Reduction in emissions for Kystruten - a hydrogen feasibility study

Design of an energy system for emissions reduction

of at least 75 % compared to a 2010 baseline,

using hydrogen as the main fuel supply

Magnus Vestrheim

Eirik Aardal Lorentzen

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Magnus Vestrheim
Eirik Aardal Lorentzen

Department of Mechanical- and Marine Engineering
Western Norway University of Applied Sciences
NO-5063 Bergen, Norway

IMM 2020-M74

Høgskulen på Vestlandet

Fakultet for Ingeniør- og Naturvitskap

Institutt for maskin- og marinfag

Inndalsveien 28

NO-5063 Bergen, Norge

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Author(s), student number:	Magnus Vestrheim, 572008
	Eirik Aardal Lorentzen, 150049
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Supervisor at HVL:	Velaug Myrseth Oltedal
Assigned by:	Hub for Ocean
Contact person:	Mark Purkis
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Preface

This bachelor thesis is written at the Department of Mechanical and Marine engineering at Western University of Applied sciences (WNUAS) in the study program Energy technology. The aim of this feasibility study is to examine if a 75% reduction in emissions utilizing hydrogen as main fuel supply, compared to a 2010 base line of a diesel consumption of 200 tonnes for a Kystruten round trip, is possible.

The internal supervisor for this project has been Velaug Myrseth Oltedal, assisting leader of the Department of Mechanical and Marine Engineering at WNUAS. The group thanks the internal supervisor for weekly meetings discussing the project, and for valuable help and advice regarding the project.

The external supervisor for this project has been Mark Purkis, trainee in Renewable energy and hydrogen value chain at Ocean Hyway Cluster. The group thanks the external supervisor for weekly meetings discussing the project, and for valuable help and advice regarding the project. Trond Strømgren and Steinar Frøyen Kostøl also have kindly provided valuable advice regarding the project. Erik Iansenn, CEO at Selfa Artic, has provided the group a spreadsheet of energy calculations regarding an emission free Kystruten.

The group thanks the supervisors for a final proofreading, beyond normal working hours, of this thesis and is aware that this is not required for supervisors to do.

The group went on a study trip to Fosnavåg with financial support provided by Ocean Hyway Cluster. Here the group visited Havyard Group ASA, Myklebust Verft and Ulmatec Baro AS. The trip started 22. January from Bergen and the group travelled to Florø with Hurtigruten. The 24. January the study trip ended, and the group travelled by airplane to Bergen. The group is grateful for the opportunity received to visit world leading companies within their industry and found the study trip most interesting and educational.

Abstract

The aim of this thesis is to examine if a reduction in emissions for the Kystruten operator of 75 % using hydrogen as the main fuel supply is possible, when compared to a 2010 baseline with an assumed diesel consumption of 200 tonnes diesel for a round trip Bergen-Kirkenes-Bergen.

To present a realistic case, lifetime emissions from the different fuels has been necessary to include. Lifetime emissions, for diesel and natural gas, include emissions all the way from field exploration until the fuel is stored onboard the ship. The emission factor of the Norwegian power grid is based on a life cycle analysis from the different electrical energy generation technologies used in Norway.

Hydrogen can be produced by various technologies, leading to differing emissions of greenhouse gasses. Currently *steam methane reforming* (SMR) is the commonly used technology to produce hydrogen, in which the mission factor is 9,5 kg CO_2-eq/kg H_2. *Carbon Capture and Storage* (CCS) is a technology where the emitted CO_2 is captured and stored. CCS has the potential to capture and store up to 90 % of emissions from the SMR process.

Water electrolysis is another method to produce hydrogen. This is an energy demanding process requiring 55 kWh/kg produced H_2. In 2018, the Norwegian electricity mix had an emission factor of 18,9 g CO_2-eq/kWh, which is significantly lower than the emissions from steam reforming. Consequently, using electrolysis powered by the Norwegian power grid, will reduce emissions from the hydrogen production process.

Results show that in order to achieve the 75 % reduction in emissions compared to the 2010 baseline, hydrogen produced from electrolysis powered by the Norwegian power grid in a hybrid system with *liquefied natural gas* (LNG) would achieve the 75 % reduction in emissions. This would require storage tanks onboard the Kystruten ships equivalent to 4,7 tonnes and 6,7 tonnes for hydrogen and LNG respectively.

Sammendrag

Målet med denne oppgaven er å studere om en reduksjon i utslipp på 75 % ved bruk av hydrogen som hoveddrivstoff er mulig sammenlignet med utslipp fra 2010, med et antatt dieselforbruk på 200 tonn for en rundtur Bergen-Kirkenes-Bergen.

For å få et realistisk bilde over utslipp fra de forskjellige drivstoffene har det vært nødvendig å inkludere utslipp fra hele livsløpet til de forskjellige drivstoffene. Dette inkluderer for diesel og naturgass utslipp fra utforsking etter felt til drivstoffet er i tanken på skipet. Norsk kraftnetts CO_2 innhold er beregnet ut fra en livsløpsanalyse fra de forskjellige metodene å generere elektrisk energi på brukt i Norge.

Hydrogen kan bli produsert fra forskjellige teknologier, som innehar ulikt utslipp av klimagasser. I dag er reformering av naturgass den vanligste produksjonsmetoden, med utslipp på 9,5 kg CO_2-eq/kg H_2. Karbonfangst er en teknologi som fanger CO_2 og lagrer den. Dette har potensiale for å fange og lagre opp til 90 % av CO_2 utslipp forbundet med hydrogenproduksjonsprosessen ved reformering av naturgass.

Elektrolyse av vann er en annen måte å fremstille hydrogen på. Dette er en energikrevende prosess med energibehov 55 kWh/kg produsert H_2. Ved bruk av det norske kraftnettet, vil norsk energimiks inneha et karboninnhold i form av 18,9 g CO_2-eq/kWh, noe som fører til betydelig mindre utslipp sammenlignet med reformering av naturgass.

Resultatet viser at for å oppnå målsetningen med 75 % reduksjonen i utslipp sammenlignet med utgangspunktet fra 2010, vil hydrogen produsert ved elektrolyse driftet av norsk kraftnett i et hybrid system med LNG oppnå en tilfredsstillende reduksjon. Lagringstanker ombord på Kystruten skipene krever lagringskapasitet på 4,7 tonn og 6,7 tonn for hydrogen og LNG henholdsvis.

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1 Introduction

Hydrogen as an energy carrier has received increasing attention due to the green energy transition currently happening in the world. Renewable energy sources, like wind and solar, are intermittent and depends on uncontrollable factors such as sunshine and wind, to convert into electrical energy. While the electrical energy conversion is none constant, the electrical energy demand is. This results in increased attention for methods of energy storage. In periods of surplus energy conversion, hydrogen can be produced using electrolysis and later be converted into electrical energy in periods of energy shortages.

The worlds total energy consumption in 2016 was 400 EJ. Approximately 3 % of this was used to produce hydrogen. Pure hydrogen exists naturally only in very small amounts and has to be produced by separating it from chemical compounds, like water. This is why hydrogen is an energy carrier, not an energy source. Hydrogen is most often produced by severing the chemical bond from carbon fuel like oil and *natural gas* (NG) or by electrolysis of water. [1]

Almost all hydrogen produced today is used as a feedstock in process industry, for example in ammonia production, methanol production and in oil refineries. These industries makes up 90% of the world's hydrogen consumption. [1]

The prospect of a zero emission fuel for maritime industry would be relevant for several of the UN's Sustainable Development goals, nr 7, 9, 13 and 14 [2]. UN's *International Maritime Organization* (IMO) has decided that emissions in the maritime industry worldwide shall have a decrease in emissions of 50 % within 2050, compared to emissions from 2008 [3]. Norway has an ambition that within 2030 all ships should be fuelled by biofuel or be low- or zero emission vessels, and that within 2050 the transport sector shall be virtually emission free. [4]

Currently, there is a lot of ongoing research in Norway on how hydrogen could be an important energy carrier in a low emission society. DNV-GL has written a synthesis report on the future utilization of hydrogen in Norway [5]. NCE Maritime Clean Tech, a maritime cluster, has made a report of the future value chain of liquid hydrogen in Norway [6]. An ongoing project, GKP7H2, where Trond Strømgren at Ocean Hyway Cluster is the project lead, is a high-speed passenger vessel which utilizes hydrogen as the main fuel supply in a hybrid system with batteries. This project led to the project “Pilot hydrogen passasjerbåt og pilotrute Florø-Måløy” [7]. These literature references have been a main source of information for this work.

The overall goal of the project is a bid for a hypothetical tender. The tender includes operation of 5 ships running on a similar schedule of today. Emission reduction of at least 75 % when compared to a 2010 baseline with 200 tonnes diesel consumption for a round trip Bergen-Kirkenes-Bergen, using hydrogen and the main fuel supply. The tender should include a technical specification of the ship’s energy system as well as an evaluation considering safety, environmental, and economic factors.

In 2017 Samferdselsdepartementet put out 3 tenders of operation of Kystruten. Havila won one of the tenders and from 2021 they will operate 4 of the 11 Kystruten ships [8]. The remaining 7 ships will be operated by Hurtigruten. The Havila Kystruten ships will initially run on LNG, but are designed for future use of hydrogen and is currently designing and developing the technology to make this a reality.

In this thesis, studies of the hypothetical case of 5 of 11 eleven ship running on hydrogen is performed. The main goal for this thesis is to achieve a 75 % reduction in emissions when compared to the 2010 baseline. While 5 of the ships should use hydrogen as main fuel supply, the other 6 ship operated by Hurtigruten may use another fuel. During the 11 days round trip from Bergen-Kirkenes-Bergen, fuel and bunkering demand is calculated in the result section of the thesis.

2 Background

The maritime industry faces challenges making the right decisions to comply with both short term local emissions regulations imposed by the IMO [9] and the long term climate legislation under consideration by the IMO [10], while remaining economically competitive with traditional fossil solutions for fuel.

A range of fuels and technologies are available for ships to reduce their emissions; however, the reduction potential varies significantly depending on primary energy source, fuel processing, engine and the supply chain. Use of different fuels will require different energy systems, methods for storage and bunkering technologies. Alternative energy systems include pure gas, dual- and multi fuel engines, marine *fuel cells* (FC), battery-electric systems and gas/steam turbines.

It is expected that a global transition towards greater use of renewable energy will lead to an abundance of affordable renewable electrical energy conversion on land. This energy can be used to produce hydrogen for maritime industry and be a potential zero emission option for fuel. [11]

Hydrogen consumption in transport industry has the potential to reduce national emissions of CO_2 in Norway by roughly 500 000 tonnes/year. This is approximately 1 % of the total national CO_2 emissions. [5]

2.1 Marine fuels

2.1.1 Energy density

The energy density of a fuel can be specified in terms of mass (gravimetric energy density) and volume (volumetric energy density), which represent energy content per mass/ or volume unit, respectively. The energy density of a fuel determines how applicable the fuel is for certain ship types. Since available storage space is limited on ships, the volumetric energy density will be most vital for considering fuels for marine use. [11]

When storage systems are also taken into consideration, LNG requires 40 % more volume than *marine diesel oil* (MDO) and hydrogen 40-50 % more than LNG. Considering both volumetric energy density and storage system, the vessel endurance range indicates how often a vessel has to bunker in general, irrespective of size. [11]

Fuel	**MDO**	**LNG**	**LH_2**	**CGH_2**
Vessel endurance range [11]	Months	Weeks	Days	Hours-days

Table 1: Vessel endurance by fuel [11]

Table 1 presents endurance ranges and bunkering intervals for the different fuels. Due to LNG and hydrogen's lower volumetric energy density when compared to MDO, bunkering occurs more often.

2.2 Hydrogen

Hydrogen is the lightest and smallest element. Due to the fact that hydrogen reacts very easily with other substances, there is very little pure hydrogen on earth, and only 0,5 parts per million in the atmosphere. Hydrogen needs to be produced by separating the hydrogen from its chemical bonds with other elements. [5]

Hydrogen is an energy carrier and a widely used chemical commodity. It can be produced using different processes such as by reforming of *natural gas* (NG) and electrolysis of water using electrical energy. Hydrogen is most commonly used in FC's for electricity generation. [5]

In Norway all 225 000 tonnes of hydrogen produced each year is for industry processes. Most of this hydrogen is used to produce methanol at Tjeldbergodden (Equinor) and ammonia at Herøya (Yara). The hydrogen market today is relatively closed; big consumers of hydrogen normally produces their own hydrogen. Only 4 % of the worlds hydrogen production is sold in a free market. [5]

At Tjeldbergodden, Equinor uses about 112 500 tonnes of gaseous hydrogen each year, with an additional 5 500 tonnes of hydrogen being recirculated and used for heating together with NG. There also is an excess production capacity of about 15 tonnes/day [6]. At Herøya the yearly demand of hydrogen is about 70 000 tonnes. Both production facilities produce hydrogen locally by SMR currently without CCS. [5]

If a global market for hydrogen emerges it would be possible for many of today's hydrogen producers to increase hydrogen production for sale to an open market. The future global hydrogen market is dependent on technological and political development. The International Renewable Energy Agency (IRENA) estimates an additional 8 EJ in 2050 in addition to the current global hydrogen demand. [12]

2.2.1 Production

The most used technologies for producing hydrogen is SMR, gasification from fossil fuels or biogas and water electrolysis.

2.2.1.1 Electrolysis

Hydrogen production from electrolysis uses electrical energy to separate hydrogen and oxygen in water molecules. Two methods for water electrolysis is currently dominating, *alkaline electrolysis* (AE) and *proton exchange membrane* (PEM) electrolysis. High temperature electrolysis with *Solid Oxide Electrolysis* (SOE) is in experimental stage and not currently available on the market. Electrolysers are differentiated by the electrolyte materials and the temperature they are operating at. The efficiency of hydrogen production is a measurement of how much energy is needed to produce a certain amount of hydrogen. Hydrogen produced from electrolysis is called green hydrogen.

2.2.1.1.1 Alkaline electrolysis

AE is a well-known technology and has been used to produce hydrogen for over a hundred years by among other Norsk Hydro. The anode gets oxidized while the cathode gets reduced, which results in separation of water molecules:

$$2H_2O + 2e^- \rightarrow 2H_2 + 2OH^-$$

Hydrogen is produced at the cathode. The charged hydroxyl ion moves towards the cathode where electrons are absorbed, and hydroxyl ions oxidizes and forms water and oxygen:

$$2OH^- \rightarrow H_2O + \frac{1}{2}\,O_2 + 2e^-$$

AE operates at temperatures between 60-80 °C, has an efficiency of 55-69 % [13] and results in very pure hydrogen. [1]

2.2.1.1.2 PEM electrolysis

PEM electrolysis has been used since 1966 and is today a mature technology, with possibly higher potential for efficiency- and cost reduction than alkalic electrolysis. PEM electrolysis has roughly the same operating temperature as alkaline, but currently exhibits lower efficiency, 55-66 %, and lower purity of produced hydrogen when compared to AE [5]. NCE Maritime Clean Tech stated an electricity demand for PEM electrolysis hydrogen production of 55 kWh/kg H_2. [6]

2.2.1.2 Steam Methane Reforming

SMR is currently the most common production method for hydrogen. It is estimated that 68 % of the world’s hydrogen production is based on reforming of NG. The same process can be used to produce hydrogen from biogas and light hydrocarbons like liquid petroleum gas and naphtha. The process normally consists of five steps:

1. Two-step removal of sulphur removal of hydrogen sulphide.
2. Reformation of methane and water to hydrogen, carbon oxide (CO) and small amounts of carbon dioxide (CO_2).
3. Reformation of CO and water to CO_2 and hydrogen.
4. Removal of CO_2 from hydrogen flow
5. Reformation of remaining CO and CO_2 back to methane.

The method has an efficiency of about 70-85 % from gas to hydrogen based on *lower heating value* (LHV) [5]. Hydrogen produced from SMR is called grey hydrogen.

2.2.1.3 CCS

Because SMR produces CO_2 during the reformation process it largely mitigates the zero emissions benefits from using hydrogen as fuel. Utilizing CCS technology, 56-90 % of the CO_2 emissions from the SMR process can be captured and stored [14]. CCS technology is still in an early phase, but commercially available technologies for CCS exists. Hydrogen produced from SMR with CCS technology utilized is called blue hydrogen.

CCS consists of three stages, namely capture, transport and storage. Each of these processes have unique challenges to overcome.

Capture is the first of these stages and is essential for the entire idea of CCS. It revolves around capture of the CO_2. In SMR, one of the steps is to separate CO_2 from the hydrogen with the use of Pd-membranes to produce pure hydrogen gas.[15]
The most mature technology for CCS is absorption with solvents, such as amine technology. Here CO_2 is captured by an amine solvent, a liquid consisting of amines and water. A different technology for CCS is cold capture system Cryocap developed by Air Liquide. This technology uses low temperatures to compress, liquefy and then separates the gasses [16].

The second stage is the transportation of CO_2 to a suited location. This can be done by pipeline or by temporary storage in tanks followed by transportation by ship, train or truck. Transportation by pipeline is an efficient and green way for transportation, but a complete CO_2 pipeline network can be expensive to construct. This results in the need for other ways of transportation until large scale, cost efficient pipeline production is established. [15]

Transportation in tanks is a flexible way of transportation that require less investment costs when compared to pipelines. It is however a less efficient way compared to a pipeline. Personnel will be required along the entire transportation in the different stages like loading, unloading and the transportation itself. If the main production of hydrogen will be at Tjeldbergodden, one could make use of tank transport of CO_2 until the production is of such a scale that the construction of a pipeline will be more profitable. [15]

The last of stages is storage, where the captured CO_2 gets stored in a permanent location to prevent it from ever leaking out to the atmosphere. In Norway the use of depleted oil and gas reservoirs under the seabed is used for permanent storage. These reservoirs have been containing oil and gas for millions of years and therefore one can assume that they have the required properties to contain the CO_2 gas for long-term storage. [15]

In terms of storage, CO_2 storage has been in operation at the Sleipner oil field since 1996. Currently plans are being made for a large-scale storage facility at Smeaheia. 1 000 000 tonnes CO_2 is captured and stored from the Sleipner oil field annually [17].

The use of CCS will increase of both CAPEX and OPEX due to additional equipment that is needed. It can however reduce some taxation from CO_2 release, but this is largely dependent on the government policies. The technology for both SMR and CCS are likely to decrease in cost as it becomes more widespread.

2.2.2 CertifHy

CertifHy [18] is a project where the aim is to create a European framework and a path forward for concrete and actionable guarantee of origin for hydrogen. There are two CertifHy guaranties of origin currently, CertifHy Green Hydrogen and CertifHy Low-Carbon Hydrogen.

CertifHy Green Hydrogen is low carbon hydrogen produced using renewable sources like biomass, solar or wind energy. CertifHy Low-Carbon Hydrogen is hydrogen produced by non-renewable energy sources with low carbon impact which is defined 60 % less than conventional production process of reforming natural gas, which makes the threshold 4,36 kg CO_2-eq/kg hydrogen.

