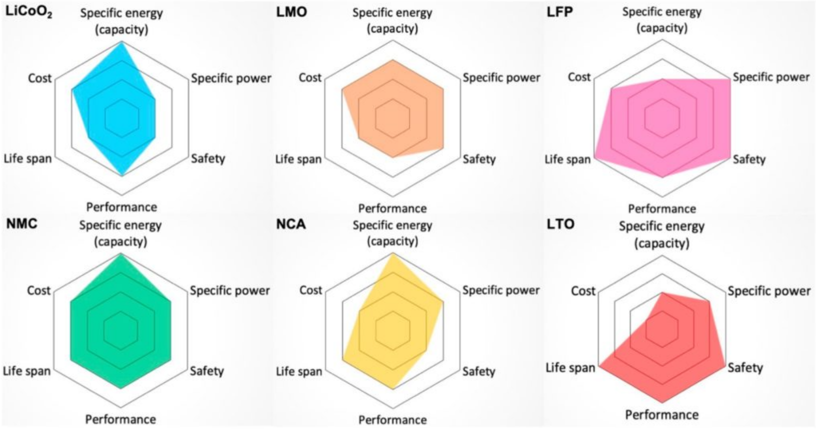


Figure 66: Comparision of six different Li-ion types [151].

Of the six presented batteries, Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Iron Phosphate (LFP), and Lithium Manganese Oxide (LMO) are usually considered the best and most viable options for propulsion. The most common alternative is the LFP battery, chemically known as $LiFePO_4$. Its most prominent benefits are a long life cycle, good durability, and relatively safe in terms of battery standards. The main drawback of LFP batteries is the low energy density. One could make a case for NMC and LMO batteries, but in order to utilize batteries in a propulsion system, especially operating in water, safety is vital. Based on these factors, LFP is the preferred choice for the vessel in our case, even though the energy density is lower compared to the other alternatives. An energy density of 160 Wh/kg will be used in calculations in this report.

State of charge for Li-ion batteries

State of charge (SOC) refers to the maximum amount of charge that is shifted in between the electrodes and indicates the charge level of the battery cell. This value will vary from 0 % to 100 %, with 0 % being completely discharged whereas 100 % means fully charged.

For Li-ion batteries, it is recommended to keep the SOC between 20 % and 90 %. Discharging a battery under 20 % SOC will lead to a drop in nominal voltage, as illustrated in Figure 67. Operating under this state for a long time may cause the dissolution of metals and further cause undesirable effects resulting in a shorter lifetime for the battery. High voltage values, usually obtained over 90 % SOC, may lead to an unstable battery, decreasing battery life. A worst-case scenario could culminate in a fire caused by oxidation of electrolytes, generation of CO_2 on the cathodic end, and temperature rise [152].

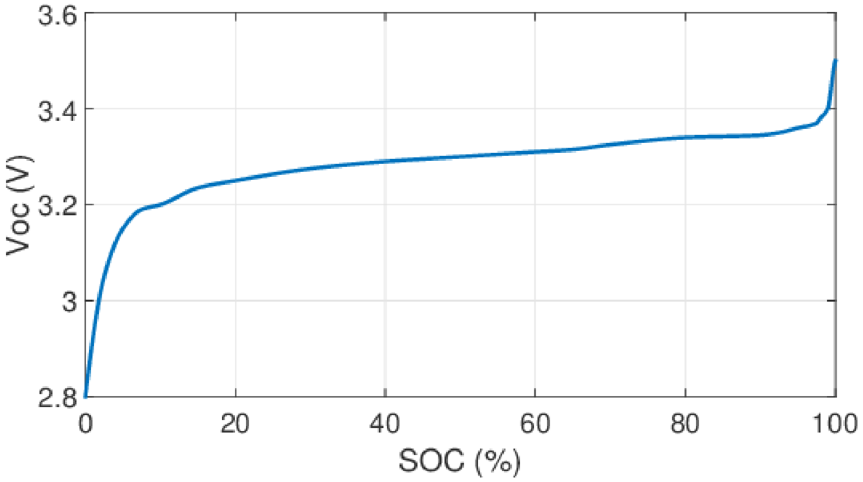


Figure 67: Typical voltage over state of charge for batteries [153].

Over time the capacity of the battery will degrade. In order to retain the same driving range over a longer period, the battery has to expand its bandwidth, increasing the SOC interval, illustrated in Figure 68. With an increased SOC interval, the battery will be exposed to stress, reducing the lifespan of the battery.[154]

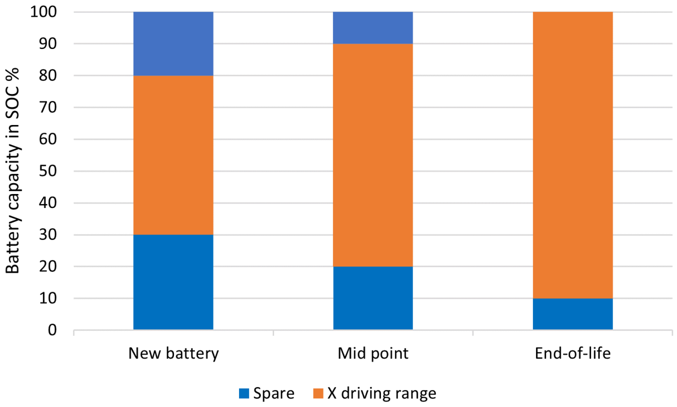


Figure 68: SOC development for Li-battery.

7.2 Diesel Engine

The current system uses a Steyr 145bhp diesel engine for propulsion. The first versions of the Sounder USV utilized an integrated flywheel generator, but this is not the case anymore as Kongsberg now favours dynamos. Diesel engines are the most used engines for ships as they provide long durability combined with a low cost. Over 90 % of merchant ships utilize diesel engines as their main propulsion source, and almost all generators are driven by diesel. Unfortunately, diesel engines are also characterized by a high level of environmentally damaging emissions, especially if they are used in a power area which is not optimal for the engine.

Today, larger ships usually operate with a low-speed two-stroke engine, or a medium-speed four-stroke engine. The difference between a two-stroke and a four-stroke engine is the revolutions needed to complete a power stroke. A two-stroke will complete a power stroke for every revolution, whereas a four-stroke will complete a power stroke for every two revolutions. Low-speed engines operate up to 300 rpm, whereas medium-speed engines operate between 300-1000 rpm [155].

The Steyr motor is a high-speed four-stroke diesel engine, operating at a speed well above 1000 rpm. This engine is suitable for smaller vessels, which is the case for the Sounder USV. A four-stroke engine is usually more complex and less powerful compared to a two-stroke engine. However, a two-stroke engine would consume more fuel following a larger power output, which makes the four-stroke engine better in terms of specific fuel consumption and volumetric-and thermal efficiency. [156]

A four-stroke diesel engine involves four steps, illustrated in Figure 69:

1. Initially only air is injected into the cylinder part of the engine.
2. The motion of the piston compresses the air, heating it to a higher temperature. When the piston is close to the top of the cylinder, fuel is injected under high pressure through a number of precisely machined holes in the tip of the fuel injector. The fuel enters the engine in the form of a fine spray and the surface of each droplet quickly begins to vaporize on its path through the hot air.
3. Spontaneous ignition takes place without the need for a spark and rapid expansion of the combusting mixture increases the pressure in the cylinder, forcing the piston down, powering the vehicle.
4. When the piston is close to its lowest position, the exhaust valve starts to open and the exhaust stroke then drives the spent gasses out of the combustion chamber before the cycle is repeated [157] [158].

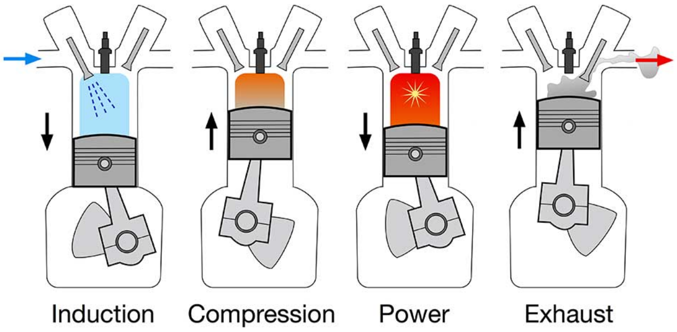


Figure 69: Illustration of the four stages in a four-stroke diesel engine [159].

The small explosions in the cylinder applies force downwards, turning a crankshaft, a cylindrical axle beneath the engine. This force applied by the piston causes a spinning motion which generates torque.

Torque

Torque is a turning force, measuring the force which may cause an object to turn, or rotate, about an axis. It is measured by taking the distance from the pivot point at which you are applying the force, and multiplying it by how much force you are putting in. If we push down with the same amount of force, only the distance from the pivot point matters [160].

The turning force measured at the crankshaft is the engine torque, but not the final torque delivered to the propeller. The crankshaft is connected to a transmission gear with a fixed ratio, describing how big the gear is compared to the gear it connects with at the crankshaft. The gear ratio for the Sounder USV is 1.76:1, meaning that for every 1.76 revolutions the engine performs, the propeller completes one revolution. The driving gear, located at the crankshaft, drives the other gear and carries the torque of the crankshaft. When the gears are connected, the teeth of the driving gear are pushing with a force on the teeth of the other gear. The force where the two gears meet is the same, conveying Newton's third law of motion. However, since the diameter of the other gear is 1.76 times greater than the driving gear, the torque reached the propeller is also 1.76 times bigger as the distance from the pivot increases. Figure 70 illustrates how a larger driven gear will increase the torque, but decrease the speed.

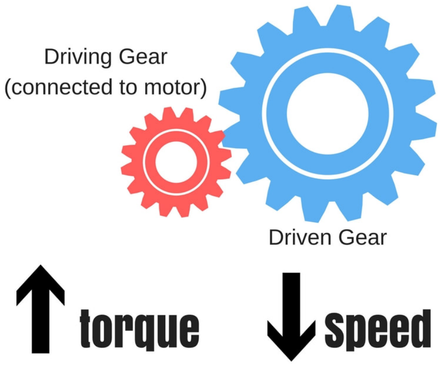


Figure 70: Example of a reduction gear [161]

By slowing down the propeller, the slippage, or waste, is minimized, contributing to a more efficient system. However, some propellers can not handle the speed some of the high-speed diesel engines ramp up. Therefore, a reduction gear is a crucial part of a sufficient propulsion system, but may come with friction losses.

A standard combustion engine will use some time to build up the maximum torque. As there are a lot of moving parts right through the drivetrain, the engine has to use a lot of its energy to overcome the friction between these parts. Another contributing factor is the engine speed, which needs to ramp up to bring the optimal amount of fuel and air into play. This results in a torque curve increasing as the engine goes faster and faster. However, the torque curve will eventually drop as the mechanical resistance starts to dominate, and the cylinder can not pull any more air and fuel fast enough to create more power.

An electric motor has a very different torque curve, as the engine does not rely on fuel and air flow. Instead, the torque relies on the current flow, which is instant, and therefore an em-motor produces maximum torque instantly. This can be used to fill in some of the torque lag in a regular combustion engine. After a certain speed, the torque in an em-motor will drop dramatically, often in the area where the ICE reaches its maximum. Electromotive force (emf) is also generated in the opposite direction when putting an electrical spin into the em-motor, resisting the current flow. After a certain rpm, the emf overpowers the current in the motor, leading to a drop in torque delivery.

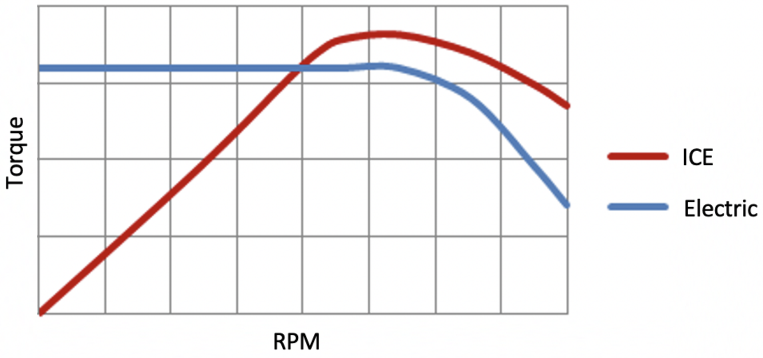


Figure 71: Figure of torque development from ICE and electric motor. Insipired by: [162].

An engine with a lot of torque is not necessarily a powerful engine. A torque-loaded engine results in a faster power delivery. Mathematically power can be expressed as torque times rpm, illustrated in equation 6

$$P = F \cdot v = F \cdot \frac{s}{t} = \frac{\tau}{t} = \tau \cdot \text{rpm} \tag{6}$$

P is power, F is force, v is speed, s is distance, t is time, τ is torque and rpm is revolutions per minute. If the torque was constant, the power would ramp up directly with rpm, and a high torque would subsequently ramp up the power more quickly. In the acceleration phase, it is ideal with a high torque delivery. Once the engine has reached its "maintenance speed", it is not necessary with an overwhelming torque delivery. The advantage of a dual-functioning system is therefore a more energy-efficient acceleration phase, which might enhance fuel savings [163].

Power

The power generated from the engine is usually expressed as kW or horsepower, hp. When accounting for ICEs, the engine power is usually the output power an engine may maintain over a longer period through certified tests. Horsepower was defined by James Watt as he discovered that a horse could lift 330 pounds of water 100 feet each minute, resulting in 33 000 foot-pounds/minute. After his death, it was decided that one hp would equal 745.7 Watt, named after James himself. Another term commonly used in marine engine terms is bhp, brake horsepower, which is the hp of the engine without considering losses caused by different parts of the engine. These losses usually come from the generator, water pump, and other auxiliary parts. Shaft horsepower is the power transmitted along the propeller shaft to the propeller [164].

Power is needed mainly for two reasons, for propulsion and hotel load. In order to provide propulsive power, the engine has to deliver power which reaches the propeller, resulting in rotational spin from the propeller. In general, power and speed are related by equation 7

$$P = k \cdot V^n \tag{7}$$

P is effective power, k is a constant for a specific ship type and propeller combination, V is the ship speed and n is dependent on hull form characteristics. Usually, the relationship between the power and the ship speed is near cubic, resulting in a simplified expression

$$P = k \cdot V^3$$

Hotel load is the electricity needed for different systems on the ship, excluding propulsion power. Such systems could be radars, communication, lightning and controlswitches [148].

7.3 The Prevalence of Hybrid and Electric Propulsion in the Future

Hybrid propulsion systems are an expanding industry as manufacturers strive to reduce GHG emissions. DNV GL has over the last years reported the explosive growth of hybrid or electric vessels in the maritime sector, illustrated in Figure 72. The numbers indicate a growing market for electrical propulsion, and with further development, the numbers are not expected to slow down. According to a report by DNV released in November 2019, 185 vessels used batteries as an energy source for various operations on board. In addition to these ships, 185 battery-supplied vessels were under construction. The blue columns presented in figure 72 represent vessels in operation, whereas the orange columns represent vessels under construction. Note that the numbers are for the shipping industry and do not specify whether or not they are used as the vessels primary energy source (fully electric propulsion), as an additional energy source(hybrid propulsion), or for peak shaving [165].

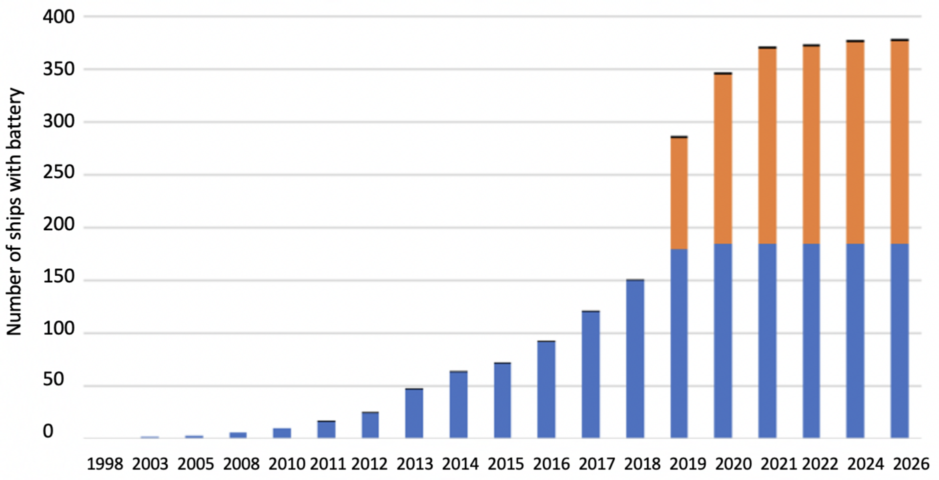


Figure 72: Development of batteries in ship. Inspired by Klimakur [165].

As illustrated in Table 26, the max indicated energy density for a Li-ion battery is around 250 Wh/kg. The most energy-dense Li-ion batteries are NMC batteries and will most likely substitute LFP as the leading battery used for marine propulsion in the future. However, at the moment, the safety regulations does not justify NMC as a viable option on par with LFP.

