Bachelor's project

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

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Sustainability Transition of the Maritime Transport Sector

A Quantitative Feasibility Study of Lithium Ion Batteries, Hydrogen and Ammonia Produced from Offshore Wind Power

Bachelor's project in Engineering Renewable Energy
Supervisor: Odne Stokke Burheim

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Preface

The maritime transport sector is responsible for around 3% of the world's anthropogenic CO_2-emissions. A sustainability transition of this sector, could therefore be a crucial factor in reaching objectives set by The Paris Agreement. As this thesis will present, the use of hydrogen, Li-ion batteries and ammonia could be feasible alternatives as fuels in order to accomplish this transition.

This thesis is submitted as the last part of the study program *Bachelor in Engineering, Renewable Energy* at the Norwegian University of Science and Technology, NTNU. The thesis is a product of the course *Bachelor Thesis Renewable Energy* (TFNE3001) and accounts for 20 out of 30 credits in the sixth and last semester. The thesis is written in collaboration between two students, Fridtjof Falkgård Riege and Erlend Thabiso Rømyhr Sehube.

The TERRAVERA Foundation is a non-profit organization dedicated to bridging the gap between scientists, students and businesses in order to achieve a sustainable future. This thesis is intended to be a small contribution to the vast amount of data needed to achieve these objectives.

The group would like to express our gratitude towards our internal supervisor at NTNU, Odne Stokke Burheim. His guidance, weekly meetings and motivation have been a key factor for the outcome of this thesis. We also would like to thank representatives from the TERRAVERA Foundation, especially Gyda Bjercke, for a great deal of motivation and the feeling of contributing towards a sustainable future beyond our education.

Trondheim, 20.05.2021

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Abstract

Climate change and environmental degradation are an existential threat to the world. 97% of scientists agree that the temperature is rising as a result of human activities such as greenhouse gas emissions. This is a growing concern amongst politicians, business leaders and people in general. The maritime transport sector is responsible for around 3% of the world's anthropogenic CO_2 emissions. A sustainability transition of this sector, could therefore be a crucial factor in reaching objectives set by The Paris Agreement, as well as other organizations.

A quantitative analysis of hydrogen, Li-ion batteries, and ammonia produced by offshore wind power is presented in this thesis, with the aim of analyzing their feasibility as fuels in maritime applications. This study describes the technological and physical opportunities and challenges it may present, as well as the environmental footprint. With the purpose of analyzing a broad spectrum of ships in the sector, the renewable fuels are analyzed based on the attributes in a cargo ship, passenger ferry and high-speed craft. In order to give a conclusive answer to if the use of hydrogen, Li-ion and ammonia are feasible alternatives, the financial feasibility and aspects beyond this thesis's limitation are considered as essential. This thesis's findings and conclusion are therefore meant to be regarded as indicative rather than definite.

A thorough analysis of the properties of each fuel, requirements of each ship and the environmental footprint of the fuels are conducted. The information is mainly retrieved by a literature study on the different aspects. The properties of each fuel and the requirements of each ship were analyzed by implementing the values in Microsoft Excel, and thereby calculating several factors that could affect the assessment of the utilization of the given fuels. Based on the factors that are established, a proposal of which fuel could be feasible in each ship. It is concluded that the utilization of hydrogen is feasible as fuel in high-speed crafts, and could reduce the global warming potential by at least 84%. It is concluded that the utilization of Li-ion batteries is feasible as fuel in passenger ferries, and could reduce the global warming potential by at least 60%. It is also concluded that the utilization of ammonia is feasible in cargo ships, and could reduce the global warming potential by at least 69%.

Abstract in Norwegian

Klimaendringer og miljøødeleggelser er en eksistensiell trussel for kloden. 97% av forskere er enig at temperaturøkningen er et resultat av menneskers klimagassutslipp. Dette er en økende bekymring blant politikere, arbeidsgivere og mennesker i samfunnet generelt. Den maritime transportsektoren står for 3% av det menneskeskapte CO_2-utslipp. En bærekraftsomstilling i denne sektoren kan derfor være en avgjørende faktor i å nå klimamålene satt i Parisavtalen, samt andre organisasjoner.

En kvantitativ analyse om hvorvidt hydrogen, Li-ion batterier og ammoniakk produsert fra offshore vindkraft, kan være gjennomførbare alternativ som drivstoff i maritime skip. Denne studien tar for seg de teknologiske og fysiske mulighetene og utfordringene dette vil medføre, samt miljøvirkningene av dette. For å studere et bredt spekter av ulike skip, blir de fornybare drivstoffene studert opp mot egenskapene til et cargoskip, ferje og hurtigbåt. For å kunne gi et klart svar på om bruken av hydrogen, Li-ion batterier eller ammoniakk er gjennomførbare alternativ, er den økonomiske virkningen, samt andre faktorer ut over de begrensningene som er satt i denne oppgaven, vurdert som essensielle. Funnene og konklusjonen for denne oppgaven er derfor tiltenkt å være indikasjon på gjennomførbarheten og ikke et definitivt svar.

En grundig analyse av egenskapene til hvert drivstoff, begrensningene til hvert skip og miljøvirkningene av hvert drivstoff er gjennomført. Informasjonen er hovedsakelig basert på en litteraturstudie av disse variablene. Egenskapene til hvert drivstoff og begrensningene til hvert skip ble analysert ved å implementere verdiene i Microsoft Excel, og deretter beregne ulike faktorer som kan påvirke evalueringen av gjennomførbarheten til disse drivstoffene. Basert på de utregnede faktorene, er det lagt frem et forslag til hvilke drivstoff som kan være gjennomførbare i hvert skip. Det er konkludert med at hydrogen er gjennomførbart som drivstoff i hurtigbåter, med en mulig reduksjon av global oppvarmingseffekt på minst 84%. Bruken av Li-ion batterier konkluderes med å være gjennomførbart som drivstoff i ferjer, med en mulig reduksjon av global oppvarmingseffekt på minst 60%. Bruken av ammoniakk konkluderes med å være gjennomførbart som drivstoff i cargo skip, med en mulig reduksjon av global oppvarmingseffekt på minst 69%.

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List of Symbols and Abbreviations

Symbol	***Description***	***Unit***
ρ	the air density	kg/m^3
P	Electric power	W
1,4-DCB	1,4-dichlorobenzene;	-
A	The swept area of the blade.	m
ASV	Asymptotic value	-
AVV	Average value	-
CFC-11	Trichlorofluoromethane	-
CO_2	Carbon dioxide	-
Cp	Power Coefficient	-
H_2	Hydrogen	-
eq	Equivalent	-
Fe	Iron	-
GW	Giga Watt	10^9 W
inf	Infinity	-
kg eq	Kilograms equivalents	-
kWh	kilowatt-hour	-
LBV	Lower-bound value	-
LHV	Lower-heating value	-
Li-ion	Lithium-ion	-
m^2	Square metre	-
m^3	Cubic metre	-
MW	Mega Watt	10^6 W
N	Nitrogen	-
NH_3	Ammonia	-
NMVOC	Nonmethane volatile organic carbon	-
PM10	Particulate matter less than 10 µm in diameter	-
P	Phosphor	-
SO_2	Sulfur dioxide	-

List of Terms

Term	***Description***
CED	Primary energy demand
Anode	The electrode where the oxidation occurs
Cathode	The electrode where the reduction occurs
Container ship	A cargo ship that carries all of its load in truck-size intermodal containers
DOD	Depth of Discharge
Dry bulk carrier	A merchant ship designed specifically to transport unpackaged bulk cargo in its cargo holds, such as wheat, coal, ore, steel coils, and cement.
DWT	Deadweight tonnage, a measure of how much weight a ship can carry.
Electrolysis	A method of driving an otherwise non-spontaneous chemical reaction with a direct electric current (DC).
Energy density	The sum of energy contained in a given volume unit. Volumetric energy density is another term for the same thing.
Fuel cell	A part that transforms chemical potential energy (such as that derived from hydrogen) into electricity.
Global warming potential (GWP)	The heat consumed by any greenhouse gas in the atmosphere, expressed as a multiple of the amount of heat absorbed by the same mass of carbon dioxide (CO 2)
Multi-purpose vessel	A seagoing ship that is built for the carriage of a wide range of cargoes.
NMC	Lithium manganese cobalt oxide
Oxidation	A molecule, atom, or ion that is losing electrons
Reefer ship	A refrigerated container ship used to transport perishable cargo that needs temperature regulation
Roll-on/roll-off vessel	Cargo ship designed to transport wheeled cargo, on and off the ship on their own wheels.
Specific energy	The amount of energy contained in a unit of mass. Gravimetric energy density is another name for it.
Tanker	A ship designed to transport or store liquids or gases in bulk
UCTE	Union for the Co-ordination of Transmission of Electricity
Well-to-wheel/wake	An examination of the efficiencies and emissions associated with receiving fuel (well-to-tank) and using it (tank-to-wheel/wake).

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1 Introduction

Climate change and environmental degradation are an existential threat to the world. Year after year, Earth's average temperature continues to rise. 97% of all scientist agree that the temperatures are increasing due to human activities related to emissions of greenhouse gases (GHG), like carbon dioxide (CO_2) and methane (CH_4). There are several activities, industries and markets that are responsible for this development. This is a growing concern amongst politicians, business leaders and people in general. Several programs have been developed to address these issues. In 2015, the Paris Agreement was signed by 196 countries across the world. The Paris Agreement is a legally binding international treaty on climate change, with the goal to limit global warming to well below 2° Celsius as soon as possible. Transitioning to renewable energy while meeting growing energy demand is one of the necessary actions to accomplish this. This is achieved by replacing energy sources such as coal, gas and oil, with renewable energy sources such as wind, solar and hydropower.[1–3]

Along with the energy transition, one of the most important contributions would be to transition the transportation sector to renewable fuels. The International Maritime Organization (IMO) and the European Union (EU) have recognized that significant progress in the maritime sector is needed. This has created many incentives amongst politicians and business leaders across several countries and industries to explore the possibilities it presents. This introduces a number of opportunities and challenges, that requires a crucial need for research into how to best exploit the opportunities and mitigate the challenges. [3, 4]

The TERRAVERA Foundation is a non-profit organization dedicated to bridging the gap between scientists, students, and businesses in order to achieve a sustainable future. Their aim is to create a platform for knowledge-sharing regarding sustainability so that anyone could access reliable, relevant and understandable information. Thus, giving anyone, be that entrepreneurs, established companies or people in general, applicable knowledge to contribute towards sustainability in either their business or everyday decisions. This thesis is intended to be a small contribution to the vast amount of data needed to achieve these objectives. The basis for why this thesis is initiated, the problem description, as well as the thesis' structure and limitations are presented in this section. [5]

1.1 IMO and the EU Green Deal

The maritime sector is responsible for around 3% of the global of total anthropogenic CO_2 emissions. Based on two major factors, an annual global GDP (Gross domestic product) growth rate of 3%, and an annual growth rate in the amount of foreign trade in tons transported, for example 6%, projected emissions could increase by 150-250% by 2050. This projection is based on a business-as-usual scenario with an efficiency improvement of 1%. 250% growth is a worst-case scenario. It could stabilize, but it would a drastic change in the energy surge for the maritime sector. Over the last five years, there has been a significant rise in the global emphasis on greenhouse gas reductions. Nonetheless, it is a contentious topic as to how GHG emissions should be allocated across the maritime sector, and the International Maritime Organization (IMO) is under an immense pressure from the EU commission and other key players [6].

IMO was founded in 1948 during the UN convention in Genève to serve as the global maritime organization in charge of regulating international shipping. As of 2020, the IMO has 173 UN member nations, with the aim of being the world's leading maritime organization. The main goal of the IMO is to conduct and sustain a large and substantive collection of maritime regulations concerning, safety at sea, the climate, legal relationships, optimization at sea, and technical applications. One of IMOs key points of interest is the implementing of new guidelines, directives, vessel rating systems. In recent years also includes shifting the focus on reduction for the maritime GHG emissions. By implementing the use of alternative fuels, technological development and sector regulations in the form of Energy Efficiency Operational Indicator, Energy Efficiency Design Index and Ship Energy Efficiency Management Plan, IMO aims to control the global maritime industry's energy efficiency and GHG emissions [7].

The EU committee has agreed to make Europe climate-neutral by 2050 under the banner of the European Green Deal. With the purpose of climate neutrality, they intend to raise economic pressure by enacting climate legislation, carbon taxes, and renewable fuel regulations, as well as funding and expanding market-proven research and development. Aside from the EU committee and the European Green Deal, independent study organisations, national maritime bodies, maritime companies, port authorities, and classification societies are also placing significant pressure on IMO's ambitious plans. By implementing Rightship's Existing Vessel Design Index , the Environmental Ship Index, the Sea Cargo Charter, the Poseidon Principles, Rightship's Existing Vessel Design Index and the Clean Shipping Index, the aim is to increase the emphasis on sustainability for the maritime transport sector. As a result of the IMO sustainability strategy, the degree of ambition is at two completely different levels. Figure 1.1 depicts the various strategies and metrics in order for IMO to reach their sustainability goals for the maritime sector. This illustrates the complexity and magnitude of information and research needed for achieving these objectives. [8, 9].

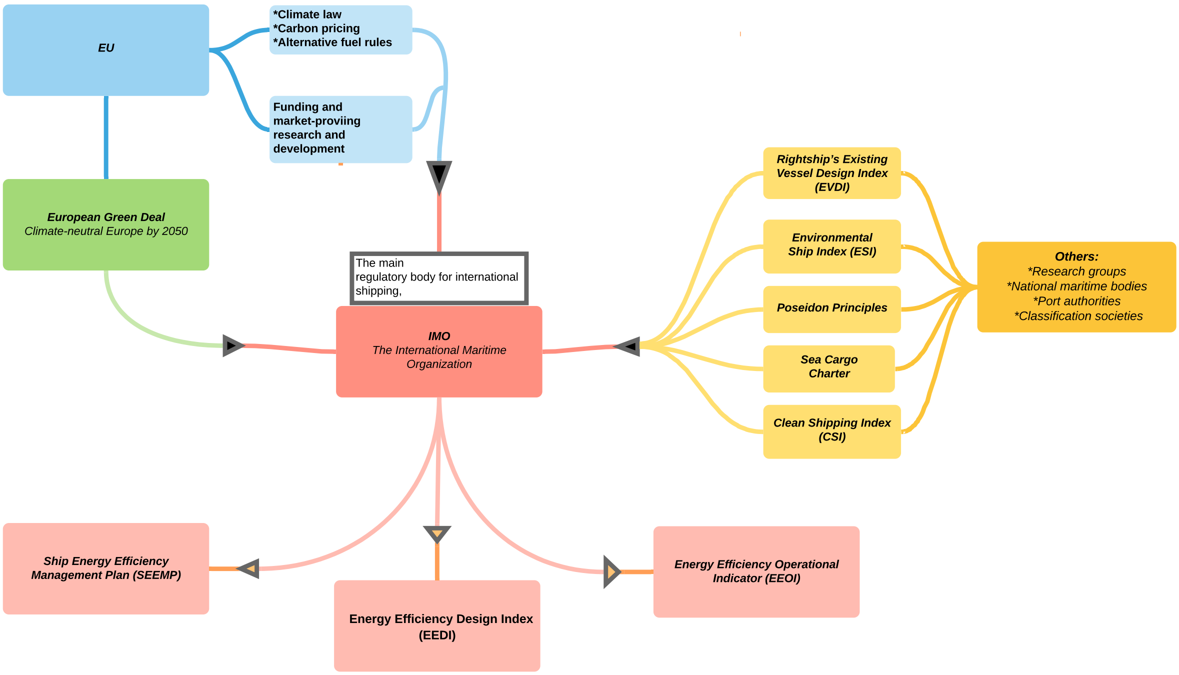

Figure 1.1: IMO sustainability strategies

1.2 Offshore Wind

The offshore wind industry has an ambition of increasing the capacity from 17 to 90 GW over the next decade. This would account for 15% of the development in the global wind power industry. In contrast to how the word "offshore" is commonly used in the marine industry, offshore wind power covers inshore water areas such as fjords, lakes, and shallow seas, as well as deeper-water areas, generating a vast potential to cover the comprehensive energy transition. There are stronger winds available offshore, resulting in a higher average energy output per installed capacity, compared to onshore wind farms. In contrast, a mediocre 3MW onshore wind turbine produces enough energy to power 1500 homes in a year. An offshore wind turbine with a capacity of 3.6 MW would provide enough energy for 3300 households per year. Due to wind energy being a clean and renewable energy source as well as being one of the most cost-effective sources of electricity, wind energy will be detrimental to the sustainability transition in several industries. [10, 11]

1.2.1 Physical Limits of Wind Energy Within the Atmosphere

The power coefficient Cp, also known as wind turbine efficiency, expresses the relationship between output energy divided by available kinetic energy from the wind, as shown in equation 1.1. Windspeed, angle of attack, rpm, and other parameters all influence the performance of a single wind turbine. When wind turbine analyses are performed, the power coefficient is often used as a defining parameter.

$$C_p = \frac{Electric\ energy\ produced}{Total\ available\ energy\ from\ wind} = \frac{P}{\frac{1}{2}\rho U^3 A} \tag{1.1}$$

Equation 1.1 is a universal equation that follows the relationship between maximum energy output divided by total kinetic energy input from the wind. P is the power, ρ is the air density, U is the wind velocity, and A is the swept area of the blade. There are additional conditional variables to the Cp-coefficient, but the three most elementary parameters are: wind turbine wake properties, number of blades, and friction- and drag forces.

Consider a futuristic scenario in which the wake properties, materials, number of blades, and friction- and drag forces of a wind turbine are optimized to the theoretical and physical limits, with the aim to convert close to 90-99 percent of the kinetical energy from the wind to mechanical energy. As a result of Albert Betz's 1919 assertion, the theoretical boundary for any wind turbine is 59.3 percent conversion rate from total wind input capacity. For example, if the goal is to use the total input energy that floats over the turbine blades, the exit windspeed from the blade must equal zero velocity speed. As a consequence, the wind will have no chance to float over or vanish through the turbine, resulting in a power coefficient Cp of zero [12].

1.2.2 Fix-base and Floating Wind Turbines

The working theory of wind power is simple: using blades, one converts wind energy to mechanical energy, and the rotational momentum converts mechanical energy to electricity through a generator. Offshore wind is usually built in two different ways. The most common type is fix-based, which assumes relatively shallow waters and allows the wind turbines' foundation to be anchored to the seabed. The second type is constructed in the deep sea. Floating wind turbines for deep sea water are in the early stages of production and implementation using today's technology and developments. The technologies are mature enough for commercial-scale growth, and innovations are driving the costs down. The key benefits and drawbacks of offshore wind are summarised in the table 1.1 [13, 14].

1.2.3 Future Expectations for Offshore Wind

From table 1.1, one of the disadvantages of offshore wind is the high cost of the technology used to transport energy from the turbines. The vast surplus expense of building colossal offshore wind turbines with high production energy is expected to be offset by less required units as well as performance improvements associated with newer, more technologically advanced turbines. Since the cost of producing a large number of foundations is a consideration in any project, reducing the number of turbines would result in less array

Table 1.1: Pros and cons for offshore wind.

Positive	Negative
Wind speed and direction are more stable at these sites, making them more competitive than onshore wind farms	Expensive technology associated with energy transferring from the turbines
Visual impact is minimal	More difficult to reach; longer wait times needed to resolve any possible issues
Potential to be designed larger than onshore wind turbines can therefore harness more energy	Higher operating and repair costs as a result of greater wear and tear from wind, seawater and waves compared to onshore wind farms

cabling runs, lowering the scale of the installation. The potential size limit for a wind turbine is not addressed by the Betz limit or the Cp equation 1.1, only the theoretical boundary for the conversion rate from total wind input capacity. With a wind-swept area of over 43 000 m^2, a rotor diameter of 236 m a hub height of 150 m, Vestas intends to install the first prototype of the new 15MW turbine in 2022 and expand production in 2024. Larger offshore wind turbines are expected in the future as material, blade, and generator technologies develop [15–17].

1.3 Current Status of the Maritime Transport Sector

On January 1, 2017, the world commercial fleet totaled 93,161 vessels with a combined gross tonnage of 1.86 billion DWT, carrying out 90% of global trade. Cargo ships are divided into seven types based on the cargo they carry. General cargo vessels, container ships, tankers, multi-purpose vessels, dry bulk carriers, reefer ships, and roll-on/roll-off vessels are the different types of vessels. The total sheer of ships is shown in table reftab:vesselshare, sorted by type, with ferries and high-speed boats belonging to the "other" category. [18, 19]

Table 1.2: The total global maritime fleet, organised by vessel class

Type:	2017
Oil tankers	28,7%
Dry bulk carriers	42,8%
General cargo ships	4,0%
Container ships	13,2%
Other	11,3%

1.4 Problem Description and Limitation

There are several opportunities to reduce the environmental impact and advance the maritime transport sector towards sustainability. This thesis will investigate the feasibility of using hydrogen, lithium-ion (Li-ion) batteries or ammonia produced by wind energy as an alternative to conventional fossil fuels. The maritime transport sector includes various ships, with diverse attributes. The attributes involves its technological and physical performance, its function both in society and to the ship owner, amongst several other things. With the purpose of analyzing a broad spectrum of ships, the given renewable fuels are analyzed based on the attributes in a cargo ship, passenger ferry and high-speed craft. The problem description is therefore established as followed:

Is the sustainability transition of the maritime transport sector feasible through the use of either hydrogen, Li-ion batteries or ammonia as fuel, when produced by offshore wind power?

Limitations

As mentioned, there are several aspects to consider when assessing the possibility of a sustainable transitioning of the maritime sector. This thesis limits the research by focusing on the technological and physical opportunities and challenges it may present, as well as the environmental footprint. The financial feasibility of this transition is not taken to account in this thesis, but would be essential when assessing the actual feasibility. When new technologies and fuels are to be implemented, the degree of retrofit and possible consequence of retrofitting are essential to analyze, both practically and economically when evaluating the feasibility. This is also not addressed in this thesis. Further assumptions and limitations are presented when relevant in the methodology and result section.

Structure

The aim of this thesis is to demonstrate the technological, physical, and environmental feasibility of a sustainability transition in the maritime transport sector. To highlight the motive for the thesis, chapter 1 introduces the problem description and initiatives that could benefit from the findings. Chapter 2 presents the technical and physical aspects of using the renewable fuels in ships. This also includes literature studies assessing the environmental footprint of these fuels. Chapter 3 presents the methodology that has been used. This describes how, and why the data acquisition has been conducted. Chapter 4 presents the results of the different aspects related to the problem description, followed by a discussion regarding the impact of these findings. Chapter 5 presents an evaluation to what should be investigated further in order to give a more conclusive assessment to the problem description. Chapter 6 presents the conclusion of this thesis, based on the results and discussion. Most of the data is obtained from literature reviews, which could lead to sources of error throughout this thesis, and the limitations could prevent a definitive conclusion of the problem description. As a result, the findings reported in this study should be regarded as indicative rather than exact.

2 Renewable Fuels

Fossil fuels have been the main input in transportation, as well as industrial production and electricity production since the industrial revolution. It has been a fundamental driver of the economic, technological and social development ever since. Due to several negative impacts regarding both on global warming, as well as human health, there has been an increasing demand for replacing fossil fuels with sustainable and renewable fuels. [20, 21]

This chapter examines three renewable fuels that could be used in the maritime transport sector. The fuels are first described from the production to the use of these fuels in ships, and the challenges or opportunities this may present. This thesis focuses mainly on the physical and technological aspect this involves, but the fundamental aspects regarding economics and prices are also covered. Lastly, a literature study of each fuel's potential environmental footprint is presented.

2.1 Hydrogen

Hydrogen is not a primary energy source like gas and coal. Hydrogen is an energy carrier that needs to be obtained from other energy sources. Therefore, the environmental and energy performance of hydrogen energy systems depend on the hydrogen donor and which energy source that is used in the conversion process. The hydrogen provides electricity and heat through fuel cell stacks and hydrogen fuel cell vehicles. [22]

2.1.1 Hydrogen Production Methods

To produce hydrogen, it must be separated from other elements in the molecules where it occurs. The two most common methods for producing hydrogen are steam reforming and electrolysis. To separate the different technologies used with either steam reforming or electrolysis, it is common to colour separate. [22, 23]

The most common production of hydrogen is grey hydrogen. Grey hydrogen comes from natural gas. Steam reforming produces the hydrogen by separating hydrogen atoms from carbon atoms in methane. High temperature steam under a specific pressure reacts with methane in the presence of a catalyst to produce hydrogen, carbon monoxide (CO) and carbon dioxide (CO_2). The production of grey hydrogen emits about 10kg of CO_2 per kg of hydrogen. [24]

Blue hydrogen also uses steam reforming as grey hydrogen, but the emissions generated from the steam reforming process are captured and stored. Using industrial carbon capture and storage (CCS), CO_2-emissions can be reduced with around 80-90%. [24]

Green hydrogen is a result of using renewable energy in water electrolysis. Water electrolysis uses electricity to decompose water into hydrogen gas and oxygen. A 100 % effective electrolyzer needs 39 kWh of electricity to generate 1 kg of hydrogen. Today's devices need up to 48 kWh/kg of energy. When using renewable energy, green hydrogen is often referred to as "clean hydrogen". This production method is the most promising methods as many companies and political groups intends to build an entire strategy to support green hydrogen. With high production of hydropower and growing production of wind energy, Norway is in a good position to start mass producing green hydrogen meeting the growing demand from different industries. [24, 25]

2.1.2 PEM Fuel Cell

PEMFC (Proton Exchange Membrane Fuel Cell) is one of many alternative technologies to produce clean electric energy. Due to its high efficiency, renewable energy source and low emissions, the fuel cell is of high interest relative to the traditional combustion engines. The technology is under a constant development stage to enhance the materials, cost aspect, structure, along with the efficiency of the fuel cell.

The anode and the cathode for a PEMFC contains highly conductive material. The electrodes is constructed with a high-surface area material impregnated with an electrocatalyst, containing Platinum. It is essential to achieve a constant flow of protons and electrons from the anode to the cathode. Platinum boost the chemical reaction where the hydrogen is separated in to protons and electrons. The proton exchange membrane (PEM) allows only protons to pass trough. A polymeric membrane is used as the material and serves as an ionic conductor.

Both hydrogen and oxygen is fed in to the fuel cell at each node. Hydrogen is oxidized at the anode and the oxygen is reduced at the cathode. Hydrogen (H_2) enters the anode there the chemical reaction separates the hydrogen into electrons (e^-) and protons (H^+) described in formula 2.1.

The electrolyte membrane separates the anode from the cathode. The purpose for this is to transfer the protons (H^+) from the anode to the cathode, at the same time electrons from the anode reaction is carried over an external circuit load. Oxygen (O_2) is fed into the cathode, receiving both the electrons (e^-) and protons (H^+). An exothermic reaction occur, Oxygen is reduced to H_2O and heat is generated, illustrated in formula 2.2 [26].

$$2H_2 \rightarrow 4H^+ + 4e^-(Anode) \tag{2.1}$$

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O(Cathode) \tag{2.2}$$

The entire process for the PEMFC is illustrated in figure 2.1. Unused H_2 from the chemical reaction is recirculated, purposely to be used again.

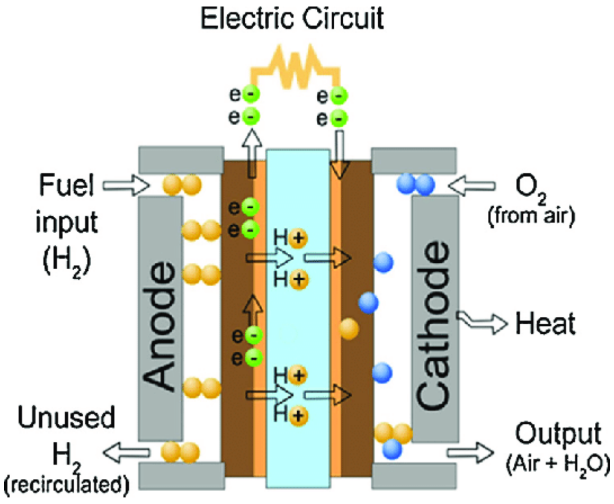

Figure 2.1: Illustration of PEMFC [27]

2.1.3 Hydrogen to Propulsion

The PEMFC have a great beneficial advantage when it comes to the transport sector, energy demanding industry, maritime sector and within energy storage. A conventional combustion power plant generate electricity at efficiency of around 33-35%, where as a fuel-cell based system can generate energy at efficiencies up to 60%. The fuel-cell system have the superiority to use more than 60% of the fuel energy, corresponding to a 50% reduction in consumption compared to a petrol based combustion engine. The electricity generated from the PEMFC is used to power an electric engine [28].