2.3 Liquified natural gas (LNG)

Havila is currently building four new ships intended to be put into operation in 2021 [19]. The four Kystruten ships are designed to operate on LNG [20]. Using LNG as a future supplementary fuel along with *liquid hydrogen* (LH_2) is a viable option. This would imply splitting the onboard storage into several discrete tanks, which could be filled with either LH_2 or LNG depending on LH_2 availability. The gasses could then be mixed in the evaporator and fed into a gas engine which needs to have variable timing in order to handle the different combustion properties of the gasses and gas mixtures or; be converted to electrical energy in a FC LNG gas generator hybrid system. [21]

LNG projects are currently struggling to receive funding due to investors beliefs that the technology will be superseded by new lower carbon solutions . This coincides with the problem LH_2 industry currently have, that there is little to no LH_2 available. A solution to both problems is to encourage the LNG industry to build their ships with their storage tanks, cryogenic pumps and evaporators in such a way that they are capable of operating at the lower temperature LH_2 inhibits. LNG ships could be sold LH_2-ready, thus reducing the risk of the investment, and at the same time starting the market of LH_2.[21]

The technology required for employing LNG as fuel in maritime applications is readily available. Piston engines include low- and high-pressure 2-stroke engines, and low pressure 4-stroke engines. Some FC allows internal reforming of LNG, such as the Solid Oxide FC [1]. LNG gas turbine is an option. This is expensive equipment with high efficiency. Gas turbines are used in military vessels and is rarely utilized in the maritime industry due to the high cost. [22]

2.4 Hydrogen as a storage medium and power-to-X

The market for renewable energy in electricity generation has risen as a result of the green energy transition. Photovoltaics and wind power are the energy sources that have seen the greatest expansion. Both of these energy sources are intermittent, and the availability of the sources varies over time. At the same time supplying electricity requires balancing of supply and demand. This results in energy storage now playing an important role in an electricity generation system.

Hydrogen can be produced by electrolysis of water by surplus electricity produced by renewables. If the energy demand is higher than supply, the surplus hydrogen can help close the gap. [1]

2.5 Hydrogen as fuel

The energy hydrogen contains can be used either thermally in heat engines or chemically in FC's. When hydrogen is burned with pure oxygen, water is formed:

$$2H_2 + O_2 \rightarrow 2H_2O$$

In contrast to combustion of fuels consisting of hydrocarbons, such as MDO, no carbon dioxide is formed in this process. However, unlike in FC's where no *nitrogen oxides* (NOx) is formed, hydrogen combusted with air produces NOx. During combustion of hydrogen, very high temperatures are reached at around 2000-3000 °C, depending on the air-fuel ratio, and oxygen content of the combustion air. [11]

Although hydrogen is a potent fuel with high energy content and good combustion properties, combustion of hydrogen is rarely used. Only in space travel is hydrogen used as fuel for combustion engines and in industry where hydrogen is a by-product and occasionally co-combusted with other fuels. Little further research and development on hydrogen internal combustion engines has been done in the recent past. [21]

Given the technical progress FC's have made in recent years, and the technical requirements applying to hydrogen powered internal combustion engines, the use of hydrogen as a fuel is almost exclusively in FC's. To narrow down the scope of this thesis, FC's is what is focused upon.

2.5.1 Methods of converting fuel to power

Hydrogen is a flexible energy carrier and many methods are available for converting hydrogen into power on a ship. Each has specific energy efficiencies and storage requirements, which in turn will affect the bunkering solution. [21]

2.5.1.1 Fuel Cells

FC's are used to convert chemical energy to electrical energy in a chemical process without combustion. FC's are comparable to batteries; the difference is that a FC needs an external supply of air and fuel. In the FC's the energy contained in hydrogen is converted to thermal- and electrical energy.

Many different FC technologies exist with their own specifications, strengths and weaknesses. The name of the FC is often based on the electrolyte used in the FC. Two different categories exist, low- and high temperature FC, where the operating temperature define which category a FC should be placed in. For high temperature FC's waste heat recovery can be implemented, increasing overall efficiency for the FC. [1]

In Table 2 an overview of the different FC's is presented. Data is extracted from the report "Shell Hydrogen Study Energy Of The Future?" [1].

Type	Temperature (°C)	Electrolyte	Power	Efficiency %	CAPEX (USD/kW_{el})	Maturity	Category
Alkaline FC	60-90	Potassium hydroxide	Up to 250 kW	60-70	200-700	Established but limited to special applications	Low temperature
PEM FC	50-90	Polymer membrane	500 W - 400 kW	35-70	3000-4000 (stationary) 500 (mobile)	Early market/mature Leading FC-type	Low temperature
Phosphoric Acid FC	160-220	Phosphoric acid	Up to several 10 MW	35-45	4000-5000	Mature (low volume)	High temperature
Molten Carbonate FC	600-700	Carbonate melt	From a couple of 100 kW to several MW	65-70	4000-6000	Early market	High temperature
Solide Oxide FC	700-1000	Solid ceramic oxide	From a couple of 100 kW to several MW	60-80	3000-4000	Mature (volume rising)	High temperature

Table 2: Properties and specifications of different FC's [1]

2.5.1.1.1 Alkaline FC (AFC)

The AFC was the first FC developed, used initially for space travel. The AFC operates at low temperatures. Key advantages include rapid attainment of operating temperatures and compact design. The cheap electrolyte makes the investments costs relatively low.

The main problem of AFC is the low CO_2 tolerance and therefore it is dependent on a supply of very pure gasses especially pure oxygen. Despite further developments in the AFC technology, AFC remains inferior to the PMC considering output power and durability. [1]

2.5.1.1.2 Proton exchange membrane FC (PEMFC)

PEMFC operates at low temperatures and is the leading FC type on the market. Of all of the FC types, PEM has the highest potential for cost reduction with regards to production volume. In the long term, production costs of 30 $/kW are considered to be achievable, which is comparable to *internal combustion* (IC) engines today. [1]

Platinum is used as a catalyst which leads to high production costs. The catalyst is poisoned by sulphur and carbon monoxide and therefore PEMFC requires pure hydrogen as fuel. [1]

2.5.1.1.3 Phosphoric acid FC (PAFC)

The power density, flexibility and efficiency (40 %) for the PAFC are all low, although using waste heat recovery may increase the overall efficiency to 80 %. Because of the aggressive electrolyte (phosphoric acid), this FC is less suitable for small output ranges and mobility usages. Further potential for cost reduction is expected to be low. [1]

2.5.1.1.4 Molten carbonate FC (MCFC)

The MCFC is categorized as a high temperature FC. As the name states, molten carbonate is used as the electrolyte. The MCFC operates in temperature ranges 600-700 °C. It has high electrical efficiencies of over 60 % and can reach up to 85 % when waste heat recovery is implemented. The high temperature allows use of hydrogen containing gas as fuel, NG. [1]

2.5.1.1.5 Solid oxide FC (SOFC)

SOFC is a high temperature FC that operates in temperature ranges 500-1000 °C, and the electrolyte consists of a solid porous ceramic material. SOFC covers a large range of applications such as decentralized power supply (a few kW) to power plants (several MW). Because of the high operating temperatures, SOFC requires long start-up times. It has high efficiencies at 60-70 %.

The high operating temperatures allows for internal reforming of hydrogen rich gas or liquid fuels, but when hydrocarbon fuel is used, CO_2 is emitted. Reaching operating temperatures could take up to 4-5 hours, which makes the start-up time high. [1]

2.5.1.2 Combustion of hydrogen in a gas engine or turbine

An effect of LNG being used as fuel on ships is that a range of gas engines are being used to power ships. These could be adapted to run on hydrogen relatively easily, mainly changing the timing to take the higher flame speed into account along with combustion temperature. However, it is still in development stages and no useful values for efficiencies exists. [21]

2.5.1.3 Hydrogen co-combustion

Hydrogen could be co-combusted with diesel, up to 80 % of diesel energy and may be displaced in a diesel engine or mixed across the full range of concentrations with NG in a gas engine or turbine. An engine can be set for a specific hydrogen concentration. However, a continuing varying range will require dynamic timing adjustment, something that is possible with modern engines but not for older ones. A lack of real word implementation and testing makes efficiencies not available. [21]

2.5.1.4 Methods of converting fuel to power considered

Due to the lack of real world implementation and little further research of hydrogen co-combustion and combustion, the method of converting hydrogen to energy considered is FC’s.

PAFC and MCFC technologies have not been viewed as relevant for this feasibility study because of the lower market availability and efficiency compared to the other high temperature FC alternative, the SOFC. Due to the tight schedule of Kystruten and the hybrid energy system, low start up times is required and therefore are high temperature FC’s is not an option in case of this thesis.

The AFC and PEMFC are mature technologies available on the market. Due to the future prospect of PEMFC’s potential for higher efficiency and lower production costs, PEMFC is the FC selected in this thesis.

2.6 States of hydrogen

Hydrogen exists at gaseous form under *standard temperature and pressure* (STP). Its boiling point is - 252,76 °C, which is close to absolute zero temperature at - 273,15 °C. Below this temperature hydrogen is liquid and above it is gaseous at atmospheric pressure. [1]

Methods of production of hydrogen results in gaseous hydrogen at relatively low pressures. Finding volume efficient ways to store hydrogen is challenging. For more volume efficient storage of hydrogen, it is stored as either compressed gaseous hydrogen (CGH_2) or LH_2. Properties of different states of hydrogen is presented in Table 3.

	H_2 at STP	CGH_2 at 250 bar (no tank)	LH_2 (no tank)
Density [kg/m3]	0,09	18	71
Gravimetric energy density [kWh/kg]	33,33	33,33	33,33
Volumetric energy density [kWh/m3]	2,78	594	2343

Table 3: Properties of hydrogen at different states [7]

Due to limited storage volume on ships, high volumetric energy density is an important property for fuels for ships.

Hydrogen has the lowest volumetric energy content among commonly used fuels. 0,01709 MJ/L at STP which is much lower than for instance petrol at 35 MJ/L. Methods for increasing hydrogen's volumetric energy content include among others compressing or liquefying the hydrogen. [11]

2.6.1 Compressed hydrogen

By increasing the pressure of the hydrogen to 300 bar, a density of about 20 kg/m^3 is achieved. At 700 bar, which is the standard storage pressure for cars, density of 40 kg/m^3 is achieved. Compressing hydrogen demands different amounts of energy depending on the end pressure of the CGH_2. Compression to 30 bar demands energy equivalent to 4-5 % of the original energy content. Further compression to 350 or 750 bar demands further 4-8 % of the original energy content. This results in storage of CGH_2 being a balance between CAPEX for sufficient storage volume and costs for compression. [5]

There are several different technologies to compress the hydrogen. The most commonly used is mechanical compressors. For mechanical compressors, reciprocating piston compressors are the most commonly used. They are ideal for moderate flow and high-pressure applications. [23]

Hydrogen molecules are small and can diffuse through many materials. This is mainly a concern for CGH_2. There are two safety concerns for this behaviour, metal embrittlement and eventually fracture and gas leaks. [11]

Storing hydrogen gas at pressure in steel cylinders is the easiest method of storing hydrogen and the most widely adopted for small amounts. In case of Kystruten, huge storage tanks would be necessary to achieve in a 75 % reduction in emissions, due to CGH_2 lower volumetric energy density as compared to LH_2.

The main advantages for storing hydrogen as CGH_2 is simplicity, indefinite storage time and no purity limits on the hydrogen. [1]

2.6.2 Liquid hydrogen (LH_2)

Cooling hydrogen to a temperature of -253°C at atmospheric pressure results in liquefaction of hydrogen. LH_2 has a density of 71 kg/m^3 which is considerably higher than what achieved by compression to either 350 or 700 bars at ambient temperatures.

The liquefaction process requires clean hydrogen, several cycles of compression, liquid-nitrogen or helium cooling and expansion by the Joule Thompson (JT) effect; when a real gas expands adiabatically through a porous plug cooling or heating takes place. In case of liquefaction of hydrogen, cooling takes place [6].

To minimize the cost per kg LH_2 of production, there are trade-offs between CAPEX and OPEX. Hydrogen is a standardized product; the liquefaction method is not much of concern other than the cost and reliability of the process. Two primary methods or cycles of liquefaction is preferred, namely The Reverse Helium Cycle and The Claud Cycle. [6]

Today the energy required to liquify hydrogen is 25-35 % of the original energy content. Theoretical minimum energy to liquify hydrogen is 3,3 kWh/kg according to NCE Maritime Clean Tech, which is 10 % of the gravimetric energy content [6]. They also stated that energy demand for production of LH_2 by the Claud Cycle is 12,7- 10,8 kWh/kg LH_2. In this thesis, value for energy demand for liquefaction at 10,8 kWh/kg LH_2 is used.

Liquefaction of hydrogen is expensive compared to compression and is a process with large-scale advantages. The larger the production plant, the cheaper the CAPEX and OPEX is compared to produced units. [24]

Today experience with gaseous hydrogen within Norwegian businesses are extensive. On the other hand, Norway inhibits no experience with LH_2 and the low temperatures included. Norway has extensive competence with LNG, and this experience could to an extent be utilized for LH_2 bunkering. Hydrogen has different properties and needs to be stored at a much lower temperature than LNG to prevent the liquid from vaporizing. Currently there are no production plants of LH_2 in Norway, and only 3 of the kind in Europe. In the USA there is more experience with LH_2 due to aerospace purposes [5]. According to NCE Maritime Clean Tech, the global hydrogen liquefaction capacity is 350 tonnes/day. [6]

Equinor, Air Liquide and BKK are planning production of LH_2 from electrolysis in Norway at Mongstad in 2024. From a market perspective Equinor holds demand of 5 tonnes/day as a minimum, with a preferred market of 10-15 tonnes/day. The project also includes bunkering and distribution of the hydrogen. [6]

The three production plants for LH_2 in operation in Europe have a daily production of about 20 tonnes/day. In October 2018 Linde announced plans to double the production capacity at their production facility in Leuna to 10 tonnes/day from 2021, increasing production in Europe to 25 tonnes/day. LH_2 production in Europe is presented in Table 4.

Producer	Country	Production process	Capacity [tonnes/day]
Air Liquide	France	SMR	10
Air Products	Netherlands	SMR	5
Linde	Germany	SMR	5

Table 4: Production plants in Europe [6]

2.6.3 Comparison between LH_2 and CGH_2

LH_2 has many benefits for hydrogen infrastructure compared to CGH_2. LH_2's relatively high density allows for minimum costs for distribution, 167 \$/kg H_2 for a cryogenic liquid trailer compared to 783 \$/kg H_2 for a compressed gaseous trailer. LH_2 pumps can deliver a large throughput with a relatively low footprint. [25]

Liquifying hydrogen is an energy demanding process. It requires 3 times the energy to liquefy hydrogen compared to compressing hydrogen to 700 bar [21]. Boil-off may occur during the liquefaction and storage of LH_2 [25]. LH_2 losses are not well qualified or quantified, and more research and analysis needs to be done to evaluate their impact on costs.

Volumetric energy density is a vital factor for the possibility for hydrogen operation of the 5 Kystruten ships from the hypothetical tender. In case of such large volumes of hydrogen consumption, LH_2 proves to be the best option due to LH_2's higher volumetric energy density compared to CGH_2. A comparison between the two methods of storage is presented in Table 5.

	Advantages	Disadvantages
CGH_2	• No purity limits • Requires less power • More experience exists • Bunkering facilities for land-based transport is somewhat established • More available compared to LH_2	• Low volumetric energy density • Require more storage volume • Hydrogen molecule leaks
LH_2	• High volumetric energy density • Require less storage volume • Do not require high pressure • Do not require local bunkering facilities. • Cheaper transport (currency/mass hydrogen)	• More expensive to produce • Require more power • Boil off losses • Lower holding time • No global marketplace

Table 5: LH2 vs CGH2

2.7 Safety

The different methods of storage of hydrogen demand different safety measures. Hydrogen is the lightest of all the gases and compared to methane diffuses three times as fast in air. Hydrogen gas is flammable in concentrations between 4-75 vol % in air and is easily ignitable compared to other gasses.

There is some disagreement and uncertainty based on available information when it comes to specific safety measures and consequences of hydrogen leaks, especially for LH_2. Use of hydrogen as an energy carrier in transport is a relatively new utilization for hydrogen. The main risks associated with leaks and accumulation of hydrogen is that the hydrogen is easily flammable and has a major explosion risk. For compressed hydrogen it is important that storage-tanks and systems are designed taken these matters into consideration. Since hydrogen is the lightest of the gasses, gas leaks will disperse quickly into the atmosphere under ambient conditions. Because of this, it is preferable to have storage tanks in an area open to the atmosphere.

The temperature of LH_2 is so low that all gasses, except for helium, will undergo a state change and solidify if directly exposed to LH_2. A major leak of LH_2 may result in nearby air to solidify, and the hydrogen vapor formed will be at such low temperatures that it is not buoyant and may form an accumulation of hydrogen vapor. [21]

A minor leak of LH_2 will rapidly evaporate, releasing flammable gasses. Outdoors this gas will quickly disperse due to buoyancy and present minimal hazards. Indoors, gas detectors should identify the leak and the correct application of hazardous area zoning should prevent an ignition. If a major leak occurs the evaporation will not be quick enough to prevent an accumulation of LH_2 to form a pool on the surface. This will present a significant cryogenic and explosive risk. [21]

Direktoratet for samfunnssikkerhet og beredskap (DSB) categorizes hydrogen as a dangerous substance and handling and use of hydrogen falls under guidelines for such facilities. DSB has published guidelines for handling of hydrogen [26]. Norwegian regulations considering dangerous substances [27] apply to hydrogen. This is a central document which set demands for implementing preventative safety measures and risk handling.

Ships that are designed for using hydrogen as fuel have to comply to IMO's demands for fuels with flashpoint below 60°C which is stated in part A in the IGF-Code (Code of safety for ships using gases or other low flashpoint liquids) [28]. Here a number of functional requirements are needed for conducting a comprehensive risk analysis. This means that an extensive "alternative design process" has to be completed before approval. The main purpose of this is to demonstrate that hydrogen as fuel is as safe as ships running on conventional fuels. Until hydrogen-specific regulatory framework is developed, all ships that use hydrogen as fuel has to complete this process. [5]

The standard ISO 20519, standard for LNG bunkering, will be used for bunkering of LH_2 until new standards and guidelines are provided for LH_2.

Norwegian flag state hydrogen ships have to be approved by Sjøfartsdirektoratet before they can start operating. Today there are no laws for onboard hydrogen storage, hence onboard hydrogen storage face huge regulatory challenges [5]. From 2021 Norled will operate a new ferry using hydrogen as fuel. From this project, regulations and guidelines for onboard hydrogen storage and fuel cells will be formed [7]. Extensive risk analyses of FC location and infrastructure like air supply and heat exchange will be covered in these studies.

DNV-GL has developed rules for classification that includes procedural and technical requirements related to obtaining and retaining a class certificate. The rules represent all requirements adopted by the society as basis for classification [29].

2.8 Storage tanks

The way an energy carrier is stored is influenced by its energy content. Hydrogen has relatively high gravimetric energy density and low volumetric energy density when compared to other fuels. This translates into large storage tanks necessary for storing the same amount of energy as for example MDO. Different tanks and technologies are used for storing CGH_2 and LH_2.

