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Hydrogen in the Maritime Sector

A feasibility study on hydrogen as fuel in Norwegian ferries

Arturo Goodwin
Katrine Hildre Storaker

Supervisor: Linda Nøstbakken

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Preface

This thesis was written as a part of the Energy, Natural Resources and the Environment master profile at NHH. Our thesis aims to evaluate hydrogen as a possible zero-emission fuel in Norwegian ferries. With the recent ruling stating that all new ferry tenders should require the use of low- and zero-emission technology, hydrogen seemed an interesting case to consider. Despite the relevance of hydrogen as an alternative fuel in the maritime sector, there have been few studies on the topic. Although a route specific case study should be performed before considering the implementation of hydrogen, we believe our analysis provides a solid background of the routes which should be considered first.

We want to sincerely thank our supervisor, Linda Nøstbakken, for her advice and guidance throughout the process. Over the course of the semester she has given us valuable feedback and patiently answered our many questions, which ultimately resulted in a thesis that we can both be proud of. Additionally, we would like to thank Per Christer Lund at DNV GL for initially suggesting such an interesting topic. We are also deeply grateful for the help we have received from Christian Michelsen Research (CMR) Prototech here in Bergen. We especially want to thank Ivan Østvik for providing us with an understanding of how a fuel cell system would operate in a ferry, and for valuable discussions and insight throughout the semester. Finally, we want to thank Sogn og Fjordane Fylkeskommune for letting us participate in the hydrogen seminar in Førde this fall, where we came in contact with many helpful people in the industry.

To our parents and family, we must express our profound gratitude for providing us both with unfailing support and continuous encouragement throughout our years of study, and especially during the process of writing this thesis. Finally, we would like to thank each other for a great collaboration.

We hope that our thesis will be as interesting to read, as it was for us writing it.

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Arturo Goodwin   Katrine Hildre Storaker

Abstract

To ensure emission reductions in the maritime sector, the Norwegian Parliament has established that all new ferry tenders should include a requirement for the use of low- and zero-emission technology where it is technologically feasible. Battery technology has proven successful as a zero-emission alternative on shorter ferry routes, but has difficulty providing sufficient amounts of energy for the longer routes. Hydrogen technology, on the other hand, can achieve ranges comparable to conventional fuels, and is becoming increasingly popular as a zero-emission fuel in transportation. This thesis provides an assessment of using hydrogen on the longer ferry routes, both in terms of environmental impact and economic implications. When comparing hydrogen to the most realistic alternative, liquid natural gas, we find that hydrogen is in most cases a less cost-efficient way to reduce emissions. Even though hydrogen eliminates emissions completely, its price being too high coupled with expensive fuel cell technology, makes hydrogen powered ferries less competitive. Nevertheless, there could be reasons for hydrogen ferries to be introduced, and an overview of which routes should be considered first will be laid forth in this thesis. Given future price reductions in hydrogen and fuel cell technology, hydrogen could be a viable zero-emission alternative fuel for longer routes with tender contracts ending further into the future.

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Abbreviations

CO_2	Carbon dioxide
EAC	Equivalent annual cost
EU ETS	European Union Emission Trading Scheme
EUR	Euro
FCEV	Fuel cell electric vehicle
H_2	Hydrogen
HP	Horsepower
kW	Kilowatt
kWh	Kilowatt hour
l	Liter
LNG	Liquefied natural gas
m^3	Cubic meter
MF	Ferries power by motors
MGO	Marine gas oil
MJ	Mega joule
MNOK	Million NOK
NOK	Norwegian krone
NO_x	Nitrogen oxides
NPRA	Norwegian Public Roads Administration
PCU	Passenger car unit
PEMFC	Proton exchange membrane fuel cell
USD	US dollar

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1. Introduction

This year, the Norwegian Parliament established that all new ferry tenders should include a requirement for the use of low- and zero-emission technology. The decision is based on the desire for a green shift in the maritime sector to reduce CO_2 emissions, and the fact that the first battery driven ferry, MF Ampere, has proven successful since it started operating earlier this year. Studies have shown that it is possible and could actually be profitable to implement electric ferries on many of the shorter routes in Norway. The operators of the longer ferry routes, however, have voiced concerns regarding the implementation of zero-emission technology. These routes are of a different dimension than those that have been successful for electric ferries, and do not currently have an option for zero-emission technology. Today, some of the longer routes are fueled by natural gas, which achieve lower emissions than conventional fuels. Nevertheless, according to the Norwegian Parliament, natural gas should not be considered a low emission alternative.