2.1.4 Hydrogen Storage

The advancement of hydrogen fuel cell technologies in application is highly dependent on the development of hydrogen storage. Hydrogen has the highest specific energy content of any fuel, but has a very low volumetric energy. The technical challenge in the transportation sectors revolves around storage of hydrogen within the constraints of weight, volume, and safety of the vehicle. There are two main storage methods of hydrogen. Either with high-pressure tanks, with hydrogen in gas state, or storing hydrogen as a liquid state. Storage of gaseous hydrogen requires a tank pressurized up to 700bar. Storage of liquid hydrogen requires cryogenic temperatures, due to the boiling point at 1atm being around 20K. [29, 30]

There are different requirements for stationary and portable applications. Stationary applications are less restrictive than in portable applications. The restrictions usually involves weight and volume requirements. A fuel cell vehicle needs enough hydrogen to provide the expected driving range, as well as the ability to refuel the vehicle easily and rapidly. In comparison to conventional petroleum fueled vehicles, the weight and volume of hydrogen storage systems are currently too large to satisfy the range requirements. The United States has established The Fuel Cell Technologies Office (FCTO) to conduct research and development to advance hydrogen storage systems and meet the targets set by the U.S. Department of Energy (DOE). FCTO is pursuing two strategic objectives, aiming for both near-term and long-term solutions. The near-term objectives focus on compressed gas storage, using advanced systems capable of reaching 700bar. The long-term objectives focus on cold or cryogenic-compressed hydrogen storage. Cold or cryogenic-compressed hydrogen storage has the benefit of being able to store the same amount of hydrogen in smaller volumes or at lower pressures. Higher hydrogen densities can be achieved by using lower temperatures, as shown in Figure 2.2. [29–31]

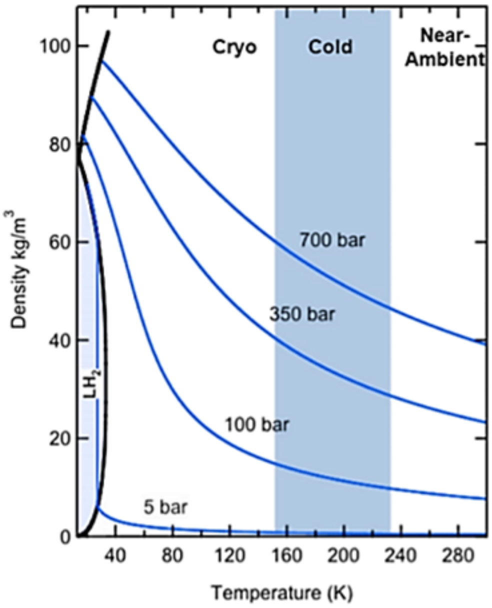

Figure 2.2: The correlation between cold or cryogenic-compressed hydrogen storage and hydrogen densities. [31]

The ability to store the same amount of hydrogen in smaller volumes, as depicted in figure 2.2, would improve the challenges regarding hydrogen storage systems. It is necessary to develop insulated systems that minimize heat leakage in order to establish these systems. This allows hydrogen to be stored for longer periods of time without having to be vented. [30, 31]

2.2 Battery

An electric battery is a component that has a stored energy in chemical form, and that can emit it in electrical form. In electrochemistry, a battery is any kind of device that converts chemical energy directly into electric energy. While the term battery technically refers to an assembly of two or more galvanic cells capable of converting electricity, it is generally applied to a single cell of this kind. The common denominator for one or more cells, they are made up by three universal components: an anode, a cathode and an electrolyte; a chemical substance which react chemically with the anode and cathode.

Nonetheless, the operable battery is not a recent invention; Alessandro Volta, an Italian physicist, invented the first basic battery, which was labelled the "voltaic pile" by about 1800. Volta continued the work of his compatriot Luigi Galvani by conducting a series of tests on electrochemical phenomena in the 1790s. Volta mixed alternating silver disks, a heavy oxidation agent, with a strong reducing agent metal in the case of zinc. Putting together the "pile" in the manner of a sandwich, an electrolyser, a wet cloth soaked in brine or sodium hydroxide, was put in between the layers, thus the term "voltaic pile". Experiments related to the discovery aided Michael Faraday in discovering the quantitative laws of electrochemistry (about 1834). To this day, Faraday's laws have established the bias of modern battery technology, providing the exact relationship between the sum of electrode materials and the desired electric power. [32, 33]

2.2.1 Principles of Operation

The discovery of Alessandro Volta illustrates the working principles of operation for every electrochemical cell. The anode is normally a metal that oxidizes (the need to release electrons) at a reduction potential that is 0.5V to 4.0V higher than the cathode. The anode material for the voltaic pile was silver (Ag), and the cathode material was zinc (Zn). The cathode, in contrast to the anode, comprises metals or sulphide with a heavy reducing agent, reduced in oxidation by accepting electrons and ions into its structure. The primary purpose of the electrolyte, which consists of a solvent and one or more chemicals that dissociate into ions in the solvent, is to maintain electrical neutrality in each part of the cell. By establishing a conductive connection through an external circuit (electric motor), the electrons will stream from the strong oxidising anode to the reducing cathode. With the help from ions from the electrolyte, the continues current running from the anode to the cathode will be balanced out from the ions [33].

2.2.2 Li-ion Battery

One of the most used battery technology today is a Li-ion battery. They are widely used in laptops, mobile phones and other consumer electronics, as well as in electric vehicles with growing popularity. The lithium-ion battery is an advanced technology that relies on lithium ions as a critical component of its electrochemistry. Lithium atoms in the anode are ionized and separated from their electrons during the discharge cycle. The lithium ions travel from the anode via the electrolyte to the cathode, where they recombine with their electrons and become electrically neutral. Lithium is the third smallest element behind hydrogen and helium. The small size enables the lithium ions to move through a micropermeable separator between the anode and cathode. One of the major advantages of this is that Li-ion batteries are capable of having a high voltage and charge storage per unit mass and unit volume, compared to other battery technologies. There are many different combinations of materials used for the electrodes. The most common combination in vehicles is lithium manganese oxide as the cathode, and graphite as the anode. [34, 35]

Li-ion batteries have many advantages compared to other rechargeable battery technologies. With a charge efficiency of 99 percent and a low discharge loss, the energy transfer from the Li-ion battery to the electric motor is small, leading to an extremely high efficiency. Furthermore, the energy density is the highest of any battery technology today with a range of 100-265 Wh/kg and 250-670 Wh/L. It also can deliver up to 3.6 volts, which is 3 times higher than technologies such as Nickel-Metal Hybride (Ni-MH) or Nickel-Cadmium (Ni-Cd) batteries. As a result, Li-ion batteries can deliver large amounts of current for high-power applications, which is important in the use of vehicles. Comparatively, Li-ion batteries also has the advantage of being a low maintenance battery, and do not require to have scheduled cycling to prolong the battery's life. [34, 36]

The most serious disadvantage of a Li-ion battery is with regards to safety, which is compromised by overheating and potential damage at high voltages. In order to reduce the possibility of overheating, the batteries requires many safety mechanisms to cool the system. In order to limit the peak voltage of each cell, a protection circuit is required. This could limit the performance and increase the weight of the battery pack. Another factor that is a concern with Li-ion batteries is its capacity deterioration due to aging. The loss of capacity could affect the battery whether or not the battery is in use. [34–37]

2.3 Ammonia

At standard pressure and temperature (STP), ammonia is a colourless gas with a strong pungent odour. The chemical compound was mentioned in scripts as far ago as the 13th century by alchemists, and today ammonia is a well-known chemical substance with a vast usage spectre, especially in fertilizers. In nature, ammonia is frequently formed in limited quantities, from nitrogenous animal and vegetable matter. It occurs naturally throughout the entire environment, in the soil, water, air, plants, animals and humans. [38].

2.3.1 Understanding Ammonia

With a boiling point of 239.75 K, pure ammonia at room temperature will vaporize. In a concentrated form, the substance is both hazardous and caustic with strict reporting requirements by facilities that produce, store, or use it in significant quantities. Due to its chemical properties, it can easily be liquefied with a moderate pressure of 7,402 Atm at

293.15 K, compared to liquid hydrogen at 20.35 K. One of the overall benefits is the fact that ammonia is a widely used substance in modern society. Given the broad usage in the modern industry, especially in fertilizers, the infrastructure for production, storage and transportation has been under constant development for decades. Technology within the transportation, production and storage sector has made it safe and efficient for shipping worldwide[39].

Ammonia, is made up of 1 nitrogen atom and 3 hydrogen atoms. Furthermore, in terms of boiling temperature and condensation pressure, ammonia's thermal properties are similar to those of propane, making it appealing as a hydrogen and energy carrier. There is no carbon attached to the molecule, making ammonia carbon-free, producing no CO_2 during combustion as compared to traditional fossil fuels. But this does not necessarily mean that NH_3 is carbon-free. Production of ammonia is the detrimental factor in its carbon print[40].

2.3.2 Production

The Haber-Bosch process, which converts nitrogen and hydrogen to ammonia, remains a key element for industrial production. When developed, the method transformed both the efficiency in which ammonia was produced and had an enormous impact on global agriculture, because of the sudden availability of fertilizers. To this day, some consider this process to be one of the most significant scientific discoveries of all time. The Haber-Bosch process has not changed abundantly since the fundamental discovery in 1908. Nonetheless, the source of pure hydrogen and nitrogen has been constantly evolving over the decades, despite the fact that the method is theoretically the same. By combining nitrogen (N_2) directly from the air with hydrogen gas (H_2), the Haber-Bosch process makes the following reaction occur:

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g) \tag{2.3}$$

According to equation 2.3, 177 kg of H_2 and 823 kg of N_2 are theoretically necessary to produce 1 ton of ammonia.

Since the reaction occurs in a volumetric apparatus and generates heat, high pressure at a low temperature can increase the dividend. The reaction temperature is usually about 350-600 dg with a pressure of about 150-300 atm, resulting in an overall energy-demanding process when air separation and hydrogen demand are considered.

The commercial production of ammonia today is nothing but green. Industrial ammonia production emits the most CO_2 of any chemical-making reaction. In 2014, the world's total production was 176 million metric tons, contributing to 1% of the global CO_2 emission. Hydrogen continues to be the most important driver of the massive energy demand for manufacturing. There are three ways to generate hydrogen, one of which emits more radiation than the others. Coal reforming, natural gas reforming, and water electrolysis are all options. The most popular, but also the most polluting, method is to reform coal or natural gas. There isn't a more subtle approach than reforming natural gas. When fossil fuels are reformed, they return the same volume of CO_2 to the atmosphere.

One might contend that electrolysis of water is carbon neutral, although this is highly dependent on the energy supply[41, 42].

2.3.3 Round-Trip Efficiency

In the future implementation of ammonia for the transportation sector, round-trip efficiency is a key aspect of the future energy demand. Taking into consideration the total energy required from the primary renewable energy source for ammonia -synthesis and its delivery on demand. A common representation of round-trip efficiency is the total energy demand required from a wind turbine to meet the needs for the compulsory demand of propulsion, moving a ship from A to B. Currently, with today's technology, the round-trip efficiency of liquid ammonia is estimated between 11-19%

Technological advances in electrolysis and hydrogen fuel cells will affect the feasibility of ammonia as renewable energy storage mediums, energy source and vectors, while developments in ammonia synthesis and decomposition, combustion, and/or fuel cells will make ammonia use more competitive. One will experience a great improvement in the round-trip efficiency in the upcoming years. [43]

2.3.4 Ammonia to Propulsion

The use of ammonia as a fuel for internal combustion engines (ICE) and turbines will be the subject of this study. In order to utilize ammonia in engines that are used for combusting fossil fuels such as marine diesel, it requires some slight modifications. The modification includes the addition of ammonia injectors and a control system for this injection. This is needed to avoid spills and is also essential if the engine is to operate on dual fuel applications. The corrosive parts in the engine also need to be replaced with stainless steel to avoid corrosion. Since ammonia (NH_3) contains 17.8 % hydrogen by mass, its use in PEMFC is a possibility, but will not be taken into account due to a realistic scenario.

In terms of condensation pressure and boiling temperature, ammonia (NH_3) has similar thermal properties to propane (C_3H_8), as shown in table 2.1. Another important aspect is that ammonia can be generated using green renewable energy, has an incredibly long storage life, can be stored at low pressure, is a natural refrigerant, and no CO_2 is produced during combustion. But ammonia presents two major problems as a combustible fuel. [44]

Table 2.1: Fundemental combustion characteristics and thermal properties of hydrocarbon and ammonia fuels. [38]

Fuel	NH_3	H_2	CH_4	C_3H_8
Boiling temperature (1atm)[°C]	-33.4	-253	-161	-42.1
Condensation pressure 25°C [atm]	9.9	-	-	9.4
LHV [Mj/kg]	18.6	120	50	46.4
Flammability limit (equivalalence ratio)	0.63-1.40	0.1-7.1	0.5-1.7	0.51-2.50
Abiatic flame temperature [°C]	1800	2110	1950	2000
Max laminar burning velocity [m/s]	0.07	2.91	0.37	0.43
Min auto ignition temperature [°C]	650	520	630	450

To begin, as shown in table 2.1, the LHV, flame temperature, and maximum laminar burning velocity are all quite low when compared to conventional fuels. The maximum laminar burning velocity is about one fifth of methane (CH3), and a narrower combustible range is exhibited. The struggle to maintain a constant flame during turbine combustion or combustion at low RPM in ICE is a direct conserve of this problem.In order to overcome ammonia's resistance to combustion, stronger igniters, a compacted combustion chamber, and longer spark plugs can be used in ICE to allow ammonia combustion, as well as the use of a swirl burner to blend the gases inside the turbine. Secondly, when ammonia (NH_3) ignites, the nitrogen (N) can and will react with the oxygen(O), producing NOx pollution during combustion. To further reduce NOX emissions, a new combustion method known as "rich-lean two-stage combustion" was created. [38, 45, 46]

2.4 The Future Ship and Retrofit

As the world moves toward a more sustainable and renewable society, green political incentives such as CO_2 pricing and quotas would have a significant effect on the maritime industry, both economically and reputation. This will put every investor in a quandary on whether to buy new or ships suited for retrofitting. The term retrofitting is the process of adding new hardware or functionality to existing structures. In the case of ships, the implementation of new technology, propulsion systems, efficiency optimisation and renewable fuels. With the goal of investigating how much energy demand, and thus CO_2-emissions, can be reduced using retrofittable and validated technical solutions. [47]

2.5 Life Cycle Assessment

When analyzing different technologies and their impact towards a sustainable future it is important to know its environmental impact. To get a full assessment of its environmental impact, the product or service should be assessed back to the raw materials. This type of analysis is called a Life Cycle Assessment (LCA). As a result, when studying the environmental footprint of various technologies, this thesis focuses on different LCAs. [48]

LCA is science-based and a comparative analysis and assessment of the environmental impacts of products or services. All the steps in the life cycle of a product are included in the assessment. This covers the extraction of raw materials from the environment, the production of materials and the final product, the transportation needed across these steps and their impact when in use and in waste removal and/or recycling. LCA focuses on the physical life cycle of the product, thus differs from the marketing life cycle which focuses on the introduction of the product to market, producing and selling of the product until it is taken out of the market. In 1993 the basic guidelines for LCA were structured. The structure for LCA includes four components which is listed below, and depicted in figure 2.3:

1. Goal definition and scoping
2. Inventory analysis
3. Impact assessment
4. Improvement assessment (Interpretation)

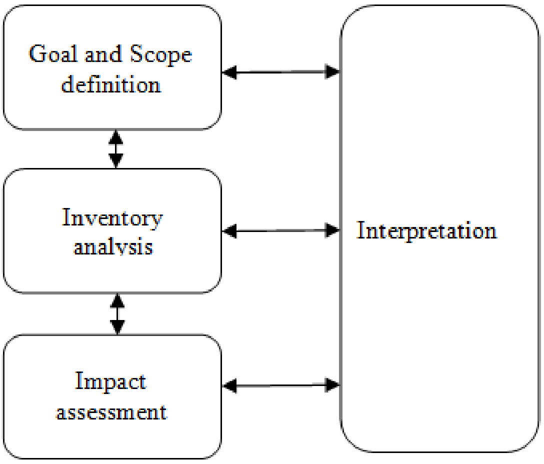

Figure 2.3: Structure of LCAs. [49]

The goal-definition component defines the reason for performing a study, its goal and the system to be analyzed. It also sets boundaries to the system, such as technical and geographic boundaries. The inventory analysis is the most scientific component of LCA. It analyzes all activities related to materials and energy acquisition, manufacturing, use and waste management. Every part is analyzed concerning the raw material extraction, intermediate products, the product and how waste removal or recycling effects the results. The result of this stage of the analysis is an inventory table, which lists all inputs and outputs per functional unit. For example, energy values will be converted to the cumulative energy demand (CED). CED is an aggregation of the inventory, but it can also be included in the impact assessment to augment the results of the specific impact categories. The impact assessment is important to give sufficient comparative assessments of product systems and a better understanding of systems investigated. The impact categories can be grouped into input and output-related categories. The input related categories focus on resource depletions of factors such as abiotic and biotic resources and land use. The output related categories focus on factors such as ecological and human health. This can be assessed through pollution of greenhouse gases, human toxicological impacts, radiation and so forth. The structure of the impact assessment is divided into four steps which is listed below. [48–50]

1. Classification
2. Characterization
3. Normalization
4. Valuation

Classification is the process when the input and output parameters of the inventory table to the impact categories. For example, factors such as carbon dioxide, methane and nitrogen oxides can be classified to "global warming". The characterization step converts the data to indicate the contribution of the product system per functional unit to the category being assessed. The amount of CO_2 equivalents is calculated when analyzing the case of global warming. To allow comparisons of the global warming impacts of different gases, an index called "Global Warming Potential" (GWP) was developed. GWP is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time. Carbon dioxide is the reference point for this index. GWP is 1 for CO_2, and the higher this number is, the more that given gas will warm the earth compared to CO_2. The GWP can also be presented as a measure of the amount of kg CO_2 per unit mass or distance. [48, 49, 51]

2.6 The Environmental Footprint of Hydrogen

There are several ways to produce hydrogen. The most common method is natural gas steam methane reforming. Electrolytic hydrogen based on electricity from renewable resources could contribute the global need for a sustainable energy supply. This thesis bases its assessment of hydrogen on Ramchandra Bhandari, Clemens A. Trudewind and

Petra Zapp's paper from 2014 on the LCA of hydrogen production via electrolysis. Because of differences in system boundary assumptions, system sizes, environmental impact assessment methods and other parameters it is reasonable not to make direct comparisons of results from different LCA studies. That paper reviewed and collected data from twenty-one studies that address the LCA of hydrogen production technologies. The biggest contributor to global warming and other environmental impacts is in the production phase of hydrogen. This thesis will focus on the results from the assessment based on electricity from wind energy. [52, 53]

2.6.1 Assumptions from the Literature Study

There are different electrolyzers that can be used when producing hydrogen from electrolysis. The most extended technology worldwide is alkaline water electrolysis. The paper bases the electrolyzer performance regarding the specifications of an alkaline water electrolyzer. This is a mature technology which are both reliable and safe. Due to advancements in this technology, advanced alkaline electrolyzers with working temperatures up to 150 DEGREES C are developed, which would make the technology suitable for large scale hydrogen production. [52, 54]

The papers assumption when analyzing the technical aspect of hydrogen production from electrolysis is based on alkaline electrolyzers. Factors such as manufacturing, installation and operation of wind farms has been considered within the system boundary. This is because the majority of environmental impacts take place during this phase in electrolytic technologies. The impact of hydrogen production plant manufacturing and installation, in addition to the plant operation has been considered. When analyzing wind based electrolysis, the assumption for the system is three 50kW wind turbines with an electrolyzer having hydrogen production capacity of 30Nm^3/h. This electrolyzer has the electricity to hydrogen efficiency of 85%. Iron is primarily used in manufacturing of the wind turbines and hydrogen storage and accounts for 37.4% of the resources used. Limestone is used for the wind turbines' concrete foundations and accounts for 35.5% of the major resources. Coal is consumed to produce iron, steel and concrete, and accounts for 20.8% of the resources used. The remaining 6.3% of the resources is from oil and natural gas with 4.7% and 1.5% respectively, both which is primarily used in wind turbines manufacturing. Water is consumed both during the electrolyzer process and in upstream processes. The total consumption rate for water is 26.7 L/kg H_2. 45% of the water is used in the electrolyzer, 38% is used in the wind turbine manufacturing and about 17% is used manufacturing of hydrogen storage vessels. Table 2.2 summarizes the resource consumption values in the process. [52]

Table 2.2: Consumption of aggregated energy in a wind electrolysis system. *0.3 is the original vale, but is rounded up to 1. [52]

Resource	Total [g/kgH_2]	Wind turbines [%]	Electrolysis [%]	Storage [%]
Coal	214.7	68	5	27
Iron (Fe)	212.2	64	6	30
Iron scrap	174.2	53	8	39
Limestone	366.6	96	1*	3
Natural gas	16.2	72	15	13
Oil	48.3	76	13	11

In this system, the average energy consumption was 25.34kWh/kg H_2. Manufacturing of wind turbines stood for 72.6% of the energy consumption. Storage and electrolysis stood for 31.6% and 4.8% respectively. The majority of CO_2 came from manufacturing an installation of wind turbines. Table 2.3 gives an overview of air emission values for the system.

Table 2.3: Aggregated air emissions from wind based electrolysis.

Air emission	Total [g/kgH_2]	Wind turbines [%]	Electrolysis [%]	Storage [%]
Carbon dioxide	950	78	4	18
Carbon monoxide	0.9	80	4	16
Methane	0.3	92	3	5
Nitrogen oxides	4.7	46	47	7
Nitrous oxides	0.05	67	6	27
Non-methane hydrocarbons	4.4	63	7	30
Particulates	28.7	94	1	5
Sulfur dioxide	6.1	62	26	12

One of the most important factors regarding all emission categories is the electricity supply. Which fuel is used to generate grid electricity is thus very important in environmental analysis. In figure 2.4 shows the air emission values while operating the same electrolyzer system using two power supply systems. It compares the emissions using the UCTE grid mix which consists of 17% hydro and renewables, 29% nuclear and the rest fossil fuel, and an Icelandic electricity grid mix which consists of 82% hydro and 18% geothermal. The Icelandic grid mix (IS mix) can be compared to a Norwegian grid mix which consists of 88% hydro and 10% wind power. Using Icelandic grid mix the paper calculates that emissions can be reduced by more than 90% if the required electricity is supplied by renewable resources instead of fossil fuel. [23, 52, 55]

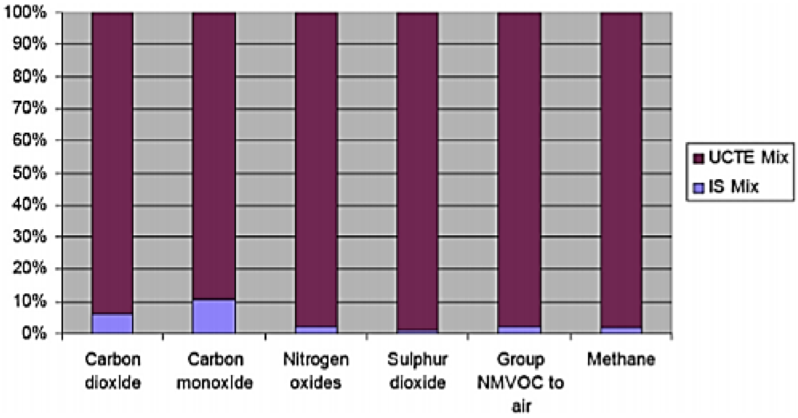

Figure 2.4: Comparison of emission based on UCTE grid mix and Icelandic grid mix. [52]

2.6.2 Results from the Literature Study

The global warming potential varies based on which electricity supply that is used. This paper has summarized every GWP from the 21 studies that they have analyzed as shown in figure 2.5. The time period of which the GWP is analyzed is 100 years. There are some varying values that is presented by an extended line. [52]

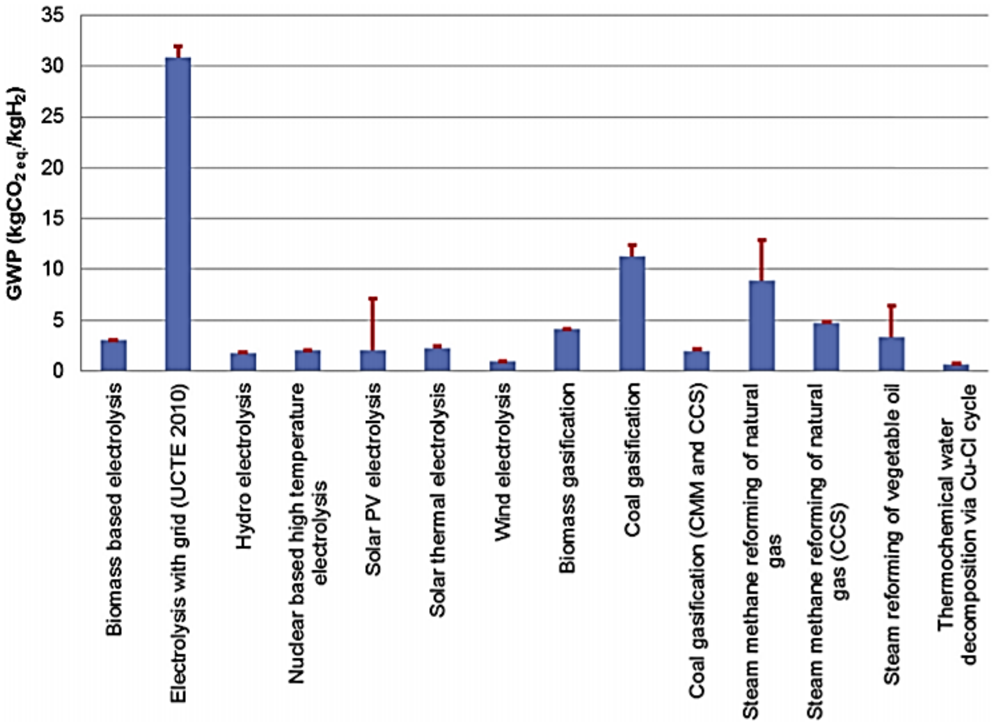

Figure 2.5: Summarized GWP values based on both electrolytic and non-electrolytic technologies. [52]

Electrolysis based on wind power ranks as the best technology, followed by hydropower. All the 21 studies that have been summarized presented the same value for wind-based electrolysis. The value is 0.97kg CO_2 eq / kg H_2. It is assumed that hydropower performs worse than wind energy because of massive civil works during the construction phase. The figure also presents the difference in using renewable energy as the electricity supply compared to UCTE grid mix and steam methane reforming technologies. Steam methane reforming is the most used technology for producing hydrogen. Values for steam methane reforming of natural gas varies from 8.9 to 12.9 kg CO_2 eq / kg H_2. Coal gasification performs the worst of conventional technologies. The GWP of coal gasification can be reduced to level renewable technologies when applying CCS and Coal Mine Methane (CMM) measures during coal mining and coal gasification. UCTE grid mix have a GWP which is over 30 times higher than wind-based electrolysis. [52, 56, 57]

Figure 2.6 shows that the environmental impact from wind-based electrolysis is relatively small, but that the wind turbine itself is the major contributor. [52]

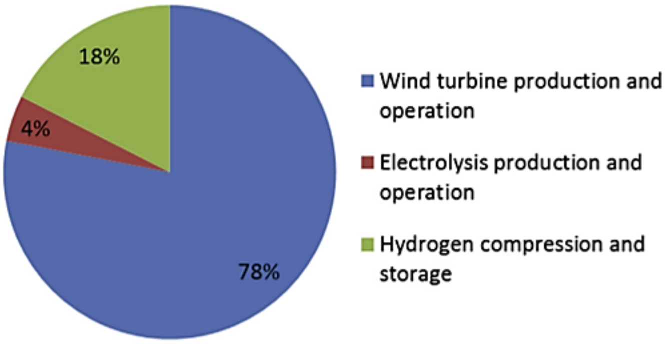

Figure 2.6: Share of GWP based on wind power. [52]

The second most analyzed impact category is acidification potential (AP). Which in this case focuses on the amount of sulfur dioxide is produced per unit mass of hydrogen. Wind based electrolytic method ranks as the second-best technology, behind thermochemical water decomposition. The results are shown in figure 2.7. [52]

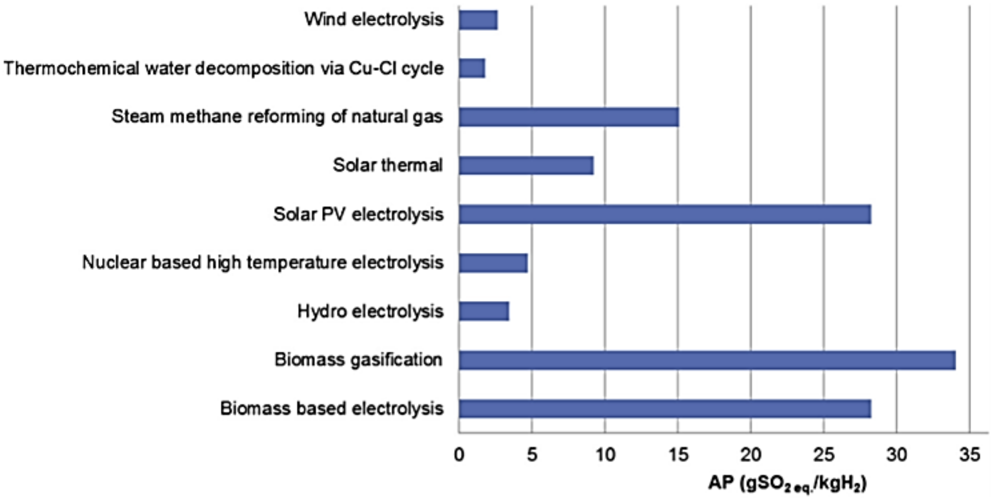

Figure 2.7: Summarized AP values based on both electrolytic and non-electrolytic technologies. [52]

When analyzing the environmental impacts on the use of hydrogen, it is important to also look at the impacts during the use and disposal phase. in 2017 Sara Evangelisti, Carla Tagliaferri, Dan J. L. Brett and Paola Lettieri wrote a study of a LCA of a polymer electrolyte membrane fuel cell system for passenger vehicles. They compared the use of fuel cell vehicles (FCV) with battery electric vehicles (BEV) and more conventional internal combustion engine vehicles (ICEV). The global warming potential is given per unit distance to demonstrate much CO_2 that can be released in use. The results are shown in figure 2.8.[53]