Figure 73 shows the expected energy density used in the future marine industry for specific cell chemistries. In 5 years, the expected energy density used for batteries in the marine sector will be in the 300-350 Wh/kg region, twice of what is standard in the marine industry today. In 15-20 years, it is expected that technological development has come so far that lithium-air batteries, utilizing air on the cathode, will be available for marine use with an estimated energy density of 950 Wh/kg. Such batteries would make hybrid and electrical propulsion a more viable option as they can provide a much better endurance for less mass [166].

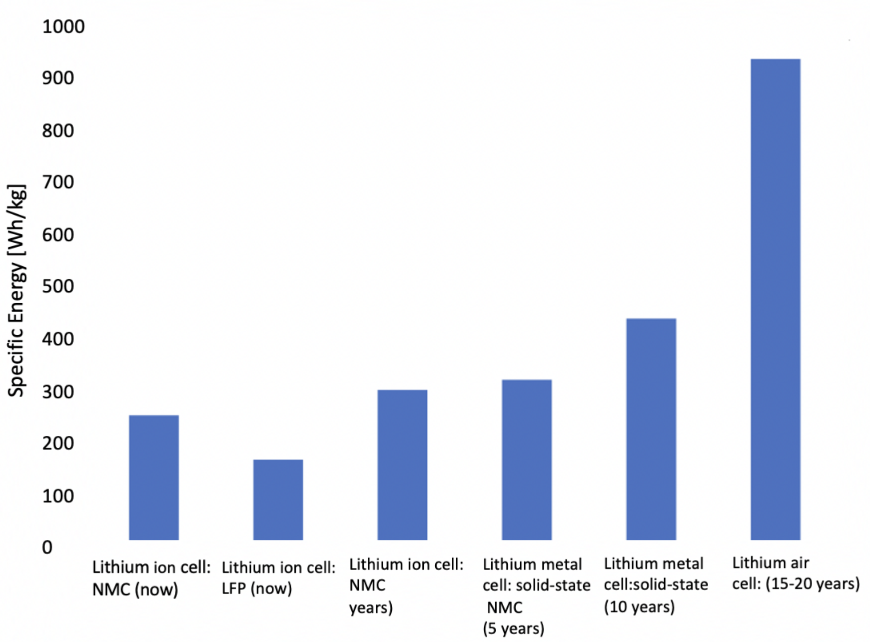


Figure 73: Specific energy of cell chemistry's expected to be used in marine over the next 5-20 years. Inspired by: [166].

7.4 Energy Utilization

In order to utilize the energy stored in a battery, the vessel has to use an electric motor to convert the electrical energy to mechanical energy for propulsion. Where an ICE consists of several complex parts requiring regular maintenance, an el-motor is much simpler and lighter. The basic principle of an electric motor revolves around Faraday's law of induction, creating a force when an alternating current reacts with a charging electric field. An el-motor can achieve efficiency up to 95 %, significantly higher than an ICE engine, operating at 35-45 % efficiency [167].

7.5 Emission

The most substantial part of the emission estimations for the electrical system will be related to the production of the Li-ion battery. The charging should also be considered a factor when accounting for the emissions.

7.5.1 System Production

Various studies for the production of Li-ion batteries suggest a large variation of GWP values. A report by the Maritime Battery Forum (MBF) in cooperation with Grenland Energy, ABB, and DNV GL suggests that GWP for Li-ion batteries in ferries and larger ships is 273-285 kg CO_2-eq per kWh, or 76-79 kg CO_2-eq per MJ of battery capacity. Compared to studies for Li-ion batteries used in EVs, suggesting GWP of 60-173 kg CO_2-eq/kWh or 16.67-48 kg CO_2-eq/Mj, the emissions related to the maritime sector are substantially higher. The difference in emissions between batteries in EVs and the maritime sector may result from more packaging and additional safety regulations. Therefore, it is rational to expect a GWP per kWh capacity for marine batteries to be in the same order of magnitude and most likely in the same range as EV batteries [168].

A comprehensive summary of different studies on Li-ion batteries by ICCT suggests a broader bandwidth when estimating emissions related to battery production, ranging from 30-494 kg CO_2-eq per kWh. The wide range of values might indicate how important the methodological part of the analysis is, greatly influencing the final conclusions of each analysis. An overview of all the studies are shown in Table 27.

Table 27: Study on emission related to batteryproduction.

Production related emissions for battery [kg CO_2-eq/kWh]	**Additional notes**	**Published**	**Reference**
56	30 kWh battery made in the EU	2017	Messagie [169]
96-127	Chinese electricity used to make the battery	2017	Hao et al [170]
150-200	Assumes battery manufacturing in Asia	2017	Romare and Dahllöf [169]
106	Manufacturing inventories come primarily from ecoinvent database	2017	Wolframm and Wiedmann [171]
194-494	Manufacturing process energy represents 80 % of battery emissions. Manufactured in East Asia	2016	Ambrose and Kendal [172]
30-50	US electricty used	2016	Dunn et al [169]
157	BEV will have positive environmental impact after 70 000 km. compared to ICE vehicles	2016	Ellingsen, Strømman and Singh [173]
140	Based on Ford Focus BEV	2016	Kim et al [174]
110	Reveals significant variety in carbon intensities reported across literature based on methodology and chemistry .	2016	Peters et al [175]
73	Indiacted that BEV create 50 % less GHG emissions compared to ICE powered vehicles	2015	Nealer, Reichmuth, and Anairj [176]
200-250	Battery chemistries will have an affect on emissions	2011	Majeau-Bettez, Hawkins and Strömmank [177]

As indicated by the different sources, it is nearly impossible to estimate an exact emission output for Li-ion batteries. However, with further technological development, it is necessary to estimate. The emissions related to battery manufacturing are influenced by which electricity mix is used to produce the battery cells. The numbers from the rapport by MBF are based on the global electricity mix, a mix associated with higher emissions compared to a Norwegian electricity mix. Based on the numbers presented in the table, a battery production emission of 100 kg CO_2-eq per kWh is estimated and will be used for further calculations.

Figure 74 illustrates the percentagewise emission distribution for all the components in a typical Li-ion battery. The three largest emission contributors for the Li-ion battery are related to the cathode mix, aluminium and cell production.

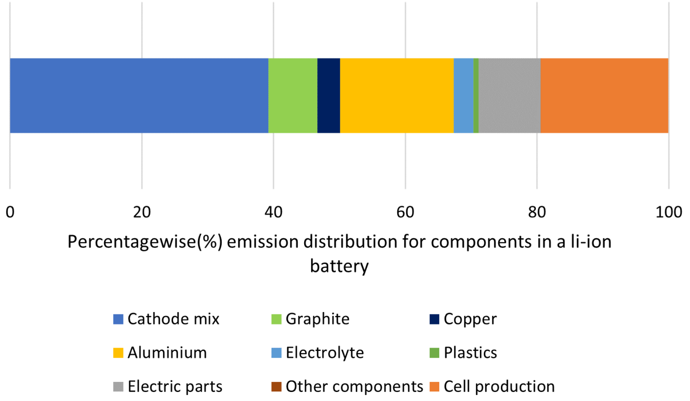


Figure 74: Typical emission distribution for the different parts in an Li-ion battery [178].

In order to utilize an electric propulsion system, the battery has to convert its stored energy through an electric motor. A typical marine el-motor is usually lighter than an ICE engine but has emissions related to the production phase. An average result between two sources, Nordelöf et al. and Hawkins et al., suggests a production emission factor of 7.1 kg CO_2-eq/kg [8].

7.5.2 Fuel Usage

Emissions related to the use phase for batteries are primarily due to electricity used to charge the battery. Possible charging opportunities are mainly on-shore charging, off-shore charging from larger generator sets on ships, or directly from the ICE. The ideal alternative is to utilize on-shore charging, as the electricity is more likely to derive from a renewable energy source compared to generator sets and ICE, which use fossil fuels to generate electricity.

As with the production of batteries, the use phase is affected by which source is preferred. Assuming the Sounder USV will mainly operate in the northern regions, two different approaches will be assessed; one for a Nordic electricity mix and one for a Norwegian electricity mix. The values of these mixes are presented in table 28.

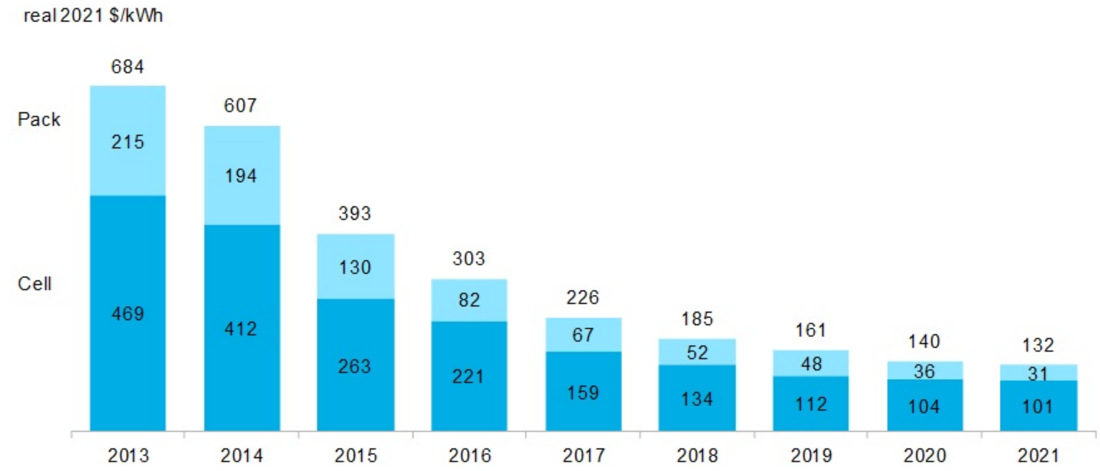
Table 28: Emissions related to two electricity mixes.

Fuel/Energy carrier	**fuel cycle emission factor kg CO_2-eq/MJ**	**Reference**
Electricity (Nordic)	31	[179]
Electricity (Norwegian)	5.9	[179]

7.6 Cost of Hybrid Propulsion

The economy part of the hybrid propulsion system consists of the initial investment cost related to the equipment needed for the propulsion system, as well as the cost related to fuel usage. When accounting for fuel cost, the data is based on average values over an extended period as the prices tend to fluctuate.

Figure 75 illustrates the average price for EV batteries over the last nine years. In 2021 the average price for a combined battery pack and battery cell was 132 USD/kWh, under 20 % of the price in 2013. However, the prices for batteries used in heavy-duty marine applications are considerably higher, primarily due to insulation requirements, cooling equipment, and fire fighting equipment [180] [166].



Source: BloombergNEF.

Figure 75: development of price related to EV batteries in \$/kWh [180].

Figure 76 shows the price development from 2015-2020, as well as the predicted prices for the future. Compared to the 2020 prices for EVs, the marine prices are nearly 3.9 times more expensive.

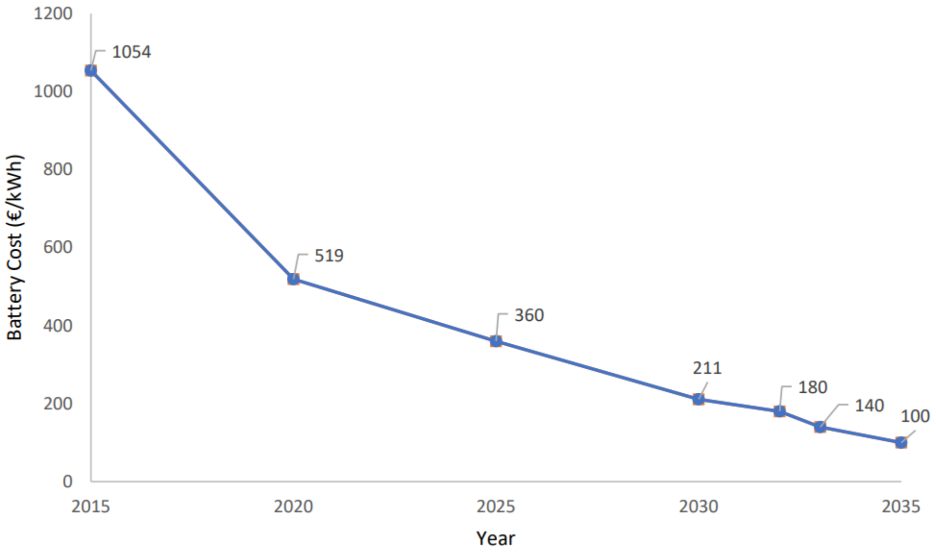


Figure 76: Development of price for Marine batteries as well as future prices [166].

When estimating a price for the battery, an easy estimation is to use the marine prices for a heavy-duty battery pack. However, the Sounder USV is not a big vessel, closer to an EV in size than a large ship. Some of the marine batteries can store multiple MWh of energy, considerably more than what is expected to fit in the Sounder USV. The safety factor is still a quite important parameter, upping the price towards the heavy-duty region. An estimation of 4000 NOK/kWh will be used in the case study, a slightly lower price than for heavy-duty marine application, but well above the price for EVs.

The electricity price is based on an average price for February 2022 in Norway, estimated to be 1.5 NOK/kWh. The electric motor price, 325 000 NOK/piece, is gathered from Evoy AS, an electric motor manufacturer based in Florø, Norway [115] [181].

A summary of the costs are presented in Table 29.

Table 29: Hybrid component cost.

Component/Fuel	Cost and unit	Reference
Battery	4000 NOK/kWh	[166] [180]
Diesel engine	93 140 NOK/piece	[11]
Electricity	1.50 NOK/kWh	[181]
Diesel	19.88 NOK/L	[12]
El motor	325 000 NOK/piece	[115]

7.7 Feasibility and Technology Readiness Level

Li-ion batteries for marine propulsion are commercially available, with high technological maturity, equalling a TRL of 9. In order to charge the batteries, a plug-in solution may be implemented, as on-shore charging adds flexibility to the vessel in addition to charging from the conventional engine. However, this presupposes a widespread and available on-shore infrastructure. The Sounder might also be connected to larger ships or fleets, opening for off-shore charging from larger generator sets on board of ships.

Electricity is available all over Norway, most coming from renewable energy sources. In 2021, 98 % of the electricity produced originated from renewable energy sources. Hydropower and wind power are the biggest suppliers, accounting for 97 % of this share, whereas other renewable energy sources make up 1 % of the electricity produced. Hydropower alone accounted for 88 % of the electricity produced and is by far the most important source of electricity in Norway [123].

Even though most of the electricity produced in Norway comes from renewable energy sources, there is no guarantee that the energy used originates from renewable energy sources. As Norway is a part of a Nordic energy market, which is further connected to the European energy market, some of the electricity might come from cheap carbon based energy. This will influence the emissions related to the electricity mixes [182].

Infrastructure

Charging stations for small boats are not widely used compared to EV-charging stations. In May 2021, the world's first rapid charging station for leisure boats started operating in Florø, located on the western coast of Norway. Currently, the market is small, as private electrical boats are uncommon. Looking at charging stations for ferries might be a viable option, as they represent a future charging alternative for privatized boats, utilizing excess energy [183].

In Norway, 55 battery charging stations and 92 shore power stations are built for ferries as of April 2022. The Norwegian coastal administration has established an overview of the established stations in Figure 77. The orange circles represent battery charging stations, whereas the yellow triangle symbols represent shore power stations. As seen from the figure, the western coastline dominates the geographical locations for the power stations, sharply declining North of Trondheim [184].

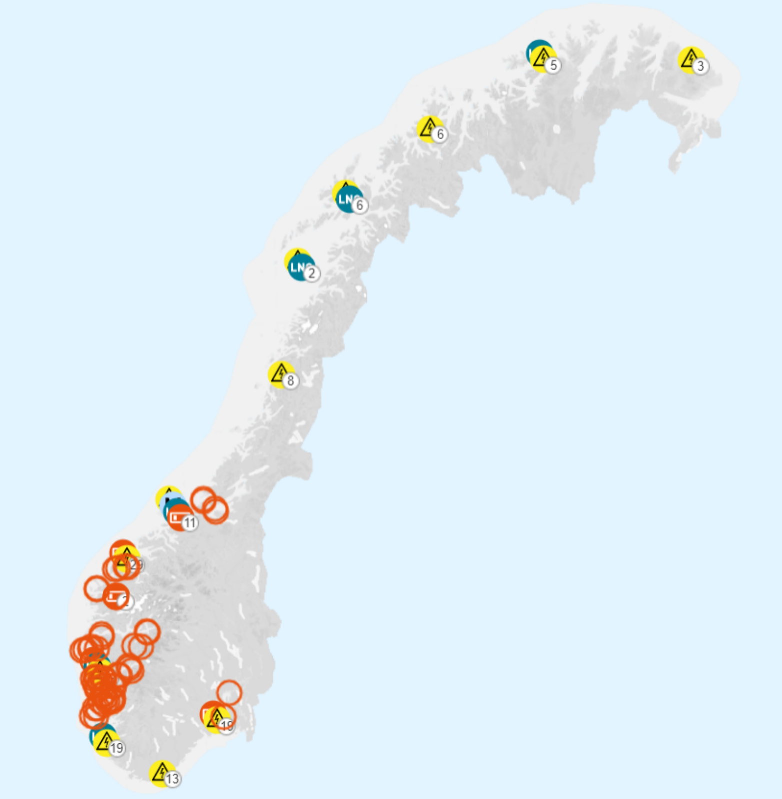


Figure 77: Infrastructure of possible charging stations in Norway [185].