By reducing the challenges that comes with hydrogen storage and to make approval easier, most of the concepts today have storage tanks above deck open to the atmosphere. Considering safety this solution is much less challenging than storage below deck. [5]

Havyard's initial design for the 4 Kystruten ships which shall operate Kystruten from 2021, includes a LH_2 storage tank with 3,5 tonnes storage capacity [30]. In case of the hypothetical case of the 5 Kystruten ships where a 75 % reduction is required, a storage tank with storage capacity of 3,5 tonnes, assuming bunkering locations from section 4.2.1.1, would not be sufficient for the required reduction Appendix 9.3.

Different variables determine a storage tank's gravimetric and volumetric concentration, as presented in Table 6 [31]. The product of volumetric specifications and mass stored in onboard storage tanks represents the outer volume of the onboard storage tank.

Tank [psi]	Gravimetric specifications (empty tank mass/ H_2 stored) [kg/kg]	Volumetric specifications (Outer tank volume L/kg H_2 stored) [L/kg]
2200, carbon steel	103,4	105,7
2015, aluminium	72,37	130
5000, composite	19,44	65,31
7000, composite	16,21	49,69
LH_2	8,7	24,8

Table 6: Storage tank specifications [31]

2.8.1 Liquid Hydrogen

LH_2 needs to be stored in cryogenic vessels. Cryogenic vessels are metallic double walled vessels with insulation between the walls. To minimize losses of stored hydrogen due to thermal effects, thermal- radiation, convection and conduction has to be taken into consideration when designing the tank. [32]

Cryogenic storage tanks are perhaps the part of the LH_2 value chain with the highest technology readiness level. Linde offers stationary cryogenic storage tanks for LH_2 with a capacity of 300 m^3 [33]. Peter Gerstl, head of product management at Linde, indicates a price for a 3,4 tonnes storage tank with 15 days holding time at 500 000 € [34].

2.8.1.1 Boil off

A heat leak from the environment to cryogenic storage tank will always occur and result in some of the LH_2 stored in the tank evaporating. This will lead to a pressure build up in the tank linearly proportional to storage time [32]. To avoid over pressurization, the boil off gas has to be released, which may just be a valve or a re-liquefaction process [35]. Typical rates of boil off is 0,2-0,5 % each day [13].

2.8.2 CGH_2

Hydrogen stored as a compressed gas is often used in less energy demanding methods of transport like trucks or trains. Compressed gaseous hydrogen is stored at different pressures depending on application, for example 700 bar for cars and 350 bar for busses and trains.

Storing at high pressures comes with considerably higher costs than for lower pressures. As a consequence, vehicles with more space available often store CGH_2 at lower pressures.

Compression to 350 or 700 bar requires 8-13 %, 4-5 % for 50 bar and an additional 4-8 % for 350-700bar, of the original energy content of the hydrogen [5]. Thus a balance between investment costs for adequate storage volume and costs associated with compression is required. [13]

2.9 Hydrogen transportation

There exist four current methods of transporting hydrogen

For smaller amounts and distances, CGH_2 is transported by trucks. This is used today for industrial purposes and for existing hydrogen filling stations. Larger volumes are transported as LH_2 in specially designed cryogenic tank trucks. A 20 feet ISO container can transport 400 kg LH_2. [36]

For larger distances, hydrogen could be transported onboard trains. The same storage tanks for CGH_2 and LH_2 could be loaded on the train. A given distance between the storage tank and the train tracks has to be considered, as sparks from the tracks could ignite the stored hydrogen. [36]

Hydrogen transport by ship is deemed the only realistic option for hydrogen transport from Europe to Norway. Hydrogen can be transported as LH_2 in storage tanks onboard the ship. Currently no such ship exists. Kawasaki [37] is currently testing a LH_2 transport vessel with 11 000 tonnes storage capacity, which is supposed to transport LH_2 from Australia to Japan. [36]

Existing pipelines for gas export could potentially be used to transport pure H_2 or as an additive in NG. Mixing H_2 and NG may require significant modifications to existing infrastructure. In addition, there are fundamental regulatory barriers to H_2 as an additive in NG in the main pipeline for gas transport in Europe. Transportation of H_2 in pipelines is deemed an unlikely option [36].

2.10 Bunkering

Infrastructure for hydrogen bunkering has not yet been tested in commercial scale. Tested and approved technology and methods for CGH_2 filling for land-based transport; cars, busses, trains and trucks exist. Filling time for a car is 3-5 min (6 kg at 750 bar) and for trains 20 min (94 kg at 350 bar). Existing methods and technology can, to an extent, be used for hydrogen bunkering. Development and approval of regulations for hydrogen bunkering has to be finalized before commissioning of hydrogen maritime vessels. [7]

2.10.1 CGH_2

Hydrogen is stored as a gas and transported to the vessels. Flow rate of hydrogen has to be controlled to prevent excessive adiabatic heating. Adiabatic heating is when heat is released during adiabatic compression which can soften the pressure valves leading to failure.

There are two key methods for transferring CGH_2 to the ships.

2.10.1.1 Pressure balancing

Bunkered CGH_2 is at a higher pressure than the ship has stored. After connecting the ship to the bunkered hydrogen, the bunkered hydrogen will flow into the storage tank of the ship under its own pressure. This method does not require compressors but needs a large storage capacity. When the pressure of the bunkered hydrogen reaches the pressure of the stored hydrogen it will no longer fill the storage tanks. [21]

2.10.1.2 Compressing the gas into the ship

A high output compressor is used to move the hydrogen from a low-pressure store at the port, to the ship. This allows control of the flow rate but requires expensive equipment. [21]

2.10.2 LH_2

Hydrogen stored as LH_2 at the bunkering location and is transferred to the ship using cryogenic pumps. Currently there are no experience with bunkering of LH_2, but experience from LNG bunkering could be applicable [21]. LH_2 can be directly filled from tank truck to the ship. This means that no infrastructure is needed at the bunkering location for filling of hydrogen other than a road for the truck.

When comparing LNG bunkering to LH_2 bunkering, the most important difference is LH_2's lower boiling point. This calls for shorter fill lines compared to LNG bunkering, to minimize the cooling process before bunkering. It is estimated by NCE Maritime Clean Tech [6] that a 1 tonne fill process may take up to 40 minutes for cooldown, 30 minutes for LH_2 transfer and 30 minutes for purge and warm-up prior to disconnect. This can be partially handled by pre-cooling the bunkered hydrogen before the ship arrive for bunkering. A transfer flow rate of 1000-2000 kg in 20-40 minutes was deemed possible regardless of filling method [6]. In this thesis, bunkering rate of two tonnes/hour is assumed.

Bunkering is also possible with a ship-to-ship solution. Moss Maritime in cooperation with Equinor, Wilhelmsen, Viking Cruises and DNV-GL, has developed a design for a LH_2 bunker ship. According to Sintef [38] it will have a storage capacity of 500 tonnes, using submerged cryogenic pumps to unload stored LH_2 at a rate of 300 m^3/hour. The bunker ship will be loaded at a liquefaction terminal and fill at a rate of 600 m^3/hour. After a maximum laden voyage of 25 days, it will return to the terminal, unloading any excess hydrogen vapor for reliquification.

2.10.3 Bunkering locations

In 2017 NCE Maritime Clean Tech and Selfa Artic revealed a new concept for zero emission for the new Kystruten ships at “Zero konferansen”. The concept includes 8 bunkering stations scattered along the Norwegian coast line along with 36 stations for shore power [39]. The hydrogen bunkering locations includes Bergen, Ålesund, Trondheim, Sandnessjøen, Bodø, Tromsø, Honningsvåg and Kirkenes.

All these bunkering locations, except Sandnessjøen, has been used in this thesis. The docking time at Sandnessjøen, both northbound and southbound, is too low to be able to start bunkering, see Appendix 9.2. In order to keep schedule as similar as the one of today [40], Sandnessjøen has not been used as a bunkering location.

2.11 Emissions

The dominant fuel used in maritime industry is currently residual fuel, or MDO which accounted for 72 % of all fuel consumed in 2015 [41]. MDO is the residue product of crude oil in refineries and combustion release high levels of air pollutants.

A key feature of many of the alternative fuels for maritime industry being considered is the potential for less emissions and better environmental performance within some or all emission aspects, making them options for ship owners to comply with current and future environmental restrictions.

The eleven Kystruten ships, known as Hurtigruten, and their expedition vessels was responsible for 5,1 % of the domestic emissions Norway from maritime traffic, emitting a total of 242 000 tonnes of CO_2 in 2017. [42]

2.11.1 Pollution

Pollution comes in several different varieties, and can be defined as the release of harmful substances and energies in larger quantities than the system can dispose of them. The type of pollution regarding matter is divided into their affected area resulting in the subcategories air pollution, earth pollution and water pollution. In the case of a shift from diesel to hydrogen, the decrease in air pollution will be relevant. [43]

Air pollution for the most part regards released gasses, most notably CO_2, but also includes the release of particulates such as ranging from 1 to 100 μm being classified as dust and smaller than 1 μm being classified as fumes.

With the use of fossil substances such as coal, oil or NG as fuel, emitting CO_2 is inevitable. Coal and oil however also release gasses such as NOx and *sulphur oxide* (SOx), that both can cause environmental harm and be damaging to human health. [44]

To reduce emissions of NOx and SOx, the change from coal and oil to natural gas have been explored, but the emission of CO_2 will still occur. Hydrogen on the other hand can be used as fuel without any release of CO_2, with the only emission being water. So the use of hydrogen as a fuel will not result in any pollution at point of use, which is relevant for limiting local pollution, such as in the Geirangerfjord where use of tourist ships and ferries that release CO_2 will be completely prohibited from 2026. [45]

2.11.2 CO_2 equivalents

Statistics of *greenhouse gas* (GHG) emissions of CO_2 also normally includes methane, nitrous oxides and fluorine gasses. All these gasses have a global warming potential but has different effects on warming and lifetime in the atmosphere. To compare them, they are converted into CO_2 equivalents [46].

2.11.3 Well to Wake emissions

The well-to-wake GHG emissions includes emissions from production, transport and storage, as well as combustion/conversion to mechanical energy onboard the ship. The well-to-wake emissions for a fuel will vary depending on where the fuel is produced, mode of transport and storage, and different ship design.

The resulting comparative measure of WTW emissions is the mass of CO_2-equivalents per unit of shaft output energy. Data from well to tank emissions for LNG used in this thesis is presented in the report "Natural gas as a ship fuel: Assessment of greenhouse gas and air pollutant reduction potential" [41]. WTT presented in this report is emissions from the North Sea transported to Netherland. The WTT values here possibly are higher than what would be in case of transporting and processing the gas and oil in Norway.

2.11.4 Emissions from hydrogen

Hydrogen comes with different emissions depending on production method. Using the Norwegian electricity mix to produce hydrogen by electrolysis of water does have some emissions due to the emission factor from the power grid used. The emission factor for the Norwegian electricity mix was in 2018 18,9 g CO_2/kWh [47]. This emission factor is based on a life cycle analysis from the different electrical energy generation methods in Norway and their share in the Norwegian power grid. This results in the total emission factor for the Norwegian power grid. This emission factor also has to be taken into consideration when state change processes, like liquefaction, are present. [6]

When using the SMR process to produce hydrogen an emission factor of 9 kg CO_2-eq/kg H_2 has been stated in NCE Maritime Clean Tech's report [6]. They also state that it is possible to capture up to 95 % of emitted CO_2 from SMR, making the emission factor below 1 kg CO_2-eq/ kg H_2. IEAGHG on the other hand state a CCS capability of 56-90 % [14]. 90 % CCS capability used as CCS capability in this thesis.

When calculating emissions from SMR, emissions from gas extraction has to be included. Emissions at 1-5 kg CO_2/kg H_2 has been based on US gas production. Calculations made by Equinor shows that expected carbon footprint from gas extraction on the Norwegian continental shelf is about 0,5-0,6 kg CO_2/kg H_2 [6]. In case of hydrogen production from the SMR process at Tjeldbergodden, an emission factor for gas extraction from the Norwegian continental shelf of 0,5 kg CO_2/kg H_2 is used in this thesis.

2.11.5 Emission standards

IMO is an agency of the United Nations that has been formed to promote maritime safety. IMO ship pollution rules are contained in the "International Convention on the Prevention of Pollution from Ships" known as MARPOL 73/78. The NOx emission limits of MARPOL apply to diesel engines, which is defined by any reciprocating engine running on liquid fuel or dual fuel. The limits are set depending on maximum operating speed. Tier I and II limits are global while Tier III limits only apply in NOx emission Control Areas, as is the case for Norway. [48]

Emissions of SOx, NOx and *particular matter* (PM) from ships depend on the fuel used and the engine/converter used. LNG energy converters running by the Otto combustion principle have in common that emissions of local pollutants are very low and at least meet the current strictest emission requirements, such as the IMO Tier III NOx limit [48], regardless of fuel type. For converters running on the diesel cycle, emissions of all types of local pollutants are higher than converters running on the Otto-cycle. For SOx and PM, somewhat higher emissions levels relate to the higher share of pilot diesel fuel to ignite the gas. DNV-GL claims that both concepts can reduce such local emissions more than 95 % compared to MDO [11].

Ships powered by FCs have no local pollutants [11]. NOx and SOx standard values for MDO and LNG are presented in the report "Klima- og miljøregnskap for energigass i Norge" [49] and shown in Table 7.

Emissions	LNG	MDO
NOx [g NOx/kg fuel]	4	45
SO_2 [g SO_2/kg fuel]	0	1,184

Table 7: NOx and SOx emissions LNG and MDO [49]

2.12 Hydrogen energy system

In this section, the components in a hydrogen energy system are briefly mentioned.

2.12.1.1 Storage tanks

Storage tanks is necessary for storing the hydrogen onboard the ships. Storage tank specifications depends on the state and storage volume of the hydrogen. Havila's design for the 4 Kystruten ships that will be put into operation 2021, include a 3,5 tonnes storage tank for future use of hydrogen as fuel, delivered by Linde. [30] As previously mentioned, this would not be sufficient in case of the 75 % reduction in emissions required from the hypothetical tender, Appendix 9.3.

2.12.1.2 FC

FC's are needed to convert the chemical energy in the hydrogen to electrical and thermal energy. Havila's design for the four reel Kystruten ships include 3,1 MW installed power PEM FC delivered by Powercell for a future hydrogen energy system [30]. FC has optimal efficiency and lifetime when operated at a constant given load. In this thesis it is assumed that optimal load is 50 % [50].

2.12.1.3 Cooling/ air supply

An external supply of air as fuel and as cooling is required to keep the FC's at the optimal operating temperature to achieve maximum efficiency. Air supply is required as the oxidizer of the reaction.

2.12.1.4 Battery pack

Batteries are needed to cover rapid load variations to keep the FC at optimal operation percentage. Storage components with good transient capabilities can be used to cover for the limited load variations acceptable in FC. Batteries can be suitable for this purpose since the discharging time of batteries are low.

2.12.1.5 Power electronic converters for FC

DC/DC converters are used in FC systems for power conducting purposes. The FC's output voltage varies with the load current and the age of the fuel cell. The efficiency of the FC is reduced with output ripple current. With a DC/DC converter the output current is regulated [51]. Losses from DC/DC converters is in the range of 5 %. [22]

2.12.1.6 El-motor and thrusters

Havila's design from 2017 [30] include a PM electrical motor delivered by Kongsberg Gruppen called Azipull. It also includes Azipull tunnel thrusters [52]. In order to reduce the scope of this thesis, el-motors are not much studied other than its efficiency.

2.12.2 LNG energy system

In order to reduce the scope of this study, the LNG energy system is not much studied. LNG energy systems are a mature technology within Norwegian maritime industry, and somewhat standardized.

2.12.2.1 Storage tanks

Cryogenic storage tanks for LNG is available on the market and are well established in the Norwegian industry.

2.12.2.2 Energy converter

When it comes to converting the LNG to either electrical or mechanical energy, there are some different options. Some FC, like the SOFC accepts NG as fuel [1]. Gas turbines and *internal combustion engines* (ICE) for NG also exists. To narrow down the scope of this thesis our supervisor advised the group to focus on ICE. The LNG dual fuel ICE engine has maximum efficiency and lifetime when operated at a constant load. In this thesis an optimal load of 85 % is assumed.

The *dual-fuel compression ignition* (DF-CI) ICE uses the same principle as the diesel engine. Gas fuel is injected into the piston together with a small amount of liquid fuel to help ignition start. Some LNG ICE uses *spark ignition* (SI) however this is rarely the case. [22]

It is beneficial to have more than one engine to avoid only having one load-curve. Because of this more than one optimal load can be achieved. Havila's design for their four Kystruten ships. include two nine-cylinder gas generators and two six-cylinder gas generator of combined installed power at 8,1 MW. In our hypothetical tender, batteries will cover peaks in power and store surplus energy, meaning multiple load curves for the LNG gas generators are not required.

2.12.3 Batteries

Energy storage in batteries is one of the most rapidly increasing markets for energy storage. High efficiency, charging and discharging time along with potentially zero emission makes batteries a good option for energy storage.

Battery system design is a trade-off between weight, lifetime, charging/discharging time and size. The number of discharges reduces the lifetime. The amount of energy stored discharged from a battery is called depth of discharge (DoD). The more energy percentage discharged from a fully charged battery until new charging, the lower the lifetime of the battery.

In addition, the C-rate has to considered when designing the battery system. 1C corresponds to the power required to charge the battery from empty to full in one hour. 0,5C means 2 hours, 2C means 0,5 hours. The end of life time for a battery is defined as when the battery capacity is 80 % of the original battery capacity [22]. C-rate and their losses are presented in Table 8.

C-rate	Beginning of lifetime losses [%]	End of lifetime losses [%]
0,5	0,7	1,2
1	1,3	2,2
2	2,6	4,4
3	3,9	6,6

Table 8: C-rate and associated losses, BoL and EoL [22]

The power path for a ship will not be constant during an operation. Acceleration, deceleration and change of the resistance in the sea due to waves, all changes the power demand. Batteries help to cover peaks in the power path while operating either the FC or LNG DF IC engine at a constant load due to the rapid discharge time of the batteries.

2.12.4 Hybrid system

Hybrid systems include two or more technologies to supply the energy demand. This could lead to an increase in efficiency of the system and reduce overall emissions. Hybrid solutions also open up the possibility for peak-shaving. This means the peaks in an energy demand curve caused by thrusting or increased energy demand due to weather can be covered by a secondary power supply, like batteries, and in this case to keep either the FC's or LNG ICE at a constant load. [50]

2.13 Economics

Different production methods and states of hydrogen includes a wide range in price point per unit hydrogen. OPEX and CAPEX costs for production and state change also vary.

2.13.1 Prices

When studying prices for hydrogen it is necessary to include different production methods.
In the current market hydrogen is far from competitive with fossil fuels. According to NCE Maritime Clean Tech [6] the current merchant price of LH_2 delivered in Norway is 15,4 €/kg which is more than eight times more in €/kWh than MDO. However, future incentives for zero emission fuels and further taxation on emissions can help close the gap.