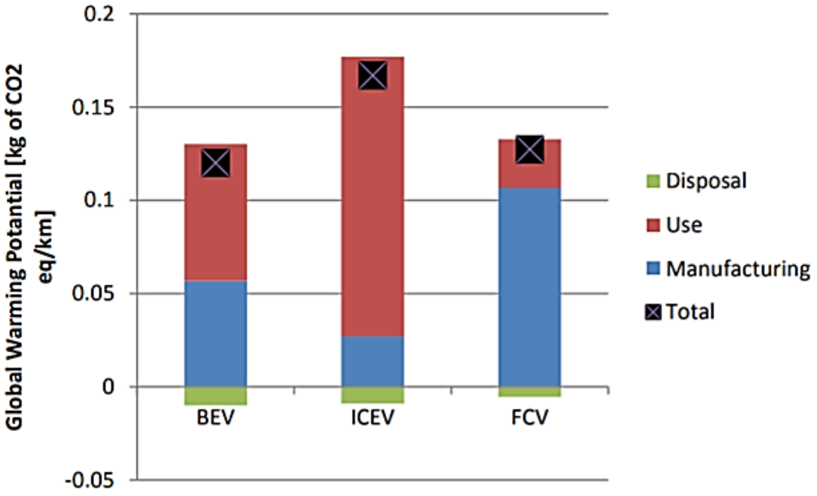

Figure 2.8: Share of GWP throughout different phases of hydrogen. [53]

The GWP highlights the difference in the different parts of the vehicle's life cycle. It is assumed a hydrogen consumption of 0.85kg/100km. In this situation it is assumed that the manufacturing process used a combination of technologies, such as steam reforming, electrolysis, and steam cracking. The PEM fuel cell used for this analysis has a specific power of 0.6kW/kg. The results show that the GWP is approximately 0.025kg CO_2 eq/km in use, and 0.11kg CO_2 eq/km in the manufacturing phase. [53]

2.7 The Environmental Footprint of Lithium-ion Battery

Electric vehicles do not have any tailpipe emissions, but the production of the batteries impact the environment. A life cycle assessment should therefore be applied when analyzing the environmental impact. This thesis bases its assumption on lithium-ion batteries from Linda Ager-Wick Ellingsen, Guillaume Majeau-Bettez, Bhawna Singh, Akhilesh Kumar Srivastava, Lars Ole Valøen, and Anders Hammer Strømman's study from 2013. This study was carried out as a process-based life cycle assessment to provide a transparent inventory for a lithium-ion nickel-cobalt-manganese traction battery. It bases its study on primary data and aimed to report its cradle-to-gate impacts. [37]

2.7.1 Assumptions from the Literature Study

Lithium-ion (Li-ion) batteries is the preferred option of traction batteries due to advances in battery technology. There are several types of Li-ion batteries using different compositions of cathode materials. This study's findings are based on a LCA of a lithium manganese cobalt oxide (NMC) traction battery due to its high specific energy, which makes them applicable in electric vehicles. The battery cell accounts for 60% of the total weight of a battery vehicle pack, which weighs 253 kg. The energy capacity is 26.6 kWh and has an efficiency around 95%. The life cycle of a battery is often referred to the number of cycles the battery can perform until its nominal capacity falls below 80% of its initial rated capacity. The battery is expected to reach a nominal cycle life 1000 cycles with 100% depth of discharge (DOD), but it is expanded to 5000 cycles at 50% DOD. [37, 58]

The assembly of the battery are grouped into four components. It consists of the battery cells, packaging, battery management and cooling. The inventory included in these components is shown in figure 2.9. [37]

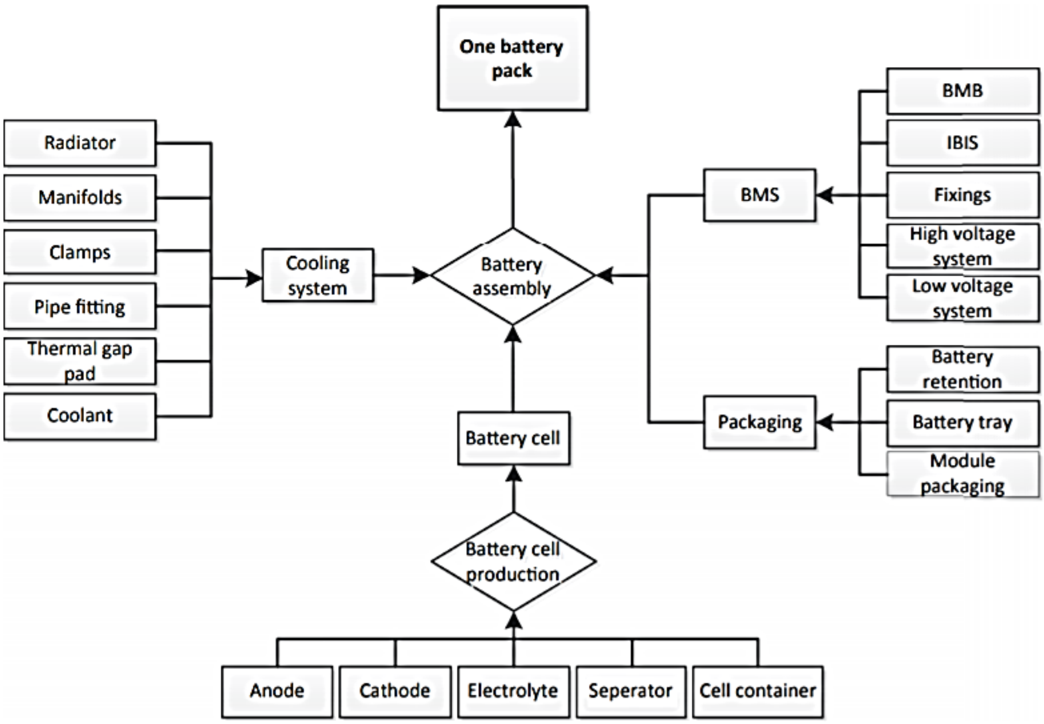

Figure 2.9: Main components in the battery cell assembly including inventory. [37]

To manufacture the battery cell there are several processes that is required. The energy requirements includes coating of electrode pastes to metallic foils used as current collectors, application of solvent to slurrify mixtures, baking of coated foils, slitting to size, welding of current collectors to tabs, filling of electrolyte and initial charging of the finished cell. Most of the energy consumption, however, derives from the service of various dry rooms that are critical to the quality of the battery cells. The data for energy consumption is based information on manufacturer over an 18-month period. Over time, there is a substantial difference in energy usage in relation to production output. Three values for electricity use are provided in this study. Lower-bound value (LBV), asymptotic value (ASV) and the average value (AVV). The LBV is the most energy-efficient month at 586 MJ per kWh battery cell capacity, the ASV is set at 960 MJ/kWh and the AVV is set at 2318MJ/kWh. The actual assembly of the battery requires little energy due to it usually being a manual process performed by laborers. The only energy requirement is in the welding process. This amounts to 0.014MJ/kWh of the battery capacity. [37, 59]

2.7.2 Results from the Literature Study

The study categories the environmental effects associated with the production of the battery in 13 groups. The energy requirements of battery cell production have the most significant impact on the performance. Separating the findings by LBV, ASV, and AVV values reveals the differences. The 13 impact groups consists of: Global warming potential (GWP), fossil depletion potential (FDP), ozone depletion potential (ODP), photo oxidation formation potential (POFP), particulate matter formation potential (PMFP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), freshwater toxicity potential (FETP), marine toxicity potential (METP), terrestrial eutrophication potential (TETP), human toxicity potential (HTP), and metal depletion potential (MDP). The results are shown in table 2.4. [37]

Table 2.4: Environmental impact dependent on lower, asymptotic and average value. [37]

		Functional unit One battery pack			**Mass [kg^{-1}]**			**Cycle capacity [kWh^{-1}]**		
Impact	**Units**	**LBV**	**ASV**	**AVV**	**LBV**	**ASV**	**AVV**	**LBV**	**ASV**	**AVV**
$\mathbf{GWP}_{100}$	**kg $\mathbf{CO}_{2-eq}$**	4580	6390	12960	18	25	51	172	240	487
FDP	**kg oil-eq**	1320	1820	3630	5.2	7.2	14	49.5	68.3	136.6
$\mathbf{ODP}_{inf}$	**kg CFC-11-eq**	$2.8 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$	$6.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$2.6 \cdot 10^{-6}$	$1.1 \cdot 10^{-5}$	$1.4 \cdot 10^{-5}$	$2.4 \cdot 10^{-5}$
POFP	**kg NMVOC**	18	22	38	$7.2 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$	$1.5 \cdot 10^{-1}$	$6.8 \cdot 10^{-1}$	$8.4 \cdot 10^{-1}$	1.4
PMFP	**kg PM10-eq**	16	18	26	$6.1 \cdot 10^{-2}$	$7 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$	$5.8 \cdot 10^{-1}$	$6.7 \cdot 10^{-1}$	$9.7 \cdot 10^{-1}$
$\mathbf{TAP}_{100}$	**kg $\mathbf{SO}_{2-eq}$**	51	59	85	$2.0 \cdot 10^{-1}$	$2.3 \cdot 10^{-1}$	$3.4 \cdot 10^{-1}$	1.9	2.2	3.2
FEP	**kg P-eq**	8	8.7	11	$3.2 \cdot 10^{-2}$	$3.4 \cdot 10^{-2}$	$4.4 \cdot 10^{-2}$	$3.0 \cdot 10^{-1}$	$3.3 \cdot 10^{-1}$	$4.2 \cdot 10^{-1}$
MEP	**kg N-eq**	6.4	6.7	7.8	$2.5 \cdot 10^{-2}$	$2.6 \cdot 10^{-2}$	$3.1 \cdot 10^{-2}$	$2.4 \cdot 10^{-1}$	$2.5 \cdot 10^{-1}$	$2.9 \cdot 10^{-1}$
$\mathbf{FETP}_{inf}$	**kg 1.4-DB-eq**	256	267	308	1	1.1	1.2	9.6	10	11.6
$\mathbf{METP}_{inf}$	**kg 1.4-DB-eq**	276	287	329	1.1	1.1	1.3	10.4	10.8	12.4
$\mathbf{TETP}_{inf}$	**kg 1.4-DB-eq**	1.3	1.4	1.6	$5.2 \cdot 10^{-3}$	$5.4 \cdot 10^{-3}$	$6.2 \cdot 10^{-3}$	$5.0 \cdot 10^{-2}$	$5.2 \cdot 10^{-2}$	$5.9 \cdot 10^{-2}$
$\mathbf{HTP}_{inf}$	**kg 1.4-DB-eq**	15900	16340	18110	63	64	71	596	614	681
MDP	**kg Fe-eq**	4100	4120	4180	16	16	17	154	155	157

The values that reflect large-scale production volumes is the LBV. This thesis will therefore focus on the LBV values. The cradle-to-gate GWP of the battery is 4.6 tonnes CO_2 equivalents in a 100-year perspective. The GWP per unit mass is 18 CO_2 equivalents and is 172 CO_2 equivalents per cycle capacity. The energy source, which includes fossil fuels such as coal and natural gas, is the largest contributor to the GWP. 51% of the total GWP impact derive from combustion of natural gas and coal in power plants to fulfill the energy requirements during the manufacturing phase. To reduce the environmental impact, more renewable energy can be used as the main electricity source in manufacturing. Figure 2.10 depicts the GWP when various energy sources are used. The diagram also shows how the GWP is influenced by various sections of the cradle-to-gate cycle. [37, 60]

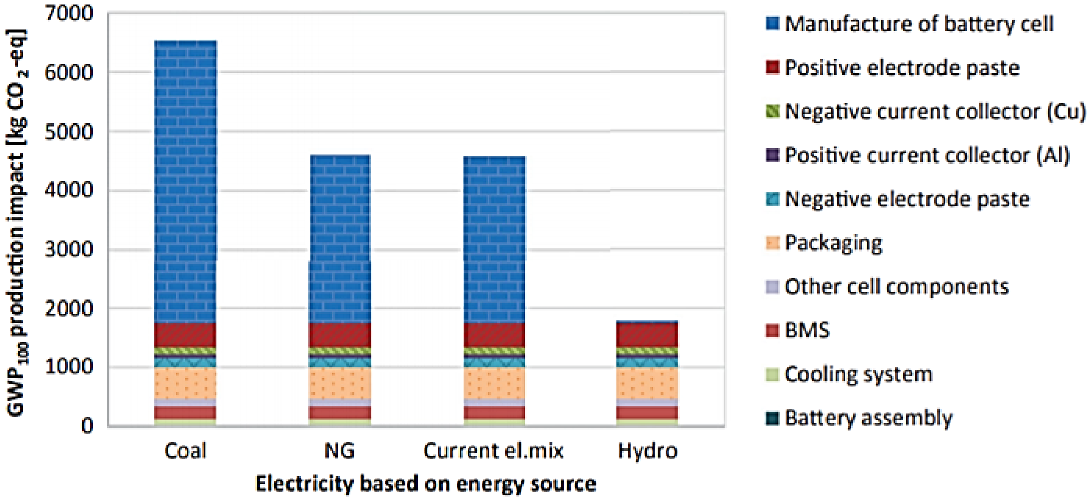

Figure 2.10: Impact on GWP from different energy sources. [37]

Battery cells that are produced with hydro power can decrease the total GWP of about 60%. This can also be applied to other renewable energy sources such as wind power, if not more. Natural gas and coal extraction for the purpose of combusting in power plants to meet energy demands accounts for 32% of the battery's FDP. 31% of the battery's total ODP stems from the use of crude oil, uranium and natural gas to fulfill the energy requirements. Figure 2.11 depicts the impact of all 13 categories by the various sections of the cradle-to-gate cycle.

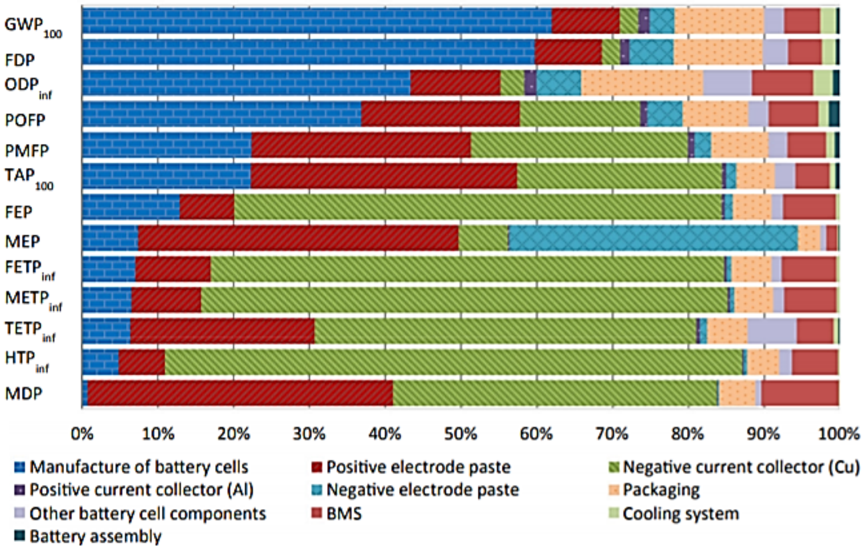

Figure 2.11: The environmental impact of all 13 categories during the different phases. [37]

A ReCiPe approach was used in this study to reduce many of the long lists of life cycle inventory results to a small number of indicator ratings. The relative severity of an environmental impact category is expressed by these ratings. The use of nickel sulfate induces most of the positive electrode paste's impacts, but manganese is responsible for 86 percent of the paste's MDP. As a consequence of using the ReCiPe method, the use of lithium has no MDP impact, which results in an underestimated MDP value. It is unlikely that lithium will be recycled because only selected materials such as cobalt and nickel are being recycled. The study emphasizes that studies have shown that lithium do not have a big impact on the abiotic depletion potential in Li-ion batteries. The use of primary copper in the negative current collector contributes to a significant portion of the battery's impact in several categories. It indirectly contributes to the disposal of sulfidic tailings, which cause 65% of freshwater ecotoxicity potential (FETP), 62% of freshwater eutrophication potential (FEP), 54% of marine ecotoxicity potential METP) and 53% of human toxicity potential. Both the positive and negative electrode uses a solvent, N-methyl-2-pyrrolidone (NMP) in their paste. That solvent causes the only significant contribution of the negative paste. In order to produce this solvent, dimethylamine is needed, for which contributes to 75% of the battery's total marine eutrophication potential (MEP). [37, 60, 61]

The cumulative production impact of the battery is divided by the total distance the battery covers during its service life in the vehicle to determine the GWP impact for a given distance driven. The distance is determined by the battery's cycle life and the EV's powertrain efficiency for a given initial nominal energy capacity. How different parameters affect how production impacts are distributed in the use phase is shown in figure 2.12. [37, 62]

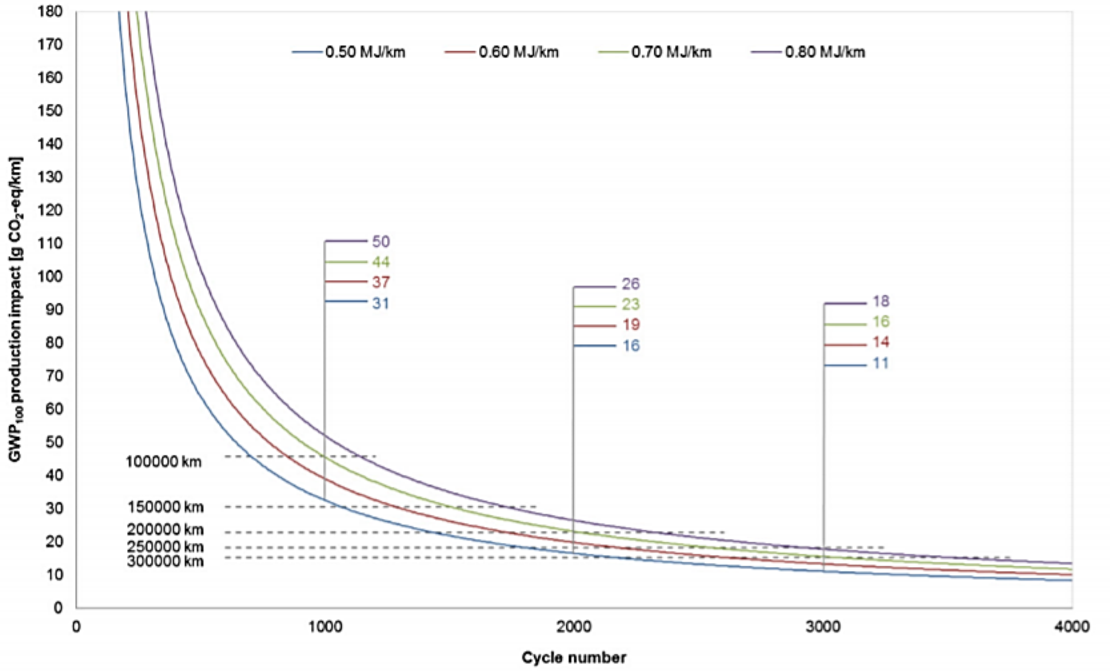

Figure 2.12: Impact on the GWP in the use phase. [37]

An 80% DOD is assumed, with a power loss of 0.0008% per cycle from the initial capacity in this analysis. The GWP of which the impact of production is measured in g CO_2 per unit distance is a decaying function of cycle numbers. Due to the slow gradual degradation of batteries, increasing the number of charge-discharge cycles during the battery's usage period nearly doubles the driving distance for the same initial impact. When assessing whether BEV is environmentally preferable to an ICEV the lower cycle numbers are critical. There are different conclusions of the assessment of the environmental performance, depending on the assumptions regarding range and/or battery cycle numbers. If the assumed life cycle of a battery with a powertrain efficiency of 0.50MJ/km is 3000cycles, it results in a GWP of 11g CO_2 eq/km. If the same battery has a life cycle of 1000 cycles, it will result in a GWP of 31g CO_2 eq/km. [37, 59]

2.8 The Environmental Footprint of Ammonia

Ammonia is one of the main fertilizers in the world. Ammonia can also be burned directly in internal combustion (ICE) and generators. According to IMO, a tanker emits in the range of 2.9-33g of CO_2/tonnes-kilometer dependent on the size of the tanker, whilst other types such as Ro-Ro, the emissions could go up to 65g CO_2/tonnes-kilometer. To see if ammonia would be applicable, the GHG emissions needs to be analyzed. Vehicles fueled with ammonia do not produce direct tail pipe CO_2 emissions. Its environmental impact should therefore be assessed by a cradle to grave life cycle assessment. This thesis bases its assumption on Yusuf Bicer and Ibrahim Dincer's study from 2018. This study was carried out as an assessment of ammonia to replace heavy fuel oils in the engines of maritime transportation vehicles. [63, 64]

2.8.1 Assumptions from the Literature Study

Ammonia (NH_3) contains three atoms of hydrogen and one atom of nitrogen. This study bases its assumption on that the hydrogen is produced by electrolysis based on renewable sources such as geothermal energy, biomass and municipal waste. In this study, the ammonia is produced by the Haber-Bosch process. The electrolyzer has an energy requirement of 53 kWh electricity to generate 1kg of hydrogen. The nitrogen is supplied through air separation process. The electrical work for the process, cooling water, surplus heat and groundwork for air separation facility are all considered. The electricity required to compress the air is based on the United States grid mix. In this study it assumed an energy requirement of 0.42kWh electricity per kg of nitrogen. Transportation of nitrogen to the ammonia synthesis plant is not accounted for based on the assumption that the ammonia synthesis plant is located near the air separation plant. However, the transportation of ammonia to the sea port are taken into account. [63]

The study's aim is to compare the environmental impact of ammonia and hydrogen-fueled marine transportation tankers and ships to traditional heavy fuel oil-fueled marine transportation tankers and ships from cradle to grave. Dual fuel options are also considered and analyzed. This is due to ammonia having difficulty of combusting and therefore could eliminate these problems with using ignition from heavy fuel oil. Entire life cycle steps from resource extraction to disposal during the lifetime are considered. The factors that this study focuses on is global warming potential (GWP) in a time horizon of 500 years, acidification potential (AP), abiotic depletion potential (ADP), stratospheric ozone layer depletion (ODP), marine eco-toxicity and marine sediment ecotoxicity. The environmental impacts in this study is a function which determines the impacts per tonne-kilometer (tkm) cruise travel. A tonne-kilometer is a unit of measure of goods transport which represent of one tonne by a vehicle, in this case a vessel, over a distance of one kilometer. In the LCA all stages including feedstock recovery and transportation, fuel production and transportation, and fuel consumption in the vessels. Figure 2.13 shows the system boundaries of this study. [63, 65]

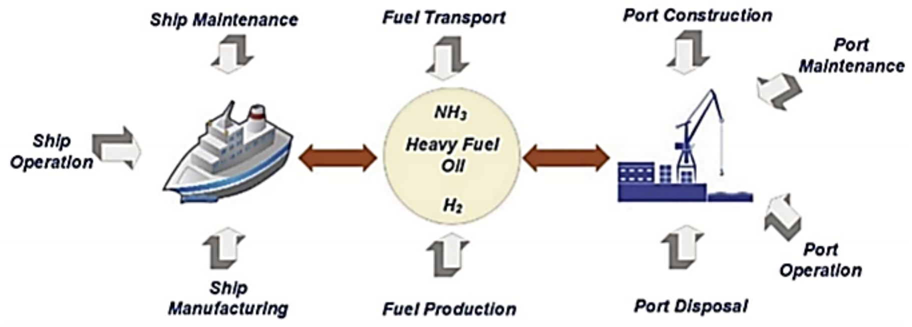

Figure 2.13: The system boundaries in this literature study. [63]

The study evaluates the environmental impact of various fuels on two separate transoceanic ships. Both ships are slow speed vehicles which include two-stroke cycle with cross engines of 4-12 cylinders. Slow speed marine diesel engines are categorized as slow speed when having an average speed of about 15 knots. The two ships are analyzed are a transoceanic tanker and freight ship. The trip is assumed to be from pacific to international port in order to determine the average power consumptions. The trip is broken down into parts, with travel through reduced-speed zones included (RSZ). In the RSZ the ship consumes less fuel and uses a lower load factor, thus emitting less contaminants compared to when travelling at cruising speed. The ships travel through a RSZ before and after entering a port. When arriving at the port, the ships will hotel and burn fuel dockside using mainly auxiliary engines. The distance, speed, duration and load factor for this study's transoceanic tanker and freight ships are shown in table 2.5 and table 2.6, respectively. These trip scenarios and values are the values that power consumption and emissions are derived from. [63, 66]

Table 2.5: Distance, speed, duration and load factor of transoceanic tanker. Values from International Journal of Hydrogen Energy. [63]

	Distance [km]	Speed [kn]	Time [h]	Load factor
Cruise	11441	15	410	0.83
RSZ 1	75	15	2708	0.83
RSZ 2	46	15	1661	0.83
Hotel 1	-	-	58	0.26
Hotel 2	-	-	58	0.26

Table 2.6: Distance, speed, duration and load factor of transoceanic freight ship. Values from International journal of Hydrogen Energy. [63]

	Distance [km]	Speed [kn]	Time [h]	Load factor
Cruise	4271	18	128	0.6
RSZ 1	187	18	6	0.6
RSZ 2	46	18	1	0.6
Hotel 1	-	-	22	0.2
Hotel 2	-	-	22	0.2

2.8.2 Results from the Literature Study

The results for each category shows the impact based on their production method and the difference in use of transoceanic freight ships and tanker. As compared to a tanker, transoceanic freight ships have higher impact values due to their higher energy consumption rate per tkm. Figure 2.14 shows the GWP given in kg CO_2 per tkm. Using ammonia in the marine engines can decrease total greenhouse gas emissions up to 69% per tkm. The greenhouse gas emissions for ammonia derived from biomass and heavy fuel oil fueled tankers are mainly caused by operation of tanker (76.5%). Maintenance and operation of the port account for 20.8%, while tanker manufacturing accounts for 2.81%. [63]

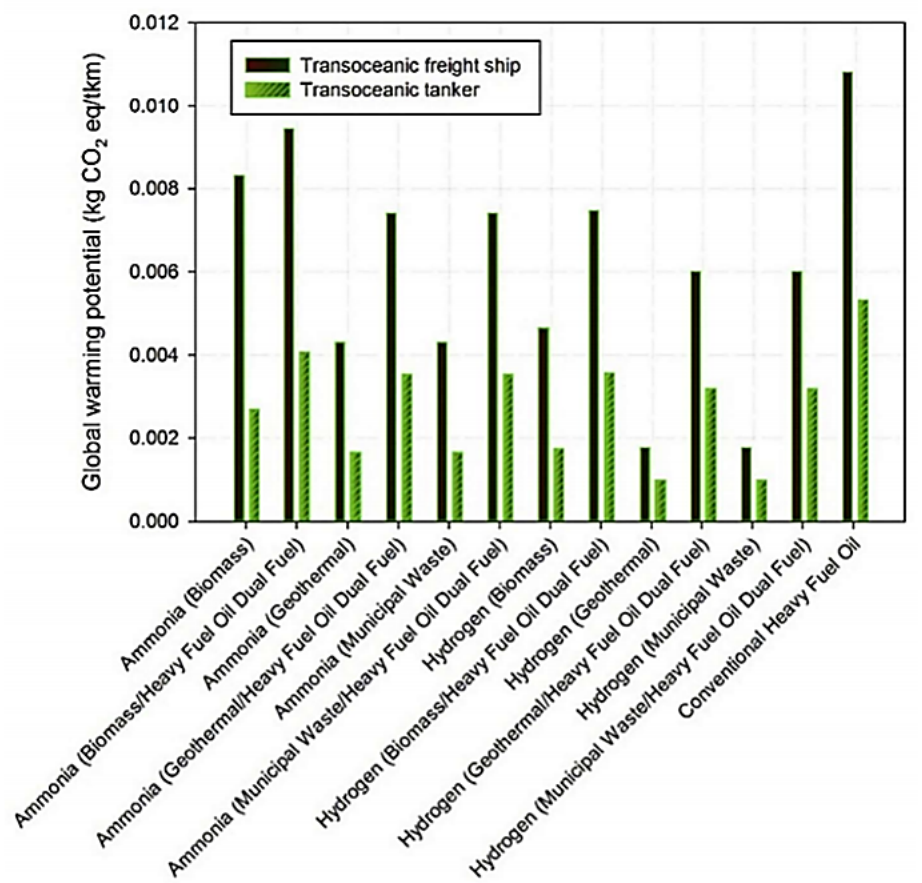

Figure 2.14: GWP for transoceanic tanker and freight ship based on ammonia and hydrogen from different production methods and compositions [63]

The toxic substances on the marine sediment and aquatic environment are the main concerns of marine sediment ecotoxicity and marine aquatic ecotoxicity categories. Marine sediment ecotoxicity refers to impacts of toxic substances on marine sediment ecosystems. This indicator is given in kg of 1.4-dichlorobenzene equivalents (1.4-DB eq) per kg of emission. Marine aquatic ecotoxicity refers to impacts of toxic substances on marine aquatic ecosystems. Emissions in the water, soil and air are all included. This indicator is also given in 1.4-DB eq per kg of emission. Figure 2.15 shows the marine sediment ecotoxicity values.[63, 67, 68]