As all new ferry tenders must now include a requirement to implement low- and zero-emission technology, a zero-emission solution for the longer routes should be considered. In this thesis, we investigate the possibility of using hydrogen as fuel for the longer ferry routes. Hydrogen has the possibility to achieve zero emission from production to consumption, and is becoming increasingly popular as a substitute for conventional fuels in the transport sector. We will therefore attempt to answer the following question: ***Under what conditions could hydrogen be an efficient fuel for Norwegian ferries?***

To answer this, we will start by providing an overview of the status quo of the Norwegian ferry fleet, and discuss why hydrogen is an interesting energy carrier to consider. We also present a literature review to consider the studies that have already been done on the subject, and what we can learn from these. In chapters 5 and 6 the data and model are explained, before we present our results in chapter 7. The results are focused on the implementation of hydrogen, but we include liquid natural gas as an alternative for comparison and show the abatement costs for each option. We compare the abatement costs to different price estimates for carbon emissions before presenting a sensitivity analysis to see how our results vary with a change in price and technology cost. In chapter 8 we give a brief discussion of other parameters that are relevant to our results.

2. The Norwegian ferry fleet

Due to the geography and sparse coastal population in Norway, ferries are an important and necessary part of the Norwegian transport infrastructure, as they provide connections and shortcuts for the coastal population. However, they are also among the largest contributors to emissions from the maritime sector in Norway. There is huge potential for emission reductions, and efforts are being made to find new low- and zero-emission solutions. In this chapter, we will start by presenting an overview of the status quo of the Norwegian ferry fleet and the characteristics of the most common ferries operating in Norway today, namely the conventional diesel ferries and the low-emission liquid natural gas (LNG) fueled ferries. Thereafter, we proceed by discussing the new regulations and incentives, which push operators to invest in more environmentally friendly technology. Finally, we look at some of the alternative technologies currently available, mainly electrification and biofuels. Hydrogen is not included, as it will be discussed in depth in chapter 3.

2.1 Status quo of the Norwegian ferry fleet

The Norwegian ferry fleet consists of 180 ferries operating on over 100 ferry routes along the coast, which contain in total over 430 different connections (Siemens, 2015). Several different companies operate the routes; like Norled, Fjord1, Torghatten trafikkselskap, Boreal, Bjørklid and FosenNamsos Sjø, to mention a few.

The current ferry fleet varies a lot in terms of size, installed capacity and age. There are ferries with an installed capacity of over 10,000 kilowatts (kW), or 13,400 horsepower (HP), which can transport up to 212 cars, but also smaller ferries with an installed capacity as low as 200 kW (270 HP) (Opdal, 2010).[1] While both horsepower and kilowatts are measures of power, we will mainly use kilowatts as measurement for the installed capacity on the ferries.

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[1] 1 kW = 1.34 HP.

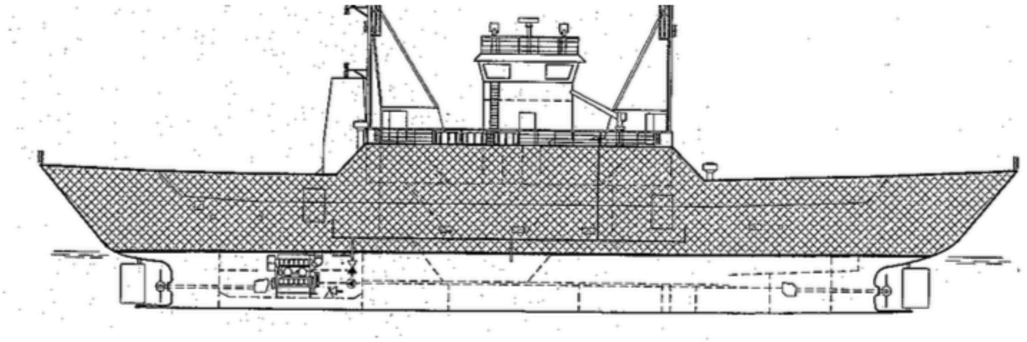

Figure 2.1: Traditional double ended ferry design (Fjellstrand, 2012).