2.13.1.1 Grey hydrogen

At the moment, grey hydrogen is the cheapest type of hydrogen. According to IEA [53] the current market price is 1,5 €/kg H_2. The main variable for resulting price for grey hydrogen is the price of NG which varies around the world.

However, IEA estimates a structural rise in NG prices due to market forces. Europe has experienced volatilely in NG prices as Europe become more linked in the spot market for NG.

Grey hydrogen's CO_2 emissions carry a cost in increasing number that is decided from jurisdictions around the world. In Norway the CO_2 emission tax in 2020 is 1,08 NOK/Sm_3 for LNG, which is an increase from 1,02 NOK/Sm_3 in 2019 [54]. This means while green- and blue hydrogen's future price is expected to drop, grey hydrogen´s future price is expected to increase as taxation on CO_2 emission tax increases yearly.

2.13.1.2 Blue hydrogen

The price of blue hydrogen also is mainly influenced by the price of NG. The second most influential variable is the cost of CCS. According to IEA [53] the prices for CCS currently are in the range of 50-70 €/tonCO_2. This puts blue hydrogen above the price point of that of grey hydrogen, but as previously mentioned, when taxes and fees for CO_2 emissions rises, it helps closing the gap of the price point.

Once the process of CCS is standardized and matured the cost is likely to decline. Innovation should reveal more opportunities for utilizing the captured CO_2, which may further reduce the price of blue hydrogen, and help closing the gap in price point between blue and grey hydrogen sooner than assumed. [53]

2.13.1.3 Green hydrogen

Considering the price of green hydrogen, which is between 3,5 and 5 €/kg H_2 currently according to IEA [53], new variables are presented.

The most critical variable for the price of green hydrogen is the cost of renewable and environmentally friendly electricity. Electrolysis is a very energy demanding process and needs large amounts of electricity. NVE [55] has estimated that the price of electricity can increase from a 2020 baseline of 0,31 NOK/kWh to 0,36 NOK/kWh in 2030. The energy required kWh/kg H_2 depends on the electrolyser utilized. PEM electrolysis has an energy demand of 55 kWh/kg H_2 according to NCE Maritime Clean Tech [6].

Cost of wind- and solar power has declined a lot for the past decade and is expected to decline even more. Installed power has risen dramatically the past decade and is expected to rise more.

With these intermittent energy sources, it is useful to store spare electricity and hydrogen production from electrolysis is a viable option [53].

The second most critical variable is the cost of electrolysis. Currently global electrolysis capacity is limited and costly. It is expected that an increase in production capacity will reduce the cost dramatically, along with further improvements in efficiency [53].

2.13.1.3.1 Alkaline electrolysis

In 2017 Shell [1] claimed CAPEX for AE is between 1000-1200 €/kW not including installation. For comparison IEA [13] claimed in 2015 a price point of 740-1300 €/kW, and a 400 MW AE system were available for 400 €/kW. E4Tech and Element Energy [56] has estimated CAPEX for AE systems to drop from 1000-1200 €/kW in 2014 to 370-800 €/kW in 2030.

2.13.1.3.2 PEM electrolysis

PEM electrolysis possibly inhibits a higher potential efficiency and cost reduction than AE. E4Tech and Element Energy [56] claims CAPEX will decrease from 1900-2300 €/kW in 2014 to 250-1270 €/kW in 2030. For comparison NEL estimated PEM electrolysis systems today at roughly 850 €/kW (2018) and indicates that prices at 600 €/kW and 350 €/kW in 2020 and 2030 respectively. [5]

DNV-GL claims that PEM electrolysis has lower OPEX, and the difference in OPEX for the two electrolysis technology is expected to increase towards 2030 [5]. 6-10 €/kW a year for PEM electrolysis, and 13-32 €/kW a year for alkaline electrolysis for a 100 MW plant.

2.13.1.4 Liquid hydrogen

LH_2 currently has a market value of 7-8 €/kg LH_2 from a production plant in Europe. LH_2 imported to Norway from a production plant in Europe costs 15,4 €/kgLH_2 according to NCE Maritime Clean Tech [6]. According to Rambøll, companies in Norway who considers production of LH_2 estimates a production price at 6 €/kg LH_2 depending on location of the plant [57]. The price for LH_2 delivered on-site in California for a project called SF Breeze [31] could be as low as 5,4 €/kg, which is comparable to that of bio-diesel prices in Norway.

Prices for LH_2 today are based on market availability and produced by SMR without CCS. In the current market, hydrogen is far from competitive with fossil fuels. Current market price for LH_2 is eight times more in €/kWh than MDO, but there is room for reductions. Further taxations on CO_2, NO_x and SO_x along with new government incentives could help to close the gap in price between hydrogen and traditional fossil fuels.

Predicting the future prices of LH_2 depends on several variables; production volume, CAPEX, efficiency levels, energy cost for NG and electricity, distribution, prices for CCS and distribution for SMR. [5]

2.13.2 Incentives and tax-exemptions

To invest in and use new and never before commercially used technology involves a risk. To fund the extra costs of new environmentally friendly technology, it is necessary to receive funding to make it feasible. In Norway several incentives are available for projects that meets their requirements.

2.13.2.1 Enova

Enova SF, owned by Klima- og miljødepartementet, were created in 2001 to restructure energy-usage and production. Enova invest yearly 2 billion NOK from Energifondet, to projects and technologies that contributes to a greener Norway. [58]

Enova invests in companies that chooses energy efficient and environmentally friendly solutions. 7. November 2018 Havila received 87 998 784 NOK in funding for energy efficiency initiatives for their four Kystruten ships that shall be put into operation in 2021 [59].

2.13.2.2 Pilot-E

Pilot-E is a funding offer for Norwegian industry established by Innovasjon Norge, Forskningsrådet and Enova. The goal for the aid is that new products and services in environmentally friendly energy technology gets quicker developed and utilized to contribute to emission reduction in Norway as well internationally. Pilot-E will follow the project from idea to market. In 2019 four projects received in total 95 MNOK.

2.13.2.3 Nox-fondet

Created in 2007 to reduce emissions of NOx, over 15 billion NOK has been invested since 2008 in measures that reduce NOx emissions. [60]. Maximum support rate is 500 NOK/kgNox-reduced however, the funding is limited to cover up to 80 % of the costs of the initiative [57].

2.13.2.4 Carbon taxes

In order to reduce emissions nationally, the Norwegian government introduced 1991 a CO_2 fee. In 2020 the general rate of the CO_2 fee for mineral oil, which includes MDO, is 1,45 NOK/l. For LNG the CO_2 emission tax in 2020 is 1,08 NOK/Sm^3. [54]

3 Method

To gather information regarding the possibility of a 75 % reduction of CO_2, several sources regarding most aspects of hydrogen production and uses have been studied. The information presented in this study have been gathered from a collection of articles, presentations, websites, scientific papers, interviews and educational books.

The paper is built on a series of questions regarding the challenges for such a project. The main themes are: hydrogen production and distribution, ship design, economic and environmental challenges. This information has been used as a basis for calculations answering the questions posed in the project proposal, as well as a reference for comparing the results. Most of these questions have ended up in the “Results” or “Discussion” section of the paper, however the “Background” section of the paper addresses other questions the reader may have, giving an insight into the latest technology available.

4 Results

The assignment is to provide hypothetical tender offer of service of five ships running on a similar schedule of today with a 11-day duration of the round trip. Emission reduction of at least 75 % using hydrogen as the main fuel supply. The route used in this thesis is presented in Appendix 9.1.

In the result section departure intervals from Bergen for the five hypothetical ships and bunkering solutions at the bunkering location will be studied. The ships bunkers in total 13 times during the round trip, and it is assumed LNG bunkering along with hydrogen bunkering. It is also assumed that it is possible to bunker LH_2 while consuming in order to provide required energy.

Ship design, energy requirements and fuel OPEX will be presented. Calculations made is based on a round trip for one ship. This includes the hydrogen storage volume and method, the ships energy system, bunkering solution and required power from electrolysers at harbours, hydrogen and LNG consumption, emissions from different options and their associated OPEX cost.

4.1 Ship design

In this section, hydrogen production, method of storage, storage tanks and the design of the energy system onboard the ships will be covered.

4.1.1 Hydrogen production method

Emissions from SMR used is presented in Table 9.

Process	Emission [kgCO_2/kgH2]
SMR [6]	9
Gas extraction [6] (Equinor values)	0,5

Table 9: Emissions SMR[6]

Figure 11 shows that hydrogen produced from SMR, with or without CCS, would not result in the required 75 % reduction of emissions compared to a 2010 baseline. Green hydrogen produced from electrolysis is the only option that would lead to an adequate reduction in emissions. Green, blue and grey hydrogen in a hybrid energy system with LNG, would result in a reduction of 75,53, 72,3 % for green and blue hydrogen respetivly, and a 1 % increase in emissions in case of grey hydrogen. See section 4.4 for details regarding calculations.

Emissions from green hydrogen depend on the CO_2 content of the used electricity mix. "Nasjonal varedeklarasjon 2018" [47] stated the Norwegian electricity mix at 18,9 g CO_2-eq/kWh in 2018. Using values for energy demand for electrolysis and liquefaction presented in Table 10, the emissions from green LH_2 production can be calculated. Emissions from this process are described in section 4.4.3.

Process	Energy demand [kWh/kgH_2]
PEM Electrolysis	55 [6]
Liquefaction	10,8 [6]

Table 10: Energy demand electrolysis and liquefication [6]

4.1.2 State of hydrogen stored

Due to LH_2 higher volumetric energy density when compared to CGH_2, and the amount of volume that needs to be stored in the top deck, the only viable option of storage is LH_2. A 4,7 tonnes storage tank, presented in section 4.3.1, will translate into about 67m^3 LH_2 and 264 m^3 CGH_2 at 250 bar stored volume, not considering storage tank volume. Utilizing Table 6, outer volume of the storage tanks in case of LH_2 and CGH_2 at 250 bar can be calculated. Outer volume of the LH_2 storage tank would be 116 m^3.

In Table 6, volumetric specifications of 2015 psi and 5000 psi is given. Assuming 250 bar (3625 psi) is the average value of 2015 and 5000 psi, the outer volume of the storage tank in case of CGH_2 is 454 m^3. If storing CGH_2 at a higher pressure, less storage volume would be required. However, LH_2 inhibits the highest volumetric energy density of the different hydrogen states and is used as method of storage in case of the five hypothetical Kystruten ships.

The Havila Kystruten ships is 122,7 m long and 22 m wide [61]. Assuming a radius of the storage tank in case of LH_2 or CGH_2 storage of 1,5 m, the length of the tank would have to be 16,5 m and 64,3 m respectively. Figure 1 shows a sketch of the two storage tanks and a Havila

Kystruten ship from above. The left rectangle is LH_2 storage as the blue rectangle, the right blue rectangle is CGH_2 storage.

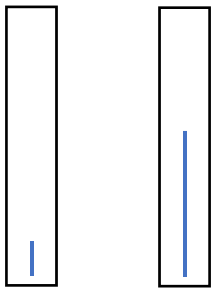

Figure 1: Area comparison LH2-CGH2 compared to ship

The company Linde offers today storage tanks for LH_2 at 300 m^3 LH_2 [6], which is equivalent to 12,1 tonnes LH_2, if volumetric specifications for storage tank is considered. Holding time of 15 days is stated and is adequate considering almost daily bunkering intervals is required. See appendix 9.2 for details of route used.

The cost of LH_2 storage tanks is unclear. The price of a LNG storage tank with less than 100 tonnes storage capacity is 80-100 USD/kg according to NCE Maritime Clean Tech [6]. A price for a 4,2 tonnes LH_2 storage tank at 625 000 USD is also stated in the same report, which indicates a price level 50 % higher than that of LNG. Assuming this, a 4,7 tonnes storage capacity LH_2 tank would cost 705 000 USD.

4.1.3 Storage tank locations

In order to reduce safety challenges associated with onboard hydrogen storage, storage tanks will be placed in a deck open to the atmosphere. This is to prevent an accumulation of hydrogen vapor inside of the ship. If a LH_2 leak occurs, the hydrogen will form a puddle on the ground. This is because the cryogenic hydrogen solidifies all nearby gasses. Eventually the hydrogen will warm up and rise because of its buoyancy. It is necessary to isolate the accumulation from any source of ignition. According to the IGF code [28], the storage tanks has to placed minimum 20 % of the ships width in from the side of the ship. This is to prevent deformation and rupture of the storage tanks in case of a collision.

Stacking of storage tanks could be a problem as an accumulation of liquid hydrogen could form in spaces between the storage tanks. Stacking of storage tanks should be avoided if possible.

4.1.4 Energy System

The goal of this thesis is to examine if a 75 % reduction in emissions compared to a baseline of 2010 is possible when hydrogen is used as the main fuel supply for the five hypothetical Kystruten ships. A hybrid energy system consisting of FC's, LNG gas generator sets, and batteries is implemented to achieve this goal.

It is assumed that the ships will be running on hydrogen until the storage tank is empty, then switching over to LNG. Batteries will cover peaks in power demand due to acceleration, rough seas and wind. Batteries will charge from the spare power of the FC's at port and when decelerating to keep a constant load for the FC and LNG system in order to achieve maximum lifetime and efficiency.

In this section the energy systems are described, along with their associated efficiencies.

4.1.4.1 FC

PEM FC is the leading FC on the market today, with high potential for cost reduction and efficiency increase. Since it operates on such low temperatures, the start up time is low which is a requirement given the tight schedule Kystruten inhibits. Optimal load to increase lifetime and efficiency is around 50 % [50]. Thus a 7 MW installed power PEM-FC system is optimal considering a constant power demand of 3,5 MW. This also opens the possibility for the FC's to deliver more energy in case of empty battery pack or high peaks in power demand.

Assuming a CAPEX for PEMFC's at 3500 USD/kW [1], investment costs for a 7 MW FC system is 24 500 000 USD.

4.1.4.2 LNG system

The LNG storage capacity is dimensioned by the smallest value of hydrogen storage content, see Appendix 9.4, and translates into 6,7 tonnes LNG. The Havila Kystrtuten ships that will operate 4 of the 11 Kystruten ships from 2021, will be delivered with 4 gas generator sets from

Rolls Royce Bergen Engines with a combined power of 8,1 MW. It is assumed that the four gas generator sets are not designed to run all together, but to allow different loads at optimal efficiency due to the engines different load curves, without the implementation of batteries.

Optimal load for an LNG engine is assumed to be 85 %. In the case of this study, a required installed power for optimal operation of the LNG system is 4,05 MW, assuming a constant power demand of 3,5 MW.

4.1.4.3 Batteries

Lithium-ion battery is currently the most common battery in autonomous and maritime applications. In the case of this study, Havila's original design of a battery pack with 6,1 MWh storage capacity is used. The C-rate of the batteries needs to be as low as possible to increase lifetime and recharging cycles.

The C-rate describes the battery's ability to discharge and charge the energy content of the battery regarding time. If assumed power requirement for acceleration is 6 MW and the duration of acceleration is 20 minutes, the energy demand is 2 MWh. The battery packs storage capacity is assumed to be 6,1 MWh and 1 C-rate, meaning the battery is capable of discharging 6,1 MWh in one hour, or 2,03 MWh in 20 minutes. This proves that a C-rate of 1 is sufficient for the trip Bergen-Trondheim from Figure 9.

4.1.4.4 Hybrid system

While docking at some ports, the FC will deliver more energy than needed for the hotel load of the ship, see Figure 9. This surplus energy has no available storage. One option to utilize this spare energy is to connect to the electricity grid and let the FC work as a power generation station temporarily. Another alternative is to lower the power of the FC while docking, which would have a negative impact on the efficiency and possibly the lifetime of the FC, or increase the capacity of the battery pack.

An optimal solution where all excess energy converted is stored for later use could be developed. However, the group has not gained access to real world data onboard power and energy requirements since this is highly confidential information. To estimate this type of data would require extensive calculations and simulations which is beyond the scope of this study.

Figure 2 is an illustration of the energy system onboard the Kystruten ships.

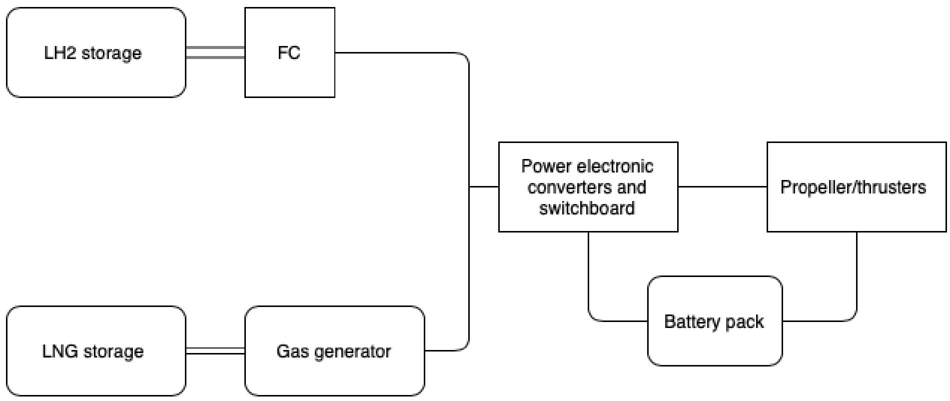

Figure 2: Hybrid energy system

The ship will be powered from the hydrogen energy system when LH_2 is available from the storage tank. Surplus energy from hotel operation and deceleration is stored in the battery pack. In case of peaks in power demand, the battery pack will deliver power equal to the gap of power demand and power delivery.

In case of no available LH_2, the LNG energy system takes over and powers the ship. Surplus energy is stored in the same way as surplus energy converted from the hydrogen energy system is stored in battery pack. Once LH_2 again is available the hydrogen energy system takes over, and the LNG energy system shuts down.

4.1.5 Efficiencies

4.1.5.1 FC

Shell claims an electrical efficiency of 30-60 % of PEM FC depending on size and application [1]. In the report "Rapport fase 2Utviklingskontrakt utslippsfri hurtigbåt, Doffin 2017-138144" [7] efficiency of FC used is 54 %. In a personal e-mail to Johan Burgren, Business manager at Power Cell Sweden, efficiencies of 54 % BoL (beginning of lifetime) and 46 % EoL (end of lifetime) were provided [62]. In this thesis, efficiency of PEMFC is assumed to be 54 %.

4.1.5.2 Gas generator sets

Due to lack of data provided by the producer of the Bergen C:26 gas generator sets, effective thermal efficiency is calculated by public available engine data [63]. The formula is extracted from [64].

$$\eta_e = \frac{1}{bsfc * Hn\ LNG}$$

A specific energy consumption of 7450 kJ/kWh is stated, by converting this to specific fuel consumption (bsfc) using the energy content of LNG, see Appendix 9.1, the indicated thermal efficiency can be calculated. Hn is LHV of LNG at 13,7 kWh/kg LNG. This results in effective thermal efficiency of 48,3 % for the Rolls Royce Bergen Engines Gas generator sets.