If the Sounder were to operate near the coastline of Norway, the charging alternatives are possible, if not present at the moment, certainly in the future. This could provide extra durability in electric mode, resulting in further emission savings and fuel savings.

8 Case Study

This chapter will analyze the proposed propulsion systems based on the chosen parameters; emission, endurance and cost. Parameters like feasibility and TRL will contribute when evaluating the systems, but are not involved in any of the calculations in the case study. At last, the case study provides an overall comparison of every system.

The weather conditions heavily influence propulsion and fuel usage for vessels operating at sea. The case study will therefore consider calculations based on the energy density of the fuels with minor adjustments, presenting close to a best-case scenario for each system. The energy needed for propulsion will vary for all systems, affecting each system equally. The simplified required energy consumption per day is based on the energy density of diesel, as well as an estimated endurance of 20 days, travelling at 4 knots with an 800 L tank.

$$\text{Energy required per day} = \frac{\text{volumetric energy density diesel} \cdot 800\text{L} \cdot \text{Engine efficiency}}{20 days} \tag{8}$$

$$576\ \text{MJ/day} = \frac{36\ \text{MJ/L} \cdot 800\ \text{L} \cdot 0.4}{20\ \text{days}}$$

The calculated energy requirement per day is the base for all other calculations done in the case study. All three equations shows how endurance, cost and emissions have been calculated, with only small adjustments if the properties of variables require so. All the values used in the case study calculations can be found in Appendix C.

$$\text{Endurance [days]} = \frac{\text{Volumetric energy density [MJ/L]} \cdot 800\text{L} \cdot \text{Efficiency}}{\text{Energy required per day}} \tag{9}$$

$$\text{Cost per day} = \frac{\text{Energy required per day [MJ]} \cdot \text{Fuel cost [kr/L]}}{\text{Volumetric energy density [MJ/L]} \cdot \text{Efficiency}} \tag{10}$$

$$\text{Emission per day} = \frac{\text{Energy required per day [MJ]} \cdot \text{emission factor [kg CO}_2\text{-eq/MJ]}}{\text{Efficiency}} \tag{11}$$

8.1 Current Sounder USV system

This section will go through the estimated emissions and costs results for the propulsion system of the Sounder USV, with the stated durability of 20 days. Diesel systems are characterized by GHG emissions related to use. The production emission for the ICE has been included, whereas the diesel tank emissions were neglected. The cost of the ICE was estimated to be 93 140 NOK. As with emissions, the impact of the fuel tank was neglected. Figure 30 shows that the fuel cost for one day of propulsion is 795.2 NOK. The diesel price used for this calculation was assumed to be 19.9 NOK/L.

Table 30: Properties regarding the current Sounder USV.

Endurance [days]	**Fuel emission [CO_2-eq/day]**	**System emission [kg CO_2]**	**Fuel cost [NOK/day]**	**System cost [NOK]**
20	127.6	1350	795	93 140

8.2 Biofuel Technology

This section will present biofuels' emissions, costs, and endurance when utilized in the Sounder USV. For the calculations, the volumetric energy density and the engine efficiency are used, presented earlier in Table 5.

8.2.1 Endurance of biofuel

The endurance of the Sounder USV was calculated with the use of Equation 9. A comparison of the durability for FAME, HVO, CBG, and LBG in an 800 L tank is shown in figure 78. FAME and HVO show promising results, with 18.3 and 18.8 days of endurance. Since CBG has a low specific energy density, the endurance was 4.4 days, while for LBG, the endurance is 10.2 days.

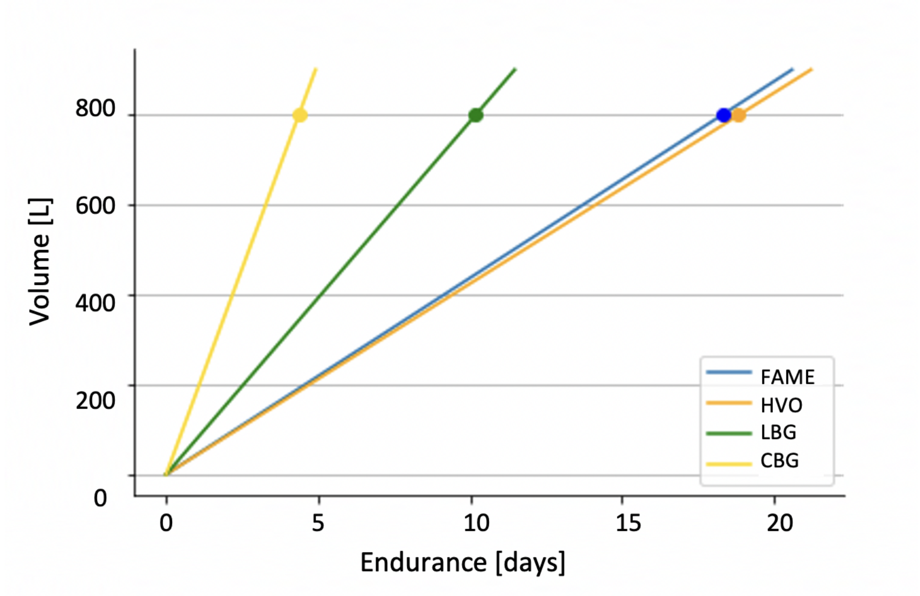


Figure 78: Endurance for HVO, FAME, CBG and LBG per Liter used.

8.2.2 Emission of biofuels

This section will present the emissions for the different biofuel systems. The emission calculations used the WtW analysis for each biofuel, and the daily energy requirement for the sounder USV.

The emissions from HVO were based on the average emissions from rapeseed and UCO. For CBG, the average emissions from cow manure and waste were used. As a result, the emissions from CBG were low. Furthermore, LBG used emission values from logging residues, and FAME, emission values from rapeseed.

Figure 79 presents the daily emissions from the biofuels used in the Sounder USV. The results show that FAME has highest emissions, whereas CBG has the lowest emissions. The results are further shown in Table 39.

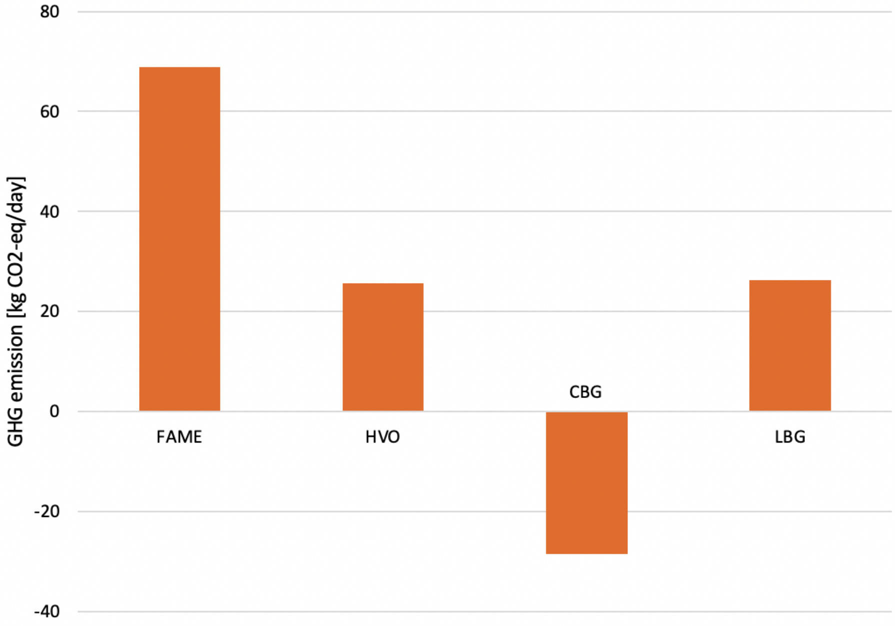


Figure 79: Daily emissions from the biofuels, Sounder USV.

Figure 80 presents the emissions for the biofuel systems. It is assumed that all systems utilize the same ICE, assumed to weigh 250 kg, with an emission factor of 5.4 kg CO_2-eq/kg. Asplans viaks research report suggest that the production emission factor for a cryogenic storage tank is 17.1 kg CO_2-eq/kg, whereas a composite fuel tank has an emission factor of 21 kg CO_2-eq/kg. For LBG the emissions from a 800 L cryogenic storage tank with a weight of 830 kg have been used. CBG, HVO and FAME utilize a composite fuel tank with an emission factor, with an assumed weight of 630 kg. As a result, the production emission for LBG is 15 543 kg CO_2-eq, whereas the production emissions for CBG, HVO and FAME are 14 580 kg CO_2-eq.

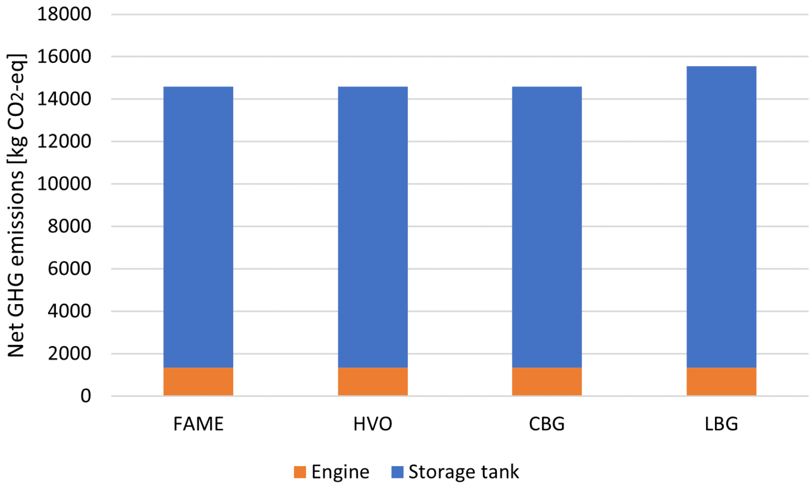


Figure 80: GHG emissions from biofuel systems.

8.2.3 Costs of biofuel

The biofuel prices are presented in Table 7 and illustrated in Figure 81. Due to its low volumetric energy density, CBG will have a higher fuel costs than the other biofuels. Therefore the price required for one day of propulsion is higher than the other biofuels.

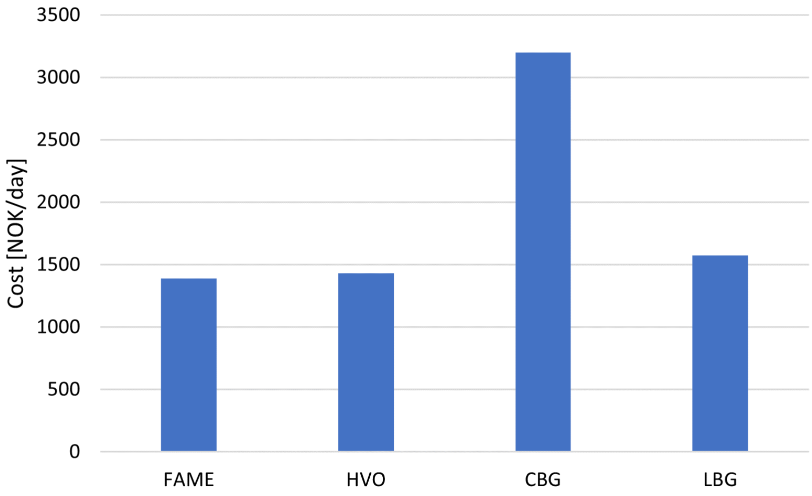


Figure 81: Cost per day of propulsion

Figure 82 presents the system costs for the biofuel systems. HVO, CBG, and FAME use an 800 L composite fuel tank, whereas LBG uses an 800 L cryogenic storage tank. The biogas system uses an SI-engine; however, the price difference between an SI- and CI- engine is neglected, resulting in an equal engine price for all systems. The system price for HVO, CBG and FAME is 153 998 NOK, whereas the price for the LBG system is 101 500 NOK, due to the price difference for the tanks.

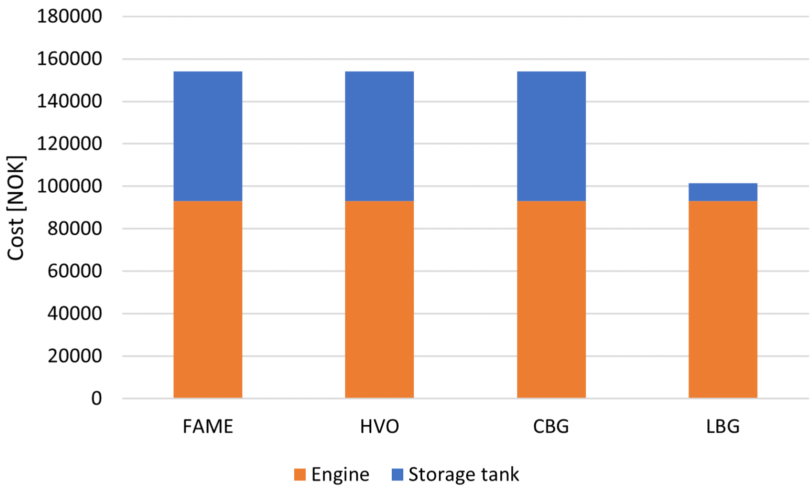


Figure 82: Costs from the biofuel systems on the Sounder USV

8.2.4 Requirements for 20 days Endurance

Table 31 presents the requirements for the biofuels to have an endurance of 20 days. HVO and FAME have an endurance of 18.8 and 18.3 days, close to current diesel durability. Therefore, minor adjustments would be needed for the systems to reach 20 days. CBG has an endurance of 4.2 days when using 800 L of fuel. In order to reach 20 days of endurance, nine 400 L tanks of CBG is required. In addition, the bunkering of CBG would be 70 % more expensive than diesel, over a period of 20 days. However, CBG is the biofuel with the lowest emissions after 20 days of propulsion. LBG would require four 400 L tanks, under half of the required amount for CBG.

Table 31: Comparison of USV sounder running various biofuels.

Fuel	**Fuel price [NOK/ 20 days]**	**System price [NOK/ 20 days]**	**GHG emissions [kg CO2-eq/20 days]**	**GHG emissions fuel [kg CO2-eq/20 days]**	**Required Storage tanks [400 L]**
FAME	27814	66364	15972	1377	2.2
HVO	28614	61460	14100	512	2.02
CBG	64000	108486	12950	-286	9.2
LBG	31504	11827	14707	527	4

Table 32 gives a summary of the advantages and disadvantages for the evaluated biofuels [186].

Table 32: Advantages and disadvantages of the biofuel systems.

Biofuel	**Advantages**	**Disadvantages**
FAME	oSimilar properties as conventional diesel o Low GHG emissions compared to diesel o TRL: 9	o Not suitable for cold temperatures o Expensive compared to diesel o Limited availability o Problem with long term storage o Microbial growth
HVO	o Highest HHV of biofuels o Drop-in-fuel o Low GHG emissions compared to diesel o TRL: 9	o Expensive compared to diesel o Limited availability
CBG	o Low GHG emissions compared to diesel o TRL: 9	o Low energy density o Low endurance o Technological advancement o Limited availability
LBG	o Low GHG emissions compared to diesel o TRL: 9	o Low energy density o Technological advancement o Limited availability

8.3 Hydrogen

The case study regarding hydrogen involves the direct use of hydrogen as a fuel. In terms of hydrogen fuel, both compressed and liquefied will be compared. For the emission calculations, a PEM fuel cell was used. Also, the calculations only included compressed hydrogen storage at 880 bar, disregarding the emission difference of a 700 bar compression. The liquefied storage is not included in the emission calculation because of the uncertainties and the disadvantages of using liquefied hydrogen in the Sounder USV. The case study also presents the different prices of a hydrogen system based on different fuel cells.

8.3.1 Endurance of hydrogen

The durability calculations will differ depending on the type of hydrogen storage system used. Therefore, endurance comparisons include both compressed (700 bar) and liquefied hydrogen. The following calculations are based on energy densities for liquefied and compressed hydrogen, and a total tank capacity of 800 L. The plotted durability is shown in figure 83.