All Norwegian ferries are double-ended shuttle ferries, i.e., they have a propeller in both ends and do not turn around when leaving the dock, as this has proven to be more efficient (Fjellstrand, 2012). The traditional design of a standard double-ended ferry is shown in Figure 2.1. The most common ferries are fueled by marine gas oil (MGO), which is a kind of diesel. However, over the last 10 years, low-emission ferries fueled by natural gas have also increased in numbers and there are currently 22 ferries fueled by LNG operating in Norway. In addition, the world's first battery driven ferry, MF Ampere, started operating the route Lavik-Oppedal earlier this year, and Fjord1 plans to implement three ferries fueled by 100% biodiesel. These new alternative technologies will be discussed with more detail in chapter 2.3. First, we take a look at the characteristics of the ferries dominating the Norwegian fleet.

2.1.1 Conventional ferries

As mentioned earlier, most of the existing ferries are fueled by MGO (Opdal, 2010). MGO is a petroleum distillate that has a lower sulfur content and lower viscosity compared to heavy oils and distillates, and has a calorific value of 42.7 MJ/kg (Kristensen, 2012). Calorific value is defined as the amount of energy produced by the complete combustion of a material or fuel and is measured in units of energy per amount of material. Meaning there is 42.7 mega joules (MJ) of energy stored in one kilo of MGO. MGO is a standardized product with established technology, and associated combustion engines and auxiliary systems are commercially available. The fuel is normally delivered by trucks to the ferry terminals or by tanker ships (DNV, 2011).

The sulfur content in MGO sold in Norway satisfies the demand set by the International Maritime Organization (IMO) of 0.1%, binding from January 1st 2015 (IMO, 2015). Also, the NO_x emissions are in accordance with IMO Tier II NO_x emission requirements for new diesel engines of 7.7 gNO_x/kWh. However, when IMO Tier III comes into force on January

1st 2016, with requirements of 2.0 gNO_x/kWh, it is likely that a selective catalytic reduction system, which reduces the NO_x emissions with up to 90%, must be installed for the MGO to remain an option for new ferries (Diesel Technology Forum, 2015). This would consequently cause higher operating and installation costs. In terms of carbon dioxide (CO_2) emissions, MGO has an emission factor of 3.2 $tCO_2/tMGO$, which is higher, compared to fuels such as LNG, biogas and hydrogen (DNV, 2011).

The cost of MGO is around 6,200 NOK/ton (Ship and Bunker, 2015). In addition to the price, one has to consider the NO_x fee. As all relevant ferry companies are part of the NO_x fund, the fee is 4 $NOK/kgNO_x$ (see chapter 2.2.3 for more information).[2] Except for the environmental tax included in the price of diesel, there is currently no CO_2 emission fee for ferries.

There are currently two competing propulsion systems in use in diesel ferries. The first one is direct mechanical operation where the diesel engine, through a reduction gear, drives the propellers. This type of propulsion system using diesel oil has an efficiency to the propeller (excluding propulsion efficiency) of about 40%. The energy losses are mainly related to heat, which is removed by cooling water and exhaust (Fjellstrand, 2012). The other propulsion system is diesel-electric, which means that the diesel is first converted to electricity in a generator, and electric motors then drive the propellers. An electric propulsion system is more complex and can better optimize operations. However, the efficiency is somewhat lower due to increased losses in energy transfer (up to 10%). The investment cost of a diesel engine varies from 3,000-6,000 NOK/kW, depending on the installed power capacity (DNV, 2011). The properties related to MGO are later summarized in Table 2.1.

2.1.2 LNG ferries

As mentioned earlier, some ferries in Norway are fueled by LNG, which is considered a low-emission technology. LNG is natural gas that has been cooled down and condensed to liquid form (DNV GL, 2015a). It is a colorless, flammable gas that can be found in permeable rocks in the Earth's crust, and mainly consist of methane, and a smaller amount of

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[2] If you are not a member of the NO_x-fund the fee to the government is 17.33 NOK/kg (Ibenholt, Skjelvik, & Myrhvold, 2014).

hydrocarbons, nitrogen and carbon dioxide (DNV, 2011). LNG has a calorific value of 55.5 MJ/kg (Kristensen, 2012).