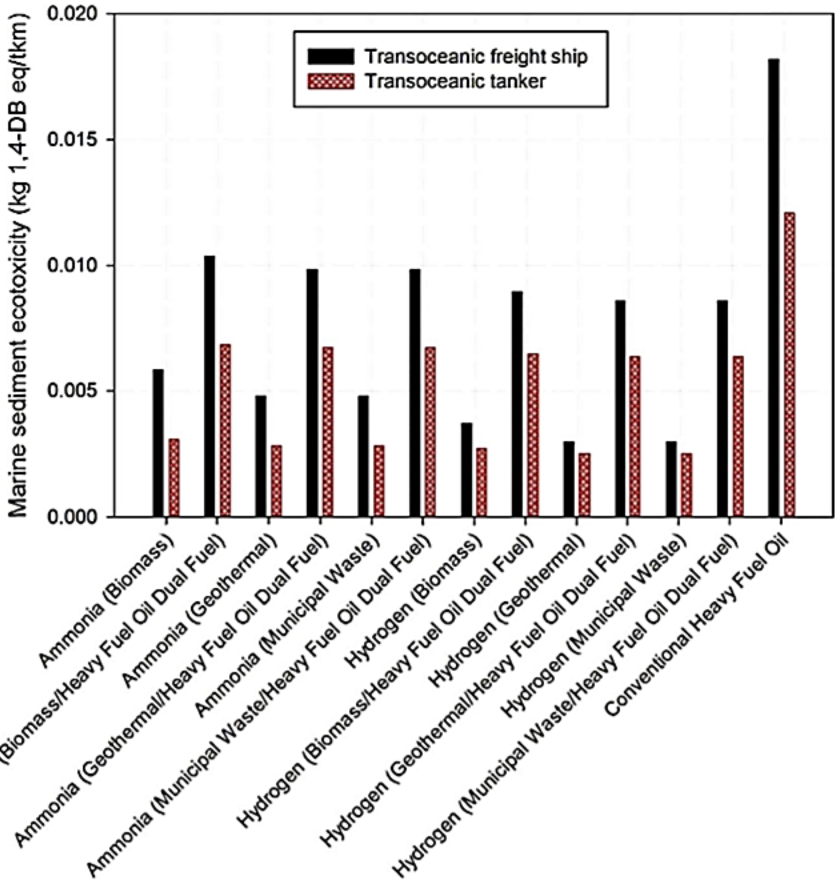

Figure 2.15: Marine sediment ecotoxicity for transoceanic tanker and freight ship based on ammonia and hydrogen from different production methods and compositions [63]

Operation of freight ships accounts for 80% of the total ecotoxicity in the ship fueled solely by ammonia. Using ammonia as a dual fuel with heavy fuel oil pollutes the environment more than using ammonia alone, but when using ammonia derived from municipal waste plant in a dual fuel engine it can reduce the ecotoxicity level about 54% compared to conventional heavy fuel oil. Marine aquatic ecotoxicity are shown in figure 2.16. [63]

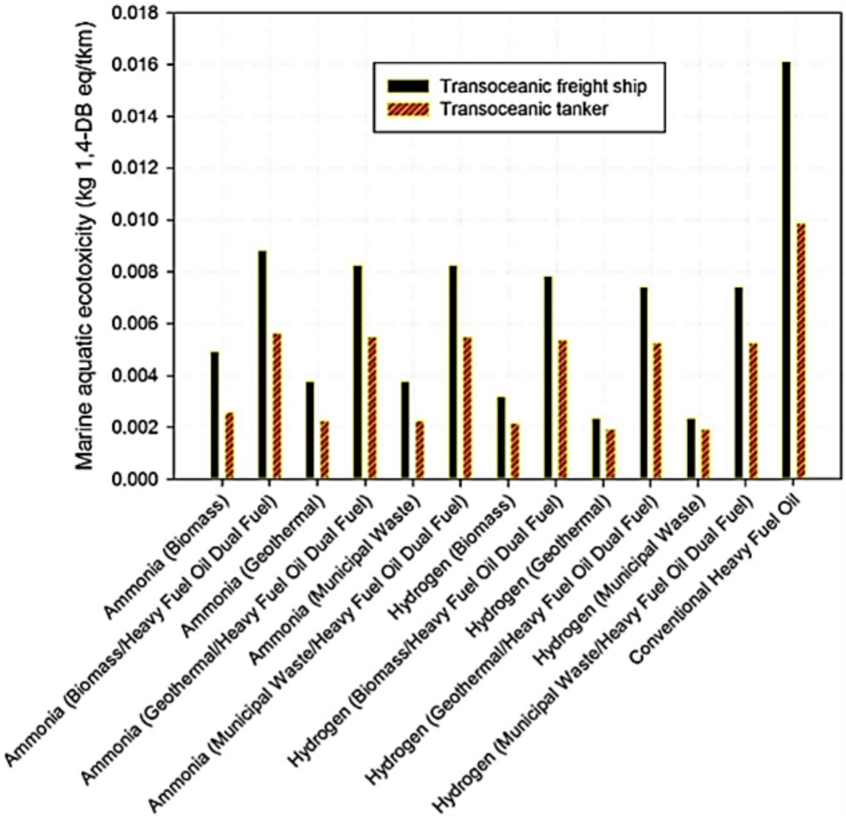

Figure 2.16: Marine aquatic ecotoxicity for transoceanic tanker and freight ship based on ammonia and hydrogen from different production methods and compositions [63]

Using ammonia from biomass as dual fuel oil tanker can reduce the emissions with about 74% compared to sole heavy fuel oil tankers. Sole use of ammonia or hydrogen could reduces the marine aquatic ecotoxicity significantly. Operation of the ship accounts for 45% of marine aquatic ecotoxicity. Natural gas accounts for 15%, whereas exploration and offshore production of heavy oil accounts for 6%. This is due to natural gas and oil-fired power plants is used for nitrogen production plant. The process contributions to marine aquatic ecotoxicity of a freight ship fueled solely by ammonia from geothermal energy is shown in figure 2.17. [63]

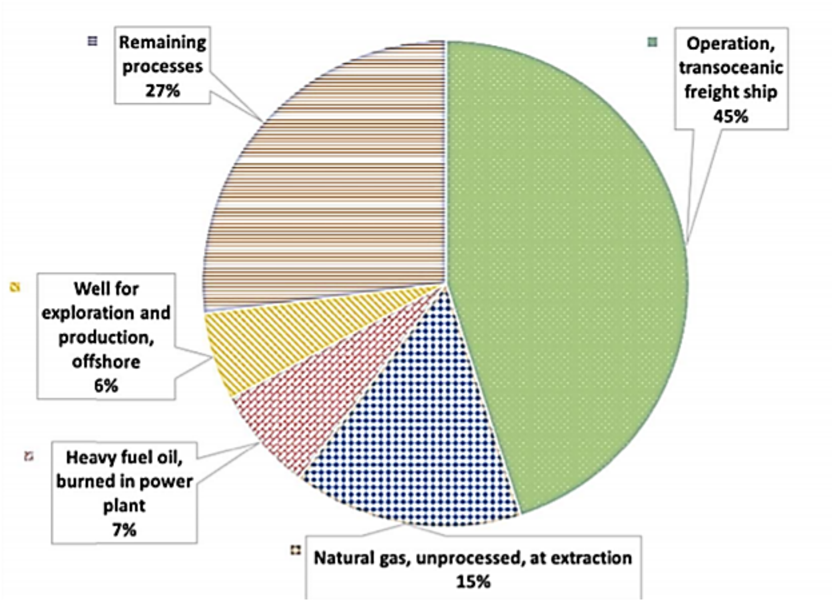

Figure 2.17: Marine aquatic ecotoxicity contributions for a freight ship fueled solely on geothermal energy based ammmonia. [63]

The acidification values are mainly caused by SO_2 and NO_X emissions. These emissions accounts for more than 90% of the overall acidification potential. Acidification substances causes a wide range of impacts on surface water, groundwater, soil, materials, organisms and ecosystems. The acidification potential is given in SO_2 equivalents per kg emission. The acidification potential for the various categories is depicted in Figure 2.18. [63, 69]

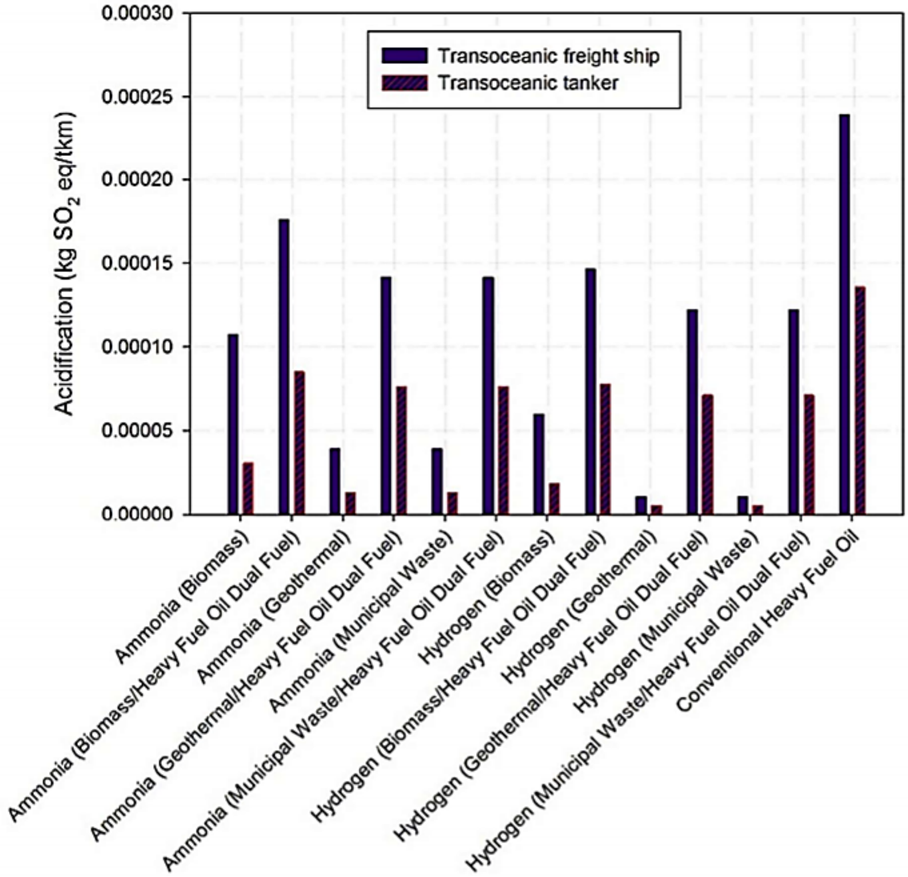

Figure 2.18: Acidification potential for transoceanic tanker and freight ship based on ammonia and hydrogen from different production methods and compositions [63]

The operation of the ships accounts for 97% of the SO_2-emission. It is a high content of sulfur in heavy fuel oil, thus almost eliminated in clean fuels as sole use of ammonia or hydrogen. The transportation process to the port has a major impact in this stage when comparing the use of hydrogen with ammonia. Because hydrogen has higher energy content per mass, the number of transports from production plant to the seaport is lower and results in a lower acidification potential than ammonia. The depletion of abiotic resources is related to extractions of fossil fuels and minerals due to inputs in the system. Based on concentration reserves and rate of deaccumulation, the abiotic depletion factor is calculated for each extraction and given in kg antimony equivalents per kg extracted. Figure 2.19 shows the abiotic depletion factor. [63, 70]

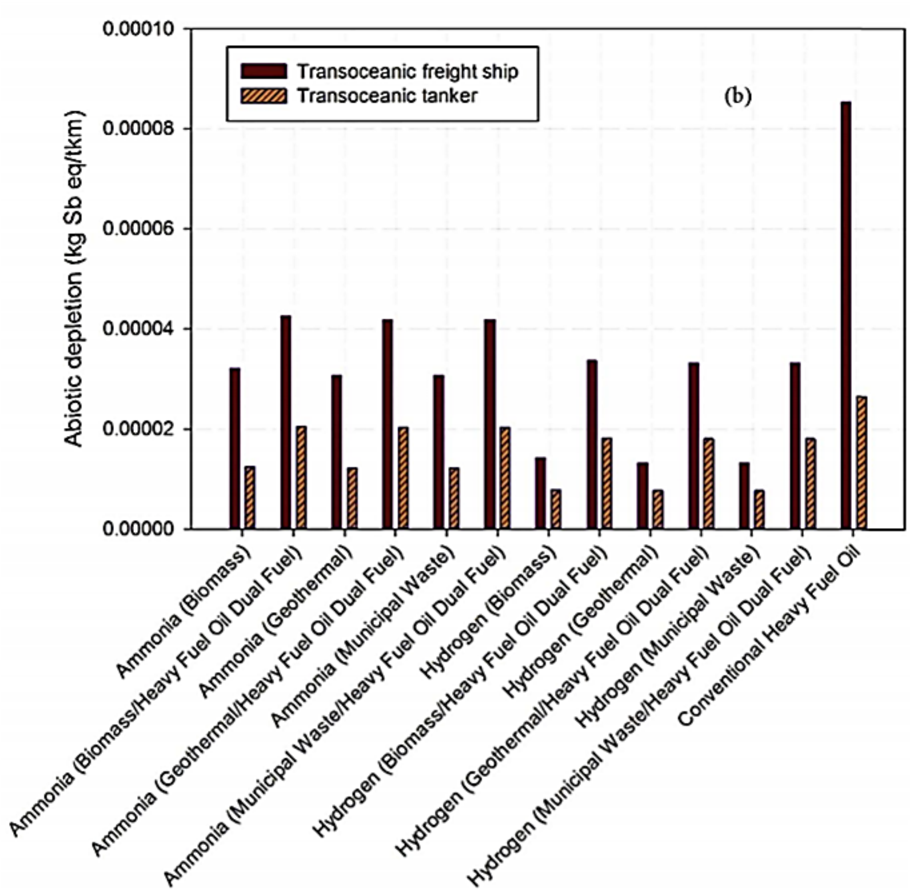

Figure 2.19: Abiotic depletion factor for transoceanic tanker and freight ship based on ammonia and hydrogen based on different production methods and compositions [63]

3 Methodology

This chapter presents the methodology used in this thesis. Description of the data acquisition is presented to give insight to how the work has been conducted. The strengths and weaknesses of the methods and assumptions used are presented to make the results reliable. The results are presented and discussed to demonstrate the technological differences between renewable sources such as hydrogen, ammonia, and lithium-ion batteries and conventional fuels. In this thesis, bio-diesel is not considered as a renewable fuel, but in the same category as conventional fossil fuels. Depending on which fuel and which aspect is being studied, a variety of sources are used. This chapter describes these sources as well as the assumptions that are used based on them.

To present a visual depiction of the value chains, a flow chart is made for each fuel, created using Lucidchart. The results are presented as graphs and tables made in excel. The calculations are also made through excel. This chapter presents how and why excel has been used to calculate the results. The results also include factors such as environmental impact and value chain to the various vessel types studied. These results are solely based on literature reviews and life cycle assessments. This chapter explains how the assumptions in these studies may vary from those in this study. For the sake of simplicity, every fuel and technology will be referred to as fuels even though a Li-ion battery is not directly a fuel. This chapter is divided into technology performance, vessel analysis, environmental impact and cost.

3.1 Fuel Performance Metrics

When analyzing different fuels which could be applied to existing vessels, it is important to understand the metrics of which these fuels is measured and compared with. Ship owners looking to phase out their current fleet to improve their carbon footprint must analyze the physical, technological and financial aspect. This section will mainly focus on the physical and technological aspect of different fuels that can be used in different vessels. This includes metrics such as the energy potential, technology performance and vessel fueling rate. The full list of the values that are used in the calculations are presented in table B.1, in appendix B. The values presented in the tables in this section will be presented with a reasonable number of significant figures, but are not the values used in the calculations.

3.1.1 Energy Potential

To measure the amount of energy that will be released from a given technology, it is useful to measure this by the amount of energy per unit weight or volume. Specific energy is given in energy content per unit weight and volumetric energy is given in energy per unit volume. Both is referred to as the energy density in each technology or fuel. Although the SI unit for specific and volumetric energy is J/kg and J/m^3 respectively, this has been converted to kWh/kg and kWh/L in this thesis. The values for specific and volumetric energy are presented in table 3.1. These values are entered into Excel and used to create a graph depicting relationship between specific and volumetric energy, and thus to show the energy potential of a given fuel in comparison to other renewable and conventional fossil fuels. The values are derived from a variety of sources depending on the available information and credibility. The methodology of extracting these values as well as the credibility of the sources are described below. This section highlights and describes the possible variance of the properties of each fuel. The variance and how these might affect the results are considered when discussing the findings. [71]

In 2020 The University of Washington, by the institute of Clean Energy released an article describing how Li-ion battery work and some of its advantages. Li-ion batteries have one of the highest energy densities of any battery technology today. The specific energy ranges from 0.10kWh/kg to 0.27kWh/kg, whilst the volumetric energy ranges from 0.25kWh/L to 0.67kWh/L. This thesis bases its assumption on this article and assume that a reasonable value for specific energy and volumetric energy is 0.18kWh/kg and 0.56kWh/L, respectively. This is slightly above-average based on the spectrum from the University of Washington. This is believed to be rational given the rapid advancement in battery technology and the fact that only high-quality batteries will be practical for ship owners. [34]

The Engineering ToolBox is a web-based toolbox that provides information on technical application design, engineering, and construction of technical applications. The toolbox provides HHV and LHV for different fuels in different states of matter. The LHV (specific energy) is given in kWh/kg is set 33.3kWh/kg. This is the same value for both liquid state and at 700bar. Iaian Staffel from the University of Birmingham provided an energy and fuel data sheet in 2011 where properties for common fuels are presented. Staffel compiled data from 26 sources to provide a comprehensive picture of each fuel's properties, with a global reach and no particular application. Based on Staffels research the volumetric energy is set at 2.41kWh/L and 1.32kWh/L, respectively for hydrogen at liquid state and at 700bar. [72, 73]

There have been a lot of studies and opinions on the use of ammonia for several decades. In order to convince people that ammonia could be used for energy, the Ammonia Energy Association was founded. They have been promoting the use of ammonia in a sustainable energy economy since 2004. Through generating, gathering, coordinating, and disseminating applicable information for the safe use of ammonia, the Ammonia Energy Association has become the leading agent of collective action for the ammonia energy industry. The executive director, Trevor Brown, wrote a literature review in 2018 on ammonia for power. This literature review presents the combustion characteristics for ammonia in comparison with other fuels. The specific energy is calculated to be 5.22kWh/kg and the volumetric energy 4.33kWh/L. [74, 75]

The same impacts are found to equate these renewable sources to the traditional use of fossil fuels. Marine diesel, crude oil, biodiesel, and LNG are the conventional fuels being investigated. NTNU together with DNV GL has provided a presentation on the future fuels and fuel converters. In this presentation the properties of marine diesel. The specific energy is calculated to 12.22kWh/kg. IOR is an Australian company which has over 70 diesel stops across Australia. They state themselves that they always have believed in continued innovation to offer the best service to its customers. They have released the fuel energy density of some of their own products including marine diesel. IOR state that the volumetric energy of marine diesel is 10.72kWh/L, with the notion that the calorific values may vary depending on the fuel composition. The volumetric energy is assumed to be 10.72kWh/L in this thesis. [76, 77]

The world nuclear association has also provided a list over specific energy of various fuels. Crude oil has a specific energy of 42-47MJ/kg, according to the data. This thesis assumes that crude oil has a specific energy of 45MJ/kg and that it is in the center of this range. This has a value of 12.5, when converted to kWh/kg. The world nuclear association provided a range of 42-46MJ/kg for normal petro-diesel. Because bio-diesel contains around 10% oxygen, whereas petro-diesel contains no oxygen it is assumed that bio-diesel has a specific energy in the lower end of this range. This thesis therefore assumes that bio-diesel has a specific energy of 42MJ/kg, which is converted to 11.67kWh/kg. The handbook of chemistry and physics by John R. Rumble states that the volumetric energy for bio-diesel is 9.17kWh/L. The volumetric energy value for crude oil, according to IOR, is 10.75kWh/kg. [77–80]

Elgas LNG is australias leading marketer of LPG gas. They are a member of The Linde Group, which is a world-leading gases and engineering company. Elgas LNG has provided information on its products including the energy content of LNG. The specific energy for LNG is presented to be 14.86kWh/kg, whilst the volumetric energy is 6.39kWh/L. The results regarding LNG of this thesis are based on these values. The total values for specific and volumetric energy are presented in table 3.1. [81, 82]

Table 3.1: Values for specific and volumetric energy

Fuel/technology	Specific energy [kWh/kg]	Volumetric energy [kWh/L]
Li-ion battery	0.18	0.56
Hydrogen (700 bar)	33.30	1.30
Hydrogen (l)	33.30	2.40
Ammonia	5.20	4.30
Marine diesel	12.20	10.70
Crude oil	12.50	10.30
Bio-diesel	11.70	9.20
LNG	14.90	6.40

3.1.2 Technology Performance

To assess the performance of each technology, it is useful to calculate the amount of power that each fuel can provide and compare this to its efficiency. When comparing different technologies and fuels, it is useful to compare based on the amount of power per unit mass or volume. Power density is given by kW/kg or kW/L. The run time is therefore not a factor in power density. Specific power is most used when analyzing the performance of engines or technologies using different fuels. Specific power is given in kW/kg and implies how much power the technology can deliver on demand. Energy and power density differs from density. Density measures the weight of fuel per volume. This gives information of how big space is needed and how much this will weigh. This thesis bases its results on the specific power. One of the most significant parameter when analyzing different technologies is the energy efficiency. The ratio of useful output to input in an energy conversion process is known as energy efficiency. In most cases, the energy efficiency is given in %. The values are derived from a variety of sources depending on the available information and credibility. The methodology of extracting these values, the credibility of the sources, as well as the assumptions made are described below. This section highlights the possible variance in efficiency. The variance are listed in D.1, in appendix D, and are considered when discussing the results.

Li-ion batteries has been continually increasing its production due to their excellent performance regarding high specific power and efficiency. This thesis bases its assumption both for efficiency and specific power on Tatsuo Horiba's article on Li-ion battery systems from 2014. The specific power is calculated to be around 2.4kW/kg with an efficiency as high as 95%. These values may vary from the quality and production of the cell. The battery's composition and application for which the battery will be used an effect on the outcome, so there is a significant uncertainty related to the specific power. [83]

It is assumed that the fuel cell is the most likely choice for transport applications in order to use hydrogen in a vessel. The most developed and used fuel cell is a proton-exchange membrane fuel cell (PEMFC). PEMFC generate electricity and operate in the opposite principle to PEM electrolysis, which consumes electricity. Professors from the Technical University of Braunschweig wrote a research article in 2019, analyzing the design of fuel cell systems for aviation. Since the fuel consumption is similar, it is assumed that the values reflect the same fuel cell systems used in ships. The professors calculated that the specific fuel cell power today is 1.6kW/kg with a possibility of future lightweight fuel cell system with a specific fuel cell power up to 8kW/kg. This thesis has assumed 1.6kW/kg in the calculations, but it is also represented with an error bar to show the future possibility of fuel cell technology. The fuel cell's composition and the application for which it will be used will have an effect on the outcome, so there is a significant uncertainty related to the specific power. The International Association for Hydrogen Energy wrote an International Journal of Hydrogen Energy in 2014. One section is about improving the PEMFC energy efficiency by optimizing the fueling rates. The journal sets the efficiency of hydrogen in PEMFC to be 40-60%. Based on advancement on the technology since the article was produced, this thesis assumes an efficiency of 57%. The results include an error bar to illustrate how the results may vary. [84–87]

The Ammonia Energy Association calculated in 2017 the efficiency for ammonia in different types of engines based on research from the Commonwealth Scientific and Industrial Research Organization (CSIRO), in Australia. CSIRO are Australia's national science agency and innovation catalyst. The efficiency results in the range of 35-40% in ICE's. Through development and improvements since the article, this thesis assumes an efficiency of 40%. The results are presented with an error bar to emphasize that it may vary. [88]

Konrad Reif on behalf of Bosch wrote in 2014 the book Diesel Engine Management. This book provides a comprehensive insight into diesel injections systems. It focuses on minimizing emissions and exhaust-gas treatment by innovations by Bosch. Bosch is the worlds largest independent supplier of parts and equipment for motor vehicles. The efficiency of diesel and bio-diesel is calculated to be in the range of 30-55%. It is also emphasized that the efficiency normally is around 42%, for which this thesis bases it assumption on, both for diesel and bio-diesel. The range is presented in the results as an error bar. [89, 90]

There are several ships that have converted to the use of LNG in ICE. Alberto Boretti on behalf of the Department of Mechanical Engineering at Prince Mohammad Bin Fahd University, Saudi Arabia, wrote an article about the advances in Diesel-LNG Internal Combustion Engines. The efficiency of diesel-LNG is calculated to be in the range of 39-50%. Based on this article, as well as Konrad Reif's book in diesel engine management, this thesis assumes an efficiency of 42%. Due to the information of most ICEs having an efficiency of 42%, that is the value that this thesis assumes to be most realistic. The range is presented in the results as an error bar. [89, 91]

The application of gas turbines in marine ships has primarily been used by the military. Many ship owners have transitioned to these types of engines due to development of the technology and decrease in cost. As a result, the use of LNG and ammonia in a gas turbine engine is covered in this thesis. The United States' Energy Department's Fossil Energy Organization has produced an article regarding how gas turbine power plants. The efficiency is calculated to be in the range of 30-80%. The energy conversion efficiency of a simple cycle gas turbine is usually around 30%. The Fossil Energy Organization states that future gas turbines with higher temperatures are likely to achieve efficiencies of 60% or more, and up to 80% if the waste heat is captured from the systems. Due to technological advancements, this study assumes that the efficiency of both LNG and ammonia-fueled turbine engines will be 60%, and that waste heat will not be prioritized. The full range is presented in the results as an error bar. [92, 93]

There are many different engines that conventional fossil fuels and ammonia can utilize. YANMAR is a well known company throughout the marine industry with a vision of producing the most efficient, reliable and durable engines. They also state that they are committed to stimulating the company growth globally through innovative technology. They mainly focus on marine diesel engines. In their products guide the dimensions and specifications of the several engines are presented. This thesis based its assumptions on the engine called 12AYM-WET. It's a 12-cylinder V-type internal combustion engine (ICE) that can be used in a variety of ships, so it is applicable the purpose of this thesis. There are several factors that would affect the results. This includes type of engine, materials used, size, application, fuel, etc. Every factor would change the composition and inevitably change the foundation for the application for which will be used. The materials required for using ammonia, for example, vary from those required for using marine diesel. Due to a lack of solid data on the usage of various fuels and lack of transparency for different types of ships, it was first assumed that the 12AYM-WET engine will run on any conventional fossil fuel. [94]

When presenting the technology performance, it is useful to show its specific power regards to the efficiency for the chosen technology. Due to high uncertainty around the credibility and realistic values the presented specific power has, the technology performance is presented solely based on its efficiency. Presenting the results with the amount of uncertainty these specific power values could lead to a completely wrong conclusion. This thesis will therefore not concentrate on this factor due to the lack of studies and reliable sources about its values in the types of vessels that are analyzed. The efficiency values are listed in table 3.2. The different technologies efficiency values are entered into excel and put in a graph to depict the differences in technology performance.

Table 3.2: Efficiency for each fuel

Fuel/technology	Efficiency [%]
Li-ion battery	95
Hydrogen (700bar)	57
Hydrogen (l)	57
Ammonia (ICE)	49
Ammonia (Turbine)	60
Marine Diesel	42
Crude Oil	27
Bio-diesel	42
LNG (ICE)	42
LNG (Turbine)	60

3.1.3 Vessel Fueling Rate

The fueling rate of renewable energy sources in comparison to available energy is an important factor when evaluating its feasibility as vessel fuels. The amount of energy required to power a given technology is referred to as the fueling rate. The fueling rate is also used to calculate the fueling time. The fueling time is referred to as the time it takes to fuel each fuel, given the energy demand the fuel poses in each ship. When analyzing the fuel rate, the rate is often given as a measure of kg fuel per unit time, for instance kg/h. It can also be presented as a measure of volume of fuel per unit time, for instance L/h. By multiplying this respectively with the fuel's specific energy or volumetric energy, the fueling rate is given in the unit of power (watt), and in this thesis presented as MW, hence showing the capacity. The values are derived from a variety of sources depending on the available information and credibility. The methodology of extracting these values as well as the credibility of the sources are described below.

In 2019, Siemens opened a battery factory for ships in Norway. Solely on their production, Siemens estimates that they can supply up to 200 passenger ferries annually. In order to charge these ferries as well as other electric vessels, the need for charging is vital. Bastø Electric is the world's largest all electric ferry which operates in Norway's busiest ferry connection, according to the ship owner. The ship owner, Bastø Fosen, has a charging system that is scheduled to go into operation in the summer of 2021. This fast-charging system has a capacity of 9MW, according to Bastø Fosen. This thesis bases its assumptions on the information from Bastø Fosen. Hence the fueling rate of Li-ion batteries presented in this thesis is 9MW. [95, 96]

The Argonne National Laboratory is a multidisciplinary science and engineering research center in USA. They have analyzed the refueling of fuel cells in heavy duty vehicles. This analysis evaluates the aspects regarding fueling a heavy duty vehicle. The maximum fueling rate both for hydrogen at liquid state and at 700bar is presented to be 7.2kg/min. By converting this to power by multiplying this with the specific energy, this thesis presents a fueling rate of 13.49MW. It is assumed to be the maximum value of this analysis due to vessels requiring more fuel than heavy duty vehicles. [97, 98]

It is assumed that the remaining liquid fuels fills at the same velocity. This bases its assumptions on the information of the fueling of a cruise ship. Windstar Cruises operates 6 ships visiting around 330 ports around the world. In their information of its cruise ships, it presents that a barge pumps 110 tons of fuel per hour. That equates to approximately 13 249L/h. This is multiplied with the specific energy of each fuel. According to this calculation, this thesis assumes a fueling rate of 42MW for ammonia, 142MW for marine diesel, 136MW for crude oil, 121MW for bio-diesel and 196MW for LNG. All the fueling rates are presented in table 3.3. It is also assumed that the fueling rate do not change when the fuel is used in either an ICE or turbine. Ammonia and LNG will therefore have the same fueling rate if it used in ICE or turbine, but it can be a difference in fueling times due to the difference in energy demand. These values are entered into excel and put in a graph with the specific energy, in order to show the fueling rate with regards to the available energy in the given fuel. [99, 100]

Table 3.3: Fueling rate for each fuel

Fuel/technology	Fueling rate [MW]
Li-ion	9.0
Hydrogen (700bar)	14.0
Hydrogen (l)	14.0
Ammonia (ICE)	42.0
Marine Diesel	142.0
Crude Oil	136.0
Bio-diesel	121.0
LNG (ICE)	426.0

When the energy demand for each fuel in the respective ship is calculated, the fueling rate is used to calculate the fueling time. The energy demand is given in kWh, so by dividing each energy demand with the fueling rate converted to kW, the fueling time is presented.