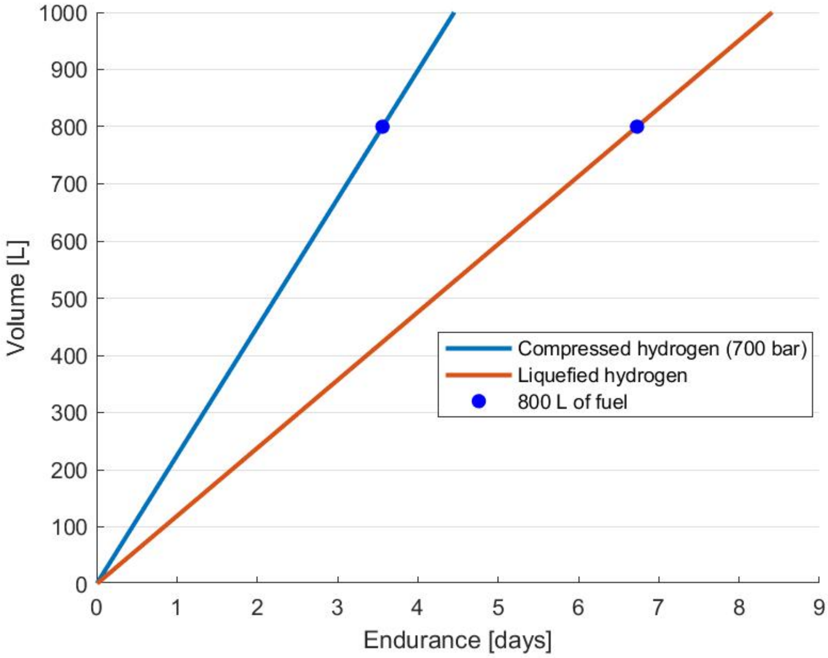


Figure 83: Durability of hydrogen based on volume of fuel.

The efficiencies used were 57 % for pure hydrogen (60 % fuel cell and 95 % electric engine). Figure 83 shows that between 3 and 7 operating days can be attained when using hydrogen. It also shows that liquefied storage can almost double the endurance of a compressed storage system. The results illustrate the importance of the type of hydrogen storage system used.

8.3.2 Emissions of hydrogen

The emission calculations shows the production of a fuel cell system and emissions during fuel production. Blue and grey hydrogen are based on natural gas, and green hydrogen is based on wind energy. It was estimated that the fuel cell and the electric motor had an installed effect of 110 kW. Due to limited information regarding the weight of the fuel tank, an estimation was made based on the study done by Lorenzo Usai, presented in the theory chapter. A tank that can store 5 kg of hydrogen weighs 105 kg.

Assuming the weight of the tank and stored hydrogen is proportional, a tank of 800 L can store 30 kg of compressed hydrogen, resulting in total tank weight of 630 kg.

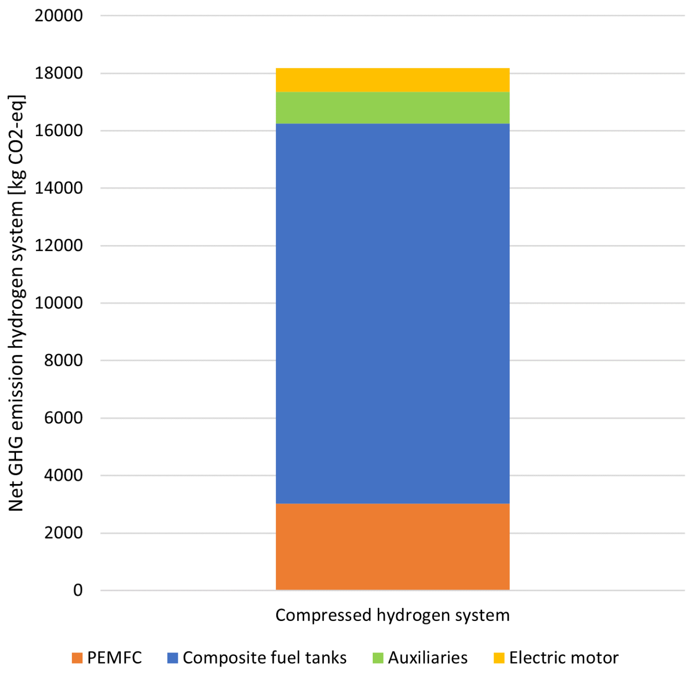


Figure 84: Emission regarding a hydrogen system.

The emissions of the hydrogen system is shown in Figure 84, showing a total emission of about 18 000 kg CO_2-eq. With the majority of emissions coming from the hydrogen tank production, contributing to 71 % of the total GHG emissions.

The emissions from fuel usage are plotted in Figure 85. Natural gas is the energy source for both blue and grey hydrogen, whereas green hydrogen is produced from wind energy. Furthermore, the emissions from a European electricity mix during the compression of hydrogen is included.

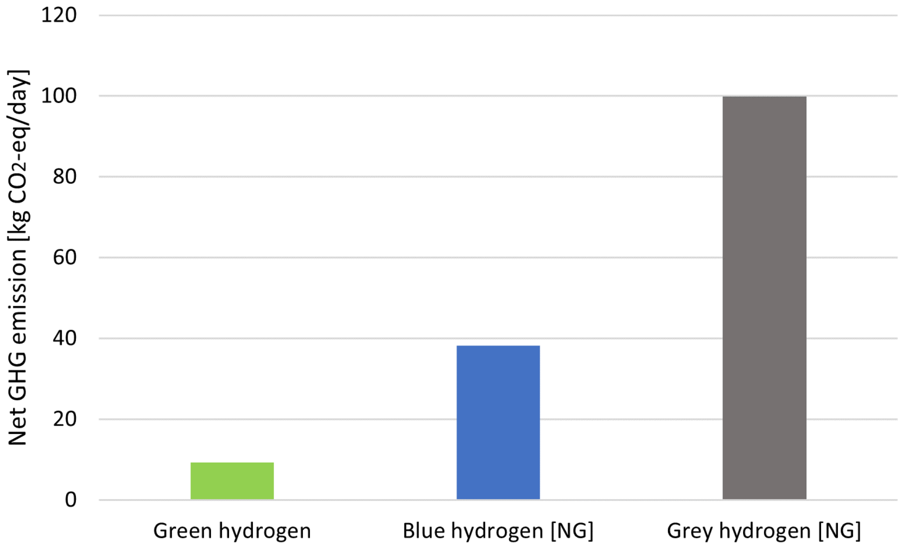


Figure 85: Emission of hydrogen fuel per day of operation.

Figure 85 shows the impact of the pathway used for hydrogen production regarding emission. Figure

85 shows that grey hydrogen is not environmentally sustainable. However, green and blue hydrogen are promising pathways emissions-wise, even when including a European electricity mix during the compression process.

8.3.3 Cost of hydrogen

The fuel and system costs for a proposed hydrogen system used in the sounder USV are presented in Figure 86 and 87. The economic calculations include the fuel cell, electric motor, and fuel tank. Calculations distinguish between three different fuel cells. Both the fuel cell and electric motor are sized to 110 kW. The hydrogen tank stores 800 L which was estimated to weigh 630 kg. For every case, a composite pressure tank has been used. The results are shown in Figure 86.

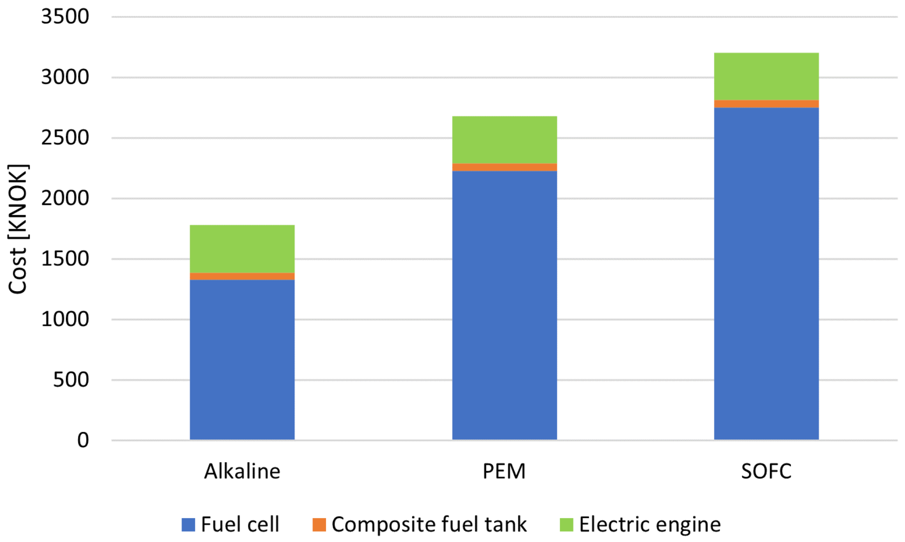


Figure 86: Cost of hydrogen system.

The most significant contributors to the cost calculations are the fuel cells. The cheapest alternative, the alkaline fuel cell, has a total cost of 1.8 million NOK. A PEM fuel cell system would result in a total system cost of 2.7 million NOK. The SOFC is the most expensive solution, with a total cost of over 3 million NOK.

The cost for hydrogen as fuel varies a lot, especially between the three types. For the following calculations, the estimated price in NOK/kg was used, and by converting units, a price of propulsion in NOK/day is shown in Figure 87. Regardless of the uncertainties of the exact prices for the different types of hydrogen, there are few uncertainties regarding the ratio between the types. Neither green nor blue hydrogen can compete with the fuel prices of grey hydrogen. The emission taxes of CO_2 is not regarded in these calculations. When comparing the system prices to the fuel prices, it is clear that the system cost is remarkably higher. The high price of the system makes the price for fuel almost negligible.

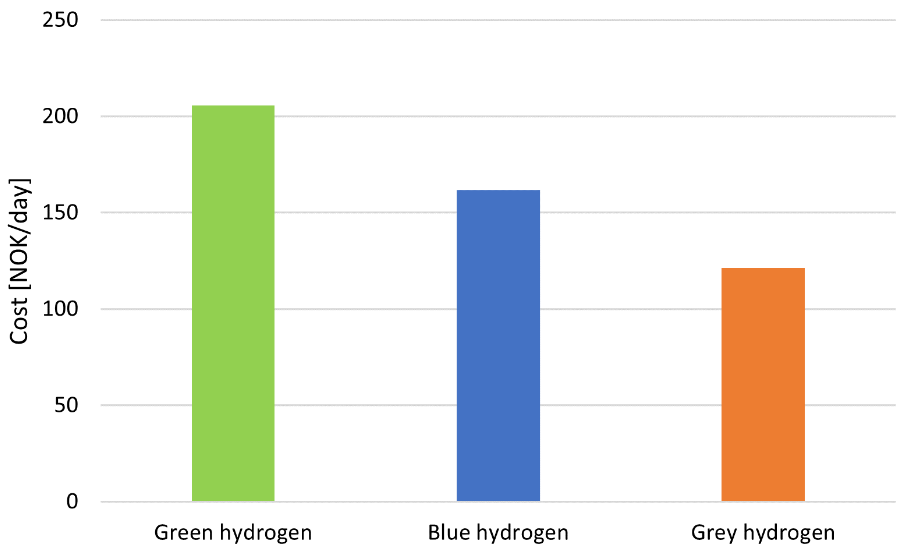


Figure 87: Fuel cost hydrogen per operating day.

8.3.4 Requirements for endurance of 20 days

Table 33 shows all the current requirements for the hydrogen system to endure for 20 days. Hydrogen has low volumetric energy, to achieve an endurance of 20 days, it would require an increase in tank size. An 800 L tank of hydrogen would result in an endurance of less than four days. By assuming proportional relationships between storage capacity and endurance, 20 days of propulsion requires 4 491 L of hydrogen. The increase in storage tanks is the only additional cost and emissions for the system. As storage tanks accounted for the majority of the emissions in the hydrogen case study, an increase in tank quantity would result in a significant increase in emissions. The total weight of the tanks would be 3 536 kg, resulting in an emission of 74 264 kg CO_2-eq.

Table 33: Requirements for 20 days endurance hydrogen.

Fuel	**Fuel price [NOK/ 20 days]**	**System price [NOK]**	**GHG emissions [kg CO2-eq/20 days]**	**Required Storage [L]**
Green	4 109	3 189 000	79 374	4 491
Blue	3 234	3 189 000	79 982	4 491

Table 34 gives a summary of the pros and cons of a hydrogen system.

Table 34: Advantages and disadvantages for a hydrogen system.

System	**Advantages**	**Disadvantages**
Hydrogen	o Low GHG fuel emission o Low fuel cost o High energy density	o High GHG emissions during system production o Expensive system o Limited availability o Low endurance o Low volumetric energy density o TRL: 5-6

8.4 Ammonia

In this section emissions, cost and endurance of ammonia will be presented. It will look at a blend of 60/40 and 80/20, ammonia and diesel.

8.4.1 Endurance of Ammonia

In the first section of the case study for ammonia, it is assumed that the tank capacity is not changed. With the two scenarios, different tank sizes are required. For the 60/40 blend, a 480 L ammonia- and 320 L diesel tank is needed. For the 80/20 blend, a 640 L ammonia- and 160 L diesel tank is needed. Observing Figure 88, the durability achieved for 60/40 blend and 80/20 blend is 12.2 and 9.6 days, respectively. This is an almost 50 % decrease in durability for the 60/40 blend, and about 60 % reduction for the 80/20 blend, compared to diesel.

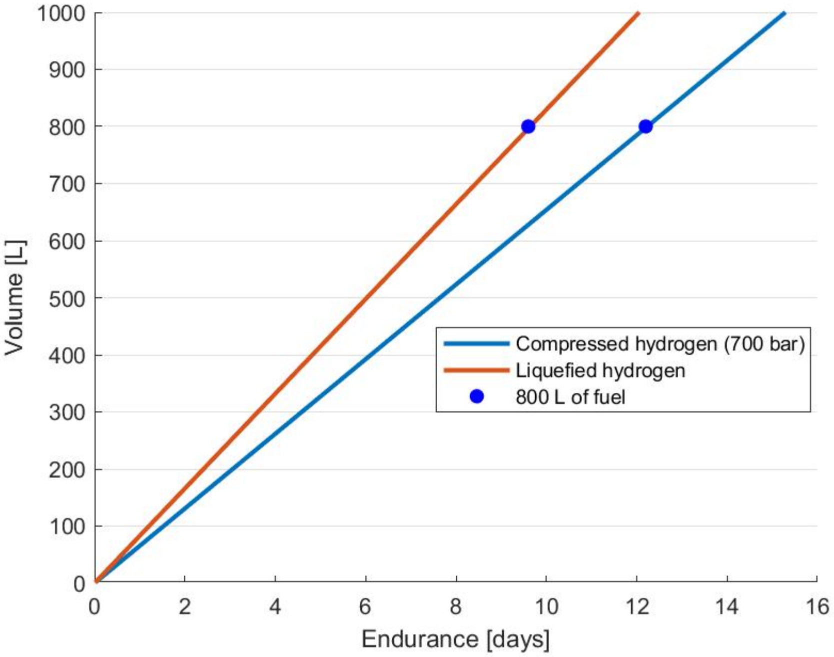


Figure 88: Durability ammonia blends.

8.4.2 Emissions of Ammonia

This section aims to evaluate a WtW analysis of amonia, which includes the production of the tank, the engine and the Haber-Bosch process. According to Asplan Viak, production of a cryogenic tank emits 17.1 kg CO_2/kg [8]. A 480 L cryogenic tank weighs about 500kg, and consequently emits a total of 9865 kg CO_2-eq. The 640 L tank, weighs 664 kg, emiting 11 354 kg CO_2-eq. The emission from production of the ICE is already calculated to be 1350 kg CO_2-eq. The best Haber-Bosch plant uses about 10 MWh/t_{NH_3}, and depending on the origins of the electricity, emissions may vary. For this report a Norwegian and Nordic energy mix has been considered and will be compared. Brown ammonia has not been compared because of its high emissions.

Figure 89 shows the emissions from an ICE with a 60/40 blend of ammonia and diesel from different production pathways for ammonia. Green ammonia with Norwegian energy mix, which has high contents of renewable energy, has the lowest emission. This is expected as almost the entire production process is from renewable sources. Almost all of the emissions are from diesel. It also shows that a big part of the emission is connected to the electricity used in the Haber-Bosch process, this can be seen from the emissions from NG with CCS, produced through the Nordic energy mix. This emission rises as high as almost 140 kg CO_2/day, which is more than 100 % diesel operation.