4.1.5.3 Other losses

Efficiencies of the hydrogen system is extracted from “Rapport fase 2Utviklingskontrakt utslippsfri hurtigbåt, Doffin 2017-138144” [7] and presented in Table 11. It is assumed that the LNG energy system utilizes the same components.

Component	Li-Ion Battery	Drivers/converters/switchboard	El-motor-propeller
Loss	1 %	6 %	27 %

Table 11: Efficiencies hydrogen energy system [7]

4.1.5.4 Hydrogen value chain system efficiency

The product of the efficiency of all of the components results in the total efficiency of the hydrogen energy system. Components included are FC, DC/DC converters and switchboard, battery and electrical motor to mechanical energy out to propeller. This results in a total efficiency of 36,7 % for the hydrogen value chain. The hydrogen value chain efficiency is presented in Figure 3.

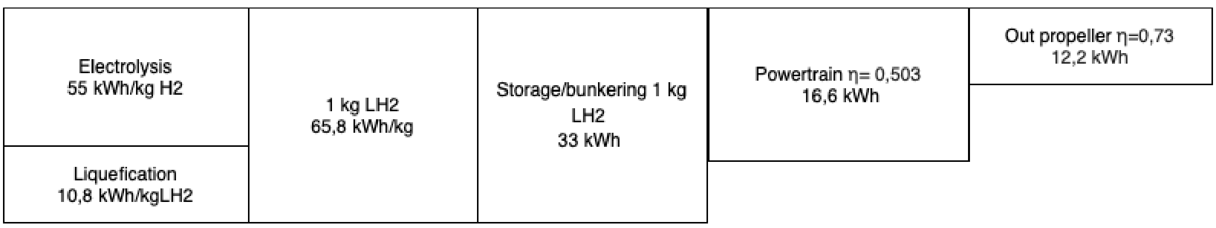

Figure 3: Hydrogen energy system efficiency

4.1.5.5 LNG energy system efficiency

The product the efficiency of all the components results in the total efficiency of the LNG energy system. Components included are LNG gas generator set, drivers/converters, DC/DC switchboards, battery and electrical motor to mechanical energy out to propeller. This results in a total efficiency of 32,8 %. The LNG system efficiency is presented in Figure 4.

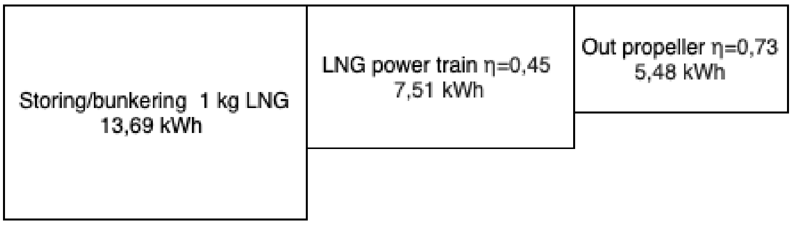

Figure 4: LNG energy system efficiency

Excluding efficiencies from hydrogen production and liquefication, the efficiency of the hydrogen energy system, 36,7 %, is higher than that of the LNG energy system, 32,8 %. This is due to the higher efficiency of the FC when compared to the calculated effective efficiency of the LNG gas generator.

4.2 Bunkering and shore side storage of hydrogen

In this section, the bunkering solution, bunkering storage capacities and required power from electrolysers assuming local production of hydrogen at bunkering harbours is presented.

4.2.1 Bunkering solution

Shorter fill lines compared to LNG bunkering are important to minimize the cooling process before bunkering, due to hydrogens lower boiling point. A simplified schematic presentation of the bunkering system is presented in Figure 5.

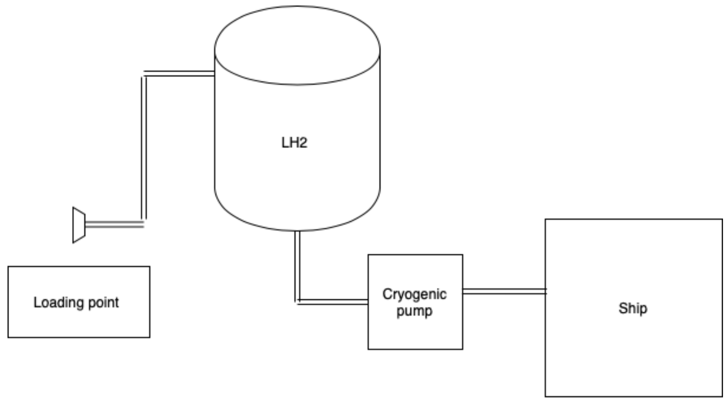

Figure 5: Bunkering solution

By pre-cooling the hydrogen before the ship arrives for bunkering, overall bunkering time can be shortened. Assuming a hydrogen transfer rate of 2 tonnes/hour, and a bunkering preparation time for connecting and disconnecting of 30 minutes [6], filling a 4,7 tonnes storage tank from empty to full would take 3 hours and 21 minutes (3,35 hours) using these assumptions.

4.2.1.1 Bunkering locations

The choice of bunkering locations are inspired by NCE Maritime Clean Tech, Selfa Artic and Zero's vision of a emission free Kystruten at the Zerokonferansen in 2017 [39]. 8 bunkering locations along the Kystruten were presented, and this thesis includes all but Sandessjøen. In order to keep a schedule as similar as that of today, Sandnessjøen is not included due to its short docking time of 10 minutes northbound and 30 minutes southbound, see appendix 9.2. The route then includes 7 assumed bunkering locations and in total 13 bunkering stops for a round trip. Bunkering locations used for this study includes; Bergen, Ålesund, Trondheim, Bodø, Tromsø, Honningsvåg and Kirkenes. This is shown in Table 12.

Harbour	Arrival	Departure	Docking time [hours, minutes]
Bergen	14:30	21:30	7 , 00
Ålesund	09:45	13:30	3 , 45
Trondheim	10:00	13:15	3 , 15
Bodø	12:40	15:00	2 , 20
Tromsø	14:15	18:30	4 , 15
Honningsvåg	11:15	14:45	3 , 30
Kirkenes	09:00	12:30	3 , 30

Table 12: Assumed bunkering locations northbound route

As shown in Table 12, docking time at bunkering locations Trondheim and Bodø has to be extended to fill a tank from empty to full, using assumptions stated in section 4.2 of the thesis at 3 hours and 21 minutes for bunkering hydrogen storage empty to full. It could be possible to shorten stops at other ports along the route to keep a similar duration of that of today or prolong the roundtrip to provide sufficient bunkering time.

Harbour	Arrival	Departure	Docking time [Hours, minutes]
Kirkenes	09:00	12:30	3 , 30
Honningsvåg	05:30	05:45	0 , 15
Tromsø	23:45	01:30	1 , 45
Bodø	02:30	03:45	1 , 15
Trondheim	06:30	09:45	3 , 15
Ålesund	00:30	01:00	0 , 30
Bergen	14:30	21:00	7 , 00

Table 13: Assumed bunkering locations southbound route

As shown in Table 13 the docking time at bunkering harbours at the southbound route would need to be extended at every harbour except Kirkenes and Bergen. If following the existing route and existing docking time at none bunkering harbours, the route has to be extended by 10 hours and 52 minutes in order to accommodate sufficient bunkering time.

4.2.1.2 Electrolysers at port

The seven ports will require different equipment to function as bunkering stations. This is due to the difference in hydrogen amount the ports will have to be able to supply. In this section, four scenarios for possible operating procedures has been assumed to find the optimal procedure for the ports.

The scenarios vary with two conditions. The first condition is based on whether the production is continuous or on demand. The continuous option assumes that the production will continue day and night to produce hydrogen and store the produced hydrogen for when the ship arrives to bunker. The on demand option assumes that the hydrogen only will be produced the day the ship arrives to bunker, resulting in more downtime.

The second condition is based on when the ship arrives. This theoretical tender is for five ships, and Kystruten operates with a total of 11 ships. This means that there will be six ships run by another company, Hurtigruten, that does not require hydrogen. A result of this is that the ports will not be required to supply hydrogen every day. With this the question get raised on how the ship will travel in regard to each other.

The first option is that the five hydrogen ships will depart from Bergen one after the other for five days with a time gap of 24 hours. The other option is that the ships will depart from Bergen every other day with a non-hydrogen ship in between, resulting in a 48 hour time gap.

This results in the four different scenarios being:

1. Continual production and 24 hour time gap.
2. Continual production and 48 hour time gap.
3. On demand production and 24 hour time gap.
4. On demand production and 48 hour time gap.

To illustrate the change difference in hydrogen demand for the seven ports, Table 14 have been made to highlight how the change from a time gap minimum of 48 hours to 24 hours affect the demand. The 48-hour time gap (Scenario 2 and 4) is illustrated by the numbers before the stroke, the red numbers, and the 24-hour time gap (Scenario 1 and 3) is illustrated by the numbers after the stroke, the black numbers.

Location	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
Bergen	4,7/4,7	0/0	0/0	4,7/0	0/0	4,7/0	0/0	4,7/4,7	0/4,7	4,7/4,7	0/4,7
Ålesund	4,7/9,4	4,7/4,7	0/0	4,7/0	4,7/0	4,7/0	4,7/0	4,7/4,7	4,7/9,4	4,7/9,4	4,7/9,4
Trondheim	4,7/4,7	0/4,7	9,4/4,7	0/0	4,7/0	4,7/0	4,7/4,7	4,7/4,7	4,7/4,7	4,7/9,4	4,7/9,4
Bodø	0/4,7	9,4/4,7	0/4,7	9,4/4,7	0/0	4,7/4,7	4,7/4,7	4,7/4,7	4,7/4,7	4,7/4,7	4,7/4,7
Tromsø	9,4/0	0/4,7	9,4/4,7	0/4,7	9,4/9,4	0/4,7	4,7/4,7	4,7/4,7	4,7/4,7	4,7/0	0/0
Honningsvåg	0/0	9,4/4,7	0/0	9,4/9,4	0/9,4	9,4/9,4	0/4,7	4,7/4,7	4,7/0	0/0	9,4/0
Kirkenes	4,7/0	0/0	4,7/4,7	0/4,7	4,7/4,7	0/4,7	4,7/4,7	0/0	0/0	4,7/0	0/0

Table 14: Daily hydrogen requirement

To show how the different scenarios change the outcome, three variables have been focused on. Those three being storage capacity, energy requirement and electrolyser power.

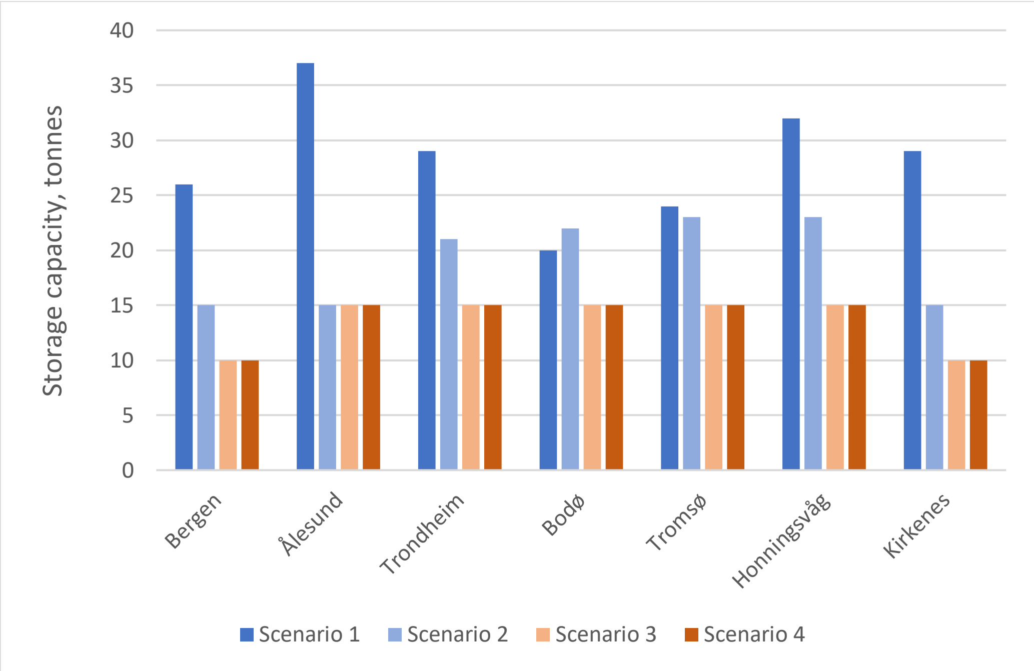

Figure 6: Storage capacity requirement for bunkering locations, tonnes.

Figure 6 shows how the different scenarios affect storage demand at each port, with scenario 1 requiring the most storage capacity, scenario 2 require the second most and 3 and 4 requiring the least.

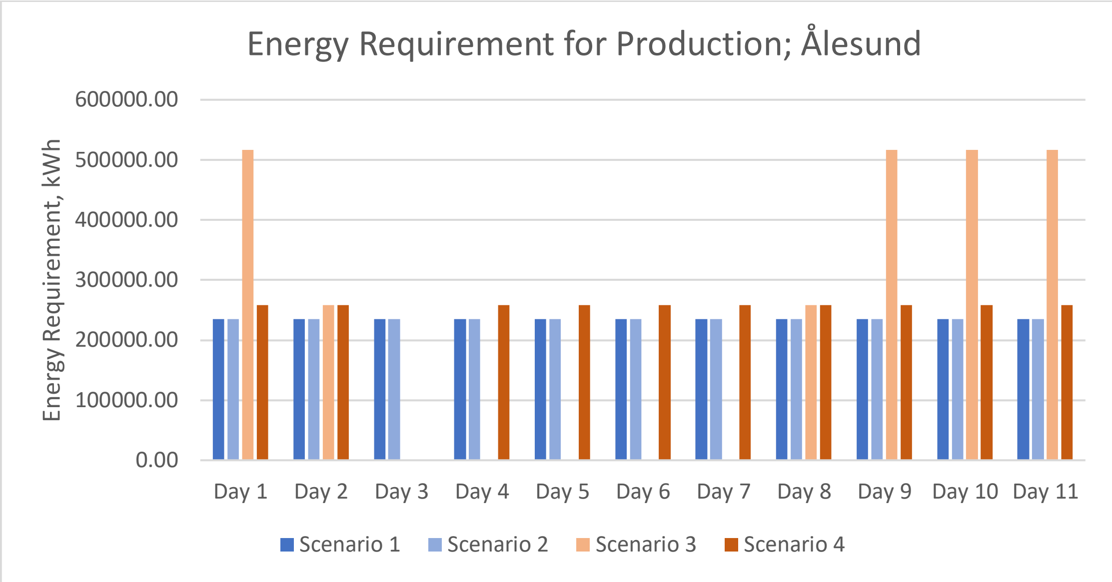

Figure 7: Energy requirement for Ålesund, kWh.

Figure 7 shows the energy requirement for the different scenarios for the port of Ålesund. Here scenario 1 and 2 require the most stable energy production, with scenario 3 having the biggest fluctuation and scenario 4 being stable except for a 1 day off time.

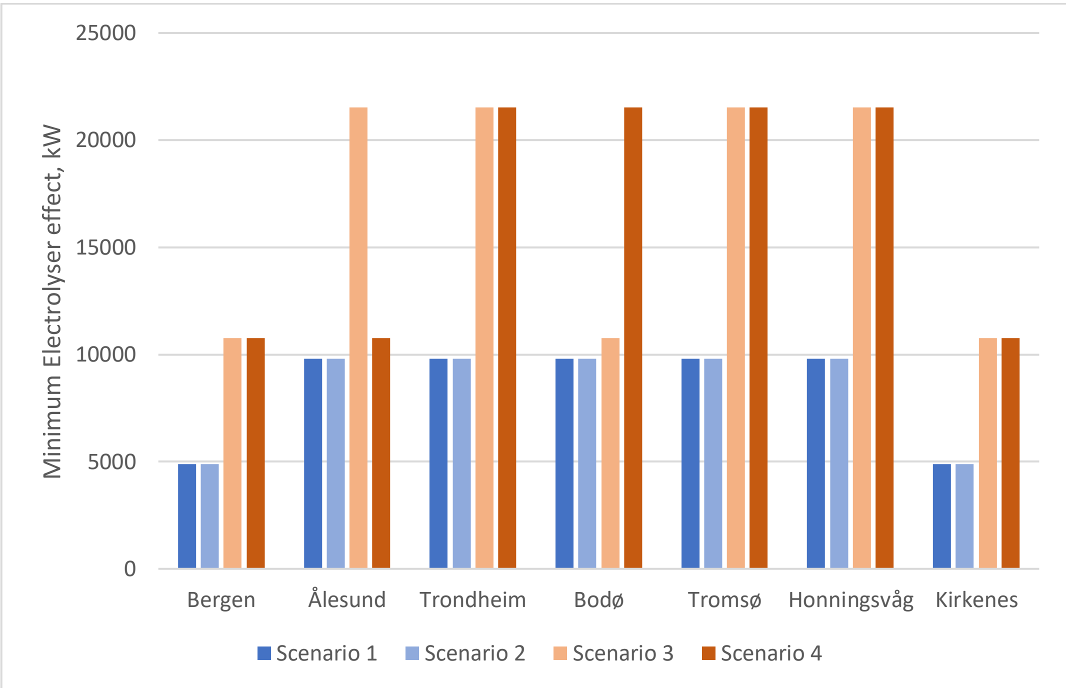

Figure 8: Electrolyser power for bunkering locations, kW.

Figure 8 shows the required power of the electrolysers in each port, with scenario 1 and 2 requiring least amount of installed power, while 3 and 4 require a larger amount of installed power due to their varying production pattern.

Depending on the scenario, the requirement of the equipment will vary. Scenario 1 or 2 will require smaller electrolysers either 4696 kW or 9792 kW as can be seen on Figure 8. Scenario 3 and 4 on the other hand will require electrolysers from 10771 kW or 21542 kW. Scenario 3 and 4 will however require less hydrogen storage capacity seen in Figure 6, which could be a deciding factor in some situations.

4.3 Energy requirements

In this section the energy consumption will be presented together with calculations for fuel consumption, storage tank capacities and an illustration of how the different components in the energy system would cooperate.

Data for installed power for propulsion and hotel operation is extracted from Eirik Iansen, CEO at Selfa Artic, from a spread sheet from their bid at the Kystruten [65]. The spread sheet presents 1,3 MW required power for hotel operation and 2,2 MW required power for propulsion. In order to keep the FC's and gas generator sets at a constant load the power delivery components run constant at 3,5 MW, separately. When at harbour, spare power from propulsion is used to charge the battery pack.

The route for the ships that is used in this study is the existing autumn route for Hurtigruten [40] presented in Table 15. To calculate the theoretical energy requirement for the round-trip Bergen-Kirkenes-Bergen, time spent at harbours and crossing at each port has to be calculated.