3.2 Vessels

In order to assess a fuel's suitability for marine use, it is essential to examine its performance in the marine applications for which it will be used. There are several different types of ships, but to assess the full range of ships this thesis focuses on a high speed vessel, passenger ferry and cargo ship. The specifications and information of the ships is derived from MarineTraffic. MarineTraffic is the world's leading provider of ship tracking and maritime intelligence. They are partnered with bodies such as The UN Conference on Trade and Development (UNCTAD) and the International Maritime Organisation (IMO). They also work on initiatives dedicated to improving productivity and reducing environmental effects with the world's leading ports, maritime businesses, and oil majors. MarineTraffic monitors vessel movements and builds a base of data gathered from its network of coastal Automatic Identification Systems (AIS) receiving stations, as well as satellite receivers. They apply algorithms and integrate complementary data sources to provide the shipping, logistics and trade industries insights into shipping activity. This thesis selected one high speed vessel, one passenger ferry and one cargo ship, all of which sailed along the Norwegian coast line. The specifications for each ship as well as how the information is used in this thesis are described below. [101]

3.2.1 High-Speed Craft

The values that are gathered from MarineTraffic is presented in table 3.4.

Through talks with Bjørn Haugland from Skift Norge it is assumed that a cargo ship sails at 50% capacity. Skift Norge is a Norwegian group made up of people from a variety of industries who share the task of ensuring that Norway's climate change targets are met. This thesis assumed that high speed vessels and passenger ferries sails at a higher

Table 3.4: General information on the high speed vessel "MS Terningen"

Vessel	High speed vessel
Engine (kW)	2880
Trip (NM)	95
Average speed (kn)	33
Length (m)	41
Weight (DWT)	159
Trip Duration (h)	2.9

capacity, due to more stops at the port. This will allow high-speed vessels and passenger ferries to load up on fuel, but it will also require more power to accelerate more frequently throughout their routes. This thesis assumes that high speed vessels and passenger ferries sails at 60% capacity. The high speed vessel analyzed in this thesis is called MS Terningen and travels from Trondheim to Kristiansund, in the middle part of Norway. According to MarineTraffic, this trip is about 95NM and 2.9 hours to complete. With the capacity rate set at 60%, the energy demand for this trip is calculated to be 5005kWh. This is the energy demand assuming 100% efficiency from the fuel. As a result, the energy demand is determined based on the efficiency of each fuel. Table 3.5 shows the energy demand for MS Terningen based on various efficiency levels. [102, 103]

Table 3.5: Energy demand for MS Terningen based on the fuel's efficiency

Fuel	Energy demand [kWh]
100% efficiency	5005
Li-ion battery	5268
Hydrogen (700 bar)	8780
Hydrogen (l)	8780
Ammonia (ICE)	10131
Ammonia (Turbine)	8341
Marine Diesel	11916
Crude Oil	18537
Bio-diesel	11916
LNG (ICE)	11916
LNG (Turbine)	8341

When analyzing the weight requirement and volumetric demand, in addition to the fueling time for each fuel, the energy demand when using these fuel is the basis of the calculations. The weight requirement is found by dividing the energy demand with the specific energy of the respective fuel. The volumetric energy is found by dividing the energy demand with the volumetric energy of the respective fuel. The fueling time is found by dividing the energy demand with the fueling rate of the respective fuel.

3.2.2 Passenger Ferry

The values that are gathered from MarineTraffic is presented in table 3.6.

Table 3.6: General information on the passenger ferry "MF Værøy"

Vessel	Passenger
Engine (kW)	5200
Trip (NM)	57
Average speed (kn)	15
Length (m)	96
Weight (DWT)	650
Trip Duration (h)	3.7

The passenger ferry analyzed in this thesis is called MF Værøy and travels from Bodø to Moskenes, in the northern part of Norway. According to MarineTraffic, this trip is about 57NM long and takes 3.7 hours to complete. With the capacity rate set at 60%, the energy demand for this trip is calculated to be 11 548kWh. This is the energy demand assuming 100% efficiency from the fuel. As a result, the energy demand is determined based on the efficiency of each fuel. Table 3.7 shows the energy demand for MF Værøy based on various efficiency levels. [104]

Table 3.7: Energy demand for MF Værøy based on the fuel's efficiency

Fuel	Energy demand [kWh]
100% efficiency	11548
Li-ion battery	10130
Hydrogen (700 bar)	16883
Hydrogen (l)	16883
Ammonia (ICE)	19481
Ammonia (Turbine)	16039
Marine Diesel	22913
Crude Oil	35642
Bio-diesel	22913
LNG (ICE)	22913
LNG (Turbine)	16039

When analyzing the weight requirement, volumetric demand, in addition to the fueling time for each fuel, the energy demand when using these fuel is the basis of the calculations. The weight requirement is found by dividing the energy demand with the specific energy of the respective fuel. The volumetric energy is found by dividing the energy demand with the volumetric energy of the respective fuel. The fueling time is found by dividing the energy demand with the fueling rate of the respective fuel.

3.2.3 Cargo Ship

The values that are gathered from MarineTraffic is presented in table X.

Table 3.8: General information on the cargo ship "Baby Hercules"

Vessel	Cargo ship
Engine (kW)	13560
Trip (NM)	1055
Average speed (kn)	11
Length (m)	240
Weight (DWT)	110861
Trip Duration (h)	96

The cargo ship analyzed in this thesis is a transoceanic cargo ship called Baby Hercules. At the time of data extraction, Baby Hercules was scheduled to travel 1055NM. According to MarineTraffic, this takes 96 hours to complete. With the capacity rate set at 50%, the energy demand for this trip is calculated to be 650 264 kWh. This is the energy demand assuming 100% efficiency from the fuel. As a result, the energy demand is determined based on the efficiency of each fuel. Table 3.9 shows the energy demand for Baby Hercules based on various efficiency levels. [105]

Table 3.9: Energy demand for Baby Hercules based on the fuel's efficiency

Fuel	Energy demand [kWh]
100% efficiency	650264
Li-ion battery	684488
Hydrogen (700 bar)	1140813
Hydrogen (l)	1140813
Ammonia (ICE)	1316323
Ammonia (Turbine)	1083773
Marine Diesel	1548247
Crude Oil	2408384
Bio-diesel	1548247
LNG (ICE)	1548247
LNG (Turbine)	1083773

When analyzing the weight requirement, volumetric demand, and the fueling time for each fuel, the energy demand when using these fuel is the basis of the calculations, as explained in appendix A. The weight requirement is found by dividing the energy demand with the specific energy of the respective fuel. The volumetric energy is found by dividing the energy demand with the volumetric energy of the respective fuel. The fueling time is found by dividing the energy demand with the fueling rate of the respective fuel. These calculations are described in appendix C

3.3 Green Energy Demand in Production

In order to evaluate the total impacts of renewable fuels, it is reasonable to analyze the energy demand needed for producing these fuels. This will be referred to as the green energy demand, due to this thesis' assessment of renewable fuels being produced by wind power. The methodology of finding these values are based on a literature review. How these values were retrieved are described in this section.

Simon Davidsson Kurland from Upsala University in Sweden, wrote an article in 2019 for the Environmental Research Communications journal. This research was conducted to investigate the energy demand for producing Li-ion batteries. The results of the research presented an energy demand in the range of 50-65kWh per kWh capacity in the battery. This thesis assumes a value in the middle of this range, resulting in a green energy demand of 58kWh/kWh capacity. [106]

In order to meet the estimated demand of hydrogen in different sectors, Dale Gardner from the US department of Energy laboratory, investigated the challenges this increasing demand could pose when produced by renewable energy sources. This included the green energy demand for producing hydrogen via electrolysis. The results show that with an electrolyzer producing hydrogen with 100% efficiency, the green energy demand is 39kWh/kg of hydrogen. It is assumed to be unrealistic having an efficiency of 100%. This thesis therefore assumes an efficiency of 80%, resulting in a green energy demand of 48kWh/kg of hydrogen. [107]

Yara is one of the leading producers of ammonia in the world. Yara together with Statkraft and Aker Horizons has recently signed a letter of intent for producing green ammonia at Herøya, Norway. Through talks with some of Yara's project managers regarding this project, they estimate that the green energy demand is 10kWh/kg ammonia. Due to Yara's long experience with ammonia production, this is assumed to be a credible estimation. [108, 109]

To analyze the green energy demand required to produce the necessary energy demand for the ships, these values are utilized, as described in appendix F. When analyzing the energy demand for Li-ion batteries, the green energy demand is multiplied with the energy demand required for each ship's trip. When analyzing the energy demand for both hydrogen and ammonia, their respective green energy demand is multiplied with the weight requirement for the respective fuel in each ship.

When researching the energy demand for producing the conventional fossil fuels, it was not found any conclusive values. There are a lot of different factors in the production phase of these values that alters the results. Due to lack of transperency in the sector, these values have not been included in this thesis.

3.4 Environmental Impact

An LCA should be used to measure the environmental impacts of the use of fuels, both renewable and conventional fossil fuels. This thesis has not conducted an LCA, but used the existing literature to assess the environmental impact of hydrogen, Li-ion battery and ammonia. The results in this thesis are based on the assumptions and results from the literature presented in section 2.6, 2.7 and 2.8. The most significant and comparable results are listed in tables in the next section. The results are then discussed and put to perspective with this thesis' focus and assumptions. GWP is the most used parameter in LCA studies and in environmental studies of renewable fuels and energy in general, and thus the main focus for this thesis.

3.5 Current Fuel Prices and an Estimated Forecast of Future Fuel Prices

This thesis do not have its main focus on the market and economic feasibility of renewable fuels in the maritime sector. However, the fuel price will be detrimental for the renewable fuels to be feasible, thus it is analyzed through a literature study what the current prices for production are, and what the estimations of renewable and conventional fossil fuels prices will be in the future. In the results, the data is evaluated as if it were being used in Baby Hercules because cargo ships are the largest contributors to GHG pollution and have the highest weight requirements and volumetric demands. Due to lack of lack of reliable sources, as well as the improbability of using Li-ion batteries in cargo ships, this is not included in the results. Because of a lack of credible sources, future LNG price estimates are also not included.

S&P Global Market Intelligence is a provider of data, research and analytics to several companies in multiple sectors. Their goal is to deliver high quality and essential intelligence in order for people, institutions and companies to make reasonable decisions. In march 2021, they released an article describing the future estimations of hydrogen. They present that it costs between 3-6.55US dollars per kg for green hydrogen. In their analysis they have highlighted that the Norwegian hydrogen company NEL ASA expects to lower the prices for hydrogen down to 1.5USD per kg by 2025. This thesis bases its assumption on that todays prices are in the middle of the presented range, giving a price of 4.8USD/kg. It also assumes that NEL will reach their targets by reducing the price to 1.5USD/kg within 2025. [110, 111]

Trevor Brown from the Ammonia Energy Association wrote an article in 2020 about the potential of green ammonia. According to this article, ammonia is currently priced at 0.65 USD/kg. This is based on information given by Argus Media. Argus Media is an independent media organisation that provide market data, business intelligence and price indexes for the global energy markets. They have long experience in the ammonia market and they have estimated that the future prices for green ammonia will be 0.24USD/kg. This thesis bases its assumption solely on the article and information given by Argus Media. [112, 113]

The current prices for marine diesel, crude oil, and LNG are all retrieved from DNV GL. DNV GL is a global organization that specializes in assurance and risk management in a variety of industries, including maritime and energy. They reported the current price growth of oil and gas in February 2021. According to DNV GL, the current price for marine diesel is 0.53USD/kg. The current price for crude oil is 0.47USD/kg, whilst the current price for LNG is 0.32USD/kg. The estimated prices for marine diesel and crude oil are retrieved by The Balance. The Balance is an American organisation with a long experience in giving advise both for personal and business finance. In May 2021, they released an oil price forecast from 2021 to 2050. According to The Balance, the price for marine diesel will increase to 1.1USD/kg by 2050, whilst the price for crude oil will increase to 0.96USD/kg. As mentioned, due to lack of reliable sources regarding the future price estimation of LNG, this is not included in this thesis. [114–117]

The current price for bio-diesel are retrieved from Neste. Neste is the world's largest producer of renewable bio-diesel. Their aim is to become a global leader in renewable and circular solutions. They update the current prices daily at their homepage to create transparency in their products. The current price as of may 2021 is registered to be 1.3USD/kg. Along with LNG, the lack of credible sources for price forecasting prevents this thesis from providing useful information on potential prices. [118, 119]

The aggregated values are presented in table 3.10. All values are given in USD/kg. This is multiplied with the weight requirement for Baby Hercules, which is listed in table C.2 in appendix C. This is to show the cost relation in USD between the current and estimated price forecast for each fuel in the analyzed trip for the cargo ship. The results are put in a graph using excel to depict this relation.

Table 3.10: The current price for fuels and the estimated price for the future

	Current price [USD/kg]	Estimated future price [USD/kg]
Hydrogen	4.80	1.50
Ammonia	0.65	0.24
Marine Diesel	0.53	1.10
Crude Oil	0.47	0.96
Bio-diesel	1.30	-
LNG	0.32	-

4 Results and Discussion

This following section will present the results based on the data collected during the study and data review. The results are derived from the methods presented in the methodology chapter. The methodology chapter addresses various data points, predictions, and assumptions that are made. As in the methodology chapter, will every fuel and technology be referred to as fuel even though a Li-ion battery is not directly a fuel.

This thesis focuses on the potential opportunities, overall energy demand, practical scenarios, and technology efficiency of renewable fuels for three different ships. In order to reflect around the findings and put them in context to if the fuels are feasible or not, the results are also discussed in this section. The findings and discussion are divided into five segments. The first segment presents the results for the three different ships regarding the weight requirements, volumetric demand, as well as the fueling time. The results are discussed to study the plausibility of the findings based on the theory presented in chapter 2, the fuel properties given in section 3.1, and the vessel properties presented in section 3.2. The second segment discusses the results from the first segment to highlight the differences, and reflect around the challenges or opportunities these requirements will present for the different ships. The third segment will put the results and discussions presented in the first and second segment into perspective and propose fuels that may be suitable for the different ships. The fourth segment presents the green energy demand that is required for producing renewable fuels, as well as the fuel price. The findings are discussed to give insights into how these variables might impact the feasibility assessment of the fuels. The fifth and last segment will present the most significant and comparable results regarding the fuel's environmental footprint found through the literature study. The findings are discussed in order to demonstrate how it could affect the feasibility assessment of the fuels.

Fuel Performance

The weight requirements, volumetric demand, and fueling time are all determined by the efficiency of the fuel and the corresponding technology, as well as the specific energy, volumetric energy and fueling rate, respectively. The values for these metrics are retrieved as descripted in section 3.1 and is the foundation for further research in this chapter. Figure 4.1 is generated using data from table 3.1, and depicts the relationship between specific and volumetric energy, and thus shows the energy potential of each fuel. High specific- and volumetric energy is the ideal fuel and is found in the far right top corner, while fuels with opposing properties will be found in the bottom left corner.

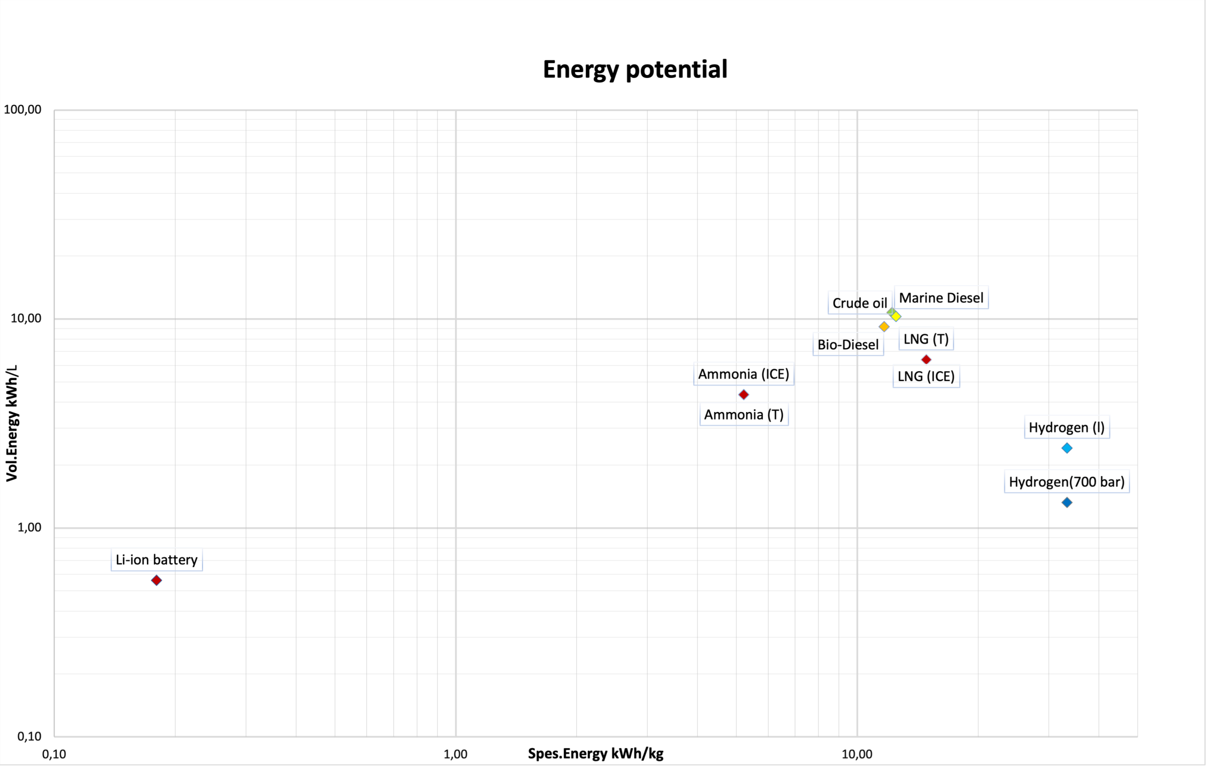

Figure 4.1: Energy potential of each fuel

The figure shows that conventional fossil fuels and biodiesel have the highest energy potential as expected through their high specific and volumetric energy. Hydrogen has the highest specific energy, but due to its low volumetric energy, the energy potential is inferior to the conventional fuel. The overall energy potential of ammonia could be regarded as the best due to a good correspondence between specific and volumetric energy. The Li-ion battery can be found in the lower left corner. To understand some of the reasons for the low rating, it should be noted that a Li-ion battery releases energy through a regulated electric discharge, whilst ammonia, hydrogen and fossil fuels are directly used in ICEs or turbines. The Li-ion battery has the lowest overall values, but the efficiency is incredibly high compared to the other fuels, as presented in table 3.2. Figure 4.2 depicts the technological performance of each fuel. In this thesis, the specific power of each fuel is not included as described in section 3.1.2. It is depicted with an error bar to emphasize to illustrate how the results may vary and where it is assumed the value is in this thesis' analysis. This variation is considered when discussing the following results.

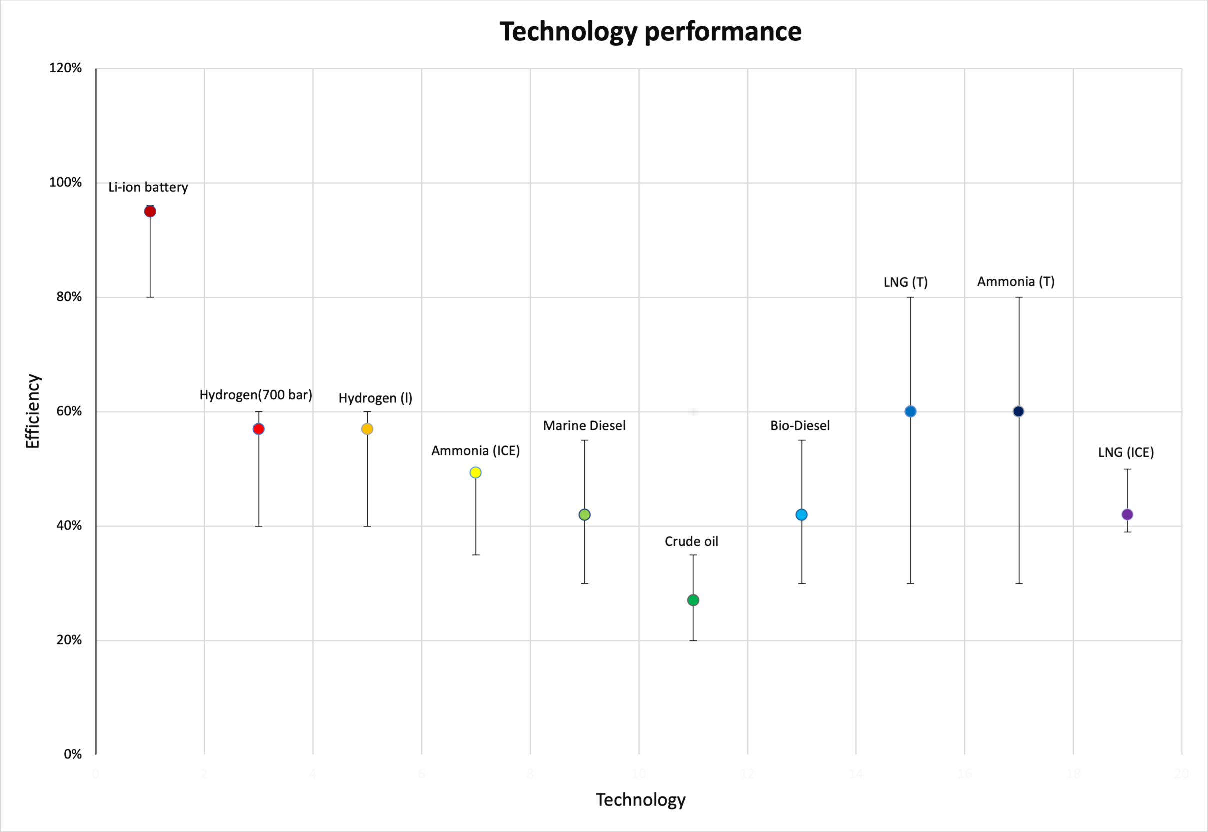

Figure 4.2: Efficiency of each fuel

Li-ion has the highest total efficiency at 95%, which translates to minimal energy loss when used. At the other end of the spectrum are conventional fossil fuels used in ICEs. Ammonia that is also used in ICE has a high performance compared to these fuels. The extensive error bar regarding fuels in turbines is due to its several technological alternatives. It is assumed that the vessels analyzed in this thesis utilizing fuels in gas turbines do not have a system for recycling the waste heat and therefore the efficiency is expected to be 60%. The application of turbines in ships may pose both advantages and disadvantages. This is considered when discussing the following results.

4.1 Requirements for Each Vessel

The following segment presents the results of the fuel requirements for each ship, and the fueling time needed for each fuel and ship. The requirements presented in this analysis are solely based on the energy demand of the ship, and the properties of each fuel. The energy demand is calculated based on the time of the trip and the engine power is set at 50 or 60% capacity. Several other factors would have been present during this trip that are not taken into account in this analysis.During the trips that have been analyzed, the amount of stops and frequency is not accounted for. Including these factors in the analysis could alter the results significantly. This is due to the energy requirement when accelerating or travelling through RSZs, are completely different from when travelling at cruising speed. As presented in section 2.8.1, the ship consumes less fuel and uses a lower load factor when travelling through RSZs. This could could imply that the requirements could be reduced if the ship often travels through RSZs. Another factor that is not accounted for in this thesis is the ship owner's requirements for fuel reserves. Presumably, every ship owner has a requirement for how much extra fuel is needed before leaving shore in order to manage possible unexpected events during the travel. The requirements would likely be increased in a realistic scenario. Other assumptions and factors that could influence the results are discussed in this section.

Table 4.1 contains details about the three separate boat classes and serves as the basis for the theses. The various values are compiled from real-time online tracking services and ship data, as presented in section 3.2, and serve as the fundament for calculations and analysis. Thus, table 4.1 presents the relationship between engine capacity, dead weight tonnage (DWT), trip length and trip duration. More information regarding the different ships is located in table A.2, in appendix A.

Table 4.1: Properties of each ship

Vessel type:	Cargo	High-speed craft	Ferry
Engine (kW)	13560,00	2880,00	5200,00
Trip (nm)	1055,00	95,00	57,00
Avg Knp	11,00	32,80	15,40
Length (M)	240,00	40,80	95,99
DWT (tonnes)	110861,00	159,00	650,00
Trip duration (h)	95,91	2,90	3,70

4.1.1 High-speed Craft

The high-speed craft analysis is based on MS Terningen, a Norwegian high-speed craft traveling from Trondheim to Brekstad to Kristiansund. MS terningen is depicted in figure 4.3 to give a sense of its size and representaion of high-speed crafts in general. Table 4.1 serves as the foundation for the data analysis, and the premises are presented in section 3.2.1. Given the assumption of a 60% total engine load, the total energy demand for the trip analyzed is 5005 kWh, as presented in table 3.5. The energy demand is the basis for which the high-speed craft's weight requirement, volumetric demand, and fueling time are calculated, as explained in section 3.2.1.

Figure 4.3: MS Terningen, a repsentative of high-speed crafts. [120]

Requirements for MS Terningen

The results regarding the weight requirements, volumetric demand, and fueling time are expressed in the table 4.2. Section 3.2.1 explains how these values are retrieved. The table is organised in the following order: weight requirement in kg, volumetric demand in m^3, and the time required to fuel the vessel given the energy requirements of each fuel. The result reflects some of the benefits and drawbacks of the various technologies and systems. Table 3.1 shows the specific and volumetric energy, which is the basis for the weight and volumetric requirements for MS Terningen.

Table 4.2: Requirements for MS Terningen

Fuel type	Weight requirements [kg]	Volumetric demand [m^3]	Fueling time [h]
Li-ion battery	29 268	9.4	0.59
Hydrogen 700bar	264	6.7	0.61
Hydrogen (l)	264	3.6	0.61
Ammonia (ICE)	1 940	2.3	0.24
Ammonia (Turbine)	1 597	1.9	0.24
Marine Diesel	975	1.1	0.13
Crude Oil	1 483	1.8	0.14
Bio-diesel	1 021	1.3	0.15
LNG (ICE)	802	1.9	0.14
LNG (Turbine)	561	1.3	0.10

4.1.2 Passenger Ferry

The passenger ferry analysis is based on MF MF Værøy, a Norwegian ferry that travels Røest-Værøy-Bodø. MF værøy is depicted in figure 4.4, to illustrate its size, and representation of passenger ferries in general. Table 4.1 serves as the foundation for the data analysis, and the premises are presented in section 3.2.2. Given the assumption of a 60% total engine load, the total energy demand for the trip analyzed is 11548kWh, as presented in table 3.7. The energy demand is the basis for which the passenger ferry's weight requirement and volumetric demand, in addition to the fueling time are calculated, as explained in section 3.2.2.

Figure 4.4: MF Værøy, a representative of passenger ferries [121]

Requirements for Passenger Ferry

The results for the weight requirement, volumetric demand, and fueling time are shown in table 4.3. Section 3.2.2 explains how these values are retrieved. The table is organised in the following order: weight requirement in kg, volumetric demand in m^3, and time required to fuel the vessel given the energy requirements of each fuel. The result reflects some of the benefits and drawbacks of the various technologies and systems. Table 3.1 shows the specific and volumetric energy, which is the basis for the weight and volumetric requirements for MF Værøy.

Table 4.3: Requirements for MF Værøy

Fuel type	Weight requirement [kg]	Volumetric demand [m^3]	Fueling time [h]
Li-ion battery	67 532	21.7	1.35
Hydrogen 700bar	608	15.4	1.41
Hydrogen (l)	608	8.4	1.41
Ammonia (ICE)	4 477	5.4	0.55
Ammonia (Turbine)	3 686	4.4	0.45
Marine Diesel	2 250	2.6	0.30
Crude Oil	3422	4.2	0.31
Bio-diesel	2 357	3	0.35
LNG (ICE)	1 850	4.3	0.32
LNG (Turbine)	1 295	3	0.23

4.1.3 Cargo Ship

The energy analysis on a cargo ship is based on the Baby Hercules, a Panna registered cargo vessel. Figure 4.5 depicts Baby Hercules to demonstrate its size and representation of cargo ships in general. Table 4.1 serves as the foundation for the data analysis, and the premises are presented in section 3.2.3. Given the assumption of a 50% total engine load, the total energy demand for the trip analyzed is 650264kWh, as presented in table 3.9. The energy demand is the basis for which the cargo ship's weight and volumetric requirements, in addition to the fueling time are calculated, as explained in section 3.2.3.