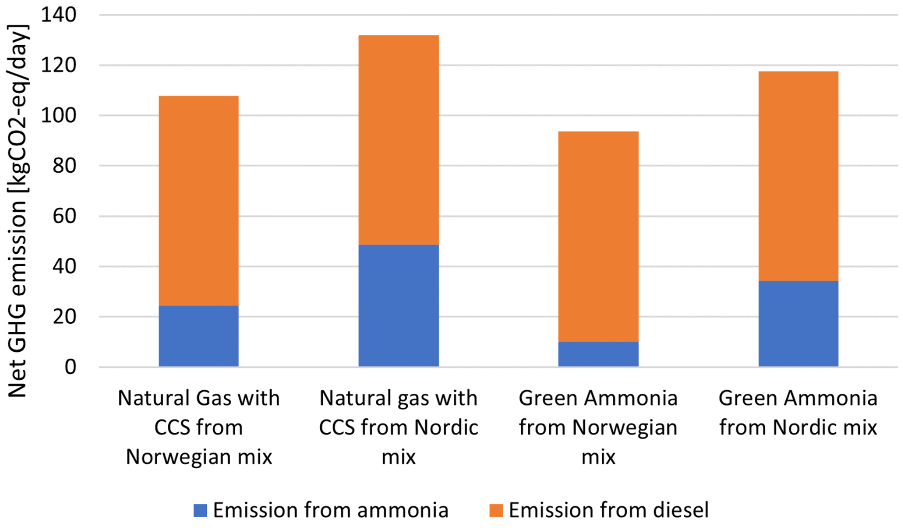


Figure 89: Emissions per day for a 60/40 ammonia diesel mix.

Naturally when substituting more traditional fossil fuel with ammonia, there will be lower emission. However, if ammonia is produced from fossil fuels, rather than renewable energy, the total fuel emissions may emit more GHG compared to conventional diesel. Still, by looking at Green Ammonia from Norwegian electricity, the results indicate that if the technology matures well enough and close to 100% ammonia is utilized in the ICE, a more sustainable marine sector can be achieved.

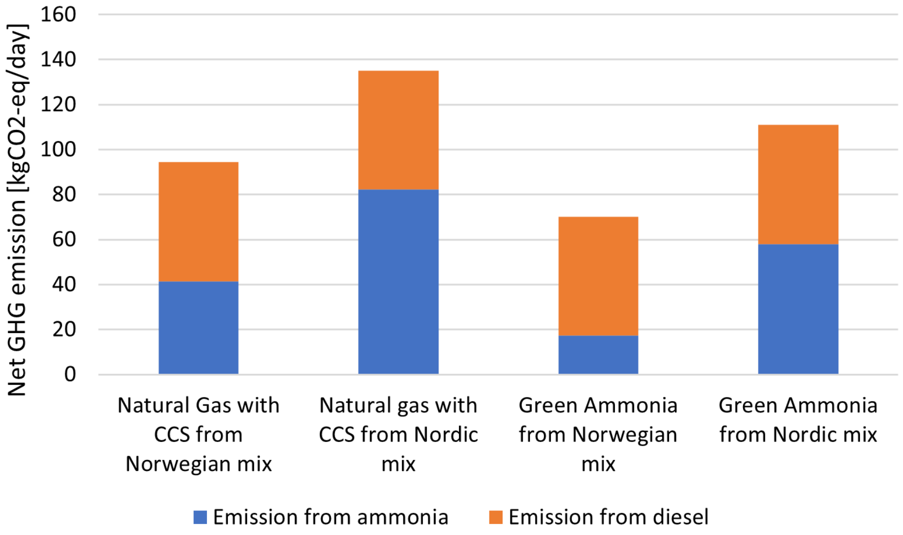


Figure 90: Emissions per day for a 80/20 ammonia diesel mix.

The report previously stated that production of cryogenic tanks to store ammonia can be emission heavy. This can be seen from Figure 91. The 80 % ammonia tank is bigger, resulting in higher emission. Nevertheless this is only a one time investment, but the accounts for a big share of the system emission. The engine remains the same for both cases, therefore engine production emissions are unchanged.

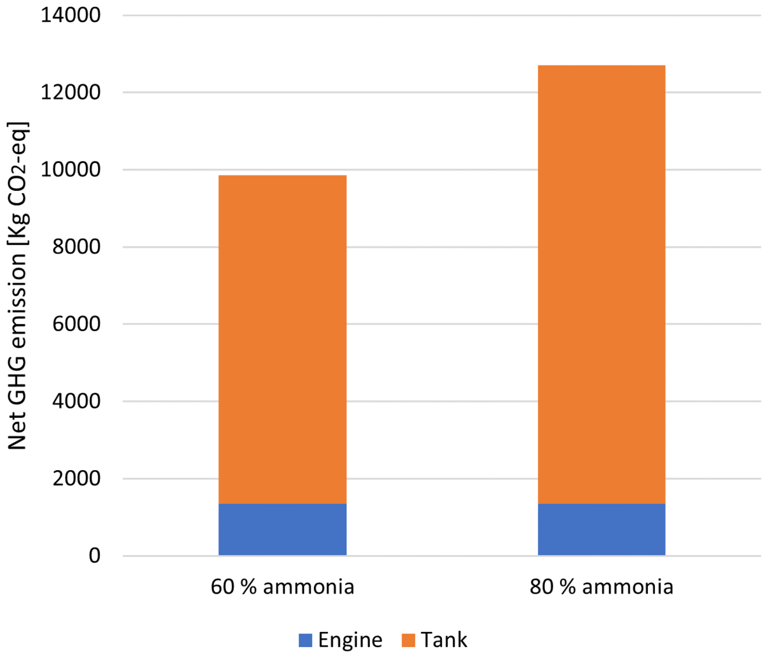


Figure 91: Ammonia system emission.

8.4.3 Cost of Ammonia

The average price for ammonia produced through natural gas 3 575 NOK/t, whereas the price for green ammonia is about 6 672 NOK/t. Substituting the current propulsion system in the sounder USV with an ammonia and diesel dual-fuel system, will result in increased cost. The ICE is estimated to cost 93 140 NOK, whereas the cryogenic storage tank costs 9,5 NOK/kg. The cryogenic tank weighs 497 kg for the 60 % ammonia blend, which results in a tank cost of 4721 NOK. For the 80 % ammonia blend, the total weight of the tank is estimated to be 664 kg, resulting in a tank cost of 6 308 NOK. Figure 92 presents the total cost for both ammonia systems. The different blends does not increase system costs significantly.

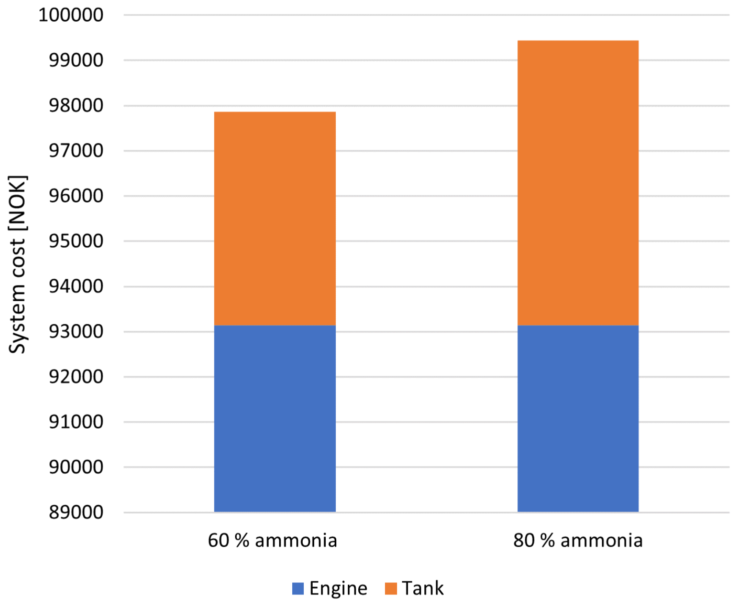


Figure 92: System cost for a 60 % and 80 %.

The prices for one day of propulsion for the two ammonia blends are illustrated in Figure 93. The cost of ammonia is based on green ammonia, the most expensive ammonia fuel. The 60 % ammonia blend is more expensive, compared to the 80 % ammonia blend. The main price contributor for 60 % ammonia blend is the diesel, whereas the costs are evenly distributed in the 80 % ammonia blend. However, in relation to the fuel content, diesel accounts for the majority of the fuel costs, indicating that higher diesel contents will increase the fuel price.

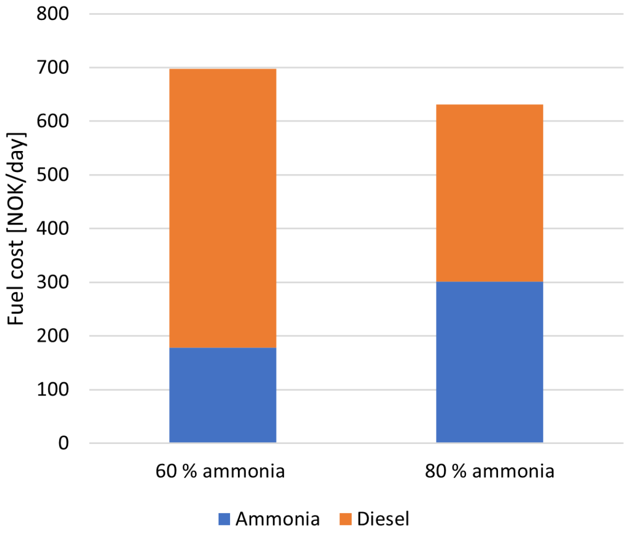


Figure 93: Cost of ammonia as a fuel.

8.4.4 Requirements for Durability of 20 Days

To be able to endure for twenty days, the total energy from ammonia and diesel must be 28 800 MJ. With a dual-fuel combustion system of 60% ammonia and 40% diesel, the tank would have to store 9966 MJ of energy as ammonia and 18 835 MJ in the form of diesel. This corresponds to a fuel tank of 784.7 L ammonia, and 523.2 L diesel. Resulting in a total tank capacity of 1308 L. However, these fuels can not be stored in the same tank, which means two separate tanks are needed. This is an overall increased tank capacity of 508 L. For the 80% ammonia and 20% diesel blend, a 1328 L ammonia tank and 332 L diesel tank is needed. This contains 16 855 MJ ammonia, and 11 944.44 MJ diesel. The combined tank size for this system is 1 660 L, which is over double the size in combined tank capacity. Table 35 shows the required system for 20 days of endurance using a 60 % green ammonia blend from Norwegian electricity. Table 36 shows the main advantages and disadvantages of ammonia as fuel.

Table 35: Requirements for 20 days endurance ammonia.

Fuel	**Fuel price [NOK/ 20 days]**	**System price [NOK]**	**GHG emissions [kg CO2-eq/20 days]**	**Required Storage [L]**
60/40	13954	97861	5781	1307
80/20	12616	99448	5283	1660

Table 36: Advantages and disadvantages for an ammonia system.

System	**Advantages**	**Disadvantages**
Ammonia	o Low GHG emission o Uses existing technology o Widespread infrastructure	o Best suited for low speed engines o Little knowledge of behavior in ICE o Little green ammonia available

8.5 Hybrid

This section will present emissions, costs and endurance for hybrid systems in the Sounder USV. Four different hybrid combinations were considered in the case study, described in Table 37.

Hybrid 1 scenario aims to remain the same weight as 800 L of diesel, dividing the weight distribution between the battery and the fuel 50/50. Hybrid 2 adds a 500 kg battery to the current 800 L diesel tank, exceeding the current weight of the propulsion system. Hybrid 3 and 4 keeps one of the 400 L diesel tanks and adds a rather heavy battery of 1000 kg and 1500 kg, respectively.

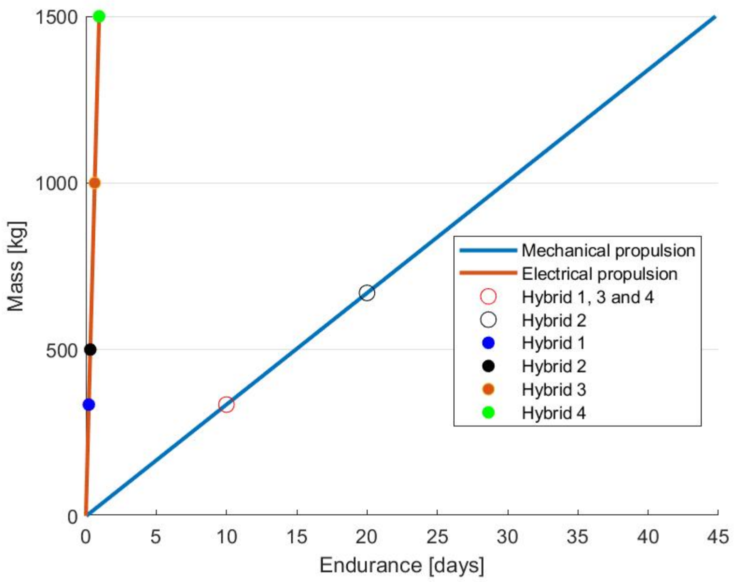
Table 37: Description of the four hybrid systems.

Name	Battery weight [kg]	Tank [L]
Hybrid 1	340	400
Hybrid 2	500	800
Hybrid 3	1000	400
Hybrid 4	1500	400

8.5.1 Endurance of Hybrid System

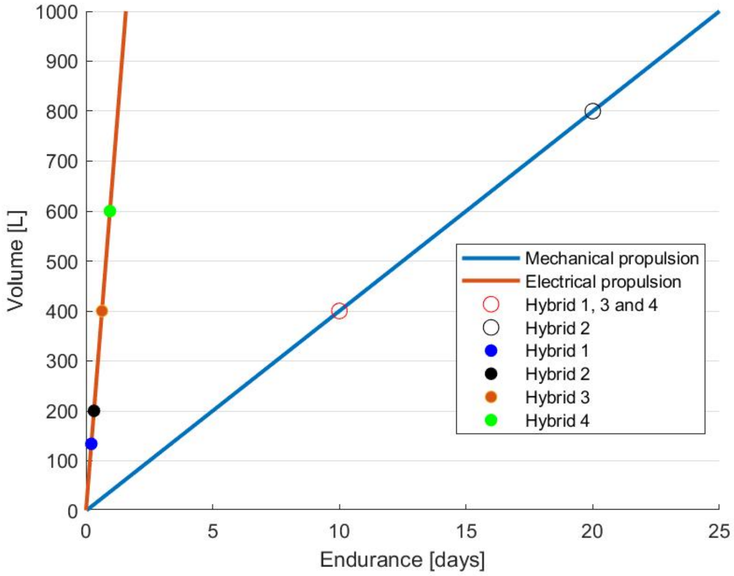
All the endurance plots are based on the energy requirement for one day of propulsion. As seen from Figure 94, mechanical propulsion outperforms electrical propulsion in terms of mass, as batteries are dense in relation to the energy they provide to the system.

Figure 94: Endurance for the different systems with regards to mass.



As with mass, batteries contribute with low endurance compared to mechanical propulsion. Figure 95 shows the endurance of the different hybrid systems. It should be noted that batteries performs slightly better in relation to volume rather than mass.

Figure 95: Endurance for the different systems with regards to volume.



8.5.2 Emission of Hybrid System

In this section the estimated values in subchapter 7.5 and 3.2 will be used as a basis for calculating emissions related to production and use of the four hybrid propulsion systems.

Figure 96 is a graphical illustration of emissions related to the production of the propulsion system. The mechanical investment accounts for the ICE, whereas the electrical investment accounts for the battery and the electric motor. The emissions related to the mechanical part do not differ for the addressed systems as they all uses the same ICE. Hybrid 4 has the highest component emissions, as it has the largest battery pack.

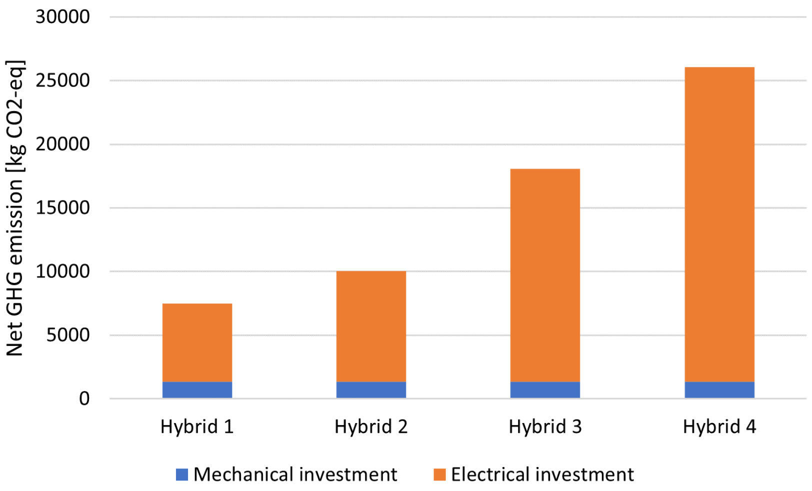


Figure 96: Emission for the different parts of the system.

Figure 97 shows how the four hybrid systems perform in terms of emissions per day related to fuel use. Both the Norwegian mix and the Nordic mix is included in this analysis. Hybrid 4 has the biggest difference between the two mixes due to the large battery package, as well as the lowest emission per day of fuel usage, in contrast to emission related to production of the propulsion system, illustrated in Figure 96.