Harbour	Hydrogen bunkering	Arrival	Departure	Docking time	Travel time to next destination
		time	time	[hours, minutes]	[hours, minutes]
Bergen	Yes	14:30	21:30	7 , 00	6 , 00
Florø		03:30	03:40	0 , 10	2 , 00
Måløy		05:40	05:50	0 , 10	2 , 40
Torvik		08:30	08:40	0 , 10	1 , 05
Ålesund	Yes	09:45	13:30	3 , 45	2 , 45
Molde		16:15	19:00	2 , 45	3 , 30
Kristansund		22:30	01:30	3 , 00	8 , 30
Trondheim	Yes	10:00	13:15	3 , 21*	9 , 00
Rørvik		22:15	22:30	0 , 15	2 , 15
Brønnøysund		01:45	01:55	0 , 10	2 , 40
Sandnessjøen		04:35	04:45	0 , 10	1 , 10
Nesna		05:55	06:05	0 , 10	3 , 40
Ørnes		09:45	09:55	0 , 10	2 , 45
Bodø	Yes	12:40	15:00	3 , 21*	4 , 00
Stamsund		19:00	19:30	0 , 30	1 , 30
Svolvær		21:00	22:00	1 , 00	3 , 00
Stokmarknes		01:00	01:15	0 , 15	1 , 30
Sortland		02:45	03:00	0 , 15	1 , 15
Risøyhamn		04:15	04:30	0 , 15	2 , 15
Harstad		06:45	07:45	1 , 00	3 , 15
Finnsnes		11:00	11:30	0 , 50	2 , 45
Tromsø	Yes	14:15	18:30	4 , 15	4 , 00
Skjervøy		22:30	22:45	0 , 15	3 , 15
Øksfjord		02:00	02:15	0 , 15	3 , 00
Hammerfest		05:15	06:00	0 , 45	2 , 45
Havøysund		08:45	09:15	0 , 30	2 , 00
Honningsvåg	Yes	11:15	14:45	3 , 30	2 , 15
Kjøllefjord		17:00	17:15	0 , 15	2 , 00
Mehamn		19:15	19:30	0 , 15	2 , 30
Berlevåg		22:00	22:15	0 , 15	1 , 45
Båtsfjord		00:00	00:15	0 , 15	3 , 00
Vardø		03:15	03:30	0 , 15	3 , 15
Vadsø		06:45	07:15	0 , 30	1 , 45
Kirkenes	Yes	09:00	12:30	3 , 30	3 , 15
Vardø		15:45	16:45	1 , 00	3 , 00
Båtsfjord		19:45	20:15	0 , 30	1 , 30
Berlevåg		21:45	22:00	0 , 25	2 , 45
Mehamn		00:45	01:00	0 , 15	1 , 45
Kjøllefjord		02:45	03:00	0 , 15	2 , 30
Honningsvåg	Yes	05:30	05:45	3 , 21*	2 , 00
Havøysund		07:45	08:00	0 , 15	2 , 45
Hammerfest		10:45	12:45	2 , 00	2 , 45
Øksfjord		15:30	15:45	0 , 15	3 , 30
Skjervøy		19:15	19:45	0 , 30	4 , 00
Tromsø	Yes	23:45	01:30	3 , 21*	2 , 45

Finnsnes		04:15	04:45	0 , 30	3 , 05
Harstad		07:50	08:30	0 , 40	2 , 15
Risøyhamn		10:45	11:00	0 , 15	1 , 30
Sortland		12:30	13:00	0 , 30	1 , 15
Stokmarknes		14:15	15:15	1 , 00	3 , 15
Svovlær		18:30	20:30	2 , 00	1 , 30
Stamsund		22:00	22:30	0 , 30	4 , 00
Bodø	Yes	02:30	03:45	3 , 21*	2 , 55
Ørnes		06:40	06:50	0 , 10	3 , 35
Nesna		10:25	10:35	0 , 10	1 , 10
Sandnessjøen		11:45	12:15	0 , 30	2 , 45
Brønnøysund		15:00	17:30	2 , 30	3 , 30
Rørvik		21:00	21:30	0 , 30	7 , 00
Trondheim	Yes	06:30	09:45	3 , 21*	6 , 45
Kristiandsund		16:30	17:00	0 , 30	4 , 00
Molde		21:00	21:30	0 , 30	3 , 00
Ålesund	Yes	00:30	01:00	3 , 21*	1 , 15
Torvik		02:15	02:30	0 , 15	2 , 45
Måløy		05:15	05:35	0 , 20	2 , 10
Florø		07:45	08:15	0 , 30	6 , 15
Bergen	Yes	14:30			

Table 15: Autumn route Hurtigruten

Docking time is time spent at harbour, and travel time is time spent from harbour to next destination. Docking time intervals with a footnote is extended to accommodate sufficient bunkering time for filling the hydrogen storage tank from empty to full. Actual time for the existing route does not represent this, but energy consumption at ports does.

The product of time spent at dock and power requirement at hotel operation is energy required when at dock. Here the altered time spent at bunkering locations is represented. The product of time spent crossing and the sum of power requirements is the energy requirement when crossing. Due to the fact that FC's and LNG engines preferably should run at a constant load, power requirements for hotel and for propulsion is both 3,5 MW. When summing up the theoretical energy demand for each step of the journey, the theoretical energy requirement for the round-trip results in a total of 951,5 MWh, see Appendix 9.3.

$$Theoretical\ energy\ demand\ [MWh] = Effect\ [MW] * Time\ spent\ at\ operation\ [h]$$

Total hydrogen solo fuel consumption is calculated by dividing the theoretical energy demand by the total efficiency of the hydrogen energy system. This results in an energy demand of 2693 MWh LH_2 or 80,8 tonnes LH_2, see Appendix 9.3.

$$Hydrogen\ solo\ fuel\ consumption\ [MWh] = \frac{Theoretical\ energy\ demand\ [MWh]}{\eta_{hydrogen\ system}}$$

By assuming a storage tank with 4,7 tonnes LH_2 storage capacity, the hydrogen consumption when combined with LNG in a hybrid energy system can be calculated. This is done by calculating the hydrogen consumption at each stage of the trip and subtracting this from the storage tank content in the previous point of the journey. When the content of the hydrogen storage is negative, the LNG system covers the gap in energy demand and available energy from hydrogen. The smallest value of hydrogen storage content also presents the dimensioning value for the LNG storage capacity, see Appendix 9.4.

The negative values of hydrogen consumption are the LNG consumption. By converting tonnes hydrogen into tonnes LNG using values for energy content for the fuels, Appendix 9.1, the LNG consumption can be calculated, Appendix 9.5. This results in hydrogen and LNG consumption of the round-trip of 64,97 tonnes and 29,7 tonnes respectively, Appendix 9.3 and 9.5.

Rough seas, acceleration and deceleration are factors which change the power demand. FC's and LNG engines has optimal efficiencies and achieves maximum lifetime when operated at a constant load. In order to achieve a constant load when variations in power demand occurs, batteries are a good option to implement into the energy system due to their fast charging and discharging time and high overall efficiency. Havila's design from 2017 for their 4 Kystruten ships include a battery pack with 6,1 MWh energy storage capacity [30]. This is implemented in this study as well.

Spare power available from FC or LNG can be used to charge the batteries. Assuming the possibility of consuming hydrogen while bunkering at harbour, the spare power from propulsion (2,2 MW) can be used to charge the batteries when either FC or LNG engine operates at a constant load. Spare power available when decelerating when arriving to port can also be used to charge the batteries. Power requirements for the different operations is presented in Table 16.

Operation	Power [MW]
Hotel	1,3
Propulsion	2,2
Acceleration (included hotel + propulsion)	6
Deceleration (included hotel + propulsion)	2

Table 16: Power requirements for the load variations

To illustrate the concept of the interaction between the different power generation and delivery options, acceleration and deceleration time is assumed to be 20 minutes. The product of power requirement for acceleration/deceleration and time spent on the operation is the energy demand for the operation.

The concept of the interaction between the different power generation and delivery options is illustrated in Figure 9.

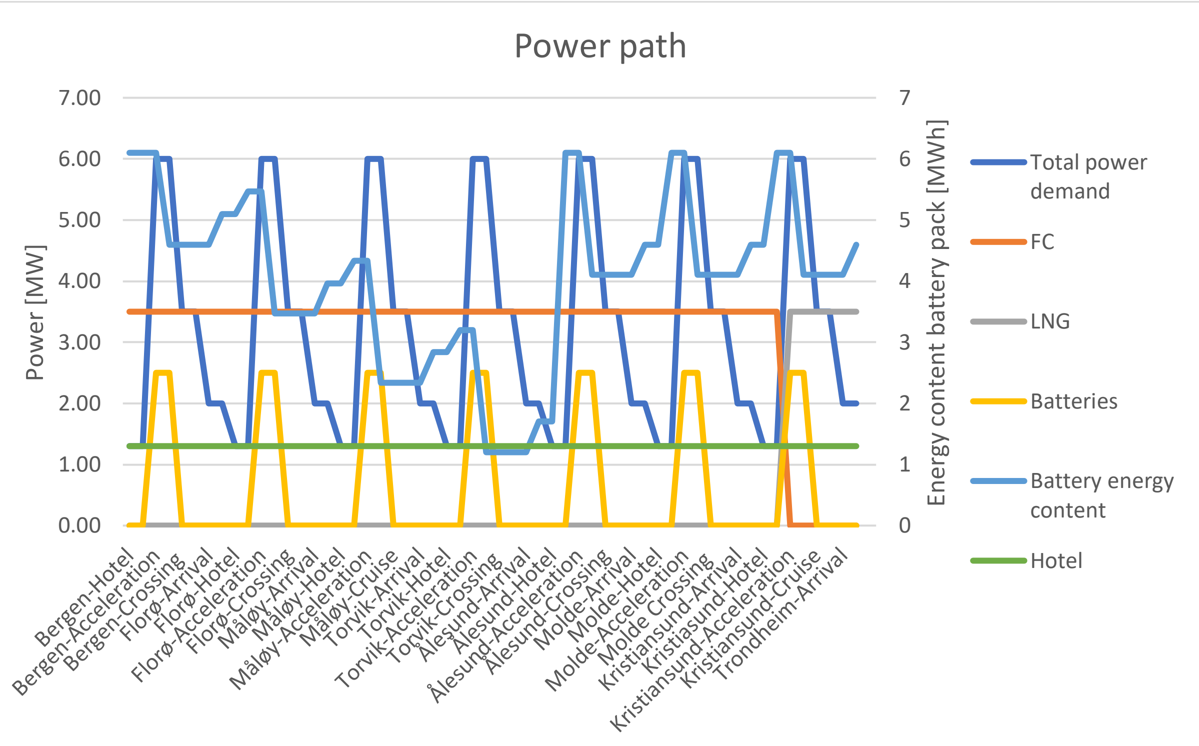

Figure 9: Power path Bergen-Trondheim, MW and MWh

The dark blue line represents the total power demand. This varies because of different power demands for the different operations, Hotel, acceleration, cruise and deceleration. In real life the total power demand would not be as constant as illustrated in Figure 9 during a given operation.

The orange line represents power from FC, and the grey LNG. These are set to a constant of 3,5 MW, the power demand for crossing. In Kristiansund the hydrogen storage is empty, and the FC stops. Now the LNG energy system starts up and runs until hydrogen once again is available.

The batteries cover differences in power demand and -delivery from acceleration in Figure 9. In practice the battery pack would need to perform peak shaving during the crossing due to peaks in power. The battery energy content represents the stored energy in the battery pack at different points of the trip in MWh.

The green line is the power requirement for hotel load at 1,3 MW.

It would not be possible to keep the FC and LNG running at a constant load in practice. Figure 9 represents how the different power generation components would cooperate in the hybrid system for an idealized system.

4.3.1 Storage

The storage volume onboard the ships are limited. No specifications for available storage volume on the Havila Kystruten ships are publicly available, nor has any information been presented to the group. The group decided to instead calculate minimum required storage volume for LH_2 tanks to achieve a reduction of emissions of 75 %.

Hydrogen consumption at all of the docks and crossings were calculated. Assuming a LH_2 storage tank of 4,7 tonnes capacity, the content of the storage tank at each point along the route was calculated, Appendix 9.3.

The dimensioning value for the LNG storage, was the lowest value for the hydrogen storage when assuming a storage tank capacity 4,7 tonnes LH_2, which is -2,46 tonnes LH_2. Given the energy content in LNG and LH_2 from Appendix 9.1, and efficiencies for the hydrogen and LNG energy system, it translates to required LNG storage capacity of 6,68 tonnes, Appendix 9.4.

Percentages of full tanks for both LNG and hydrogen storage tanks during the round trip is presented in Figure 10, Appendix 9.3 and 9.5.

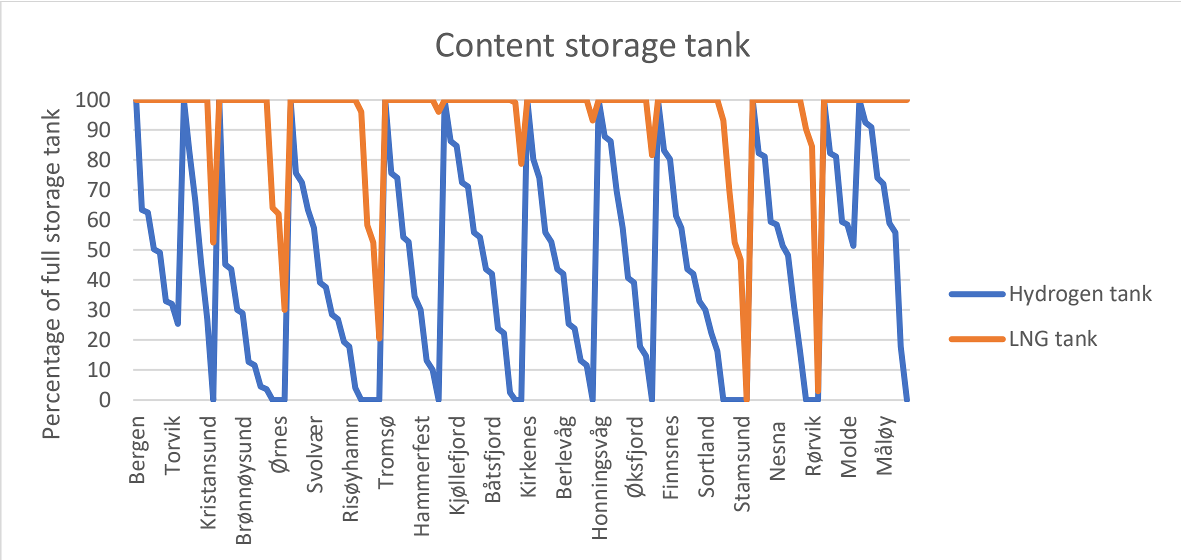

Figure 10: LNG and hydrogen storage

4.4 Emissions

When calculating emissions from the 200 tonnes of diesel assumed consumed from a round-trip and emissions from LNG consumption, fuel data from Miljødirektoratet's emission factor standards have been used [66]. Well-to-Tank emissions is extracted from the report "Natural gas as a ship fuel: Assessment of greenhouse gas and air pollutant reduction potential" by Sharafian, P. Blomerus, and W. Mérida [41].

Assuming the diesel consumption for a round-trip was 200 tonnes in 2010, it results in 718,05 tonnes CO_2-eq for a round trip Bergen-Kirkenes-Bergen. From this baseline, a potential 75 % reduction in emissions can be calculated.

The emissions from LNG is calculated by the total consumption of LNG for a round trip which is 29,7 tonnes and the emission factors for LNG and MDO presented in Table 17. Hydrogen emissions is calculated using an emission factor of 18,9 g CO_2-eq/kWh and a fuel consumption for a round trip at 64,97 tonnes LH_2.

	LNG	MDO
Emission factor [tonnes CO_2-eq/TJ] [66]	55,9	73,5
WTT [tonnes CO_2-eq/TJ] [41]	8,9	9,8

Table 17:Emissions from LNG and MDO [66] [41]

4.4.1 Grey hydrogen + LNG

Grey hydrogen produced at Tjeldbergodden processing plant includes an assumed emission factor of 9,5 $kgCO_2$-eq/kgH_2 included gas extraction, see Table 10. 617,2 CO2-eq is emitted from the H_2 production process from SMR. When including emissions from LNG combustion and emissions for hydrogen liquefaction, the total emissions is 725,4 tonnes CO_2-eq. This results in a 1 % increase in emissions when comparing to the 2010 baseline.

4.4.2 Blue Hydrogen + LNG

Assuming a CCS capability of 90 %, 90,9 tonnes CO_2-eq is emitted from the production process. When including emissions from combustion of LNG, gas extraction, and from hydrogen liquefaction, the total emissions are 199,1 tonnes CO_2-eq. This results in a reduction in emissions compared to the 2010 baseline of 72,3 % which does not achieve the required 75 % reduction.

4.4.3 Green hydrogen + LNG

When producing hydrogen from electrolysis electrical energy at 55 kWh/ kg H_2 is consumed. Additionally, 10,8 kWh/kg LH_2 is consumed in the liquefaction process. This results in an electrical energy demand of 4275 MWh to produce the necessary mass of hydrogen required for a round trip. The product of carbon content of the Norwegian electricity mix and energy demand for LH_2 production is total emissions from the hydrogen production process, which results in 80,8 tonnes CO_2-eq. Using the standard emission factor for LNG combustion along with WTT values for LNG, the emissions from LNG combustion and production results in 93,93 tonnes CO_2-eq.

The total emissions for the green LH_2 and LNG hybrid system are 175,7 tonnes CO_2-eq. The reduction in emissions when comparing to the 2010 baseline of 200 tonnes MDO for a round trip results in 75,53 % decrease in emissions by using green hydrogen and LNG.

This concludes that the green LH_2 and LNG hybrid energy system is the only option which have a required 75 % reduction in emissions compared to the 2010 baseline. However, the option of blue hydrogen is close to achieve the required reduction, assuming a CCS capability of 90 %. Further improvements in SMR technology or CCS technology may decrease emissions from blue hydrogen and achieving the required reduction.

Figure 11 illustrates the emissions from the different options.