LNG has many benefits compared to diesel, like 85-90% lower NO_x emissions and virtually zero emissions of SO_x and particles, as it does not contain sulfur. However, CO_2 emissions related to combustion are only reduced by 20-25%, and even less if we take into account production and storage. LNG has a factor of 2.75 $tCO_2/tLNG$ (DNV, 2011). The cost of LNG is around 3,550 NOK/ton (Lyse, 2015).

Norway has been in the forefront of testing gas engines in ships. In 2000, the world's first ferry fueled by natural gas, Glutra, started operating on the route Flakk-Rørvik outside Trondheim. Today, there are many gas driven ships and ferries in Norway. The efficiency of a gas engine can reach 48% and is expected to increase with the engines becoming more common. A gas engine is also more costly than a diesel engine with prices varying from 13,000 NOK/kW to 26,000 NOK/kW, depending on the installed power capacity (DNV, 2011). The biggest challenges related to LNG are possible leakages to the atmosphere as methane is very pollutant; up to 84 times the greenhouse effect of CO_2 (Hamburg, 2015). In addition, LNG needs substantially larger volumes for storage, about 3-3.5 times larger than diesel (DNV, 2011). A summary of the properties related to MGO and LNG is displayed in Table 2.1.

	Calorific value (MJ/kg)	**CO_2 factor ($tCO_2/tFuel$)**	**Price (NOK/ton)**	**Engine cost (NOK/kW)**
MGO	42.7	3.20	6,200	3,000-6,000
LNG	55.5	2.75	3,550	13,000-26,000

Table 2.1: Properties of MGO and LNG.

2.2 Towards a green shift in the ferry sector

On March 25th of this year, the Norwegian Parliament adopted a new emission commitment. The goal is to reduce emissions with at least 40% compared to the emissions in 1990 by 2030, and become a low-emission society by 2050 (Ministry of Climate and Environment, 2015). One of the prioritized areas is the transport sector. The ferry fleet is an important part of the transport network in Norway and has a huge potential for emission reductions.

2.2.1 Current CO_2 emissions

According to a study done by DNV GL for the Ministry of Climate and Environment, ferries are among the biggest contributors to emissions from the maritime sector in Norway. They conclude that the domestic maritime traffic accounts for 55% of the emissions from the Norwegian maritime sector, which amounts to 9% of national emissions. Passenger vessels, which include ferries, along with express boats and cruise ships, are the worst polluters and emit 1,090,083 tCO_2 and 16,473 tNO_x a year (DNV GL, 2014). As you can see in Figure 2.2, this accounts for 27% of the total CO_2 emissions from the domestic maritime sector, and 32% of the NO_x emissions. If this trend continues, with an increased amount of vessels and without any measures being taken, the reduction in total CO_2 emissions would have to be 63% to meet the goal of a 40% reduction in 2030 (DNV GL, 2015b). The ferries are accountable for around 400,000 tons of the CO_2 emitted (ZERO, 2008). That is the same amount of CO_2 as 174,000 cars.[3]