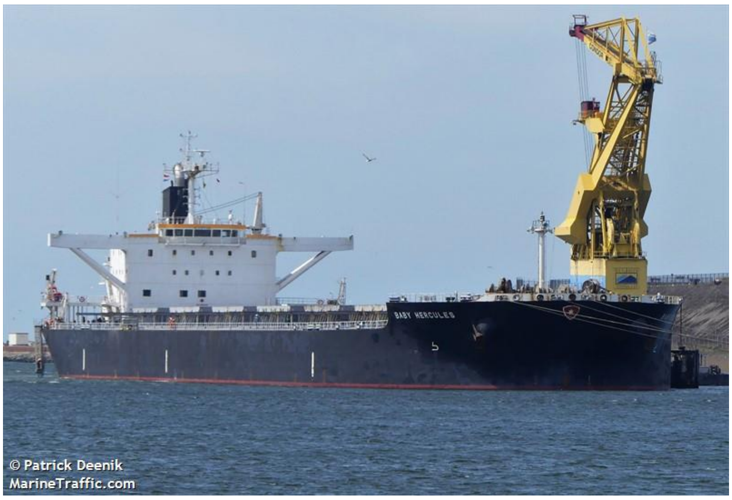

Figure 4.5: Baby Hercules, a representative of cargo ships [122]

Requirements for Cargo Ship

The results regarding the weight requirements, volumetric demand, and the fueling time are presented in the table 4.4. Section 3.2.3 explains how these values are retrieved. The table is organised in the following order: Weight requirement in kg, volumetric demand in m^3, and time required to fuel the vessel given the energy requirements of each fuel. The result reflects some of the benefits and drawbacks of the various technologies and systems. Table 3.1 shows the specific and volumetric energy, which is the basis for the weight and volumetric requirements for Baby Hercules.

Table 4.4: Requirements for Baby Hercules

Fuel type	Weight requirement [kg]	Volumetric demand [m^3]	Fueling time [h]
Li-ion battery	3 802 711	1 222	76
Hydrogen (700bar)	34 244	863	79
Hydrogen (l)	34 244	472	79
Ammonia (ICE)	252 073	304	31
Ammonia (Turbine)	207 540	250	26
Marine Diesel	126 675	144	17
Crude Oil	192 671	234	18
Bio-diesel	132 708	169	20
LNG (ICE)	104 181	242	18
LNG (Turbine)	72 927	170	13

4.1.4 Plausibility and Discussion of the Findings

One observation is the weight requirement of hydrogen fuel needed to cover the energy demand in comparison to the mass of Li-ion batteries. Whilst hydrogen has the highest specific energy, and the Li-ion battery the lowest, the results seem plausible. Another important remark is the difference in volumetric demand between hydrogen (700bar) and liquid hydrogen. The difference also seems plausible due to hydrogen having a higher density when stored in a liquid state, as described in section 2.1.4. Liquid ammonia needs double the tank size compared to conventional fossil fuels. This is expected due to ammonia having approximately half the volumetric energy of the liquid fossil fuels. The results also present a significant time difference between Li-ion batteries and hydrogen, compared to other fuels, especially fossil fuels. This is an expected result due to the difference in fueling rate, which is shown in table 3.3.

4.2 Outcome of the Requirements

The findings of the first segment advance further research and estimates. The data from the first section will be used in the following section for a more in-depth examination of the weight and volumetric requirements, as well as fueling time. Cargo ships, passenger ferries, and high-speed craft are three types of maritime ships, each with its own set of technical requirements, rate of fueling, usable space for engine and fuel capacity, weight restrictions, and energy demands. These factors are being considered when analyzing and discussing the results below.

4.2.1 Weight Requirement

Data from the table 4.2, 4.3, and 4.4 show significant differences in the weight requirements for the various fuels.

The specific energy is the key contributor to the fuel weight, as indicated by the denomination kg/kwh, which specifies the amount of energy is contained in one kg of fuel. Given a high specific energy and an extremely low density, the required mass of hydrogen to cover the energy demand is minimal compared to other fuels, shown in table 4.2, 4.3, and 4.4.

Hydrogen is the lightest atom on the periodic table; with a density of 0.07 kg/L, a cubic metre of liquid hydrogen weighs 70 kg. One cubic metre of marine diesel, on the other hand, has a density of 0.88 kg/L and weighs 880 kg. Engine efficiency would also have an impact on the weight requirement of fuels. If the efficiency is poor, total energy demand rises, leading to a higher weight requirement. The Li-ion battery has a relatively low density of 0.32 kg/L and the highest efficiency of all the fuels at 95%, but the weight requirement of batteries is extremely high. As mentioned, specific energy is the main factor in the weight requirement. As shown in table 3.1, there is a huge difference in specific energy, with hydrogen having almost 200 times the specific energy compared to Li-ion batteries. Figure 4.6 depicts the weight requirement for each fuel in the high-speed craft, passenger ferry and cargo ship analyzed in this theisis, in order to fulfil their respective energy demands. The x-axis lines the different fuels, whilst the y-axis shows the weight requirement and is represented logarithmically due to the wide range of values.

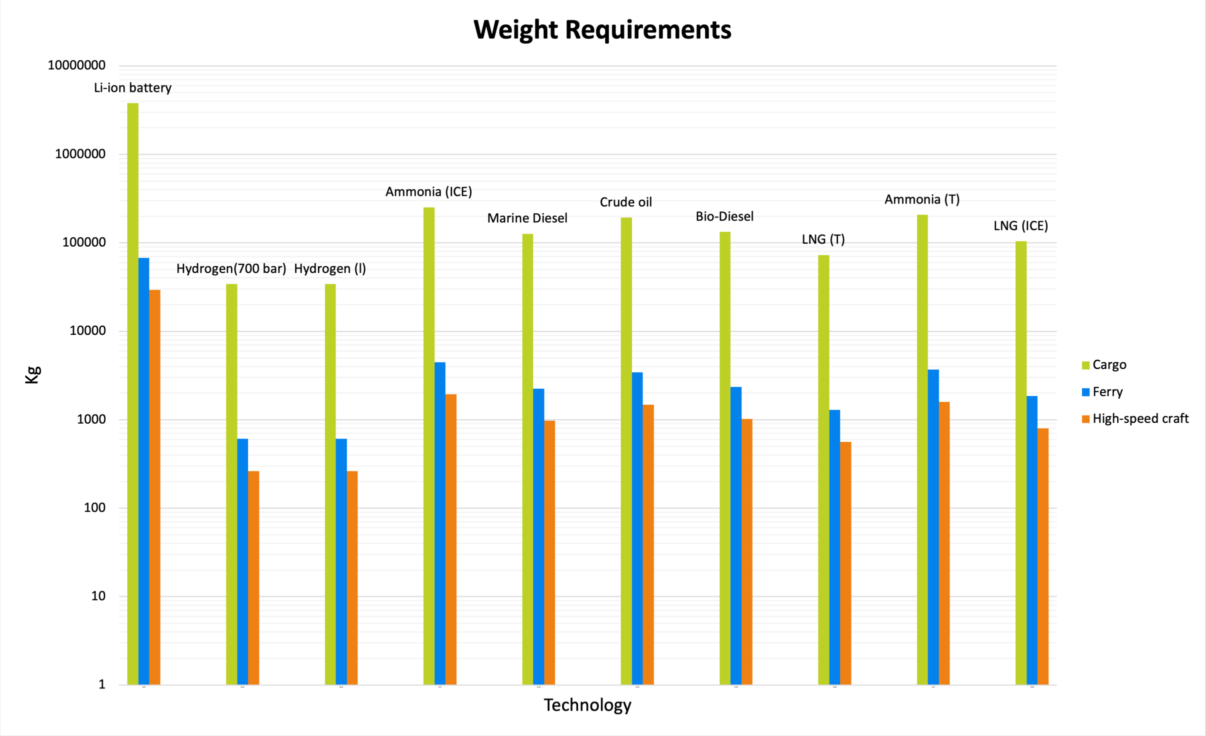

Figure 4.6: Weight requirements for each fuel in their respective ships

At the bottom of the scale, there is hydrogen, followed by LNG. As mentioned, ammonia has a specific energy of approximately half that of conventional fossil fuels, resulting in double the weight requirements. These differences are minor when compared to Li-ion batteries. Due to a logarithmic representation of the y-axis, it could be hard to comprehend the vast difference in weight requirements. In this thesis, it is believed that cargo ships and other ships of similar size would have the most difficulty transitioning to using renewable fuels. Figure 4.7 therefore depicts the weight requirements for the cargo ship with the logarithmic scale turned off. The enormous difference for a Li-ion batteries is now visible.

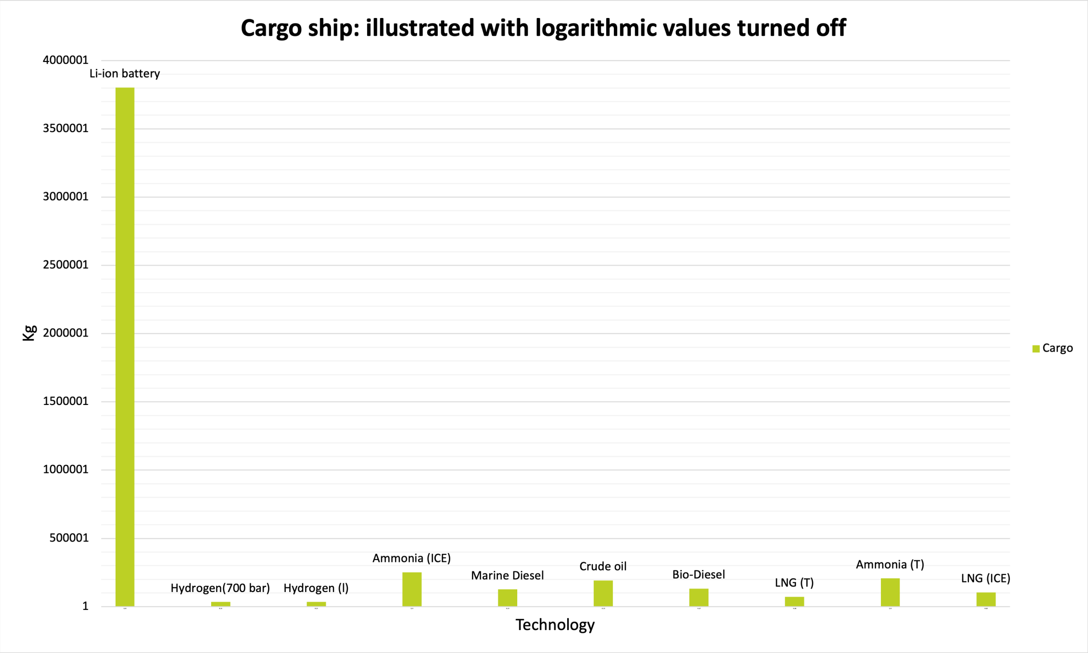

Figure 4.7: Weight requirements for Baby Hercules when logarithmic values are turned off

The DWT is the total amount of weight a ship can carry of load, fuel, supply, passengers and so forth. Table 4.5 represents the percentage of what the weight requirements accounts for of the DWT in each ship. This could present some of the challenges regarding the use of renewable fuels, compared to conventional fuels.

Table 4.5: The percentage of each fuel's weight requirement with regards to the ship's DWT, given in [%]

Fuel type	High-speed Craft	Passenger Ferry	Cargo Ship
Li-ion	18.40	8.66	3.43
Hydrogen (700bar)	0.17	0.08	0.03
Hydrogen (ICE)	0.17	0.08	0.03
Ammonia (ICE)	1.22	0.57	0.23
Ammonia (Turbine)	1.00	0.47	0.19
Marine Diesel	0.61	0.29	0.11
Crude Oil	0.93	0.44	0.17
Bio-diesel	0.64	0.30	0.12
LNG (ICE)	0.50	0.24	0.09
LNG (Turbine)	0.35	0.17	0.07

When analyzing these results, the vast difference between Li-ion batteries and other fuels could be misleading. The properties of the batteries are represented as the entire battery pack, whilst the properties of each fuel are solely based on the fuel in itself. A more suitable comparison would be to analyze the fuel together with the weight of the engine utilizing the fuel. The magnitude of different engines with distinct advantages and disadvantages lead to this factor not being included in this thesis. It is therefore uncertain what the actual percentage of the weight requirement accounts for in the DWT. For instance, could ammonia have an even bigger impact due to the weight of safety regulation technologies regarding the storage of the fuel and modifications of the engine. As described in section 2.3.4, there are some slight modifications needed to make the engine viable for the use of ammonia. It is uncertain how much this could affect the results. As predicted, due to its high specific energy, the use of hydrogen would present the lowest weight requirement of every fuel. The biggest problem with the use of hydrogen is the volumetric demand, as presented in the following section.

4.2.2 Volumetric Demand

According to the data in the tables 4.2, 4.3, and 4.4, the volumetric demand of each fuel varies significantly. The volumetric energy for the various fuels is described in table 3.1 and is the key factor in analyzing the volumetric demand. Hydrogen has the highest specific energy, but due to its extremely low density, one litre of liquid hydrogen has a total mass of 70 g, whereas hydrogen at 700 bar has a total mass of 40 g. Volumetric energy is measured in kWh/L, which explains why there is such a strong volumetric demand for hydrogen 700 bar compared to LNG, marine diesel, biodiesel, ammonia and crude oil. The volumetric energy for liquid hydrogen is approximately the double compared to hydrogen at 700 bar, resulting in a significant reduction in volumetric demand for hydrogen in the liquid state, compared to at 700bar. As shown in table 3.1, there is a big difference in volumetric energy between the fuels. This results in a big difference in the volumetric demand for each fuel in order to meet the ship's energy demand. Figure 4.8 depicts the volumetric demand for the high-speed craft, passenger ferry and cargo ship analyzed in this thesis. The x-axis lines the different fuels, whilst the y-axis shows the volumetric demand and is represented logarithmically due to the wide range of values.

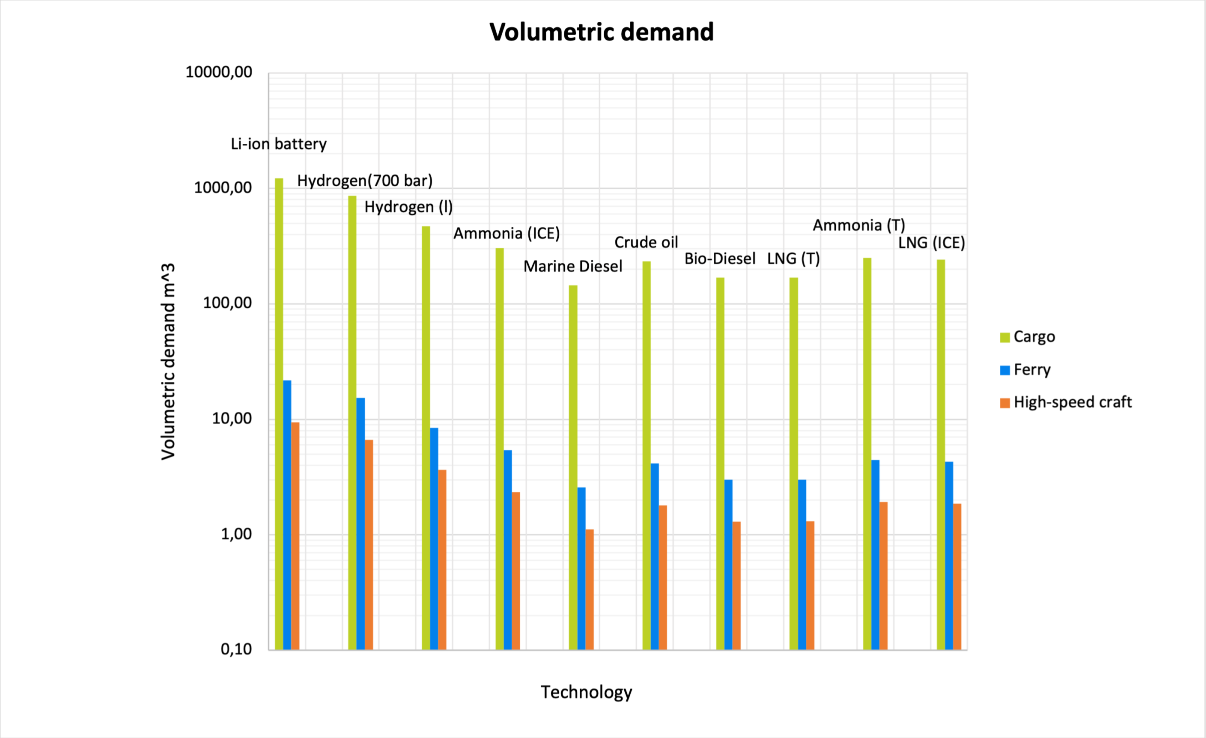

Figure 4.8: Volumetric demand of each fuel in their respective ships

Due to its high specific energy, hydrogen has an advantage regarding the weight requirement, but the low volumetric energy will counter this advantage. Hydrogen energy storage is a critical aspect to consider. Not only does hydrogen present a high volumetric demand, but how this hydrogen is stored is also a significant challenge. The volumetric demand for hydrogen at 700 bar must be met by using high-pressure tanks and liquid hydrogen at cryogenic storage temperatures of 20,35 K, which is both a remarkably energy consuming operation, as descripted in section 2.1.4. It is also uncertain how much space is required by PEMFCs in order to utilize hydrogen. This would increase the total volumetric demand even more.

Li-ion batteries have the highest volumetric demand of any fuel. This correlates to Li-ion batteries' low volumetric energy of 0.56 kWh/L, resulting in a volumetric demand approximately 8,4 times higher than marine diesel. As discussed when analyzing the weight requirements, this difference could be misleading due to the fuels being analyzed without the engine accounted for.

Figure 4.8 also depicts an interesting observation regarding ammonia. Since ammonia has approximately half the volumetric energy of marine diesel, biodiesel, and LNG, the volumetric demand is doubled in order to satisfy the energy demand of each ship. But when compared to crude oil, the difference is not that high due to crude oil's low efficiency. This could imply that the volumetric demand for ammonia is suitable for the vessels, but due to the modifications needed for adjusting the system to ammonia, it is uncertain how realistic that assumption is.

When analyzing the volumetric demand it would be beneficial to know how much space is reserved for storage and utilization of fuels in each ship, as the DWT is an indication for the impact of weight requirements. Presumably the difference in space reserved for fuel storage and utilization would vary a lot, not only between the ship categories but also between each ship, dependent on the purpose of the ship. For example, the cargo ship in this thesis is used to analyze the feasibility aspects of larger ships in the maritime transport sector. However, the purpose of every large ship is very different from ship to ship. Some large ships as Baby Hercules, carry containers with different content, some ships carries large amounts of different liquids and chemicals, and some large ships are meant for vacationing like cruise ships are. These differences in purpose would alter the restrictions regarding both weight and volume for which the fuels are to be stored and utilized. The space reserved for fuel storage and utilization can also vary a lot in high-speed vessels and passenger ferries, dependent on the lengths and trip duration the ships are designed for. These factors could vary considerably and the variation could alter the feasibility assessment regarding the volumetric demand significantly. The results of volumetric demand are still assumed to be essential because they indicate the volumetric challenges that each fuel poses.

4.2.3 Fueling Time

The next parameter is how quickly the ships can be fueled, or how much MW a vessel can be fueled using current technologies. This is referred to as the fueling time, given in hours, and the fueling rate, given in MW, as described in section 3.1.3. Fuels can have high specific and volumetric energy, but the fueling rate can be a significant disadvantage. It is important to note that the fueling rate for each ship is assumed constant. This ensures that the fuelling rate in MW for a high-speed craft is the same as for a cargo ship. This might not be the case in a realistic scenario. The demand for infrastructure and space available at the ports are presumably very different for each ship. Figure 4.9 depicts the relationship between specific energy in kWh/kg on the x-axis and the corresponding fuel rate in MW on the y-axis. This depicts the ship's fueling rate and correspondence with the amount of energy it can present. The highest vessel fueling rate is found in fossil fuels and biodiesel, indicating relatively high specific energy, as well as adequate possibilities for fueling the ships. On the other end of the spectrum, there are Li-ion batteries and hydrogen both liquid and at 700bar. This is predicted through the specific energy and fueling rate presented in table 3.1 and 3.3, respectively.

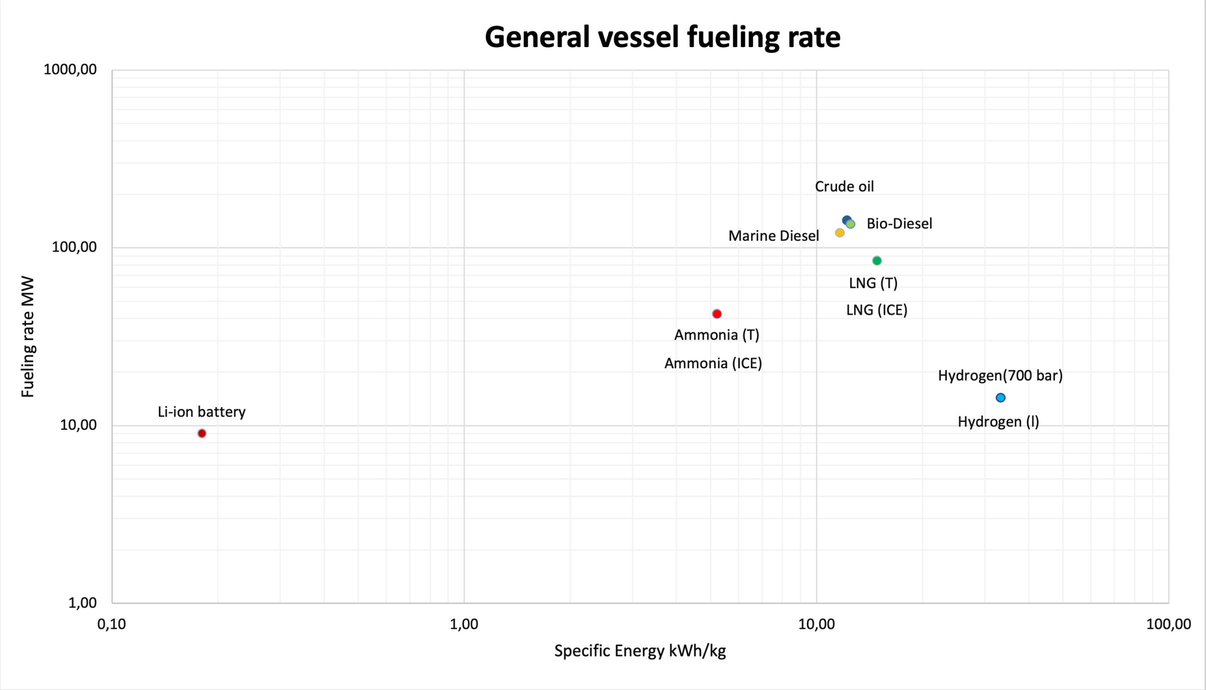

Figure 4.9: General vessel fueling rate and its correspondence with the specific energy

The difference in fueling times for the high-speed craft, passenger ferry and cargo presented in table 4.2, 4.3, and 4.4, respectively, are enormous. The overall energy demand for each ship is the first notable factor. The higher the demand, the longer the fueling time, and thus the variations between the fuels become more apparent. Figure 4.10, which compares cargo, passenger ferry, and high-speed craft, is presented with logarithmic scale in the fueling time due to the vast difference between each ship.

The most notable difference is the amount of time it takes to fuel a hydrogen or Li-ion battery driven vessel versus conventional fuels. When the overall energy demand is comparatively low, as in the case of a high-speed craft, the difference in fueling time for hydrogen and LNG is 31 minutes. This could be a minor factor if the stops at each port allows for some extra time to be reserved for fueling. The average port stops and fueling stops each ship has in their schedule is not known, and therefore it is uncertain what the impact this difference in fueling time could cause. For the cargo ship, the difference is measured in hours, if not days, rather than minutes. This could be a negligable factor due to the presumably longer stops at port in order to load and unload the cargo.

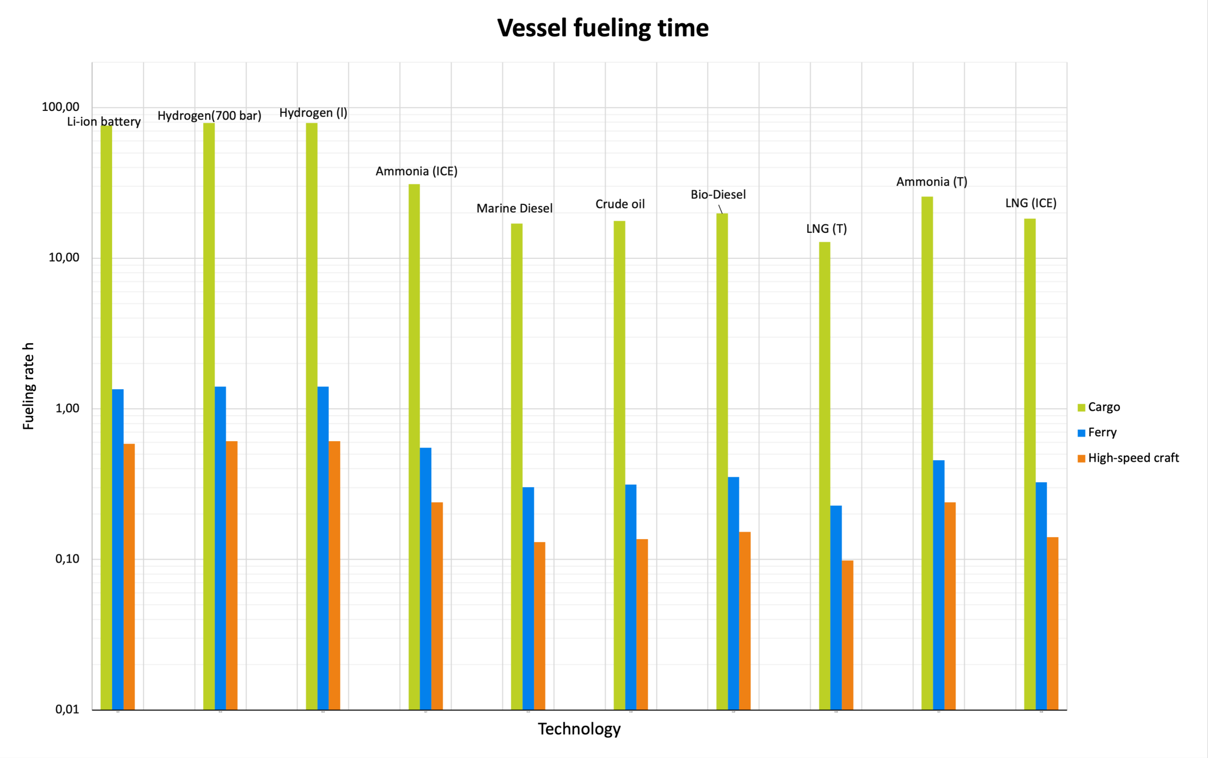

Figure 4.10: Vessel fueling time

Ammonia would have a significant benefit over hydrogen and Li-ion batteries in terms of the fueling time at which the energy demand can be met in a reasonable amount of time. For the cargo ship, the difference between LNG turbine powered propulsion and ammonia turbine powered propulsion is 13 hours. Even though ammonia has 13 hour longer fueling time compared to the other conventional fuel, it has a far less fueling time compared to hydrogen and Li-ion batteries.

The fueling rate is a highly contentious topic, particularly when it comes to the rate at which hydrogen is fuelled. The fulling rate is a relative measurement; there is no “theoretical” limit to the amount of liquid or gas that can be pumped into a tank. A garden hose, for example, can theoretically fill a cubic metre of water in minutes with the right amount of pressure, flow rate, diameter, and material strength. However, due to battery physics and power grids, there could be several drawbacks for a battery’s fueling rate and limitations in its development. As technological advances for ammonia, hydrogen, and Li-ion batteries, the future forecast indicates a higher fueling rate, especially for hydrogen and ammonia. If sometime in the future the infrastructure and technology allows for the same fueling rate for each ship, the fueling time between each fuel would only be determined on the basis of its energy demand and corresponding efficiency. Then the weight requirements and volumetric demand would be a more significant factor in assessing renewable fuels to fossil fuels. By designing a scenario in which the fuel rate is equal in each fuel, this allows for a better understanding in the possible negligence of the fueling rate factor.

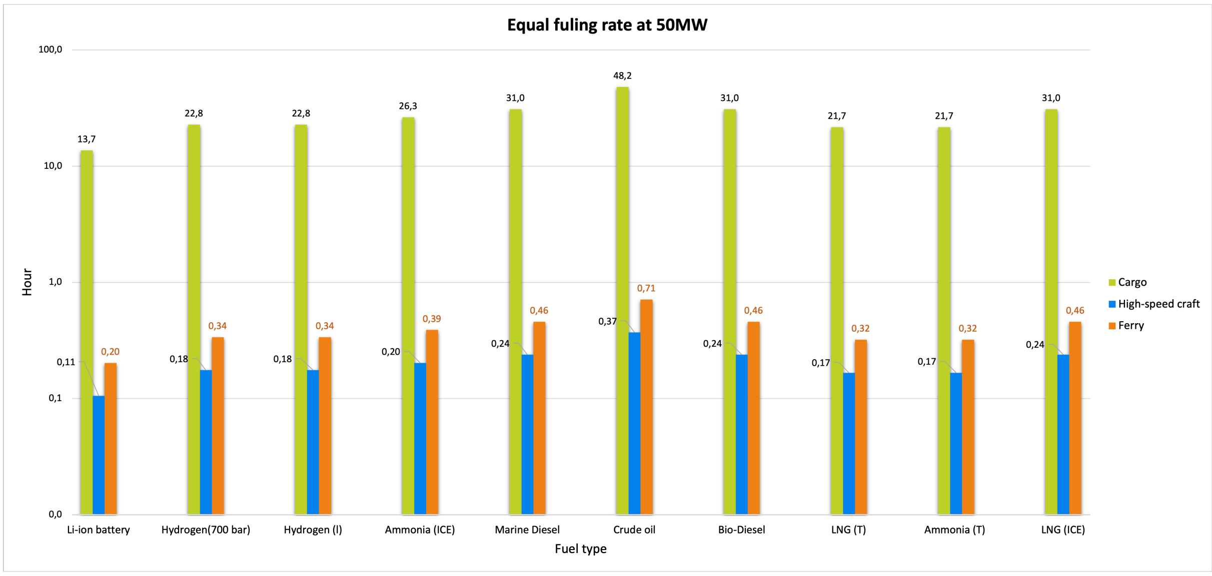

Figure 4.11: Equal fueling rate at 50 MW

Figure 4.11 compared with figure 4.10 shows how a potential future scenario with equal fueling rate could minimize the difference in fueling time. The example of an equal fueling rate set at 50MW is not meant to be realistic, but to highlight how this potential scenario could effect the results. Realistically the equal fueling rate would require the renewable fuel to increase its fueling rate to around 150MW, like the conventional fossil fuels currently has. This would require a lot of technological development and research on this factor. Due to limitations on the possible charging system for Li-ion batteries, this scenario would most likely not be relevant for the Li-ion batteries. It is assumed that it is more likely that technological development and research could increase the fueling rate significantly for both hydrogen and ammonia. The probability of hydrogen and ammonia reaching the levels of conventional fuels is still uncertain.