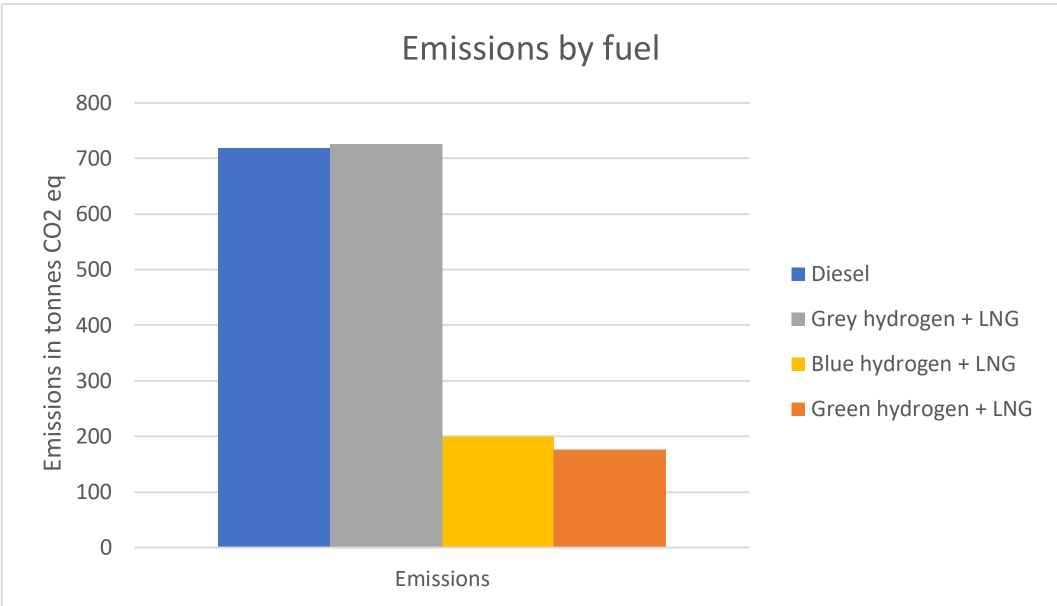

Figure 11: Emissions from the round trip, Tonnes CO_2-eq

4.4.4 NOx emissions

NOx emission factors for MDO and LNG is presented in the report «Klima- og miljøregnskap for energigass i Norge» [67] at 45 and 4 g NOx/kg fuel, respectivly. This results in case for the green hydrogen and LNG hybrid energy system a reduction compared to the 2010 baseline of 98,7 %. Reducued NOx emissions are 8865 kg NOx which could lead to 4 442 000 NOK in aid from NOx-fondet for a single round trip assuming a support rate of 500 NOK/kg NOx. Support from NOx-fondet is limited to cover maximum 80 % of the costs for the initiative. Thus, support in form of 4 442 000 NOK/round trip may not be the situasion and require further examination.

NOx emissions from the 2010 baseline and green hydrogen and LNG hybrid system are illustrated in Figure 12.

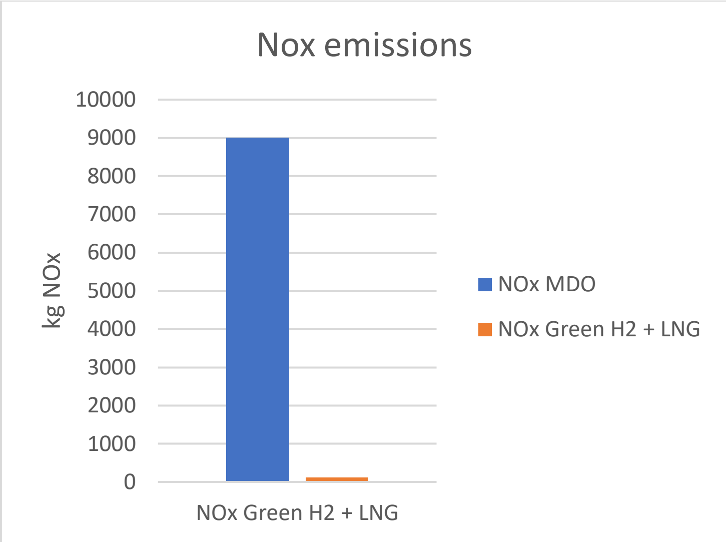

Figure 12: NOx emissions 2010 baseline and Green H2 + LNG, kg NOx

4.4.5 SOx emissions

SOx emission factor for MDO is presented in the report «Klima- og miljøregnskap for energigass i Norge» [67] at 1,184 kg SO_2/tonne fuel. This results in SO_2 emissions from the 2010 baseline at 236,8 kg SO_2. Neither NG nor hydrogen have SO_2 emissions when combusted, or chemically converted to electrical energy in case of hydrogen. This results in a 100 % reduction of SO_2 emissions compared to the 2010 baseline.

4.5 Fuel OPEX

Currently there is no global or regional marketplace for LH_2, which makes it difficult to give a precise picture of price point. Production costs are relative to production plant capacity, price of electricity or NG and distribution costs. Several studies have estimated both a current and future price point for LH_2.

The different prices for the fuel options which is presented in NCE Maritime Clean Tech's article "Norwegian future value chains for liquid hydrogen" [6] is presented in Table 18. Prices for green and blue LH_2 are currently not available. Blue LH_2 price is estimated from a 20 % increase in costs from grey LH_2 [36].

By studying the difference in current price for green and grey H_2 at 3,5-5 €/kg H_2 and 1,5 €/kg H_2 respectively, green hydrogen costs an additional 233-333 % when compared to the price of grey hydrogen. By adding this percentage to the current cost of grey LH_2, current price for green LH_2 can be estimated. Price for grey LH_2 excluding transport costs is 7-8 €/kg LH_2 from a production plant in Europe. By adding the assumed additional costs of green hydrogen, it results in a price for green hydrogen at 16,31-26,64 €/kg LH_2.

Subtracting total cost for LH_2 in Norway, 15,4 €/kg LH_2 [6], from price excluding transport, results in transportation costs of 7,9 €/kg LH_2. This results in an estimated current price for green LH_2 at 24,21-34,54 €/kg LH_2. Prices used for calculation of fuel costs for a round trip is presented in Table 18.

	Green LH_2	**Blue LH_2**	**Grey LH_2**	**LNG**	**MDO**
Current price [€/ton]	29375	18480	15400	760	610
2030 estimate [€/ton]	7500	4200	3500	760	610

Table 18: Prices in €/ton for fuel options

Multiplying these with the fuel consumption for hydrogen and LNG, Appendix 9.3 and 9.5, the different options results in fuel OPEX for a round trip Bergen-Kirkenes-Bergen. This is presented in Figure 13.

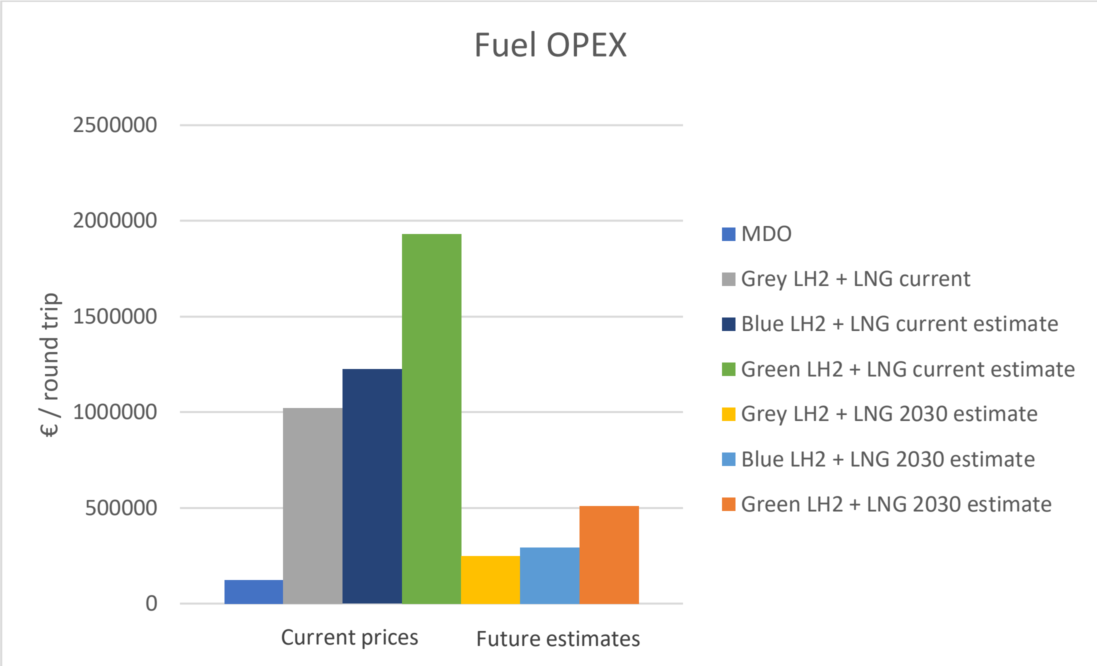

Figure 13: Fuel OPEX, €

As shown in Figure 13, hydrogen as fuel currently is far from competitive with MDO considering economics. 2030 price estimates indicate a decrease in costs for hydrogen, and the gap in price point for MDO and hydrogen alternatives decreases as a result. However, MDO is still the cheapest option; the cheapest option for future estimates, grey hydrogen + LNG, is more than twice as expensive as MDO. The estimated fuel costs for a round trip for green LH_2 in 2030 is more than 4 times as expensive compared to current MDO fuel costs.

5 Discussion

In this hydrogen feasibility study, the group had to focus on certain aspects of such a project in order to limit the scope of this thesis. Choices of energy converters and components in the hybrid energy system may not be the optimal solution. The options assumed used in this thesis is argued for in section 5.1, and other alternatives are presented. Matters not studied are also presented.

In section 5.2, emission factors for WTT value is presented and argued for. Emission factors from different technologies electrical energy generation are presented. The impact that hydrogen would have on emissions in harbours during the round trip and the current situation for maritime utilization of hydrogen is discussed.

5.1 Energy system

Hydrogen combustion and co-combustion along with other fuels is also a possibility when converting hydrogen to energy. Due to lack of experience, market availability and to limit the scope of this study, energy conversion by FC's is what is focused upon.

The choice of using PEMFC as FC's in the hydrogen energy system is based on the market availability, maturity of technology, low start up time and potential for increased efficiency and lower CAPEX in the future. Another option would be to use FC's which accepts both LH_2 and LNG as fuel, such as the SOFC. The high temperature also opens up the possibility of waste heat recovery, which would increase overall efficiency [1]. Due to the lack of experience and market availability of the SOFC it is not focused upon in this thesis.

A solution for powering the ship's hotel operation while at port is shore power. This would result in a decrease in hydrogen and LNG consumption, and possibly a decrease in emissions, and storage volume requirements for a 75 % reduction in emissions compared to the 2010 baseline.

Other alternative supplementary fuels, like biodiesel and LPG, could be considered instead of LNG. Since the four Havila Kystruten ships in operation from 2021 are designed to by fuelled by LNG, the group found it natural to use LNG as a future supplementary fuel for LH_2.

Depth of discharge (DoD) is not considered in this thesis. The lowest energy content of the battery from Figure 9 is 1,2 MWh, making the DoD 20 %. The influence of the weight of PEMFC's, hydrogen and LNG storage and battery pack on the ship is not studied in this thesis.

5.2 Emissions

WTT values for LNG and MDO used [41] are values for gas and oil extraction from the North sea and transported to Netherland. WTT values for oil and gas transported and refined in Norway may be different. Due to a lack of other relevant data, these are the values used for WTT emissions in this thesis.

The electrolysis and liquefaction process can be powered directly from electricity from hydro power plants or wind farms. NVE stated a carbon content for electricity from Norwegian hydro power plants at 6 g CO_2-eq/kWh [47]. This would lead to a reduction in emissions from green hydrogen and LNG at 83,21 % compared to the 2010 baseline. This opens up the possibility to reduce storage volume of LH_2, possibly making CAPEX and OPEX cheaper. Wind power has higher carbon content, 20 g CO_2-eq/kWh [47], than carbon content of the Norwegian power grid, which results in a 74,9 % reduction in emissions compared to the 2010 baseline if powered directly from a Norwegian wind farm.

If using the Nordic energy mix, the average carbon content of the Nordic power grid from 2013 to 2017 was 710 g/kWh [68]. This would result in an increase of emissions of both green and grey, and a 5 % reduction in case of blue hydrogen when compared to the 2010 baseline. Green hydrogen + LNG would inhibit the highest value of emissions. This is presented in Figure 14.

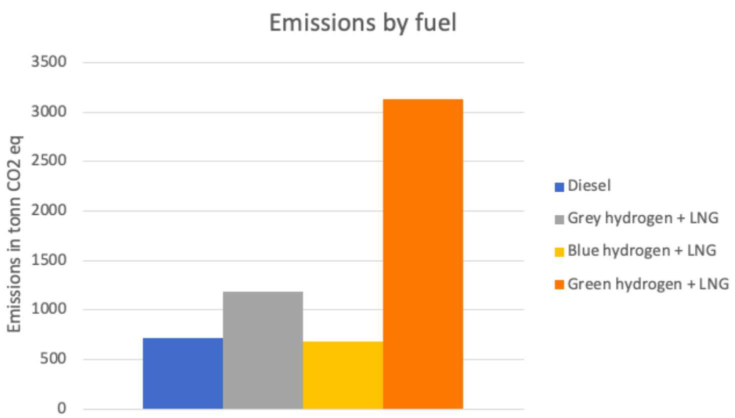

Figure 14: Emissions by fuel in case of Nordic energy mix, Tonnes CO_2-eq

In the start of a project like this. It can be argued that the use of LNG or diesel should be used until Low Carbon/Green Hydrogen is substantial enough to supply the ships, instead of using Grey Hydrogen, especially if that will result in less emissions in total. That is however not an argument that considers anything else than global emissions. The switch to hydrogen, regardless of the means of production will ensure a reduction in local emissions in exposed areas. Cities like Bergen have problems with toxic air due to local emissions where the cruise industry receives some of the blame. Another location where local emission is a factor is in the world heritage fjords, which have denied cruise liners to enter if their engines will release CO_2 during their journey. With the use of hydrogen, even hydrogen produced by SMR, one can avoid emissions in vulnerable areas.

A reduction of local emissions is not the only benefit to a transition of this type. For a major cruise liner to switch from fossil fuels to hydrogen is not just about the reduction in emissions, local or global, for the singular company, but also a symbolic gesture for the other parts of the maritime industry. It is not necessarily the lack of technology that holds hydrogen back, but rather a lack of will and funding. Without a supplier, the industry does not dare to start larger projects that will require a steady supply of hydrogen to be used as fuel. And in the same way the suppliers are not willing to invest in a Norwegian maritime hydrogen market that does not exist. This result in a status quo with hydrogen projects being a niche idea and will remain so until someone is willing to take the first step to start the process. With taking the first step, other companies can be able to follow and using their combined buying power to ensure that the hydrogen available is from a low emission source of production.

6 CONCLUSION

The results show that in order to achieve a sufficient reduction in emissions, hydrogen has to be produced from electrolysis powered from the Norwegian power grid or electricity from Norwegian hydro power plants. Neither blue nor grey hydrogen would include emissions to suffice the requirement of a 75 % reduction. LH_2 is used as method of storage, due to its higher volumetric energy density when compared to CGH_2. A LH_2 storage tank with 4,7 tonnes storage capacity in a hybrid system with FC, LNG gas generator sets and battery pack results in hydrogen and LNG consumption of 64,97 and 29,7 tonnes respectively. PEMFC's is used as energy converters for hydrogen, due to market maturity, start up time and potential for increase in efficiency and decrease in costs. Potential bunkering locations are studied with their associated bunkering capacity and power requirement of electrolysers.

The emissions from green hydrogen in a hybrid energy system with LNG and batteries from the round trip makes 175,7 tonnes CO_2-eq. This concludes in a reduction in emissions of 75,5 % when compared to the 2010 baseline of 718,05 tonnes CO_2-eq for a round trip Bergen-Kirkenes-Bergen.

In order to further validate the results, specific data, like power demand curves and engine data, would need to be disclosed by the Kystruten operator. For the way forward for this project, the authors recommend studying the economics for such as project. Further optimization of the hybrid energy system is also recommended for further studying.

7 Table and figure list

7.1 Table list

7.2 Figure list

8 REFERENCES

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9 Appendix

9.1 Data

In appendix 9.1 data for the calculations performed are presented.

Data	Value	Source
LHV LNG [GJ/ton]	49,3	[66]
LHV diesel [GJ/ton]	43,1	[66]
Emission factor LNG [ton CO_2/TJ]	55,9	[66]
Emission factor diesel [ton CO_2/TJ]	73,5	[66]
WTT emissions LNG [ton CO_2/TJ]	8,9	[41]
WTT emissions diesel [ton CO_2/TJ]	9,8	[41]
Hydrogen gravimetric energy density [kWh/kg]	33,33	[7]
LH_2 volumetric energy density [kWh/m^3]	2343	[7]
CGH_2 @ 250 bar volumetric energy density [kWh/m^3]	594	[7]
Specific energy consumption Bergen C:26 engines [kJ/kWh]	7450	[63]
Time for bunkering preparation and disconnect [hour]	0,5	assumed
Power for hotel operation [MW]	1,3	assumed
Power for propulsion [MW]	2,2	assumed
Power for acceleration [MW]	6	assumed
Power for deacceleration [MW]	2	assumed
Duration of acceleration/deacceleration [hours]	0,33	assumed
PowerCell Sweden PEM FC efficiency	0,54	N/A
Effective thermal efficiency Bergen C:26 engines	0,483	calculated
Efficiency Li-ion battery	0,99	[7]
Efficiency drivers/converters/switchboard	0,94	[7]
Efficiency el-motor to propeller	0,73	[7]
Energy demand PEM electrolysis [kWh/kg]	55	[6]
Energy demand liquefaction [kWh/kg]	10,8	[6]
Emissions SMR [kgCO_2-eq/kgH_2]	9	[6]
Emissions gas extraction Tjeldbergodden [kgCO_2-eq/kgH_2]	0,5	[6]
CCS capability	90%	[14]
Prices fuel	Table 18	[6]
Bunkering rate [kg/hour]	2000	[6]
Volumetric LH_2 tank specifications [m^3/tonne]	24,8	[31]
Volumetric CGH_2 @ 250 bar tank specifications [m^3/tonne]	96,805	[31]
SOx emissions MDO [kg SO_2/tonne fuel]	1,184	[49]
NOx emissions MDO [kg SO_2/tonne fuel]	45	[49]
NOx emissions LNG [kg SO_2/tonne fuel]	4	[49]

9.2 The Kystruten route schedule used

Days	Harbour	Hydrogen bunkering	Arrival	Departure	Docking time	Travel time	Bunkering time
					[hours]	[hours]	[hours]
Day 1	Bergen	Yes	14:30	21:30	7,00		6,00
						6,00	
Day 2	Florø		03:30	03:40	0,17		0,00
						2,00	
	Måløy		05:40	05:50	0,17		0,00
						2,67	
	Torvik		08:30	08:40	0,17		0,00
						1,08	
	Ålesund	Yes	09:45	13:30	3,75		2,75
						2,75	
	Molde		16:15	19:00	2,75		1,75
						3,50	
Day 3	Kristansund		22:30	01:30	3,00		2,00
						8,50	
	Trondheim	Yes	10:00	13:15	3,35		2,35
						9,00	
	Rørvik		22:15	22:30	0,25		0,00
						2,25	
Day 4	Brønnøysund		01:45	01:55	0,17		0,00
						2,67	
	Sandnessjøen	No	04:35	04:45	0,17		0,00
						1,17	
	Nesna		05:55	06:05	0,17		0,00
						3,67	
	Ørnes		09:45	09:55	0,17		0,00
						2,75	
	Bodø	Yes	12:40	15:00	3,35		2,35
						4,00	
	Stamsund		19:00	19:30	0,50		0,00
						1,50	
	Svolvær		21:00	22:00	1,00		0,00
						3,00	
Day 5	Stokmarknes		01:00	01:15	0,25		0,00
						1,50	
	Sortland		02:45	03:00	0,25		0,00
						1,25	
	Risøyhamn		04:15	04:30	0,25		0,00