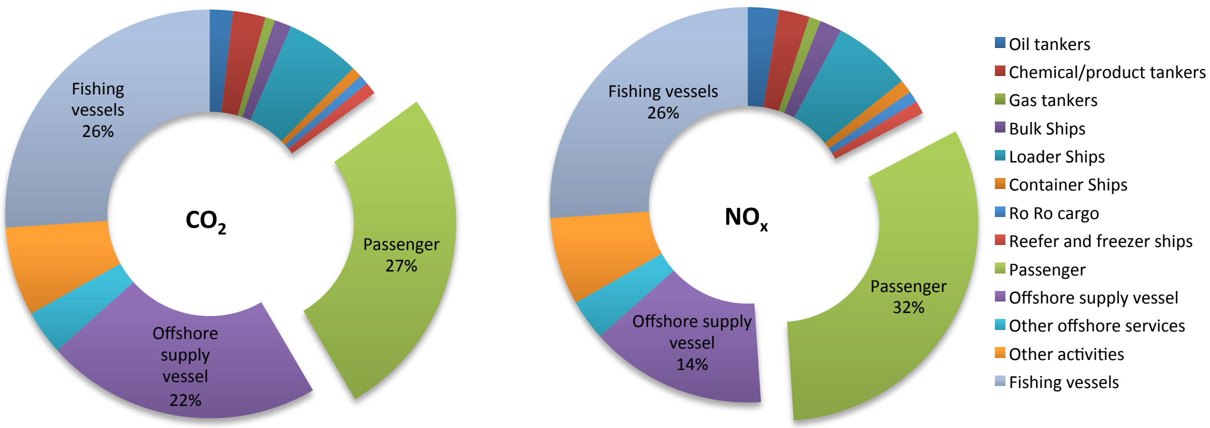

Figure 2.2: CO_2 and NO_x emissions in the Norwegian maritime sector

2.2.2 New environmental regulations

Besides having a substantial potential for reducing emissions, the ferry sector is also a great place to start testing out new technology. Ferries travel relatively short distances, at steady speeds, with relatively low energy need, and have the possibility to refuel frequently. This makes them suitable for developing and testing alternative fuels and zero-emission technology that can later be applied to bigger ships and with lower costs to contribute to a greener maritime sector. Based on this, the Norwegian government adopted in 2014 the

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[3] Assuming an average car drives 13,500 km in one year and emits 0.17 g/km.

request from the Norwegian Parliament, stating that all new ferry tenders on national roads should include a stipulation for the use of low- and zero-emission technology, where it is technologically feasible (Finance Committee, 2015). This fall, the Norwegian Parliament established that the requirement should also apply to county roads (Committee on Energy and the Environment, 2015).

To gain the rights to operate a route, the ferry companies have to participate in a tendering process. The Norwegian Public Roads Administration (NPRA) has the responsibility to secure operators for ferry connections on national roads, while county administration has the responsibility for ferry connections on county roads (Opdal, 2010). There are currently 17 national road ferry routes and 102 county road ferry routes (Ministry of Trade, Industry and Fisheries, 2014). The NPRA, or the relevant county, publishes tenders containing information about the specific route and operational requirements. In turn, the ferry companies send in their offers with operational specifications and expected costs. The relevant authority then decides who wins the tendering process and the winner typically operates the route for up to 10 years, until the next bidding process.

On September 14th 2015, the NPRA sent out the world's first ferry tender, explicitly demanding that the ferries use zero-emission technology. It states that one of the ferries should be an all-electric ferry and the other ferry should either be all-electric or use biodiesel, biogas or any optional combination of these (NPRA, 2015a). The tender applies to the ferry route Anda-Lote on E39 in Sogn og Fjordane and the contract will be binding for 10 years, starting January 1st 2018. It is likely that there will soon be more of these types of ferry tenders, as several contracts are running out within the next five years. For example, all the routes in Hordaland will be put out to tender already by 2018 (Aadland, 2015).

2.2.3 Incentive programs

A good framework and incentive programs have to be in place for ferry companies to invest in alternative fuels and zero-emissions technology. Even though the government is now demanding that the ferry companies use low- and zero-emission technology where it is technologically feasible, developing new technology is usually expensive. Below are some examples of programs in place that could incentivize the development of environmentally friendly technology in the maritime sector.

Enova

Enova, a public enterprise owned by the Ministry of Petroleum and Energy, gives economic support and counseling to promote an environmentally friendly restructuring of energy use and energy production as well as contribute to the development of energy and climate technology. From January 1st 2015, Enova took over the tasks earlier handled by Transnova, and transport is now an important focus area (Ministry of Trade, Industry and Fisheries, 2014). On the September 8th this year, Enova launched its new support scheme to reduce the emissions in the transport sector with considerable focus on the maritime sector. Enova will give funding to companies using energy technology and transport solutions that are new or that have not yet been used in Norway. This funding is supposed to help the companies in the shift towards low- and zero-emission technology (Enova, 2015). It is still not clear how much money has been allocated to the new support scheme, but in the agreement between Enova and the Ministry of Petroleum and Energy, at least 78 million NOK is being allocated this year (Hirth, 2015a).