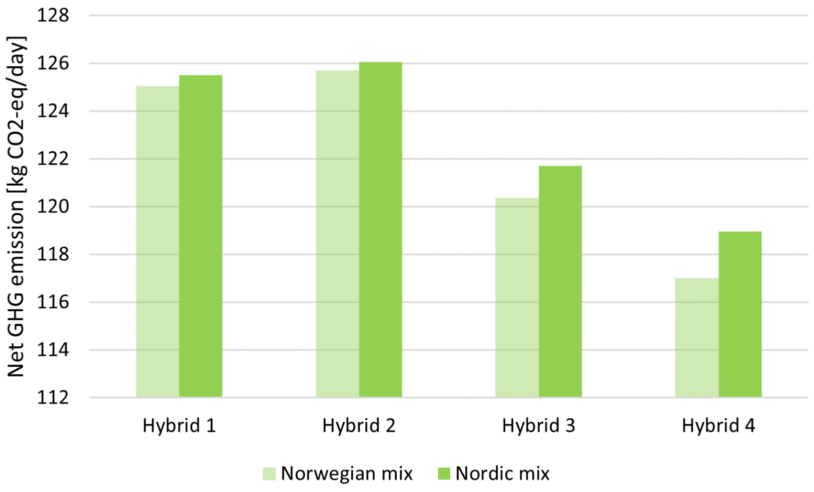


Figure 97: Emissions related to fuel for one day of emission.

8.5.3 Cost of Hybrid System

The initial investment costs related to the four hybrid propulsion systems are displayed in figure 98. The electrical investment cost varies for all four scenarios and Hybrid 4 is the most expensive system as it consists of the largest battery pack. The mechanical investment cost is unaltered for all systems.

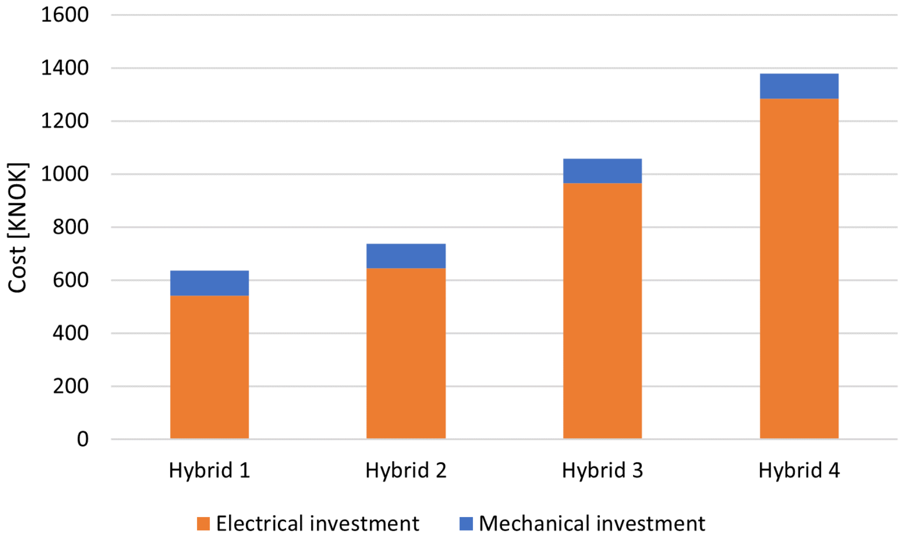


Figure 98: Initial investmentcost for the different systems.

Following the trend of emissions, Hybrid 4 has the lowest cost related to fuel use per day, illustrated in figure 99, saving 6.3 % each day compared to Hybrid 2.

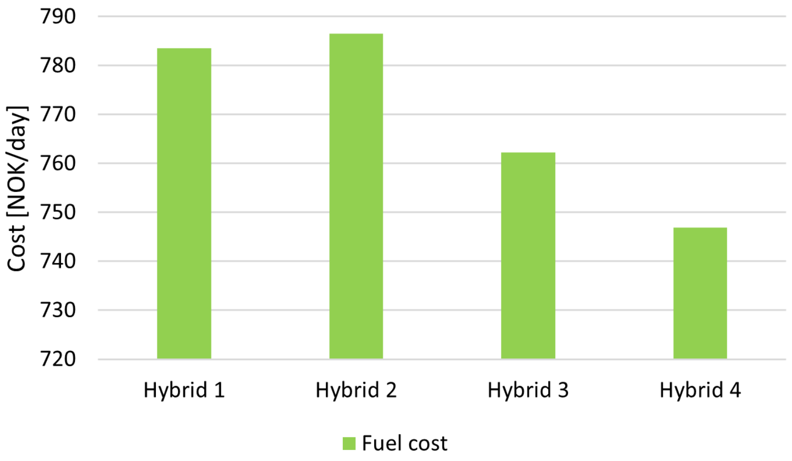


Figure 99: Fueled based cost for one day of propulsion.

8.5.4 Requirements for Endurance of 20 Days

There are numerous ways to ensure a propulsion durability of 20 days for the hybrid system. As Hybrid 2 already utilizes 800 L of diesel, the battery is simply integrated into the existing system, surpassing the 20 days of endurance. The other systems have a reduced amount of diesel fuel capacity, affecting the endurance, as the contribution from electric propulsion is small. In order to endure for 20 days with 100 % electric propulsion, over 36 tonnes of battery is needed, nearly 54 times heavier than pure mechanical propulsion for 20 days.

A short summary of the advantages and the disadvantages of the hybrid propulsion systems is presented in Table 38.

Table 38: Advantages and disadvantages of a hybrid system.

System	**Advantages**	**Disadvantages**
Hybrid	o Flexible system o TRL: 9 o Widespread infrastructure	o Expensive system costs o Limited emission savings o High system emissions o Low energy density in ESS

8.6 Comparison of the Fuels

This section compares the different systems addressed in the case study based on fuel price, system price, GHG emissions per day, system emissions and endurance with 800 L of fuel. Table 39 shows the results of the case study.

Table 39: Comparison of the different systems. *All hybrid systems endurance is their total endurance based on how the different systems are set up. They do not necessary account for the 800 L tank, but may surpass or not even reach this limit.

Fuel	**Fuel price [NOK/ day]**	**System price [NOK]**	**GHG emissions [kg CO2-eq/day]**	**System emissions [kg CO2-eq]**	**Endurance [800 L]**
Green Hydrogen	205.5	2 680 000	9.2	18 180	3.6
Blue Hydrogen	**161.68**	2 680 000	38.2	18 180	3.6
FAME	1 391	153 998	68.8	14 643	18.3
HVO	1 431	153 998	25.6	14 643	18.8
CBG	3 200	153 998	**-14.6**	14 643	4.4
LBG	1 575	101 500	26.33	15 553	10.2
Ammonia 60/40	697.6	97 862	89.1	9 898.7	12.2
Ammonia 80/20	630.84	99 448	70,2	12 704.4	8.3
Hybrid 1	783.57	635 740	125.02	7500	10.21 *
Hybrid 2	786.6	738 140	125.68	10 060	**20.315** *
Hybrid 3	762.3	1 058 140	120.34	18 060	10.63 *
Hybrid 4	746.92	1 378 140	116.98	26 060	10.95 *
Diesel	795.2	**93 140**	127.58	**1 350**	20

The fuel price per day of propulsion ranges from 161.68 NOK/day til 3200 NOK/day. Diesel has a fuel price of 795.2 NOK/day, ranking 9th of the 13 evaluated systems. All of the proposed biofuels have a high cost related to fuel price per day of propulsion, whereas both hydrogen cases are by far the cheapest alternatives. However, the initial system price of the hydrogen cases are considerably higher than the other scenarios, almost 29 times more expensive than the current diesel system. All the systems utilizing only an ICE seems to be in the same price range from 93 140-153 998 NOK. The hybrid propulsion system comes across as expensive due to the price related to the battery as well as the electric motor.

The GHG emissions range from -14.6-127.58 kg CO_2-eq per day of propulsion. CBG has the lowest emission with a negative impact utilizing already existing cow manure emission. HVO has the third lowest GHG emissions per day, while at the same time maintaining good endurance. Diesel has the highest emissions related to propulsion per day, but only 1.9 kg CO_2-eq per day of propulsion more than Hybrid 2. This is because the battery contributes with a small part of the propulsion endurance compared to the diesel fuel. For the two hydrogen cases, the daily emissions varies from 7.98 CO_2-eq per day propulsion with green hydrogen, to 46.38 CO_2-eq per day propulsion for blue hydrogen, opposite of the fuel price related to one day of propulsion.

Within system emissions, diesel has by far the lowest emissions related to the propulsion system with 1350 kg CO_2-eq. The Hybrid 4 system has the highest emissions as the battery requires a lot of energy to produce. The hydrogen cases also have substantial emissions related to the system, mostly coming from the tanks where the hydrogen is stored. The biofuels systems are also affected by the tanks required to store the fuel, but has overall slightly lower emissions compared to hydrogen.

Figure 100 displays how the total emission for the different systems develop over a period of 1 000 days. The hybrid and the hydrogen systems both have high GHG emissions related to the propulsion systems, but develop different over 1000 operating days. Whereas hybrid starts and ends with the highest GHG emissions, hydrogens low daily emissions has a better results in a low net GHG emissions after 1 000 operative days. The diesel system has the lowest emissions, but after 1000 operative days, only the hybrid system has more net GHG emission.

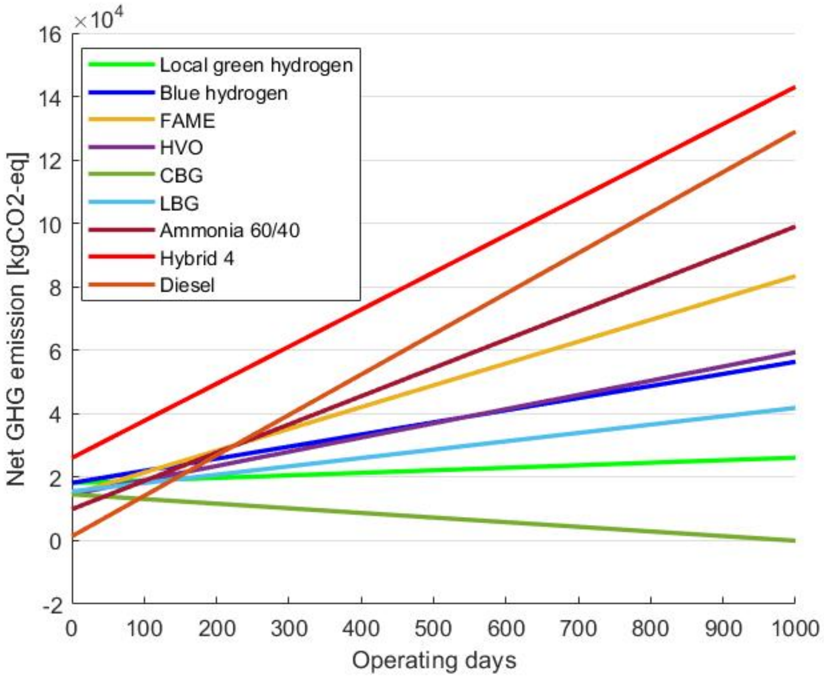


Figure 100: Total GHG emissions after 1000 days of operation.

Table 40 shows when the net GHG emissions will be lower than the diesel system. CBG will have lower net GHG emissions already after 93 operative days, whereas Hybrid 4 has to operate in 2 331 days before the system has a lower net GHG compared to diesel. Excluding the hybrid system, all systems will have a lower net emission within 222 days.

Table 40: Days before each system equals the amount of emissions with the diesel system.

Fuel	**Operating days**
Green hydrogen	142
Blue hydrogen	188
FAME	225
HVO	160
CBG	93
LBG	140
Ammonia	222
Hybrid 4	2 331

Figure 101 shows how the total price of each system will develop over a period of 1 000 operating days. Only one of the ammonia systems were considered, as the cost difference were marginal. The ammonia system is the only system with a lower cost than the diesel system after 1000 operative days, profitable already after 48 days. Even though hydrogen has the lowest cost per day, it has the highest investment cost. Table 41 shows how many days, each system requires, to equal the cost of the diesel system.

The biofuels are not included in Table 41, as both their investment and fuel costs are higher compared to the diesel system.

Uncertainties regarding cost increase with time. Therefore, cost calculations over multiple years, including fuel prices that vary over time, are not practical. Table 41 does not include the possible maintenance or reinvestment of the systems, which will most likely be necessary when assuming cost over such a long period.

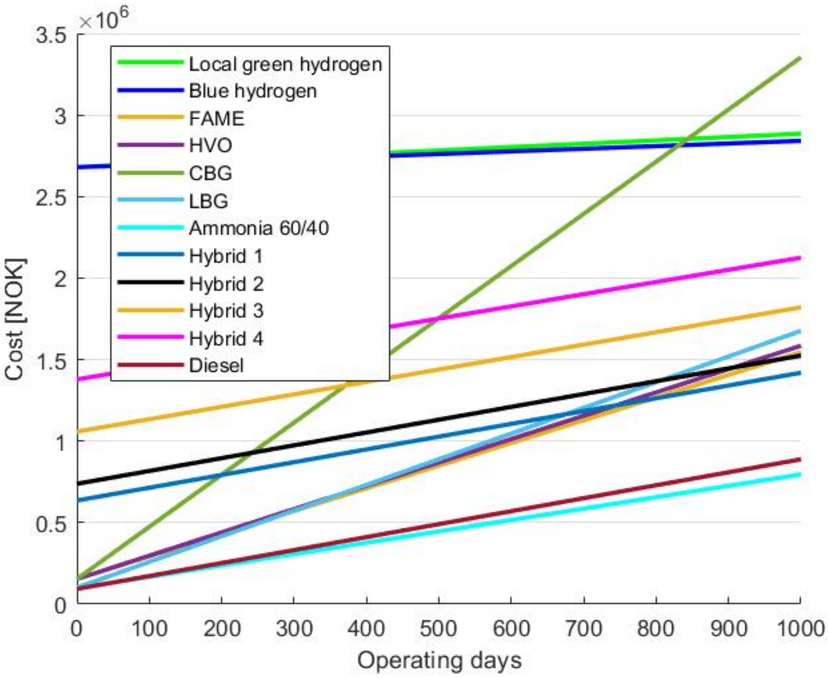


Figure 101: Total cost over time.

Table 41: Days before each system equals the cost of the diesel system.

Fuel	Operating days
Green hydrogen	4 387
Blue hydrogen	4 084
Ammonia 60/40	48
Hybrid 1	46 655
Hybrid 2	75 000
Hybrid 3	29 331
Hybrid 4	26 616

8.7 System Recommendation

A final system recommendation will be dependent on multiple factors. The aim of the report is to suggest the most sustainable energy system, therefore emission and endurance will be determining factors. In addition to emissions and endurance, the TRL explains whether or not it is an available solution. As a result, the requirements were a TRL of 9, an endurance of above 15 days using 800 L, and net GHG emission lower than diesel after 1000 days.

Table 42 shows that all of the systems fulfilled at least one of the demands. However, only two systems fulfilled all demands, HVO and FAME. They both have identical system cost and system emission but differ in fuel cost and fuel emission. In terms of emission, HVO is superior, but FAME is cheaper. Based on the described system demands and cost per emission reduction, HVO is currently the recommended solution.

Table 42: System qualification overview.

Fuel	**TRL of 9**	**Endurance of 15 days**	**Net GHG emission reduction before 1000 days**
Green Hydrogen	X	X	✓
Blue Hydrogen	X	X	✓
FAME	✓	✓	✓
HVO	✓	✓	✓
CBG	✓	X	✓
LBG	✓	X	✓
Ammonia	X	X	✓
Hybrid 1	✓	X	X
Hybrid 2	✓	✓	X
Hybrid 3	✓	X	X
Hybrid 4	✓	X	X
Diesel	✓	✓	X

9 Discussion

The following section will discuss the results devised from the case study. It will discuss the different propulsion systems based on the four areas covered in the case study: feasibility, cost, emission and endurance. Some of the systems, like hydrogen and ammonia lack essential infrastructure to become available. The discussion section will also look at what it takes for these systems to become available in the near future.

9.1 Feasibility

When considering the feasibility of the different systems it is important to consider both the accessibility of the various fuels, as well as the infrastructure for the fuels.

As of today, one production facility in Norway produces FAME, whereas no bio-refineries produce HVO, relying on import from other countries. Even though FAME currently has one production facility in Norway, the majority of FAME in Norway is also imported, as the production facility can not produce the required amount of FAME. One might therefore assume most of the HVO and FAME to be imported from other countries. The advantage of HVO compared to FAME is that it can be stored over a long period without a reduction in fuel quality, which makes it possible to import large amounts and not use it all at once.