						2,25	
	Harstad		06:45	07:45	1,00		0,00
						3,25	
	Finnsnes		11:00	11:30	0,50		0,00
						2,75	
	Tromsø	Yes	14:15	18:30	4,25		3,25
						4,00	
	Skjervøy		22:30	22:45	0,25		0,00
						3,25	
Day 6	Øksfjord		02:00	02:15	0,25		0,00
						3,00	
	Hammerfest		05:15	06:00	0,75		0,00
						2,75	
	Havøysund		08:45	09:15	0,50		0,00
						2,00	
	Honningsvåg	Yes	11:15	14:45	3,50		2,50
						2,25	
	Kjøllefjord		17:00	17:15	0,25		0,00
						2,00	
	Mehamn		19:15	19:30	0,25		0,00
						2,50	
	Berlevåg		22:00	22:15	0,25		0,00
						1,75	
Day 7	Båtsfjord		00:00	00:15	0,25		0,00
						3,00	
	Vardø		03:15	03:30	0,25		0,00
						3,25	
	Vadsø		06:45	07:15	0,50		-0,50
						1,75	
	Kirkenes	Yes	09:00	12:30	3,50		2,50
						3,25	
	Vardø		15:45	16:45	1,00		0,00
						3,00	
	Båtsfjord		19:45	20:15	0,50		0,00
						1,50	
	Berlevåg		21:45	22:00	0,25		0,00
						2,75	
Day 8	Mehamn		00:45	01:00	0,25		0,00
						1,75	
	Kjøllefjord		02:45	03:00	0,25		0,00
						2,50	
	Honningsvåg	Yes	05:30	05:45	3,35		2,35

						2,00	
	Havøysund		07:45	08:00	0,25		0,00
						2,75	
	Hammerfest		10:45	12:45	2,00		1,00
						2,75	
	Øksfjord		15:30	15:45	0,25		0,00
						3,50	
	Skjervøy		19:15	19:45	0,50		0,00
						4,00	
Day 9	Tromsø	Yes	23:45	01:30	3,35		2,35
						2,75	
	Finnsnes		04:15	04:45	0,50		0,00
						3,08	
	Harstad		07:50	08:30	0,67		0,00
						2,25	
	Risøyhamn		10:45	11:00	0,25		0,00
						1,50	
	Sortland		12:30	13:00	0,50		0,00
						1,25	
	Stokmarknes		14:15	15:15	1,00		0,00
						3,25	
	Svovlær		18:30	20:30	2,00		1,00
						1,50	
	Stamsund		22:00	22:30	0,50		0,00
						4,00	
Day 10	Bodø	Yes	02:30	03:45	3,35		2,35
						2,92	
	Ørnes		06:40	06:50	0,17		0,00
						3,58	
	Nesna		10:25	10:35	0,17		0,00
						1,17	
	Sandnessjøen	No	11:45	12:15	0,50		0,00
						2,75	
	Brønnøysund		15:00	17:30	2,50		1,50
						3,50	
	Rørvik		21:00	21:30	0,50		0,00
						7,00	
Day 11	Trondheim	Yes	06:30	09:45	3,35		2,35
						6,75	
	Kristiandsund		16:30	17:00	0,50		0,00
						4,00	
	Molde		21:00	21:30	0,50		0,00
						3,00	
Day 12	Ålesund	Yes	00:30	01:00	3,35		2,35
						1,25	
	Torvik		02:15	02:30	0,25		0,00
						2,75	
	Måløy		05:15	05:35	0,33		0,00
						2,17	
	Florø		07:45	08:15	0,50		0,00
						6,25	
	Bergen	Yes	14:30				

Dark greyed out cells are altered docking time to be sufficient for bunkering from empty to full tank. Sandessjøen has "No" in the hydrogen bunkering column because it was originally a bunkering location and later altered. All locations with nothing in the hydrogen bunkering column means no hydrogen bunkering. Bunkering time is time available for bunkering, assuming 30 minutes for preparation and 30 minutes for disconnect.

9.3 Energy calculations hydrogen for Kystruten Bergen-Kirkenes-Bergen.

Days	Theoretical energy consumption constant load	Real energy consumption constant load	Consumption of hydrogen	Content storage tank	Hydrogen consumption	Content tank	Percentage of full tank
	[MWh]	[MWh]	[tonnes hydrogen]	[tonnes hydrogen]	[tonnes hydrogen]	[tonnes hydrogen]	
				4,70			
Bergen	24,50	66,79	2,00	4,70	6,70	4,70	100,0
	21,00	57,25	1,72	2,98		2,98	63,5
Florø	0,58	1,59	0,05	2,93		2,93	62,4
	7,00	19,08	0,57	2,36		2,36	50,3
Måløy	0,58	1,59	0,05	2,31		2,31	49,2
	9,33	25,44	0,76	1,55		1,55	33,0
Torvik	0,58	1,59	0,05	1,50		1,50	32,0
	3,79	10,34	0,31	1,19		1,19	25,4
Ålesund	13,13	35,78	1,07	4,70	4,58	4,70	100,0
	9,63	26,24	0,79	3,91		3,91	83,3
Molde	9,62	26,24	0,79	3,13		3,13	66,5
	12,25	33,39	1,00	2,12		2,12	45,2
Kristansund	10,50	28,62	0,86	1,26		1,26	26,9
	29,75	81,10	2,43	-1,17		0,00	0,0
Trondheim	11,73	31,96	0,96	4,70	5,66	4,70	100,0
	31,50	85,87	2,58	2,12		2,12	45,2
Rørvik	0,87	2,39	0,07	2,05		2,05	43,7
	7,88	21,47	0,64	1,41		1,41	30,0
Brønnøysund	0,58	1,59	0,05	1,36		1,36	28,9
	9,33	25,44	0,76	0,60		0,60	12,7
Sandnessjøen	0,58	1,59	0,05	0,55		0,55	11,7
	4,08	11,13	0,33	0,22		0,22	4,6
Nesna	0,58	1,59	0,05	0,17		0,17	3,6
	12,83	34,98	1,05	-0,88		0,00	0,0
Ørnes	0,58	1,59	0,05	-0,93		0,00	0,0
	9,63	26,24	0,79	-1,72		0,00	0,0
Bodø	11,73	31,96	0,96	4,70	5,66	4,70	100,0
	14,00	38,16	1,15	3,55		3,55	75,6
Stamsund	1,75	4,77	0,14	3,41		3,41	72,6
	5,25	14,31	0,43	2,98		2,98	63,5
Svolvær	3,50	9,54	0,29	2,70		2,70	57,4
	10,50	28,62	0,86	1,84		1,84	39,1
Stokmarknes	0,88	2,39	0,07	1,77		1,77	37,6
	5,25	14,31	0,43	1,34		1,34	28,4
Sortland	0,88	2,39	0,07	1,26		1,26	26,9
	4,38	11,93	0,36	0,91		0,91	19,3

Risøyhamn	0,87	2,39	0,07	0,84		0,84	17,8
	7,88	21,47	0,64	0,19		0,19	4,1
Harstad	3,50	9,54	0,29	-0,09		0,00	0,0
	11,38	31,01	0,93	-1,03		0,00	0,0
Finnsnes	1,75	4,77	0,14	-1,17		0,00	0,0
	9,63	26,24	0,79	-1,96		0,00	0,0
Tromsø	14,88	40,55	1,22	4,70	5,92	4,70	100,0
	14,00	38,16	1,15	3,55		3,55	75,6
Skjervøy	0,87	2,39	0,07	3,48		3,48	74,1
	11,38	31,01	0,93	2,55		2,55	54,3
Øksfjord	0,88	2,39	0,07	2,48		2,48	52,8
	10,50	28,62	0,86	1,62		1,62	34,5
Hammerfest	2,63	7,16	0,21	1,41		1,41	30,0
	9,63	26,24	0,79	0,62		0,62	13,2
Havøysund	1,75	4,77	0,14	0,48		0,48	10,2
	7,00	19,08	0,57	-0,09		0,00	0,0
Honningsvåg	12,25	33,39	1,00	4,70	5,70	4,70	100,0
	7,88	21,47	0,64	4,06		4,06	86,3
Kjøllefjord	0,87	2,39	0,07	3,98		3,98	84,8
	7,00	19,08	0,57	3,41		3,41	72,6
Mehamn	0,87	2,39	0,07	3,34		3,34	71,1
	8,75	23,85	0,72	2,62		2,62	55,8
Berlevåg	0,88	2,39	0,07	2,55		2,55	54,3
	6,13	16,70	0,50	2,05		2,05	43,7
Båtsfjord	0,88	2,39	0,07	1,98		1,98	42,1
	10,50	28,62	0,86	1,12		1,12	23,9
Vardø	0,88	2,39	0,07	1,05		1,05	22,3
	11,38	31,01	0,93	0,12		0,12	2,6
Vadsø	1,75	4,77	0,14	-0,02		0,00	0,0
	6,13	16,70	0,50	-0,52		0,00	0,0
Kirkenes	12,25	33,39	1,00	4,70	5,70	4,70	100,0
	11,38	31,01	0,93	3,77		3,77	80,2
Vardø	3,50	9,54	0,29	3,48		3,48	74,1
	10,50	28,62	0,86	2,62		2,62	55,8
Båtsfjord	1,75	4,77	0,14	2,48		2,48	52,8
	5,25	14,31	0,43	2,05		2,05	43,7
Berlevåg	0,87	2,39	0,07	1,98		1,98	42,1
	9,63	26,24	0,79	1,19		1,19	25,4
Mehamn	0,88	2,39	0,07	1,12		1,12	23,9
	6,13	16,70	0,50	0,62		0,62	13,2
Kjøllefjord	0,88	2,39	0,07	0,55		0,55	11,7
	8,75	23,85	0,72	-0,17		0,00	0,0

Honningsvåg	11,73	31,96	0,96	4,70	5,66	4,70	100,0
	7,00	19,08	0,57	4,13		4,13	87,8
Havøysund	0,87	2,39	0,07	4,06		4,06	86,3
	9,63	26,24	0,79	3,27		3,27	69,5
Hammerfest	7,00	19,08	0,57	2,70		2,70	57,4
	9,63	26,24	0,79	1,91		1,91	40,6
Øksfjord	0,87	2,39	0,07	1,84		1,84	39,1
	12,25	33,39	1,00	0,84		0,84	17,8
Skjervøy	1,75	4,77	0,14	0,69		0,69	14,7
	14,00	38,16	1,15	-0,45		0,00	0,0
Tromsø	11,73	31,96	0,96	4,70	5,66	4,70	100,0
	9,63	26,24	0,79	3,91		3,91	83,3
Finnsnes	1,75	4,77	0,14	3,77		3,77	80,2
	10,79	29,42	0,88	2,89		2,89	61,4
Harstad	2,33	6,36	0,19	2,70		2,70	57,4
	7,88	21,47	0,64	2,05		2,05	43,7
Risøyhamn	0,87	2,39	0,07	1,98		1,98	42,1
	5,25	14,31	0,43	1,55		1,55	33,0
Sortland	1,75	4,77	0,14	1,41		1,41	30,0
	4,38	11,93	0,36	1,05		1,05	22,3
Stokmarknes	3,50	9,54	0,29	0,76		0,76	16,3
	11,38	31,01	0,93	-0,17		0,00	0,0
Svovlær	7,00	19,08	0,57	-0,74		0,00	0,0
	5,25	14,31	0,43	-1,17		0,00	0,0
Stamsund	1,75	4,77	0,14	-1,31		0,00	0,0
	14,00	38,16	1,15	-2,46		0,00	0,0
Bodø	11,73	31,96	0,96	4,70	5,66	4,70	100,0
	10,21	27,83	0,83	3,87		3,87	82,2
Ørnes	0,58	1,59	0,05	3,82		3,82	81,2
	12,54	34,19	1,03	2,79		2,79	59,4
Nesna	0,58	1,59	0,05	2,74		2,74	58,4
	4,08	11,13	0,33	2,41		2,41	51,3
Sandnessjøen	1,75	4,77	0,14	2,27		2,27	48,2
	9,63	26,24	0,79	1,48		1,48	31,5
Brønnøysund	8,75	23,85	0,72	0,76		0,76	16,3
	12,25	33,39	1,00	-0,24		0,00	0,0
Rørvik	1,75	4,77	0,14	-0,38		0,00	0,0
	24,50	66,79	2,00	-2,38		0,00	0,0
Trondheim	11,73	31,96	0,96	4,70	5,66	4,70	100,0
	23,63	64,40	1,93	3,87		3,87	82,2
Kristiandsund	1,75	4,77	0,14	3,82		3,82	81,2
	14,00	38,16	1,15	2,79		2,79	59,4
Molde	1,75	4,77	0,14	2,74		2,74	58,4
	10,50	28,62	0,86	2,41		2,41	51,3
Ålesund	11,73	31,96	0,96	4,70	3,25	4,70	100,0
	4,38	11,93	0,36	4,34		4,34	92,4
Torvik	0,88	2,39	0,07	4,27		4,27	90,9
	9,63	26,24	0,79	3,48		3,48	74,1
Måløy	1,17	3,18	0,10	3,39		3,39	72,1
	7,58	20,67	0,62	2,77		2,77	58,9
Florø	1,75	4,77	0,14	2,62		2,62	55,8
	21,88	59,63	1,79	0,84		0,84	17,8
Bergen	951,53	2593,85	77,82		64,97		0,0

Theoretical energy consumption is calculated from the product of bunkering/docking time intervals and Power demand, 3,5 MW.

Real energy consumption is the energy consumption when considering efficiency of the hydrogen energy system. Consumption of hydrogen is real energy consumption in MWh converted to tonnes hydrogen. Content storage tank is content at a point of the journey when subtracting the consumption from previous point. Hydrogen consumption is the total hydrogen consumption of the round trip, which is 64,97 highlighted in green. The percentage of full tank is the content of the hydrogen storage at any point of the trip compared to a full tank.

9.4 LNG tank calculations for the round-trip Bergen-Kirkenes-Bergen

Required storage capacity LNG storage [tonnes hydrogen]	2,46
Theoretical energy stored [MWh]	30,03
Real storage LNG [MWh]	91,49
Required storage capacity LNG [tonnes LNG]	6,68

From Appendix 9.3 the red highlighted value in content storage tank is the smallest value in this column. This represents the biggest gap in energy demand and availability. This results in the dimensioning value for the LNG storage capacity. By converting the gap in energy demand and availability to MWh considering the total efficiency of both the hydrogen system and the LNG system, required storage capacity of LNG can be calculated. This results in a LNG storage of 6,68 tonnes LNG storage capacity.

9.5 Energy calculations LNG for Kystruten Bergen-Kirkenes-Bergen

Days	LNG consumption	Consumption	Total real consumption	Total real consumption	Content LNG storage	% of full tank
	[tonnes hydrogen]	[tonnes hydrogen]	[MWh]	[tonnes LNG]	[tonnes]	
Bergen	0				6,68	100,0
	0				6,68	100,0
Florø	0				6,68	100,0
	0				6,68	100,0
Måløy	0				6,68	100,0
	0				6,68	100,0
Torvik	0				6,68	100,0
	0				6,68	100,0
Ålesund	0				6,68	100,0
	0				6,68	100,0
Molde	0				6,68	100,0
	0				6,68	100,0
Kristansund	0				6,68	100,0
	1,17	1,17	43,51	3,18	3,50	52,4
Trondheim	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Rørvik	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Brønnøysund	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Sandnessjøen	0		0	0	6,68	100,0
	0	0	0	0	6,68	100,0
Nesna		0	0	0	6,68	100,0
	0,88	0,88	32,85	2,40	4,28	64,1
Ørnes	0,93	0,05	1,78	0,13	4,15	62,2
	1,72	0,79	29,32	2,14	2,01	30,1
Bodø	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Stamsund	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Svolvær	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Stokmarknes	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Sortland	0		0	0	6,68	100,0
	0		0	0	6,68	100,0

Risøyhamn	0		0	0	6,68	100,0
	0	0	0	0	6,68	100,0
Harstad	0,09	0,09	3,53	0,26	6,42	96,1
	1,03	0,93	34,65	2,53	3,89	58,3
Finnsnes	1,17	0,14	5,33	0,39	3,50	52,4
	1,96	0,79	29,32	2,14	1,36	20,4
Tromsø	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Skjervøy	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Øksfjord	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Hammerfest	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Havøysund	0		0	0	6,68	100,0
	0,09	0,09	3,53	0,26	6,42	96,1
Honningsvåg	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Kjøllefjord	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Mehamn	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Berlevåg	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Båtsfjord	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Vardø	0		0	0	6,68	100,0
		0	0	0	6,68	100,0
Vadsø	0,02	0,02	0,86	0,06	6,62	99,1
	0,52	0,50	18,66	1,36	5,26	78,7
Kirkenes	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Vardø	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Båtsfjord	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Berlevåg	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Mehamn	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Kjøllefjord	0		0	0	6,68	100,0
	0,17	0,17	6,20	0,45	6,23	93,2

Honningsvåg	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Havøysund	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Hammerfest	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Øksfjord	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Skjervøy	0		0	0	6,68	100,0
	0,45	0,45	16,86	1,23	5,45	81,6
Tromsø	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Finnsnes	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Harstad	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Risøyhamn	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Sortland	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Stokmarknes	0		0	0	6,68	100,0
	0,17	0,17	6,20	0,45	6,23	93,2
Svovlær	0,74	0,57	21,32	1,56	4,67	69,9
	1,17	0,43	15,99	1,17	3,50	52,4
Stamsund	1,31	0,14	5,33	0,39	3,11	46,6
	2,46	1,15	42,65	3,11	0,00	0,0
Bodø	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Ørnes	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Nesna	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Sandnessjøen	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Brønnøysund	0		0	0	6,68	100,0
	0,24	0,24	8,86	0,65	6,03	90,3
Rørvik	0,38	0,14	5,33	0,39	5,64	84,5
	2,38	2,00	74,63	5,45	0,19	2,9
Trondheim	0		0	0	6,68	100,0
	0		0	0	6,68	100,0
Kristiandsund	0		0	0	6,68	100,0
	0		0	0	6,68	100,0

Molde	0			0	0	6,68	100,0
	0			0	0	6,68	100,0
Ålesund	0			0	0	6,68	100,0
	0			0	0	6,68	100,0
Torvik	0			0	0	6,68	100,0
	0			0	0	6,68	100,0
Måløy	0			0	0	6,68	100,0
	0			0	0	6,68	100,0
Florø	0			0	0	6,68	100,0
	0			0	0	6,68	100,0
Bergen	0			0	0	6,68	100,0
					29,70		

By utilizing LNG as fuel when there is no availability of hydrogen, i.e. when the hydrogen storage tank is empty, the total LNG consumption can be calculated by converting energy consumption in tonnes hydrogen to tonnes LNG, considering the efficiencies for both the hydrogen and LNG energy systems. Total LNG consumption for a round trip Bergen-Kirkenes-Bergen results in 29,7 tonnes LNG.

The LNG storage content is calculated by subtracting the content of a tank at a point of the journey by the energy consumption in tonnes LNG from the previous point of the journey. The percentage of storage tank is the content of the storage tank at any point of the journey compared to the LNG storage capacity.