4.3 Perspective and Proposed Fuel for Each Ship

The results presented in the first and second segment cause for further research and to put the results in perspective. This section analyzes the effects of the presented results and use this to propose which fuels that are suitable for each ship.

4.3.1 The Outcome of the Requirements

Based on the calculations, research, and analysis performed in the previous sections it is possible to propose which fuels are most appropriate. The various vessels address three distinct energy demands, weight constraints, volumetric capacities, average cruising speed, and reasonable fueling rate. The following part will conduct further research on high-speed craft, ferry and cargo, from an energy- and technological perspective, on the suitability of the renewable fuels and their corresponding systems. Because the vast majority of every ship already utilizes conventional fossil fuels, the aspects regarding their suitability to each fuel are not discussed

High-speed Craft

The first thing to establish is the criteria in which a high-speed craft operates. The travel distance is relatively short but at a high speed and it has a large energy demand compared to its size. It travels fast, and therefore requires to be light and optimize the space. Thus, the weight requirements and volumetric demand could be a crucial factor in the assessment. There are many trips on a daily basis and often located in-between well-constructed infrastructures. With those premises established, the next part is to evaluate the suitability of the various fuels.

Both hydrogen and ammonia have high efficiencies as compared to conventional fossil fuels. However, the weight requirement and volumetric demands could be some of their most significant drawbacks. The weight requirement of ammonia is quite close to the fossil fuels, but with the assumption of the extra weight needed to uphold safety regulations and engine modifications, it could have a bigger total impact when analyzing the system requirements as well. However, as presented in table 4.5, ammonia only accounts for approximately 1% of the DWT in the high-speed craft. The weight requirement of hydrogen is the best of every fuel, but has major drawback in its volumetric demand. The volumetric demand of just the hydrogen is almost as high as the Li-ion battery system. The volumetric demand is less when stored in liquid state. If the volume reserved for storage and utilization is a limiting factor, hydrogen stored at liquid state could be an important moderation. Even with the system required for storing and utilizing hydrogen, it can still be a more suitable fuel compared to Li-ion battery, regarding the total volumetric demand. However, hydrogen at 700 bar would require high-pressure storage tanks, and liquid hydrogen requires storage at cryotemperatures which both is an energy-intensive process.

Furthermore, the hydrogen fueling time is longer, but with a difference of only 31 minutes compared with LNG and presumably development in fueling rate for hydrogen, this could be considered as a negligible factor. The fueling time regarding ammonia is also assumed to be within reasonable time. The weight and volume restrictions in the high-speed craft, as well as the fueling time is the limitations for which the suitability is assessed. Hydrogen and ammonia is assumed to fulfill these requirements at an appropriate level, and therefore deemed suitable for high-speed crafts.

As mentioned, Li-ion batteries could struggle to meet the weight and volume requirements. The sheer mass of the battery pack would contribute 18.4 percent of the total DWT for the high-speed craft. The usual percentages included in the DWT is not known for certain, but presumably it is a desire to keep the fuel weight as low as possible for high-speed crafts. The high-speed craft is not big in size, and thus to be able to provide the speed, as well as comfortable commodities for the passengers a 29-tonnage battery pack can pose a problem for the high-speed craft.

Due to the uncertainty of weight and volume restrictions in a high-speed craft, as well as a long fueling time, it is assumed that Li-ion batteries is not suitable for high-speed crafts when being the only fuel. Using batteries in a dual-fuel application could alter this assumption.

Ferry

The criteria in which a ferry operates is slightly different than for a high-speed craft. The travel distance is relatively longer but at a slower speed. The docking time is presumably somewhat longer due to the time it takes for boarding and disembarkment of larger crowds and vehicles. It also has a moderate energy demand compared to size. The weight requirement and volumetric demand have an important impact on the ferry as well, but it is assumed to be not as limiting as the high-speed craft. With those premises established, the next part is to evaluate the suitability of the various fuels.

Because of the specified requirements, the Li-ion battery pack could be better suited for the ferry than the high-speed craft. Given the relationship between engine size and DWT, the total mass of the Li-ion battery would contribute 10.3% of the DWT, or nearly half of the high-speed craft, to cover the energy demand. Furthermore, the volumetric demand and fueling time of 1.35h support the assumption of Li-ion battery's suitability for the ferry.

Because of the volumetric demand, fueling rate, and total mass, fossil fuels, biodiesel, and ammonia are also well suited for the ferry. The most significant disadvantage of hydrogen is, once again, the storage condition. The ability to store 15.35m^3 of hydrogen at 700 bar may be a drawback, but the sheer volumetric demand pales in comparison to the cargo ship.

Cargo

The following conditions would govern the operation of a container ship. Long travel at a slow pace, docking time will last days due to on-and offloading of goods. The weight and volume is assumed not to play as significant role compared to the other ships. The frequency of trips are less than the others, but for longer durations. After those assumptions have been developed, the next step is to assess the suitability of the different fuels.

To start with, weight requirement is not the main problem for cargo. The main purpose of this boat category is to maximise the cargo load and transport goods in vast size in term of volume.

The mass versus DWT, is not a problem compared to high-speed craft in terms of Li-ion batteries, but the total size could create a problem. Given the calculations on Li-ion battery, its straightforward unrealistic to see a battery powered cargo ship with current battery technology. Weight problematics is not the main problem for cargo, but it's the volumetric demand and fuelling rate which create the problem. To put things in perspective, the cargo ship's volumetric demand for Li-ion batteries is calculated to be 1 222.30 m^3 4.4. The visualisation is clear: to cover the Li-ion battery volumetric demand, one will need 8.45 times greater volume than with marine diesel. Since the volumetric criteria is a theoretical expectation, the overall Li-ion battery capacity in a realistic scenario would be much higher. Furthermore, the vast gap in fuelling time, a 59.1-hour difference between marine diesel and Li-ion battery, makes it even more troublesome in a practical scenario where the distance travelled is longer than the trip analyzed in this thesis.

Both hydrogen (l) and hydrogen (700bar) have a weight advantage due to specific energy, but the storage conditions cancels out the benefit. It is a complex problem to store 862 m^3 of hydrogen (700 bar), and the energy requirements to store 472.9 m^3 of hydrogen at cryogenic temperatures would be high. Furthermore, given the low fueling time of 79.2h, 3 hours longer than the Li-ion battery, it would be difficult to envision a practical scenario with hydrogen propulsion given current technologies in terms of storage systems and fueling time. Ammonia, on the other hand, would have many advantages over hydrogen and Li-ion batteries, especially in terms of volumetric demand and fuelling time. Ammonia would have about twice the volumetric demand of marine diesel, but it would not pose a concern for cargo ships as opposed to Li-ion batteries. The needed ammonia will be stored under pressure, but nothing compared to hydrogen (700 bar). One advantage is the requisite fueling time, which is comparable to marine diesel and therefore assumed to be much more feasible than hydrogen or Li-ion batteries.

Fig 4.12 illustrates in which the high-speed craft, ferry and the cargo is proposed located based on the results and discussion. Energy potential of each fuel and proposed ship suitability.

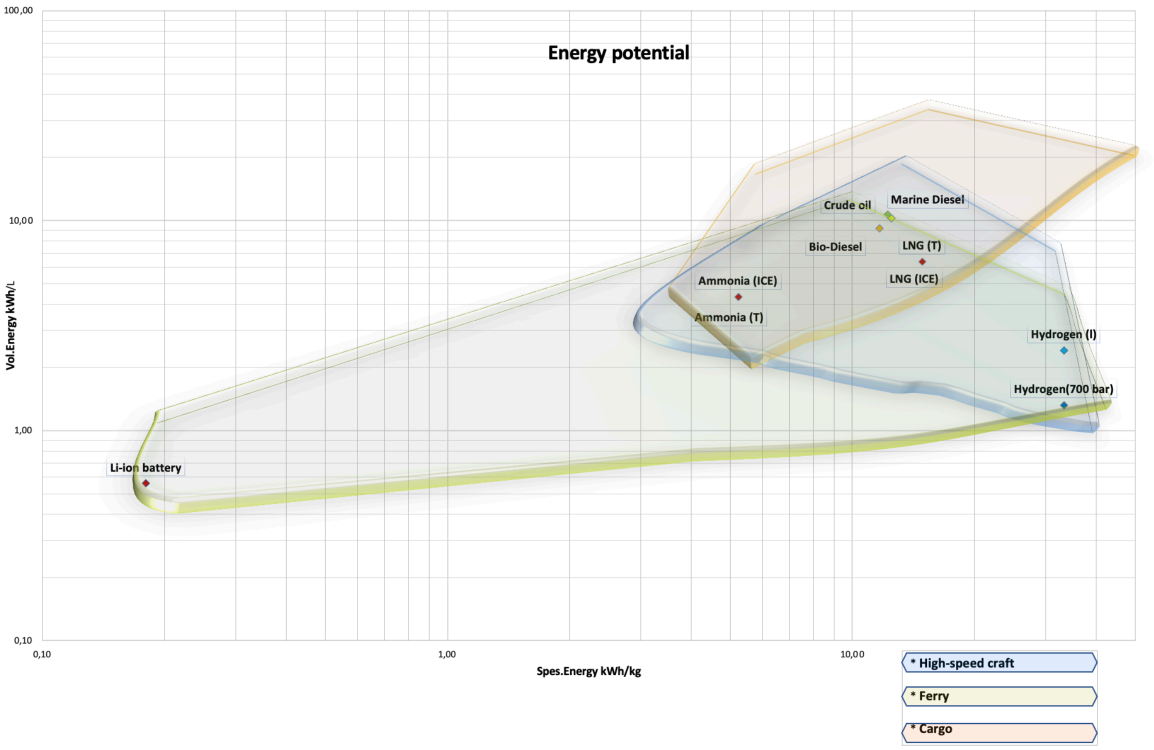

Figure 4.12: Energy potential of each fuel and proposed ship suitability

4.4 Green Energy Demand and Fuel Price Forecast

The energy transition from fossil fuels to renewables for the maritime sector may seem to be a suitable option. However, there are still some drawbacks due to the total energy demand for producing hydrogen, ammonia, and Li-ion battery propulsion. Technical advancements and optimization could close the gap in the future. Nevertheless, as it stands, overall energy demand in manufacturing is quite high, making a more complicated assessment of the feasibility of renewable fuel in the maritime transport sector.

This segment will concentrate on energy demand in terms of green production of various fuels and batteries. Based on the amount of fuel consumed by the various vessels, the total energy demand that renewables must cover to fulfil the required energy demand can be determined. As well as the importance of understanding the entire energy demand, current and future fuel/battery prices will also have an impact on the overall view.

Green Energy Demand

Table 4.6: Energy demand from renewable energy sources

Fuel type	Production	Info
Li-ion battery	58.00	kWh pr. kWh Li-ion
Hydrogen	48.00	kWh/kg
Ammonia	10.00	kWh/kg

Table 4.6 shows the green energy demand required to generate 1 kWh of Li-ion battery capacity, 1 kg of hydrogen, and 1 kg of ammonia. The values are derived from several sources as presented in section 3.3. These values express the amount of energy required to generate the battery and fuels. One important note is that while a Li-ion battery has a higher energy demand due to production, the end product is a rechargeable battery; in contrast, hydrogen and ammonia are not reusable in the same way. To gain a better understanding of the various energy demands, a visual representation of the value chains is developed.

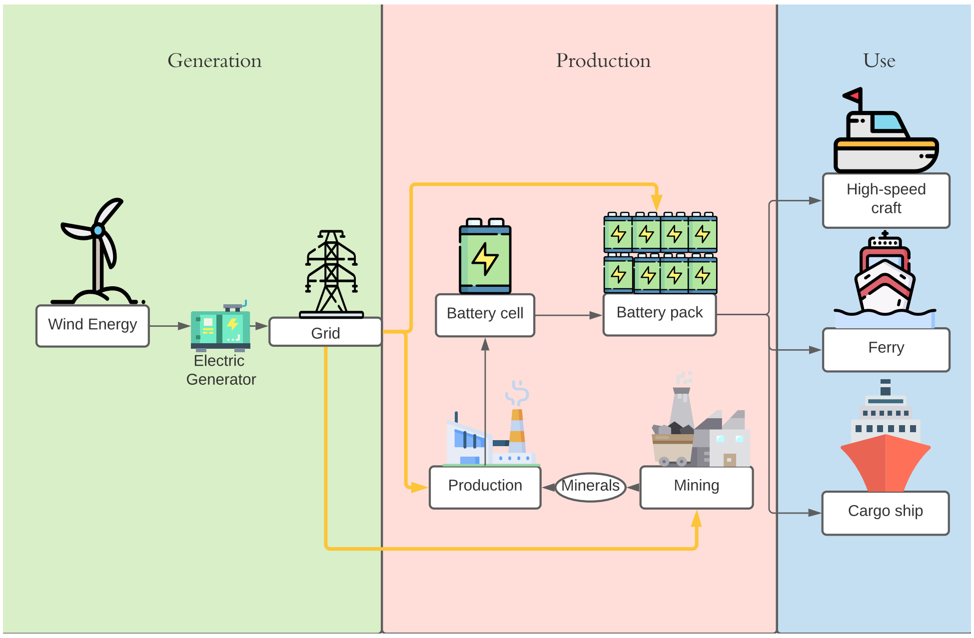

Figure 4.13: Value chain for Li-ion batteries

According to table 4.6, the necessary energy demand for producing 1 kWh of Li-battery corresponds to an input power of 58 kWh. The energy demand for Li-ion production is immense and it corresponds to the visual representation in figure 4.13. The process begins as soon as the wind turbine's blades begin to rotate, generating energy for the mining activity, battery manufacturing and assembly, as well as charging of the Li-ion battery pack. Mining, manufacturing, and assembly are the most energy-intensive activities. Again, this energy demand is based on the production of batteries; after the Li-ion battery is discharged, the energy demand equals the battery capacity.

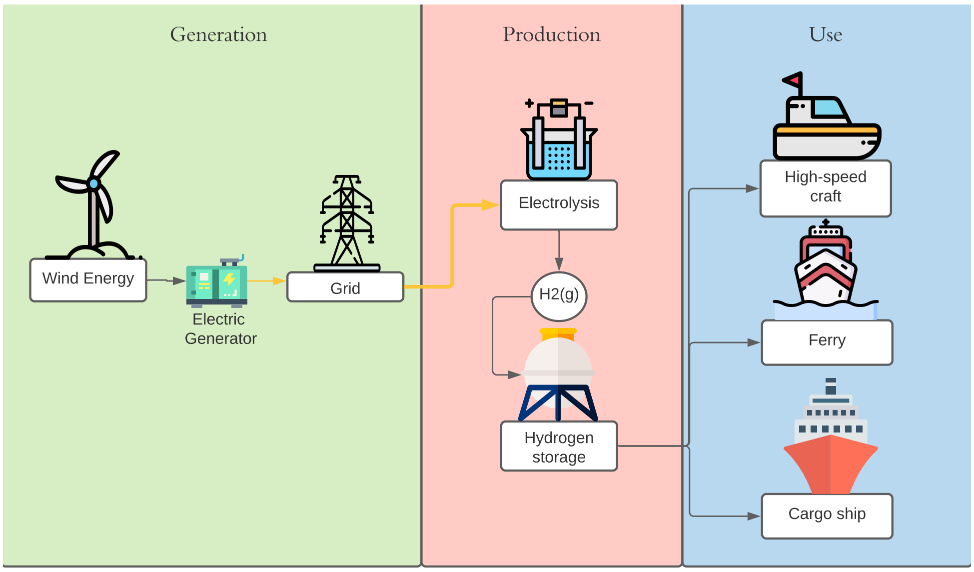

Figure 4.14: Value chain for hydrogen

Hydrogen and oxygen are produced by the electrolysis of water as described in section 2.1.1 using current technology, the total input energy for one kilo of hydrogen is 48 kWh/kg. Electricity is transmitted from wind turbines through grids to power the electrolysis process. Hydrogen is then compressed to 700 bar or cooled to cryotemperatures for further storage and use in the maritime transport sector, as illustrated in figure 4.14. When comparing hydrogen production to the production of Li-ion batteries, the energy demand is nearly identical. With optimalization and technological development for the electrolysis process, prognosis indicates a reduction in energy demand. At 100% efficiency, the theoretical limit is 39 kWh/kg per now, as explained in section 3.3.

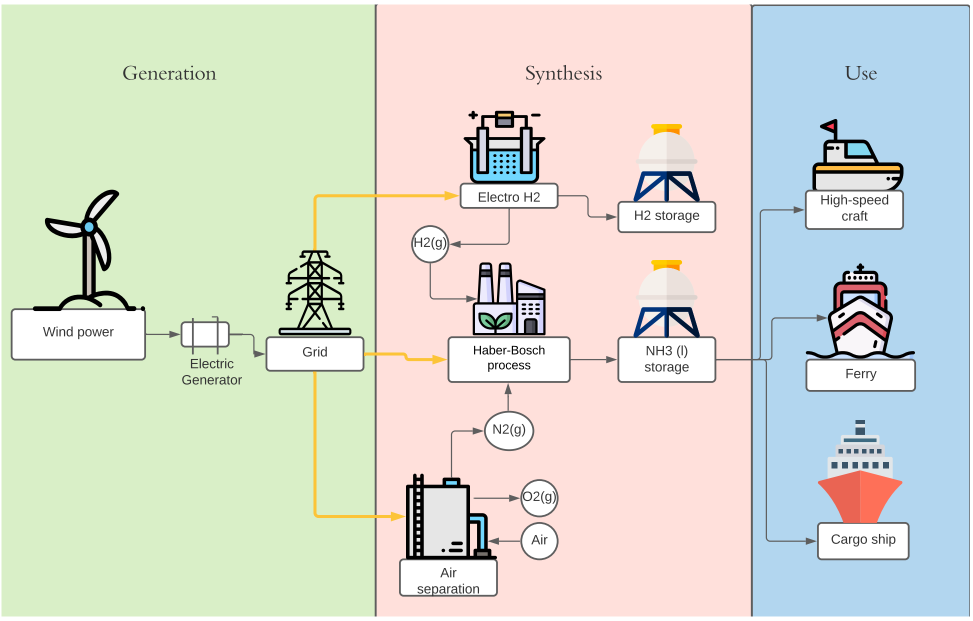

Figure 4.15: Value chain for ammonia

The production of green ammonia is a more substantial process which includes the making of hydrogen, the HB-process and air separation, illustrated in figure 4.15. For each kg of ammonia, the input energy is set to be 10 kWh, a relative low number compared to hydrogen and Li-ion battery production. Methodology section 3.3 addresses the validity of this value. There may be many reasons for why the number is so low, but it is an interesting observation considering that hydrogen production is a component of total ammonia production. One clarification can be found in the theory chapter 2.3.2, which states that it takes 177 kg of hydrogen and 823 kg of nitrogen to produce one ton of ammonia. If this is the case, current electrolysis technology will require 8.5 kWh of total energy for each kilo of ammonia generated at 10 kWh/kg, equivalent to 1.5 kWh in air separation and HB-process combined. With a 100 % efficiency in the electrolysis process, the energy for air separation and the HB-process combined will be 3.1 kWh. The fact that hydrogen is the greatest energy consumer is a common denominator for ammonia production.

The Total Green Energy Demand for the Vessels

Table 4.7 can be used to measure the total green energy demand in production by a wind farm to meet the fuel energy demand for each ship. The calculations are presented in appendix F. This will shed light on a problem with the transition to renewable energy in the maritime sector, namely the enormous energy demand that must be generated. The results regarding Li-ion batteries could be misleading. It has an enormous green energy demand, but this demand is not the demand that would be required for each of the analyzed trips. When the first stack of batteries is produced, it would only require each ship's energy demand by recharging the battery.

Table 4.7: Total green energy demand for each ship's trip

Fuel type	**High-speed craft (MWh)**	**Ferry (MWh)**	**Cargo (MWh)**
Li-ion battery	306	705	39 700
Hydrogen(700 bar)	13	30	1 678
Hydrogen (l)	13	30	1 678
Ammonia (ICE)	20	45	2 521
Ammonia (T)	16	37	2 075

A visualisation of the offshore wind park size can be created by measuring the amount of 15 MW offshore wind turbines will needed for one hour at full load to produce the total green energy demand presented in table 4.7. Table 4.8 shows the amount of 15MW offshore wind turbines to support these energy demands. The offshore wind turbine scenario is not intended to be realistic; rather, it is designed to demonstrate an important point. It is also worth mentioning that this example only evaluates the specific requirements of the chosen ships. There are 93 161 vessels in the world, with 56 000 cargo ships trading internationally and the remainder covering other commercial sectors such as ferry and high-speed crafts, as presented in section 1.3. The purpose and application could change the specific requirements and thereby alter these results significantly. However, the results could give an indication of the challenges regarding energy demand could pose for the feasibility of these renewable fuels. It should be noted that the fuels, especially Li-ion batteries, are not installed and manufactured in a matter of hours. The cumulative energy would be spread out over a longer period of time and thereby reducing the amount of required wind turbines. As mentioned in section 3.3, the total energy demand for producing conventional fossil fuels is not included in this thesis. It is uncertain what the difference in total energy demand is between renewable and conventional fossil fuels. Table 4.8 is calculated as described in section 3.3. The values are presented with a reasonable number of digits. The excact values are presented in table F.3, in appendix F.

Table 4.8: Number of 15MW offshore wind turbines to cover the energy demand

Fuel type	**High-speed craft (15MW)**	**Ferry (15MW)**	**Cargo (15MW)**
Li-ion battery	20	47	2 647
Hydrogen(700 bar)	0.9	2	112
Hydrogen (l)	0.9	2	112
Ammonia (ICE)	1.3	3	168
Ammonia (T)	1	2,5	138

Table 4.8 presents the number of offshore 15MW wind turbines required to meet the demands that are presented in table 4.7. To produce and charge the Li-ion battery pack for the cargo ship, the offshore farm has to consist of 2647 15MW wind turbines, generating 15MWh of electricity each at full load for one hour. Again, this is a highly improbable scenario, but it illustrates an assumption about cargo ships and battery propulsion; modern battery technology is unsuitable for these types of vessels as of today.The market

for Li-ion batteries is strong but not unreasonable for ferry and high-speed craft. Furthermore, because of the massive energy demand for cargo, the number of offshore wind turbines would also be high for ammonia and hydrogen, but just a fraction of what Li-ion needs. In relation to passenger ferries and high-speed crafts, the wind farm will be rather small, consisting of between one to three 15MW wind turbines. This is as predicted due to the far less energy demand for these ships on the trip that is being analyzed.

4.4.1 Fuel Price Forecast

In the maritime industry, fuel prices are a critical factor for providing low-cost transportation of goods and services while also covering maintenance, employee and benefit costs. High fuel prices would imply higher transportation costs, resulting in marginal income for service providers. For the sustainability transition in the transport sector to be feasible, it will be critical to have affordable rates for renewable fuels. Since renewable fuels are produced by electricity, renewable energy production must increase as the price falls in order to achieve this. This section presents the current prices of renewable fuels compared to conventional fossil fuels, and the estimated forecast of these prices in the future.

Figure 4.16 was developed based on the values in table 3.10. As previously stated, the cargo ship will presumably be the most difficult to transition to renewable fuels.The prices that are listed in the table 3.10 are therefore multiplied with the weight requirement for the cargo ship's trip as described in section 3.5. Figure 4.16 therefore depicts the price relation between the current and estimated price forecast for each fuel for the cargo ship's trip. The Li-ion battery is not represented in the figure by virtue of the improbability of a Li-ion battery powered cargo ship. There are also no columns reflecting future estimations for bio-diesel and LNG, due to a lack of evidence on future price forecasts, as described in section 3.5.

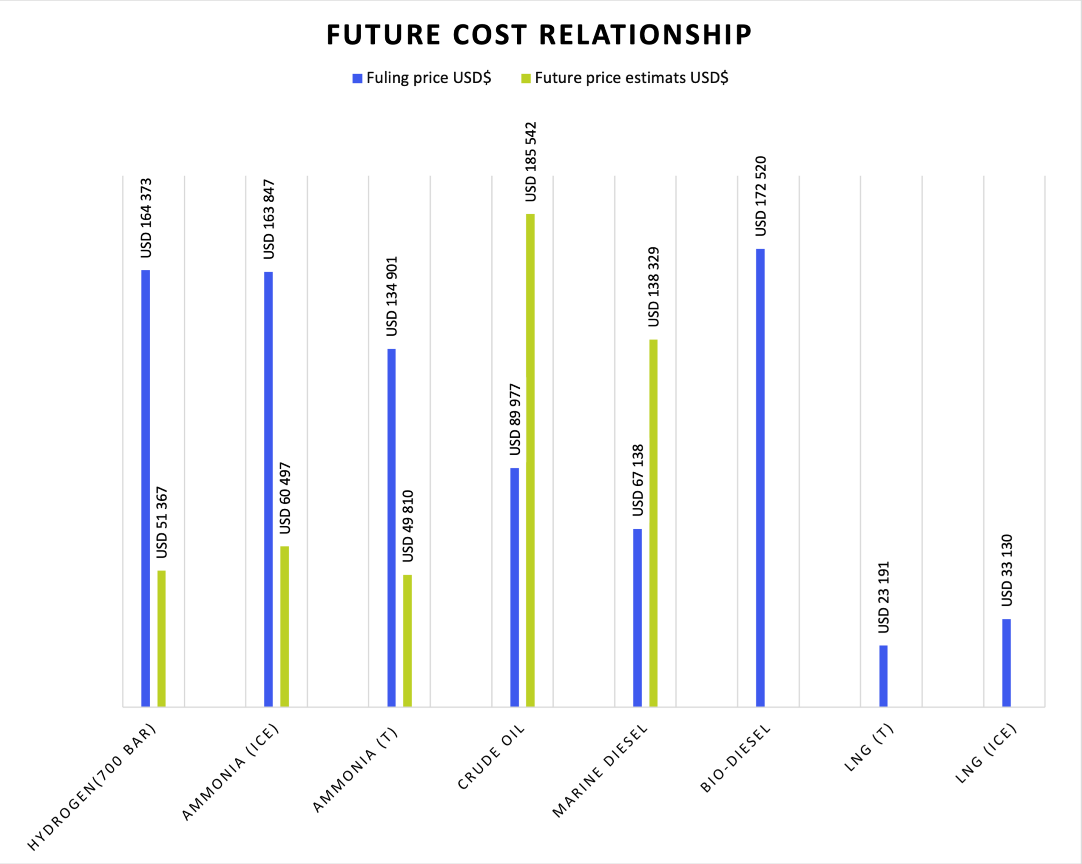

Figure 4.16: Current price and estimated price for the future

With current costs, hydrogen and ammonia are more expensive than fossil fuels. Today, hydrogen fuel will cost the shipping company at least 164 373 USD$, compared to 67 138 USD$ for marine diesel or 23 191 USD$ for a turbine-powered LNG engine. With no government incentives, it is easy to see the economic disadvantage of the use of hydrogen in a cargo ship. In the interests of the European Commission, the Green Deal by 2040, political rewards, the IMO, and other contributors as presented in section 1.1, future prices could change dramatically. With the combination of carbon pricing, modern manufacturing technologies, lower electricity costs, fossil fuel restrictions, and increased engine efficiencies, the potential fuel price scenario depicted in figure 4.16 can be expected. Ammonia has the potential to fall from a current fuel price of at least 163 847 USD$ to 60 497 USD$, while crude oil has the potential to rise from 89 977 USD$ to 185 542 USD$. This shows that the economic feasibility regarding fuel prices could be exceptional, given that the prices develop as predicted. The justification for the future price forecasts and results are clarified in section 3.5. When analyzing the economic factors, it should be noted that the implications and challenges are not limited to the price of fuels. The vast transition in infrastructure and technological development, amongst other factors, should be assessed when analyzing the economic feasibility of these fuels. As it is not analyzed in this thesis, it is uncertain what these structural changes would imply for the feasibility of renewable fuels.

4.5 Environmental Footprint of the Proposed Fuels

This section presents the most significant results from this thesis' literature study. When the results are presented, it will be followed by reflections and examinations of the meaning of the results. The different factors and assumptions that the results as based on, are discussed and put into perspective with this thesis' focus. There is a stronger emphasis on GWP than other impact categories. This is because GWP is the most used category in regards to LCA studies and environmental studies of renewable fuels and energy in general. The possible reduction of GWP is also one of the key reasons for both political and economic interest towards transitioning multiple industries, such as the maritime sector, to a more sustainable future.