Both production of hydrogen and ammonia as a fuel source relies on either fossil-based or renewable energy. Today, a large share of mass-produced hydrogen and ammonia is produced using coal or natural gas. In Norway, natural gas is well established, providing good conditions for blue hydrogen production. At the end of 2022, the construction of the first blue hydrogen factory is scheduled [187]. However, these fossil-based energy sources should be substituted with renewable energy sources to ensure environmentally friendly hydrogen and ammonia production. This will require large-scale production factories in countries where renewable energy is easily accessible and cheap. In Norway many projects are being funded, to accelerate the production of both green ammonia and hydrogen. As the world implements more renewable energy, moving towards a greener society, it is feasible to assume that green hydrogen and ammonia will replace their fossil-based equivalents.

The vast majority of li-ion batteries are made in Asia, utilizing fossil-based energy in the production phase. Batteries are therefore usually imported, when integrated in hybrid systems. FREYR, a Norwegian battery company, aims to start production of batteries in Norway, using renewable energy from wind-and hydropower in the production phase. Such development would make batteries more available in the domestic market, removing the need for imported batteries.

HVO and FAME are well-developed technologies. Currently, 7 % FAME is mixed into the conventional diesel mix in Norway, but not available as 100 % pure FAME substitute. Seven filling stations for mobile vehicles already exist for milesBio HVO100 in Norway, showing that fueling stations offering HVO100 have been established in the market. In addition, Circle K offers clean and sustainable milesBio HVO100 made of the advanced feedstock UCO. Using a feedstock that would have gone to waste reduces the emissions significantly, consequently making use of industry waste. Furthermore, the Circle K stations in Oslo, Bergen, and Trondheim are located close to the shore, making the biofuel easily accessible to the marine sector.

HVO or FAME can utilize already existing infrastructure for fossil fuels due to similarities in the bunkering and storage process [188]. Hence, a short-term solution for refilling the Sounder USV with biodiesel can be through a tank car by the coast. According to a report from the Norwegian government, two ferry connections in Norway use HVO100 as fuel, bunkering through a tank car [189]. Furthermore, the report states that several ferries built with batteries will have HVO as a backup fuel for the engine. This implies an increase in the development of HVO100 in the marine sector in Norway, having a significant role in the decarbonization of the maritime sector. However, it can be a technical challenge to use FAME as a marine fuel, due to limitations in storage time and its poor ability to handle cold temperature. Therefore, using FAME in Norway, a country with cold winters, may be a problem.

As with HVO100, Ammonia can also bunker through tank cars. As ammonia is highly toxic in high concentrations, it must be handled professionally, especially in direct contact. Ammonia has been around for some years suggesting that bunkering and transportation is possible without fatal consequences.

Similar to HVO and FAME, CBG and LBG may use already existing infrastructure, utilizing existing methane stations in Norway. However, the Norwegian coastal administration does not know about any pure bunkering facilities of LBG. Also, predicting how many filling stations will be developed in the near future is difficult.

Using CBG or LBG in the sounder, can be challenging due to its limited infrastructure. Currently, tankers transport methane over shorter distances in Norway. When transported long distance, liquefaction of the substance is necessary to increase storage capacity [189]. The infrastructure expansion of CBG and LBG is challenging to predict. Nevertheless, with big investments in biogas in Norway, it looks as if biogas will play an essential role in the global marine sector.

In contrast to the biofuels, hydrogen does not have a well-developed infrastructure basis. The establishment of hydrogen stations depends on the interest in hydrogen vessels and vice versa. Even though politicians and technology developers have expressed their enthusiasm toward hydrogen, infrastructure expansion is yet to spread across the country. It is hard to estimate whether or not growth in infrastructure will occur. However, an interesting approach is whether or not the lack of infrastructure for road vehicles will affect the hydrogen infrastructure in the marine sector. A study by Shell [88] indicated that technology readiness for busses, trains, trucks and marine applications will not be as dependent on the infrastructure for conventional cars. The study suggests that operators within these sections has a bigger benefit of developing its own infrastructure. These assumptions strengthens hydrogen as a possible marine fuel in the future.

Another aspect which makes ammonia and bioenergy great sources of fuel is that they utilizes already existing technology in the form of ICE's. Hydrogen would require an overhaul of most marine propulsion systems, integrating newly developed fuel cell technologies. Such investments would be costly, preventing potential investments or at least hesitate further prevalence of hydrogen in the marine sector. This makes ammonia and bio-fuels ideal as it makes the shift to the hydrogen economy easier, and could be a stepping stone in the direction of decarbonization of the marine sector.

9.2 Costs

Economical estimations might be one of the most challenging estimations during a case study, a well developed company like Kongsberg might benefit from individual partnership-deals with suppliers, usually lower than the general costs commercially available. This may apply for cost of fuel, but especially for cost of system components like fuel cells, ICEs and batteries.

The future biofuel prices are estimated to increase in the coming years, according to the Norwegian Environment Agency [68]. This is due to limited competition between biofuel suppliers on the Norwegian market, but also due to limitation of advanced feedstocks. Also, the price that was estimated in 2022 do not correlate with the actual prices, as it is much higher today. Furthermore, this is due to inflation, and the demand being higher than the supply.

The fuel prices for biodiesel and diesel were collected from Circle K's current fuel prices, while the prices for biogas were collected from Gasum. CBG and LBG have lower specific energy density than biodiesel and diesel resulting in a higher fuel price for one day of propulsion. The fuel price for biodiesel is substantially higher than diesel, but in return emits less GHG. Industries usually value cost over emission, and to increase usage of bio-fuels, cost must decrease. This can only be done through increased competition and production. To increase production, industries will have to invest in research and development of second and third-generation feedstocks. Also, a factor to decrease the costs of biodiesel is reducing the production costs through the use of feedstocks that dont compete with food production. Another aspect which can provoke investment in bio-fuels is government taxes on fossil-based fuels.

While high fuel prices characterize bio-fuels, ammonia and hydrogen are cheaper alternatives to conventional fossil fuels. Information on the fuel price for hydrogen was found in a European Commission report 20. Unfortunately, these estimations did not include the carbon cost. Therefore, grey and blue hydrogen estimations could have been more accurate if one were to include the carbon cost. However, when comparing the European Commission's price estimations with SP global [114] and Max Åhman at Lund University [113], the calculations add up. Therefore, despite the general uncertainties for fuel prices, the ones found were regarded as reasonable estimations.

Estimations predicting future prices are based on ongoing trends. Both Figure 45 and Figure 46 have estimated how fuel prices will change. Based on these two figures, it is plausible that the price for green hydrogen can be reduced to 1.5 $/kg in 2030, equal to 14.25 NOK/kg. Therefore, green hydrogen will be a viable alternative cost-wise, in the same price range as grey and blue hydrogen.

Today, the cost of ammonia is affordable compared to conventional diesel. Green ammonia is about 25 % of the diesel price. For the proposed scenario in the case study of 60 % ammonia, the total price of propulsion per day is lower than pure diesel. Ammonia prices are also expected to decrease as the availability of renewable energy worldwide is growing, and government taxes on NG are becoming more frequent. In light of ongoing conflicts in Europe, the natural gas price has risen. Predicting events like this is tough, and accounting for prices would make the comparisons somewhat artificial. The rise in price for NG will make brown and blue ammonia more expensive and make green ammonia more competitive earlier than expected.

With the European Union having to rely less on Russian gas, it makes the incentive to begin development of large-scale green ammonia and hydrogen plants in Europe and America, even bigger. Relying less on Russian gas, which has been a staple in the European energy sector for many years, could provoke a massive investment in renewable energy, making hydrogen, ammonia, and bio-fuels cheaper and more available than carbon-based energy.

The electricity price development will affect the price of charging for hybrid propulsion. However, since most of the propulsion is related to mechanical use with diesel fuel, the system is more sensitive to changes related to the diesel price. For the hybrid 2 system, the daily diesel costs related to one day of propulsion accounted for 99.5 % of the daily fuel costs, almost neglecting or minimizing the impact of the electricity.

If hybrid 2 increased its battery size by tenfold and halved the diesel tank, 91.3 % of the daily propulsion cost would still be related to the diesel price. However, this scenario would have a daily propulsion cost of 662.2 NOK/day, primarily due to the battery contributing with much more energy, lasting 10 times longer in electrical propulsion than the original case, replacing expensive fuel outcomes related to diesel. One day of electrical propulsion is 240 NOK, about 30 % of the price for daily use of diesel propulsion, 795.2 NOK/day. If the original hybrid 2 scenario experienced a price fall of 3 NOK/L for diesel fuel, the daily price for propulsion would be 668.5 NOK/day, slightly higher than the extreme case of a tenfold battery size as a halve diesel tank. This illustrates how the daily fuel prices may vary for several reasons but are more sensitive to diesel fuel price changes.

The investment cost made for the different systems are based on various sources, as each system requires different compositions and components. FAME and HVO utilizes the existing system in the Sounder USV, with the need for a composite fuel tank. The investment costs are therefore related to the fuel tank and the ICE. Some sources suggested that a normal diesel tank could be used to store HVO and Fame. This would have decreased investment costs related to the systems.

CBG is stored in a composite tank, whereas LBG is stored in a cryogenic tank. Biogas may be used in a modified SI engine. This means that neither CBG nor LBG can function in the CI engine in the Sounder USV. The CI engine would have to undergo a conversion to a SI engine if CBG or LPG were to be used. The price difference between the two engines were negligable. The price for the CI engine is 93 140 NOK, while the price for the composite fuel tank is 96.6 NOK/kg. Therefore, the total price for both systems with an 800 L tank would be 153 998 NOK.

Ammonias propulsion system is similar to FAME and HVO, using the same ICE, but a different fuel tank. A cryogenic tank is used as ammonia is stored as a liquid, at a low temperature. The price for the cryogenic tank is cheaper in terms of price per kg. A weakness in the analysis of the system cost is the lack of substantial information concerning the cryogenic tank. Consequently, the total investment may vary, as the cost of the tank is influenced by the weight.

The case study clearly showed that the investment cost for the hydrogen system were considerably higher than the other systems. Further development of fuel cell technology and renewable energy is expected to lower the investment costs for hydrogen systems. Both the demand and research will likely contribute to reduction in price for PEM fuel cells.

As with hydrogen, the hybrid systems had a high investment cost. The batteryprice per kWh of storage capacity was estimated to be 4000 NOK. This price is higher than whats expected for EVs, but lower than the expected price for heavy-duty marine batteries. It is expected that the price will drop in the future as illustrated in Figure 76, reaching todays EV battery price in ten years. A lower investment cost would attract possible buyers, as the risk connected with a hybrid system would be reduced.

A continuing trend amongst all the cost-related cases is that most of the systems and fuels will decrease in price with time. For the time being, using already established technology as a stepping stone until fuel cells are more commercially available looks the best option. A hybrid solution comes with high investment costs, but lower fuel cost than a conventional diesel systems. In contrast, HVO and FAME have a substantially lower investment cost, but almost twice the fuel cost for a day of propulsion compared to the diesel system. The Hydrogen system has the cheapest fuel cost per day , but with uncertainties regarding fuel tanks, the system-costs were twice as expensive as the most expensive hybrid solution. Ammonia seems like a viable option with the cheapest investment costs, excluding the diesel system, as well as about 100 NOK in savings for each day of propulsion compared to the diesel system.

9.3 Emission

There will be uncertainties when estimating emissions for new propulsion systems. This section will discuss uncertainties and weaknesses of the case study. In addition, future possibilities will be presented to show how emissions might change.

An essential factor to consider in the production phase for all systems and fuels, is where the energy required to make these components originate. Assuming most of the systems require electricity to make the different parts, the choice of electricity mix will affect the results.

The European Commission Joint Research center, appendix 4a, was used to calculate biofuels and hydrogen emissions. However, this study used a European electricity mix mainly consisting of natural gas. The report considered an average transportation distance of 50 km. Therefore, the emissions could have looked slightly different if a Norwegian electricity mix and another transportation distance had been chosen. Studies suggest that system emissions may be reduced by 20-70 % using a clean energy mix. When performing emission calculations, uncertainties will occur, emphasising the importance of consistency. Hence, the same source was used for ammonia, biofuel and hydrogen emissions.

The choice of electricity mix is most likely also the reason for the large fluctuations in emission values presented in Table 27, displaying battery production-related emissions. Some sources suggest a high production-related emission if the batteries were made in Asia, where most li-ion batteries are produced. Many Asian countries are still powered by fossil-based electricity grids. On the other hand, Dunn et al. suggest the lowest production-related emissions with a US electricity mix, instead of an Asian electricity mix.

If the fuel and fuel systems were to be made in Norway or the Nordic region, there is reason to suggest a reduction in production-related emissions. The Norwegian energy mix is considered clean, as 98 % of the electricity produced comes from renewable energy sources. Whether or not this energy stays in Norway is a question up for debate. Norway is part of a Nordic energy market with Sweden, Finland, and Denmark, which is connected to the European energy market. Without knowing the exact origin of the electricity used, it is hard to estimate the environmental impacts of the production phase.

The difference between the Nordic and the Norwegian electricity mix is quite noticeable, as the Nordic mix emits 5.25 times more per MJ used than the Norwegian mix. Emissions regarding ammonia and the hybrid system have differentiated between these two mixes. The Norwegian mix is likely based on close to 100 % renewable energy sources and without exchange to other countries. In contrast, the Nordic mix probably considers this exchange.

Figure 97 shows how great of an impact the different electricity mixes would have in terms of emission per day of propulsion for the hybrid system. The difference between the two mixes is surprisingly low, explained by the low percentage of electrical propulsion in the hybrid system. Hybrid 4 has the most notable difference, as that system has the largest battery pack, requiring more electricity to charge. If one scenario had been fully electric, the difference between the two mixes would have been more visible, especially over a 1000 days scenario, as most emissions are related to fuel use. The difference between the different mixes is better displayed in the ammonia calculations. Figure 89 and 90 show a more significant difference when using the two mixes.

The emissions calculations regarding biofuels accounted for multiple parameters. There are both advantages and disadvantages associated with the various feedstocks used for biofuel production. First-generation feedstocks can be used as a food source, meaning that excessive utilization of first generation feedstocks is not preferable. Furthermore, the production of first-generation feedstocks requires extensive land, contributing to deforestation and loss of biodiversity. Therefore, if the Sounder USV were to run on biofuels, it should use bio-fuels, mainly manufactured from advanced feedstocks.

There was a lack of data on biodiesel produced from algae and residual animal fat. Therefore, these feedstocks were evaluated, but not considered a potential source for biodiesel production, as the sources failed to specify whether or not the emissions were applied for FAME or HVO. However, studies suggest that these feedstock are characterized by low GHG emissions. In addition, the feedstocks do not compete with land use. As a result, they will not contribute to deforestation or compete with the food industry.

The conventional feedstocks considered in this report were rapeseed and sunflower. The sustainability of these feedstocks may be questionable. The GHG emissions from HVO and FAME produced from rapeseed and sunflower were relatively low and showed promising results compared to diesel. However, these emissions do not consider external factors, like land use and its effect on biodiversity. On the other hand, advanced biofuels are more sustainable and do not compete with the food industry. The emissions from advanced biofuels presented in this report are UCO, algae, and residual animal fat. Producing biofuels from used cooking oil is already a well-established method in Norway. However, producing biodiesel from residual animal fat like fish oil can contribute to sustainable biodiesel production. Norway has large amounts of fish slam that go to waste. Using this for biodiesel will contribute to a significant decrease in emissions.

The emissions from each biofuel will vary depending on the feedstock. An prominent example is CBG. When using cow manure as feedstock, the GHG emissions will be three times lower than waste. Regardless of its use, the CH_4 from cow manure would have been released into the atmosphere. The GHG emissions from LBG are presented from logging residues and was chosen due to the many logging residues in Norway. The case study indicated low GHG emissions for LBG.

The TtW emissions calculated for the biofuels were used from an f3 project. This report accounted for a small amount of CO_2 emissions from FAME but assumed the CO_2 emissions for HVO and biogas to be zero. Further, the report calculated GHG emissions such as CH_4 and N_2O. The TtW emissions from FAME are based on rapeseed. This data is suited well for the WtW calculations because the WtT also considered RME, which helped reduce the uncertainties for the total GHG emissions for FAME from rapeseed. Biofuels have lower GHG emissions compared to diesel. HVO from UCO had the lowest emissions, as advanced feedstocks are more sustainable compared to conventional feedstocks. In addition, HVO emits less emissions compared to FAME, due to the production process. FAME has the byproduct glycerol while HVO has the byproduct paraffin. Glycerol can become an issue due to problems with being disposed of in the environment [190]. In contrast, the byproduct from HVO, paraffin, is excellent fuel [13]. As a result, HVO is a more sustainable biofuel and is more suited for the sounder USV than FAME.