The NO_x fund

The NO_x fund was established by 15 cooperative business organizations after an agreement with the government and the business sector to reduce Norwegian NO_x emissions. Despite having to pay a contribution to the fund of 4 NOK/kgNO_x and commit to investigate measures to reduce emissions in own operations, the members are exempt from the governmental NO_x fee of 17.33 NOK/kgNO_x (Ibenholt, Skjelvik, & Myrhvold, 2014). As mentioned earlier, this applies to all the ferry operators, as all are members of the fund. Ships with engines with capacities above 750 kW can apply to get funding to implement new technology or other measures to reduce the emissions. The support increased in 2015 from 350 to 500 NOK/kgNO_x reduced (Hirth, 2015b). Ships with capacities below 750 kW cannot apply, as these ships are not liable to pay a tax on their NO_x-emissions (Norwegian Maritime Authority, 2011). The fund has 600 million NOK a year available for support (NHO, 2015).

The Norwegian Research Council

The Norwegian Research Council has three different programs that could be interesting for the maritime sector: ENERGIX, MAROFF and TRANSPORT 2025. ENERGIX covers among other things projects related to alternative energy technology; like batteries, biofuels and hydrogen. MAROFF supports innovation and environmental value creation in the maritime sector. The new program TRANSPORT 2025 covers the whole transport system, including maritime transportation, with focus on more sustainable transport within the economic, social and environmental framework (ZERO, 2008). These programs could possibly provide support for the development of a new ferry using environmentally friendly technology. Through the collaboration, SkatteFUNN, between the Research Council and Innovation Norway, companies can also get 20% tax deductions for R&D projects (Innovation Norway, 2015). In 2014, a total of 85 million NOK was allocated for environmental projects through the MAROFF program and SkatteFUNN (Ministry of Trade, Industry and Fisheries, 2014).

Innovation Norway

Innovation Norway supports companies across the country in their efforts to develop their competitive advantage and enhance innovation. Their Environmental Technology Scheme aims to commercialize research projects in environmental technology by providing investment grants for pilot- and demonstration projects in all kinds of enterprises (Ministry of Trade, Industry and Fisheries, 2014). Using zero-emission technology in the maritime sector is covered by this scheme and Innovation Norway has earlier given support to the development of the electric ferry Ampere. Since the creation of the scheme in 2010, 1.04 billion NOK has been granted to 237 projects. Projects in the maritime sector have been granted 78.3 million and 70% has gone to climate relevant projects (Ministry of Trade, Industry and Fisheries, 2014).

2.3 Technologically feasible options

Different technological solutions and fuel types give the opportunity to achieve low- and zero-emission ferries. Low-emission ferries can be obtained from a range of solutions, e.g. LNG, hybrid solutions with LNG/diesel and batteries, mixing biofuels in the original fuel, and improving the energy efficiency of ships resulting in less fuel consumption. However, this thesis will focus on zero-emission technology.

There are currently only three options that appear to be credible alternatives for zero-emissions technology in ferries: battery (all-electric), biofuels (biodiesel and biogas) and hydrogen (DNV GL, 2015a). As hydrogen will be discussed in more detail throughout this paper, this section will introduce the two other options, namely batteries and biofuels.

2.3.1 Battery

The development of zero-emission technology in ferries in Norway has so far focused on batteries. The battery is a technology that is especially suitable for the ferry sector in Norway given the low electricity prices and the fact that most of the routes are relatively short (DNV GL, 2015a). Siemens recently published a report saying that it would be profitable to substitute seven out of ten Norwegian ferries with all-electric or hybrid ferries. As much as 84 of 180 ferries could be electric, while 43 could use a hybrid solution (Siemens, 2015). As mentioned above, a tender has already been issued for the route Anda-Lote with the requirement that at least one of the ferries is to be battery driven.

MF Ampere

In February 2015, the first and only all-electric ferry, MF Ampere, started operating the route Lavik-Oppedal in Sogn og Fjordane with success. Ampere is operated by Norled and is a great example of how it is possible to develop a solution that is both profitable and emission-free. The ferry was developed by Fjellstrand AS and is of the type ZeroCatTM120. To be able to operate solely off batteries, low energy consumption is important. The ferry is therefore built in aluminum, with catamaran hulls, and all systems are optimized to ensure low energy consumption (Ministry of Trade, Industry and Fisheries, 2014).