4.5.1 Li-ion Battery

The study that this thesis bases its assumption on, analyzes the environmental impact of Li-ion batteries in cars. As shown in figure 2.10 the GWP could be reduced significantly if the electricity used in production stems from hydro power. This would also be the case with the use of wind power. The study suggests that using hydro power could reduce the impact of production by more than 60%. According to the LBV, the production of the battery causes 4.6 tonnes CO_2 throughout its life cycle. This is quite close to the impact a conventional vehicle has, which emits 6.1 tonnes CO_2. The production of electrical cars has been found to have almost twice as high GWP as conventional cars. To be a viable alternative, electrical cars must make up for the large production phase impacts by emitting less in the use phase. This would also apply to ships. However, it is uncertain how much of a difference the impact in production of conventional ships is compared with battery electric ships. The degree of retrofitting is also uncertain, and therefore uncertain what these effects would do to the results when analyzing the same impacts on a marine application.

The battery capacity is measured in kWh and used as a practical unit for batteries. The literature study that this thesis bases its assumption on analyzes various energy densities in terms of MJ/kWh. The values from the LBV-scenario from direct use in cell manufacture has an energy density of 586MJ/kWh and a cell density of 0.174kWh/kg. The cell density is quite close to this thesis' estimates of a cell density of 0.18kWh/kg, which makes the results reliable. This results in a GWP of 107kg CO_2/kWh from direct energy use in cell manufacture, and a GWP of 172kg CO_2 with all components in the battery included. These results could be significantly less if more renewable energy is used as the electricity provider in the manufacturing phase. Figure 2.12 also presents the effect the number of cycles delivered to the battery is important, as well as the powertrain efficiency as a crucial parameter. The number of cycles to drive a given distance will be smaller when the powertrain efficiency is lower. If the vehicle presented in figure 2.12 has a total driving distance of 200 000km, it will take a battery with a powertrain efficiency of 0.5MJ/km about 1500 cycles, whereas about 2350 cycles is demanded by a battery with a powertrain efficiency of 0.8MJ/km. This shows that the number of cycles is dependent on the powertrain efficiency, and therefore the powertrain efficiency affects the usable lifetime of the battery in the vehicle. If the powertrain efficiency is higher, the longer will the usable lifetime of the battery be. To have as long usable lifetime as possible could be an important factor for ship owners when considering Li-ion batteries for their ships. This could be due to a practical and economic factor, but this will also be a positive effect on the GWP of the battery due to lower GWP values when increasing the cycles. It is presented in 2.7.2 that the use of renewables could reduce the impact by 60%. Table 4.9 presents the GWP for Li-ion batteries in cars, and the results given a 60% reduction.

Table 4.9: GWP in a 100-year perspective, including a 60% reduction with the use of renewable energy.

GWP_{100}	[kg CO_2-eq]	[kg CO_2-eq/kWh]
Literature study	4580	172
60%-reduction	1832	69

There are several different factors that could alter these results if applied to ships. This was a study of a NCM traction battery conducted specifically for cars. There are several types of Li-ion batteries that could be preferred in ships due to cost, technical specifications and/or physical benefits. This thesis does not analyze different types, and what the pros and cons might be. When assembling and designing a battery pack, there are several different components in order to establish an effective and working battery. Each of these components has the potential to affect the battery's technological performance as well as the environmental impacts in varying degrees.

The production phase is the biggest contributor to GWP and FDP. And as stated, the use of renewable energy like wind power could reduce these impacts significantly. The other environmental impacts such as FETP and FEP is influenced by the use of copper in the negative current collector. The use of copper indirectly causes the disposal of sulfidic tailings which accounts for 65% of FETP and 62% of MEP. It also accounts for a substantial part of the METP. The disposal accounts for 54% of METP. Using a different metal could reduce the environmental impacts, but also alter the performance of the battery. It is therefore uncertain if the use of another metal actually would be beneficial of the overall assessment of the battery. An alternative to changing the metal could be to reuse copper. This could reduce the overall environmental impacts of the use of Li-ion batteries across different sectors. The reuse and recycling of materials could be an important factor in further development in the battery industry, in order to further the environmental benefits of using Li-ion batteries in vehicles, both on land and in the maritime sector. According to the literature study, it is unlikely that lithium will be recycled. This is due to the present low prices for lithium and the low lithium content in batteries. It is also concluded that despite technological breakthroughs of the use of Li-ion batteries, the planet is in no danger of running out of lithium. As of today, only selected materials, such as cobalt and nickel are being recycled. The recycling of lithium could be next step towards improving the environmental impacts. Though some researchers, as presented in section 2.7.2, have found that even though lithium is a geochemically scarce metal, the use of lithium do not have a big impact of the abiotic depletion potential. It is also uncertain how the demands for infrastructure for these solutions would affect the industry, both environmentally and economically.

4.5.2 Hydrogen and Ammonia

As presented in figure 2.14, the global warming potential in hydrogen from geothermal energy has the lowest greenhouse emissions in the entire life cycle. It resulted in 0.0017kg CO_2 per tonnes kilometer and 0.00098kg CO_2 per tonnes-kilometer, respectively for a freight ship and tanker. This literature study studies the impacts from ammonia and hydrogen derived from biomass, geothermal and municipal waste, as well as supplementary fuels to conventional fossil fuels. As seen in section 2.6.2 the GWP could reduce even more when using wind energy. This thesis bases its evaluation on the use of the renewable fuels derived from wind energy. The results imply that the use of hydrogen in vessels could reduce the GWP significantly. In order to eliminate the technical difficulty of combusting ammonia, the study researched the impact when using ammonia together with conventional fossil fuel. This thesis mainly focuses on the results when using solely ammonia, but as the study shows, even with the dual fuel it could reduce the emissions significantly. When using solely ammonia the GWP is presented to be 0.0035kg CO_2 per tonnes kilometer and 0.0016kg CO_2 per tonnes kilometer, respectively for a freight ship and tanker. The GWP of freight ship and tanker with the use of hydrogen and ammonia derived from geothermal energy, as well as conventional fossil fuel is presented in table 4.10. The GWP is presented in the unit gCO_2/tkm instead of $kgCO_2/tkm$ in this table.

Table 4.10: The GWP in a 500-year perspective values in gCO_2/tkm for hydrogen, ammonia and conventional fossil fuel, for transoceanic freight ships and transoceanic tanker.

Ship	Hydrogen	Ammonia	Conventional
Freight	1.7	3.5	11
Tanker	0.98	1.6	5.3

As shown in the table 4.10 the use of hydrogen could reduce the GWP with 84%, and the use of ammonia could reduce the GWP with 69%. This could be a decisive factor for the maritime industry transitioning towards renewable fuel. This study focuses on the environmental impact in the use of hydrogen and ammonia in big transoceanic vessels. If it were to apply smaller vessels such as a passenger ferry or high speed craft, this could reduce the results even more. This is mainly because the energy demand for operating a transoceanic ship, is significantly higher than with a smaller ship. It is uncertain how much the results would reduce when applying the same analysis on a smaller ship. Ammonia has the advantage that it has long been exported between countries through tankers, implying that the infrastructure for on-board ammonia is already in place. However, to be able to utilize ammonia in an internal combustion engine, the engine needs to be modified in order to withstand the toxic nature of ammonia. It is uncertain how substantial these modifications are, and how this could alter the performance or impact for the ship. It is also uncertain how significant the retrofitting of the ships would be and how much of an impact that would result in. But by looking at the result it is reasonable to assume that it would not affect the result that substantially that it would exceed the impacts of conventional fossil fuel. As presented in section 2.8.2, the IMO estimates that a tanker fueled with crude oil could have a GWP around 0.033kg CO_2, which is tenfold what the results from this study shows.

Some of the concerns regarding ammonia is its toxicity levels if exposed to humans. The health, safety and environment routines that already is in place for exporting ammonia could therefore be a crucial factor for it to be considered a viable option to conventional fuels. Ammonia is also degradeable, which means that it rapidly degrades to toe point that the chemical spills poses little threat to wildlife, and what remains could easily be metabolized by living organisms. Whereas oil spill, which can trigger decades of irreversible damage. When analyzing the toxicity potential of ammonia, it is also worth noticing that the impacts regarding marine sediment ecotoxicity as shown in figure 2.15, marine aquatic ecotoxicity as shown in figure 2.16 and the acidification potential as shown in figure 2.18, all show that the use of ammonia and hydrogen has a significantly lower impact than conventional fossil fuels. The difference in impact between the renewable and fossil fuels could be even higher if the electricity is derived from solely wind energy. It is uncertain how notable the difference would be. Using the assumption based on the values presented in figure 2.5 and 2.7, the use of wind energy as the sole provider of electricity in the production phase, could reduce the impacts even more than what has been analyzed in this literature study.

5 Further Work

As this thesis has conducted a feasibility study regarding important aspects of the fuel performance and technological limitations of renewable fuels. These results, as well as the assessments regarding the environmental footprint this would present, introduced multiple aspects that have not been included in this thesis' assessment. This thesis was written during one semester at the Norwegian University of Science and Technology, and the duration of which this thesis was produced limited the scope of variables included in the study. This section provides some of the aspects needed to give a conclusive answer to the feasibility of renewable fuels in the maritime transport sector.

If the maritime transport sector is to transition towards a sustainable future, it would require a massive change in the infrastructure to provide the necessary fuels and energy. As described in this thesis, the green energy demand for producing Li-ion batteries, hydrogen and ammonia is immense if it is going to replace fossil fuels. It requires a big expansion in wind energy, preferably offshore wind turbines. This thesis has mainly focused on the impacts from production and use phase of renewable fuels. A further insight into the challenges offshore wind energy to the production of each fuel might pose, should be investigated further to give a more comprehensive assessment. Investigating the energy demand for producing fossil fuels should also be analyzed in order to compare the feasibility further. The system for which Li-ion batteries, hydrogen and ammonia are stored and facilitated throughout and between countries would also require a considerable development in infrastructure. How these considerations could affect the economy, environment and market feasibility should be analyzed.

When analyzing the performance of each fuel and the feasibility of the fuels in the ships that are analyzed in this thesis, there are several aspects not included in this thesis that could alter the assessment of each fuel's performance. The weight requirement is calculated on the basis of the fuel's specific energy, assumed efficiency and the energy demand it would present in each ship. The weight of the engine systems of which the fuels are to be utilized is not analyzed, thus could alter the assessments. As explained, there would be several modifications needed to make the fuels feasible in the ships. The impacts this would present on the overall weight and required volume would be valuable to include in an assessment. The specific power each of these engines have would also alter the results and give a more complete assessment of the performance of the fuel. The technology performance in this thesis is instead limited to efficiency. Analyzing the DWT could give an indication of how much the fuel accounts for. The normal percentages in each ship are not investigated and could be an important factor for ship owners when assessing the weight requirement. As the DWT could be an indication of the effects of the weight requirements, there is not a similar indication for the volumetric demand. In each of the ships analyzed in this thesis, there is not any information regarding the space reserved for storage and utilization of the fuels. It is recommended that this factor should be investigated further, as this would influence the impact of the volumetric demand and possible complications this would pose regarding the retrofit of the ships.

The energy demand of each ship is the basis of which the weight requirement, volumetric demand, and the fueling time are calculated. In this thesis, the energy demand is derived solely from the capacity of each ship, assuming a capacity load of 50 and 60%, and the time of the trip. In a realistic scenario, a ship travels through several different zones with different local speed limits, which alters the energy demand significantly throughout the travel. The capacity load in the accelerating phase, travels through RSZs and cruising phases are completely different, and when analyzing the actual energy demand each ship requires, these factors could increase or decrease the overall energy demand from this thesis' calculation. The frequency of stops, as well as the possibility to fuel at these stops throughout these stops should also be included in this analysis. If the actual energy demand for each ship is calculated, the energy demand the fuels would pose is a minimum demand. Presumably, the ship owners also have internal requirements for having enough fuel to cover any unexpected events. To cover these requirements, the weight requirements, volumetric demand and fueling time would all increase.

Throughout this thesis, the feasibility of renewable fuels has been analyzed on the premise that the fuel is to be used as the sole fuel in the ship. The most realistic scenario, especially in the short term, could be to transition towards using a hybrid solution. As it is presented in section 4.5.2, the use of dual fuels could help the physical challenges of ammonia, and reduce the GWP significantly. The sustainability transition of cargo ships and corresponding big ships would be the most difficult to accomplish. Analyzing the feasibility and its impacts when operating on a dual fuel engine, could minimize these challenges. The use of dual fuels could also minimize the challenges affecting hydrogen and batteries in high-speed crafts and passenger ferries. A suggestion for these ships could be to utilize renewable fuels in the main engine, whilst supplementing with fossil fuels when needed in an auxiliary engine. The feasibility of this and what effects it may present would be beneficial to know before determining which solution suits each ship category best.

The most significant and important assessment to further this analysis is on the financial feasibility of the sustainability transition in the maritime transport sector. Some aspects regarding the fuel price and estimated price forecasts are presented in this thesis, but for the transition to be feasible, thorough assessments on the financial feasibility should be conducted. Every aspect included in this thesis, as well as the work suggested in this section, should all be analyzed from an economic point of view. It is assumed that all the advantages renewable fuels could have or develop, do not matter if the financial feasibility is determined to be unrealistic. The financial feasibility should, in that case, highlight which aspects that need improvement in order to bring the economy to a satisfactory level. A thorough financial feasibility study, together with a technological feasibility study, should be analyzed together to show if some challenges from an economic point of view could be solvable through modifications in the technological part, and vice versa.

6 Conclusion

This thesis's objective is to give an overview of the opportunities and challenges for the use of Li-ion batteries, hydrogen or ammonia as fuels in maritime applications. With the purpose of analyzing a broad spectrum of ships, the given renewable fuels are analyzed based on the attributes in a cargo ship, passenger ferry and high-speed craft. The aim is to provide an overview of the research question, which is as follows: **Is the sustainability transition of the maritime transport sector feasible through the use of either hydrogen, Li-ion batteries or ammonia as fuel, when produced by offshore wind power?**

In order to answer this, a thorough analysis of the properties of each fuel, requirements of each ship and the environmental footprint is analyzed. The information is mainly retrieved by a literature study on the different aspects. The sustainability transition of the maritime sector is a complex and comprehensive challenge. This thesis' focus is on the technological and physical requirements that each fuel and ship would pose. In order to give a conclusive answer to the research question, the financial feasibility, as well as the proposed aspects for further work, is considered essential. This thesis's conclusions are therefore meant to be regarded as indicative rather than definite.

The utilization of hydrogen is recommended for high-speed crafts. Its high specific energy, as well as a satisfactory volumetric demand, causes hydrogen to be deemed feasible in high-speed crafts. The results show that the use of hydrogen could reduce the GWP by at least 84%.

The utilization of Li-ion batteries is recommended for passenger ferries. Its high efficiency and satisfactory physical requirements cause Li-ion batteries to be recommended on passenger ferries. The results show that the use of Li-ion batteries could reduce the GWP by at least 60%.

The utilization of ammonia is recommended for cargo ships. Its high fuel performance and suitability for ICEs and turbines, as well as satisfactory physical requirements, causes ammonia to be recommended in cargo ships. The results show that the use of ammonia could reduce the GWP by at least 69%.

Based on the fuel performance, corresponding physical requirements and superior environmental advantages, Li-ion batteries, hydrogen and ammonia are considered as feasible options for fuels in order to accomplish the sustainability transition.

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A Vessel information

Information retrieved from MarineTraffic on Baby Hercules (Cargo), MS Terningen (high-speed craft) and MF Værøy (passenger ferry).

Table A.1: High-speed craft information

Vessel type:	Cargo	High-speed craft	Ferry
Engine (kW)	13560,00	2880,00	5200,00
Trip (nm)	1055,00	95,00	57,00
Avg Knp	11,00	32,80	15,40
Length (M)	240,00	40,80	95,99
DWT (tonnes)	110861,00	159,00	650,00
Trip duration (h)	95,91	2,90	3,70

When analyzing the weight requirement, volumetric demand, and the fueling time for each fuel, the energy demand when using these fuel is the basis of the calculations. The weight requirement is found by dividing the energy demand with the specific energy of the respective fuel. The volumetric energy is found by dividing the energy demand with the volumetric energy of the respective fuel. The fueling time is found by dividing the energy demand with the fueling rate of the respective fuel. To show the calculations for the energy demand, the values presented for cargo ship in table A.1 is used as an example. It is assumed that the ship has han average load of 50%. The engine capacity therefore 13 560kW $\cdot$ 0.5= 6 780kW. When multiplying this new engine capacity with the hour needed for the trip, the energy demand is presented in kWh. The same calculations has been executed for each ship and presented in table A.2.

Table A.2: Primary ship information

Info:	Cargo	High-speed craft	Ferry
Motor: kW	13560,00	2880	5200
Rpm	105,00	-	-
Fuel.Vol: m^3	3994,00	-	-
Fuel.Type	Marine Diesel	Marine Diesel	LNG
Efficency, %	0,42	0,42	0,42
Trip: NM	1055,00	95,00	57,00
Avg. Knp	11,00	32,80	15,40
max: Knp	12,20	34,40	16,80
L: m	240,00	40,80	95,99
Carry DWT, ton	110861,00	159,00	650,00
Full load avg.	0,50	0,60	0,60
Energy usage: kw	6780,00	1728,00	3120,00
Trip duration: h	95,91	2,90	3,70
Energy demand: kWh	650263,64	5004,88	11548,05

B Fuel performance metrics

The fuel performance metrics are listed in table B.1. The values are acquired from multiple sources and are based on assumptions derived from these sources. These values are the basis for which further calculations on the performance of each fuel in each ship. The energy potential is derived from the relationship between volumetric and specific energy.

Table B.1: Data information regarding the primary source

	Spes.Energy	Vol.Energy	Spes.power	Fueling rate	Efficiency	Density		Production
	kWh/kg	kWh/L	kW/kg	MW	%	kg/L		Kwh
Li-ion battery	0,18	0,56	2,40	9,00	0,95	0,32		58,00
Hydrogen(700 bar)	33,31	1,32	1,60	14,39	0,57	0,04		49,00
Hydrogen (l)	33,31	2,41	1,60	14,39	0,57	0,07		49,00
Ammonia (ICE)	5,22	4,33	0,24	42,32	0,49	0,83		10,00
Marine Diesel	12,22	10,72	0,24	142,06	0,42	0,88		-
Crude oil	12,50	10,28	0,24	136,17	0,27	0,82		-
Bio-Diesel	11,67	9,17	0,24	121,45	0,42	0,79		-
LNG (T)	14,86	6,39	0,70	84,65	0,60	0,43		-
Ammonia (T)	5,22	4,33	0,70	42,32	0,60	0,83		10,00
LNG (ICE)	14,86	6,39	0,24	84,65	0,42	0,43		-

C Energy and physical demand for each ship

By dividing the energy demand that the cargo ship pose, with the given efficiency rate, the energy demand of each fuel in the cargo ship can be further analyzed. The values are presented in table C.1

Table C.1: Cargo energy demand

Total energy demand based on engine efficiency	
Fuel energy demand (0.95) : kWh	684488,04
Fuel energy demand (0.60) : kWh	1083772,73
Fuel energy demand (0.57) : kWh	1140813,40
Fuel energy demand (0.49) : kWh	1316323,15
Fuel energy demand (0.27) : kWh	2408383,84
Fuel energy demand (0.42) : kWh	1548246,75

When analyzing the weight requirements, volumetric demand and fueling time. The fuel energy demand, listed in table C.1 is important. The weight requirement, given in kg, is calculated by dividing the fuel energy demand [kWh] with the specific energy [kWh/kg] of the fuel. For example, Li-ion batteries has an efficiency of 95% which equates to 684488,04kWh. Dividing this with the specific energy of 0.18 results in a fuel weight requirement of 3 802 711.32kg for the cargo ship. The volumetric demand is calculated by dividing the fuel energy demand [kWh] with the volumetric energy [kWh/L] of the fuel. For example, Li-ion batteries has an efficiency of 95% which equates to 684488,04kWh. Dividing this with the volumetric energy of 0.56kWh/L gives the volumetric demand of 1222.30m^3 for the cargo ship when converted from L to m^3. The fueling time is calculated by dividing the fuel energy demand [kWh] with the fueling rate of the fuel. For example, Li-ion batteries has an efficiency of 95% which equates to 684488,04kWh. Dividing this with the fueling rate of 9MW (converted to 9000kW), gives the fueling time of 76.05hours in the cargo ship. These calculations are done in excel for each of the fuels. The values are presented in table C.2

Table C.2: Cargo physical demand

Fuel type	Kg fuel	Fueling time (h)	Vol.demand (m^3)	Green energy demand (kWh)
Li-battery	3802711,32	76,05	1222,30	39700306,22
Hydrogen(700 bar)	34244,37	79,28	862,62	1677973,95
Hydrogen (l)	34244,37	79,27	472,88	1677973,95
Ammonia (ICE)	252072,61	31,10	303,77	2520726,06
Marine Diesel	126674,96	16,95	144,40	-
Crude oil	192670,71	17,69	234,32	-
Bio-Diesel	132707,62	19,83	168,90	-
LNG (T)	72926,82	12,80	169,63	-
Ammonia (T)	207539,78	25,61	250,10	2075397,79
LNG (ICE)	104181,17	18,29	242,33	-

By dividing the energy demand that the high-speed craft pose, with the given efficiency rate, the energy demand of each fuel in the high-speed craft can be be further analyzed. The values are presented in table C.3

Table C.3: High-speed craft energy demand

Total energy demand based on engine efficiency	
Fuel energy demand (0.95) : kWh	5268,29
Fuel energy demand (0.60) : kWh	8341,46
Fuel energy demand (0.57) : kWh	8780,49
Fuel energy demand (0.49) : kWh	10131,33
Fuel energy demand (0.27) : kWh	18536,59
Fuel energy demand (0.42) : kWh	11916,38

When analyzing the weight requirements, volumetric demand and fueling time. The fuel energy demand, listed in table C.3 is important. The weight requirement, given in kg, is calculated by dividing the fuel energy demand [kWh] with the specific energy [kWh/kg] of the fuel. For example, Li-ion batteries has an efficiency of 95% which equates to 5268,29kWh. Dividing this with the specific energy of 0.18 results in a fuel weight requirement of 29268,29kg for the high-speed craft. The volumetric demand is calculated by dividing the fuel energy demand [kWh] with the volumetric energy [kWh/L] of the fuel. For example, Li-ion batteries has an efficiency of 95% which equates to 5268,29kWh. Dividing this with the volumetric energy of 0.56kWh/L gives the volumetric demand of 9,41m^3 for the high-speed craft when converted from L to m^3. The fueling time is calculated by dividing the fuel energy demand [kWh] with the fueling rate of the fuel. For example, Li-ion batteries has an efficiency of 95% which equates to 5268,29kWh. Dividing this with the fueling rate of 9MW (converted to 9000kW), gives the fueling time of 0,59hours in the high-speed craft. These calculations are done in excel for each of the fuels. The values are presented in table C.4

Table C.4: High-speed craft physical demand

Fuel type	Kg fuel	Fueling time (h)	Vol.demand (m^3)	Green energy demand (kWh)
Li-battery	29268,29	0,59	9,41	305560,98
Hydrogen(700 bar)	263,57	0,61	6,65	12914,85
Hydrogen (l)	263,57	0,61	3,64	12914,85
Ammonia (ICE)	1940,12	0,24	2,34	19401,25
Marine Diesel	974,98	0,13	1,11	-
Crude oil	1482,93	0,14	1,80	-
Bio-Diesel	1021,41	0,15	1,30	-
LNG (T)	561,30	0,10	1,31	-
Ammonia (T)	1597,37	1,92	1,93	15973,69
LNG (ICE)	801,85	0,14	1,86	-

By dividing the energy demand that the passenger ferry pose, with the given efficiency rate, the energy demand of each fuel in the passenger ferry can be further analyzed. The values are presented in table C.5

Table C.5: Ferry energy demand

Total energy demand based on engine efficiency	
Fuel energy demand (0.95) : kWh	12155,84
Fuel energy demand (0.60) : kWh	19246,75
Fuel energy demand (0.57) : kWh	20259,74
Fuel energy demand (0.49) : kWh	23376,62
Fuel energy demand (0.27) : kWh	42770,56
Fuel energy demand (0.42) : kWh	27495,36

When analyzing the weight requirements, volumetric demand and fueling time. The fuel energy demand, listed in table C.5 is important. The weight requirement, given in kg, is calculated by dividing the fuel energy demand [kWh] with the specific energy [kWh/kg] of the fuel. For example, Li-ion batteries has an efficiency of 95% which equates to 12155,84kWh. Dividing this with the specific energy of 0.18 results in a fuel weight requirement of 67532,47kg for the passenger ferry. The volumetric demand is calculated by dividing the fuel energy demand [kWh] with the volumetric energy [kWh/L] of the fuel. For example, Li-ion batteries has an efficiency of 95% which equates to 12155,84kWh. Dividing this with the volumetric energy of 0.56kWh/L gives the volumetric demand of 21,71m^3 for the passenger when converted from L to m^3. The fueling time is calculated by dividing the fuel energy demand [kWh] with the fueling rate of the fuel. For example, Li-ion batteries has an efficiency of 95% which equates to 12155,84kWh. Dividing this with the fueling rate of 9MW (converted to 9000kW), gives the fueling time of 1.35hours in the cargo ship. These calculations are done in excel for each of the fuels. The values are presented in table C.6

Table C.6: Ferry physical demand

Fuel type	Kg fuel	Fueling time (h)	Vol.demand (m^3)	Green energy demand (kWh)
Li-battery	67532,47	1,35	21,71	705038,96
Hydrogen(700 bar)	608,15	1,41	15,35	29799,19
Hydrogen (l)	608,15	1,41	8,41	29799,19
Ammonia (ICE)	4476,57	0,55	5,40	44765,65
Marine Diesel	2249,62	0,30	2,56	-
Crude oil	3421,65	0,31	4,16	-
Bio-Diesel	2356,76	0,35	3,00	-
LNG (T)	1295,11	0,23	3,01	-
Ammonia (T)	3685,71	0,45	4,44	36857,05
LNG (ICE)	1850,16	0,32	4,30	-

D Efficiency range for various fuels

Table D.1: The maximum and minimum efficiency for the different technologies

Efficiency Technology type	Max	Min
Li-battery	96,00 %	80,00 %
Hydrogen(700 bar)	60,00 %	40,00 %
Hydrogen (l)	60,00 %	40,00 %
Ammonia (ICE)	49,00 %	35,00 %
Marine Diesel	55,00 %	30,00 %
Crude oil	35,00 %	20,00 %
Bio-Diesel	55,00 %	30,00 %
LNG (T)	80,00 %	30,00 %
Ammonia (T)	80,00 %	30,00 %
LNG (ICE)	50,00 %	39,00 %

These ranges are used to highlight how the results could vary dependent on these values. These values are set in a graph in Microsoft Excel to show this thesis's assumption and error bars to show how the results may vary.

E Scenario with equal fueling rate

To show how a potential future scenario with equal fueling rate would affect the results, the fueling time is calculated for each fuel, in each ship category. The fueling time is calculated by dividing the fuel energy demand [kWh] with the fueling rate of the fuel.

Table E.1: Table for an equal fueling rate at 50 MW

Equal fueling rate at 50MW	Cargo [h]	High-speed craft [h]	Ferry [h]
Li-battery	13,7	0,11	0,20
Hydrogen(700 bar)	22,8	0,18	0,34
Hydrogen (l)	22,8	0,18	0,34
Ammonia (ICE)	26,3	0,20	0,39
Marine Diesel	31,0	0,24	0,46
Crude oil	48,2	0,37	0,71
Bio-Diesel	31,0	0,24	0,46
LNG (T)	21,7	0,17	0,32
Ammonia (T)	21,7	0,17	0,32
LNG (ICE)	31,0	0,24	0,46

F Energy Demand in production

The values in F.1 are derived from different sources, and are the basis for the calculations regarding the energy demand in production.

Table F.1: Energy demand from renewable energy sources

Fuel type	Production	Info
Li-ion battery	58,00	kWh pr. kWh Li-ion
Hydrogen	49,00	kWh/kg
Ammonia	10,00	kWh/kg

When analyzing the energy demand for Li-ion batteries, the green energy demand is multiplied with the energy demand required for each ship's trip. When analyzing the energy demand for both hydrogen and ammonia, their respective green energy demand is multiplied with the weight requirement for the respective fuel in each ship. The difference of calculations are due to the unit of measurements listed in table F.1. The calculated values are listed in table F.2.

Table F.2: Energy demand for each ship's trip

Fuel type	High-speed craft (MWh)	Ferry (MWh)	Cargo (MWh)
Li-ion battery	305,56	705,04	39 700,31
Hydrogen(700 bar)	12,91	29,80	1 677,97
Hydrogen (l)	12,91	29,80	1 677,97
Ammonia (ICE)	19,40	44,77	2 520,73
Ammonia (T)	15,97	36,86	2 075,40

The values listed in table F.2 presents the energy demand in production for the respective ship's analyzed trip. In order to analyze the demand this would present of the offshore wind turbines, the energy demand listed in table F.2 is divided by 15MW, which is the capacity of offshore wind turbines used in this thesis. The results are thereby given in hours. It could either be evaluated as the amount of hours one single offshore wind turbine must produce at full capacity, or the amount of wind turbines required for producing at full capacity in one hour. These results are listed in table F.3.

Table F.3: Number of 15MW offshore wind turbines to cover the energy demand

Fuel type	**High-speed craft (15MW)**	**Ferry (15MW)**	**Cargo (15MW)**
Li-ion battery	20,37	47,00	2 646,69
Hydrogen(700 bar)	0,86	1,99	111,86
Hydrogen (l)	0,86	1,99	111,86
Ammonia (ICE)	1,29	2,98	168,05
Ammonia (T)	1,06	2,46	138,36

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