Although combustion of ammonia does not contribute to emission of CO_2-eq, the production pathway, as presented in the case study, matters significantly. Therefore, to lower emissions, ammonia should originate from green hydrogen, and treated through renewable energy in the Haber-Bosch process. The case study showed that using non-renewable energy in the Haber-Bosch process greatly increased emissions. In the case study, the engine emissions is a consequence of using diesel as a combustion promoter. Therefore, an ideal case would use close to 100 % ammonia for power generation, with only small percentage of pilot fuel to improve combustion. This is possible, but using large amounts of ammonia, usually leads to excessive amounts of unburnt ammonia, well over the toxicity limit of 50 ppm. Further technological research will need to be conducted, to increase the percentage of ammonia as substitute fuel, lowering emissions for the fuel.

In contrast to the biofuel and ammonia systems, emissions related to hydrogen and hybrid component production impacts the total emissions significantly. The calculations for the hydrogen system emissions were based on a life cycle analysis done by Lorenzo Usai [111]. Like biofuels, this study used a standard European electricity mix, with natural gas as a heating source. Results from this case study were scaled to fit the Sounder USV. In both the case study and the LCA by Usai, the production of the fuel tank contributed to the majority of emissions. However, the emissions for the case study accounted for a larger percentage-wise emission, as 72 % of the total emissions were related to the production of the fuel tank. In comparison, the LCA of the fuel tank only accounted for 40 % of the total emissions. The studies used to compare emission from system production used smaller components. As a result, the fuel cell and fuel tank had to be resized to meet energy demand. The fuel tank was scaled by a factor of six, whereas the fuel cell only increased by 30 % based on their original sources. This could lead to uncertainties regarding emission calculations, especially for the fuel tank. More time could have been spent researching other studies with similar tank sizes, but the benefit of consistent use of studies for the complete system was considered the best option. The emissions per kg of the scaled fuel tank was slightly higher than the fuel tanks for the biofuel case study.

The hybrid section also had a substantial part of its emission related to the production phase, mostly coming from the production of batteries. The emissions varied with battery size, as a 500 kg battery has lower emissions than the production of a 1500 kg battery.

As illustrated in Table 27the emissions related to the production phase for li-ion batteries used in EV varies from 30-494 kg CO_2-eq/kWh. The choice of 100kg CO_2-eq/kWh was estimated as a good guess, accounting for a higher environmental impact due to safety factors related to marine batteries, but also accounting for the increase in energy density over the last years.

9.4 Endurance

The following section will discuss the variations in endurance with each system. The calculations are purely based on ideal case scenarios, and even though weather greatly influences fuel consumption, it has not been accounted for. The data provided by Kongsberg showed that the stated endurance of 20 days, was dependant on weather conditions, decreasing under rough conditions. As the case study simplifies a complex scenario, some of the benefits, as well as disadvantages, might not be accounted for. A more comprehensive study with ongoing tests for each system would have been preferred, if time, money and other factors would have made it possible.

One great advantage of using biodiesel for the Sounder USV is its endurance. Both HVO and FAME would have an endurance of almost 20 days using an 800 L tank. This was mainly due to the system's high efficiency and volumetric energy density. The properties of both HVO and FAME are similar to diesel. Also, HVO has a very high cetane number, which increases the engine's combustion and has a positive effect on fuel consumption [35]. On the other hand, CBG and LBG have relatively low volumetric energy density and much shorter endurance compared to 800 L of diesel, shown in the case study in Figure 78.

As with CBG and LBG, hydrogen also provides low volumetric density, resulting 3,6 days of endurance with 800 L of fuel. Liquefaction of hydrogen almost doubles the endurance of the fuel, but is not a viable option at the moment. Still, seven days is considerably less than HVO and FAME.

A 60 % ammonia blend system was chosen because the engine already runs on diesel. Dual-fuel combustion with diesel as combustion promoter is cost-efficient and easily integrated in the Sounder USV. The blend resulted in an endurance of 12,2 days. The 80 % ammonia diesel blend resulted in a decrease in endurance, with 8,3 days, proving that higher ammonia contents leads to drastic reduction in endurance.

The endurance of the hybrid systems is mostly related to the size of the diesel tanks used in each system, as the batteries contributed to a small fraction of the endurance. Hybrid 1, 3 and 4 used 400 L diesel tanks in addition to different battery sizes, whereas hybrid 2 used 800 L diesel in addition to its battery, hence the longest endurance of the four systems. The difference between the endurance of hybrid 1 and hybrid 4 were only 0.74 days, roughly 18 hours of propulsion, whereas the difference in battery weight was 1160 kg.

In order to improve existing biofuels, multi-functional additives may be added, increasing endurance up to 2.3 % according to Circle K. Utilizing milesBIO HVO100, an improved HVO-fuel, the endurance would increase by almost half a day [80].

The type of feedstock used in production process of FAME influences the performance of the fuel. For example FAME from rapeseed has an increased resistance against cold climates. Storing FAME over longer periods of time, may result in oxidation, microbial growth and corrosion of fuel tanks, which reduces fuel quality. Hence, fuel maintenance for FAME is important to consider when storing it for fuel use.

Whether hydrogen is a well suited fuel for a smaller marine vessel like the sounder, which relies on high endurance. The answer is simple, for the current possible storage systems of pure hydrogen, is it too low of a volumetric energy density.

The current possible storage systems for pure hydrogen, provides low volumetric energy density. This may not suit smaller marine vessels with limited storage capacity, and high endurance requirements. Hence, the storage technology for pure hydrogen needs to improved before it can be commercially available for smaller vessels. If endurance was a less important factor, hydrogen could be a viable option, for a smaller vessel. Furthermore, if the marine sector would facilitate for offshore fuelling, the fast fuelling rate of hydrogen would come in handy, especially for small vessels [191].

To further improve endurance by utilizing ammonia the vessel would need to be larger. For the 60 % and 80 % ammonia blends presented in the case study, a combined tank capacity of 1300 L and 1700 L, respectively, would ensure propulsion for 20 days. How big of an impact this has on vessel size is hard to estimate, but an increase in vessel size is unavoidable.

By choosing a different system for ammonia it is unclear if more power, better fuel efficiency or lower NOx emission could be achieved. Studies show that a SI engine using gasoline as combustion promoter performed well, but failed to give a clear comparison to CI engines. The report stated earlier that using hydrogen as combustion promoter in an ICE was possible. This would of course result in a decrease in emissions, assuming both hydrogen and ammonia is produced from renewable sources. Studies suggested using the combination in an SI engine, since hydrogen has very low minimum ignition energy. This would require storage of ammonia in a metal amine, where hydrogen would be extracted from. This is far from being commercially available, and again would require a new engine, and complex storage systems. Therefore the decision was made to use the already installed ICE in the sounder USV, to minimize modifications to the current system.

Concerning performance of the chosen ammonia system, ammonias low combustion rate is more suited for lower speed engines. The diesel engine in Sounder USV operates at higher RPM, so a dual-combustion system might not be the best solution. Converting the motor to a dual-fuel system, which can always rely on diesel when higher speeds are required, could be the best solution. It would make it possible to utilize ammonia in conjunction with diesel at lower RPM, and when more work is needed, powered purely by diesel.

The challenge with electrical propulsion is the low energy density related to the ESS. Diesel fuel will have 30-50 times more usable energy than a li-ion battery, depending on the composition of the li-ion battery. Increasing the energy density in ESS would make hybrid systems more attractive, maybe even excluding the need for an ICE and relying 100 % on electric propulsion. It is plausible that the energy density will increase significantly in the next 10-20 years. An energy density of 160 Wh/kg was used in the case study, but only utilizing 70 % of this in theory as the SOC should be kept between 20 % and 90 %. The range of SOC is due to safety regulations and reasonable utilization of the battery with regards to ageing and thermal runaway. Accounting for other losses, only 63 % of the energy stored in the battery is used for propulsion.

In terms of propulsion the case study only accounts for what is possible with two different propulsion modes; electrical propulsion and mechanical propulsion. The battery is used once, without charging from onshore, generatorsets or the ICE. One advantage which is not presented in the case study, is running the ICE in its most energy efficient area, adjusting the speed to a desirable cruising speed, and utilize potential excess energy to charge the battery. Such solution might enhance savings of fuel and charge the battery, but as there will be losses related to transferring the energy from the ICE to the battery, the savings might not be as big as expected.

Another area not covered in the case study is the utilization of electric propulsion in the acceleration phase. The el-motor ramps up max torque initially, in contrast to the ICE. This is highly beneficial when accelerating, as the power is extracted quicker. One question worth considering when accounting for savings related to the acceleration-phase whether or not the Sounder USV accelerates often. The vessel operates in a s-pattern when using the sonars, which dependent on the turning radius will affect how much the vessel will need to accelerate. A tight turn will require more acceleration compared to a wider turn, as the speed going into the turn will be lower. With Kongsbergs sonar technology a tight turn might be unnecessary in terms of scanning most area, over the shortest distance. Still, acceleration is necessary and will occur several times over a longer period.

Another possible advantage not accounted for in the case study is the use of batteries in combination with ICE to take care of peak demand, using the battery as a boost. Such use would ensure that the ICE still configures in its optimum power area, saving fuel and money. This approach will also reduce the stress on the ICE as the speed is reduced, possibly reducing maintenance cost. However, accounting for such characteristics would require another, more complex approach towards the case study.

9.5 Recommendations of systems

With basis in the case study, HVO was suggested as the recommended fuel for the propulsion system, as it provides almost equal durability of the original system. HVO also emits substantially less GHG, compared to diesel, and is already comercially available with a TRL of 9. FAME provided nearly the same results, but as it performed slightly worse than HVO, as well as problems regarding storage of FAME fuel, this fuel was not recommended as a viable option.

Ammonia showed great promise throughout the case study, especially cost-wise. Based on Figure 101 it only takes the 60 % ammonia case, 48 days, to become cheaper than the diesel system. The second closest system used 4084 days to become cheaper than the original system. In comparison to the diesel system, a 60 % ammonia fuel substitute emits 30 % less GHG per day. This is significant as 40 % of the total fuel mix, is diesel. This could further be improved, if technological advancements are made, so that either a larger share of ammonia can be used, or if ammonia can be used in conjunction with HVO as a combustion promoter. The only downside to ammonia, is its TRL level. Ammonia is currently undergoing heavy research as the next zero-carbon fuel, but it is yet to become commercially available. It has however, been tested and used in ICE's, indicating applicability in the marine sector.

Hydrogen was not recommended due to high investment-costs and low volumetric energy density. Large and complex storage systems are needed to ensure the required endurance for the Sounder USV. As of now, this is not applicable in smaller vessels. In addition, the storage of hydrogen may be problematic due to safety reasons, and with smaller vessels being more vulnerable to rough weather conditions, hydrogen is more suited for larger ships.

In spite of the large investment-costs for the hydrogen system, blue hydrogen will be more economically beneficial compared to the diesel system, after 4 084 days. Further technological advancements may reduce prices for fuel cells, as well as storage tanks, reducing the price distance to the diesel system. Furthermore, hydrogen emits low amounts of GHG, with green hydrogen emitting only 6.25 % of diesels emission per day of propulsion. Even though the system emissions are almost 13.5 times larger, green hydrogen only uses 141 days to ensure negative GHG emissions compared to the diesel system.

The hybrid systems are already commercially available and a viable propulsion system. The case studies indicated that the hybrid systems were expensive, with low fuel savings compared to the diesel system. A possible solution could be to integrate more ESS, as fuel cells, or use a different fuel source for propulsion. Ammonia in combination with batteries could provide a viable option in the future, which would have decreased emissions further. This combination would however reduce the endurance of the vessel considerably. Despite a reduced endurance, customers relying on lower endurance may benefit from such system.

Conclusion

The end results from the case study are highly sensitive to estimations made throughout the report. Emissions and price estimations were the parameters with the most uncertainties, as various sources suggested different values.

HVO was suggested as the most viable option for the case study, reducing GHG emissions while maintaining a good endurance with mature technology. However, HVO is an expensive fuel, resulting in higher costs than the current diesel system. Ammonia was a cheaper alternative, providing acceptable endurance but with a current TRL below 9. Hybrid systems were expensive and provided only a marginal reduction in GHG emissions. However, some of the advantages of the hybrid system did not come across clearly in the case study. The hydrogen system had low emissions, but as it provides low endurance in combination with a low TRL, it is not a viable option at the moment.

With massive investment, the energy sector is constantly growing. New and improved technology is emerging every year, and as a result, some of the systems compared could be more viable in the near future. Especially hydrogen, ammonia, and batteries are expected to develop significantly in the marine sector. Hence, today's recommended propulsion system may not be the best solution in 10 years.

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Appendix

A Well-to-Wheel data for biofuels

Table 43: Well to Wheel analysis of biofuels from different feedstocks

Fuel type	**WTW [g CO2- eq/ MJ]**	**Reference**
FAME rapeseed	47	[63] [64]
HVO - rapeseed	40	[63] [64]
FAME - Sunflower	40	[63] [64]
HVO - Sunflower	29	[63] [64]
HVO - UCO	13	[65] [192] [64]
Biodiesel - Algae	29	[61] [64]
Biodiesel - Residual animal fat	18	[64] [62] [9]
ED95 - wheat	56.90	[9, 64, 63]
ED95 - sugarcane	33.6	[9, 64, 63]
CBG - cow manure	-37.8	[9, 64, 63]
CBG- wheat	20	[9, 64, 63]
CBG- waste	20.5	[9, 64, 63]
LBG- Logging residues	16	[9, 64, 63]

B Hydrogen

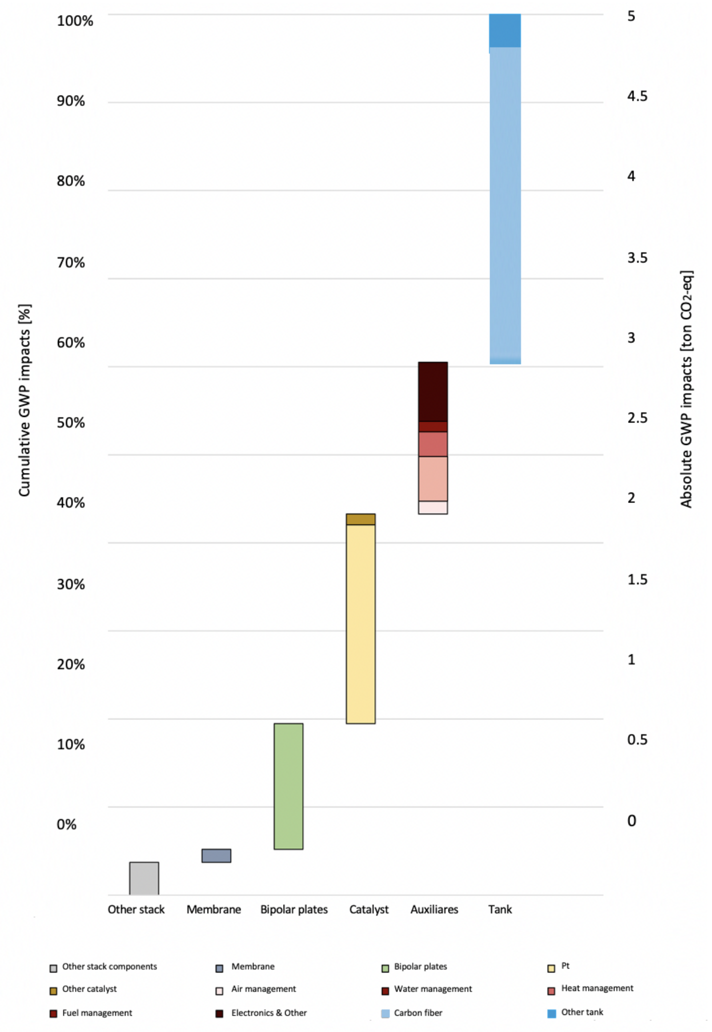

Figure 102: Cumulative system emissions for a hydrogen system [111].

C Case study

Table 44: Properties used in the case study.

Fuel	**Energy density** [MJ/kg]	**Volumetric energy density** [MJ/L]	**Emission factor** [g CO_2-eq/MJ]	**Cost** [NOK/L]	**Efficiency** [%]	**Reference**
Diesel	43	36	88.6	19.88	40	[9]
FAME	37	33	47	31.9	40	[63] [64] [12]
HVO	44	34	26.7	33.8	40	[63] [64] [12] [192]
CBG	50	9		17.5	35	[71]
LBG	50	21		20.1	35	[71]
ED95	27	21		17.8	38	[70]
Hydrogen green (70 MPa/liquefied)	120	4.5/8.5	9.1	0.92	57	[92] [112] [63]
Hydrogen blue (70 MPa)	120	4.5	37.8	0.72	57	[92] [112] [63]
Ammonia green/blue Norwegian mix	18.8	12.7	20.4/49	4.5/2.4	40	[126] [193] [131]
Ammonia green/blue Nordic mix	18.8	12.7	68.8/49	4.5/2.4	40	[126] [193] [131]
LiB Nordic/Norwegian	0.576	1.44	31/5.9	1.5 NOK/kWh	90	[179]

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