MF Ampere has an installed capacity of 900 kW and 120 passenger car units (PCU). The ferry has two battery packs of 500 kWh each and uses around 150 kWh per crossing of 5.1 km (Stensvold, 2015). The efficiency of electric propulsion using a battery can be as high as 75%. The energy losses are mainly related to heat losses during charge and discharge (1-3%), electrical losses (10%) and mechanical losses (4%) (Fjellstrand, 2012). The idea of the electric ferries is that they can charge the batteries with cheap electricity from the main grid onshore. Today, electricity prices are of about 0.3 NOK/kWh (DNV GL, 2015c). The batteries are fully charged every night, but to safely operate during the whole day, the ferry also needs 10 minutes in dock to recharge the batteries with quick connection charging facilities.

Need for land-based infrastructure

Quick charging of the batteries requires a considerable amount of energy, more than the local grid at most ferry docks can provide today (DNV GL, 2015c). Thus, investments in grid capacity have to be taken into account when considering implementing an electric ferry.

It is possible to provide the land infrastructure, but it is costly. DNV GL performed a study for Energy Norway where they looked at what investments had to be made in the local grid to be able to quickly provide sufficient electricity to ferries on 52 shorter routes, suitable for all-electric ferries. The investment costs in the grid alone ranged from zero to 80 million NOK for one ferry crossing and would in total be over 900 million NOK (DNV GL, 2015c).

Instead of investing in the local grid, it is possible to use battery packs on land to provide sufficient capacity for the transfer of power while the ferry is at quayside. This is the solution that is used for Ampere. On each dock a battery pack of 350 kWh has been installed. The battery packs are charged via the regular high voltage grid and subsequently used to quickly charge the batteries on the ferry. Either way, the investments in land infrastructure are costly and have been highlighted as an issue by the ferry companies. The equipment may have a longer lifespan than their contract and it would be hard to pay off the investment before the contract runs out. In addition, the need for land infrastructure limits the possibility for ferry companies to reuse electric ferries on other routes when their contracts end and poses a financial risk for the company (DNV GL, 2015a).

Most suitable for shorter routes

Electric ferries are also less flexible in the sense that they are currently not suitable for all ferry routes. As mentioned above, Siemens states that 84 of 180 ferries could be electric, while 43 would need a hybrid solution. Using electricity as the only energy carrier means there is a need for robust battery solutions. According to Siemens (2015), only routes with a crossing time of less than 35 min and at least 20 trips a day have an operating profile that would sufficiently reduce operating costs and cover investments. The routes exceeding 35 minutes would need a combination of diesel/battery or gas/battery due to high costs related to big batteries and quick connection charging systems (Siemens, 2015).

In addition, the two battery packs of 500 kWh onboard MF Ampere weigh in total 10 metric tons and contains five times the capacity the boat needs to go from Lavik to Oppedal. In Norway, some routes have a much longer trajectory and need a lot more energy for one crossing. Larger vessels are not suitable for electric systems due to the weight of the batteries (Greenstat, 2015). If we assume a ferry uses 1,000 kWh per crossing it would then, given the same dimensions as the batteries on Ampere, need batteries with a total capacity of 5,000 kWh (or more) that would weigh 50 metric tons.

Nevertheless, most of the ferry routes in Norway are shorter and MF Ampere has proven that batteries are a technologically feasible zero-emission option for such routes. Additionally, the access to cheap electricity will cut fuel costs and reduce CO_2 emissions.

2.3.2 Biofuel: biodiesel and biogas

Biofuel is a renewable energy carrier that can be recovered from biogenic material and produced by natural, anaerobic decomposition of organic materials such as mud, wood and compost (DNV GL, 2015b). Fjord1 will from January 1st 2016 implement three ferries using 100% biodiesel on the route Halla-Dragsvik-Vangsnes. These will be the first ferries in the world running solely off pure biodiesel. Torghatten Trafikkselskap has also ordered a new ferry running on biodiesel for the route Tjøtta-Forvik (Flaaten, 2015).

Climate neutral fuel

Even though biodiesel and biogas have more or less the same qualities as diesel and natural gas during combustion, and thus related emissions, biofuels are considered a zero-emission alternative for ferries (DNV GL, 2015b). Biofuel recovered from renewable biological raw materials is said to be “climate-neutral” as the CO_2 emitted is regarded as part of the CO_2 that would otherwise be in circulation, as opposed to CO_2 from fossil energy sources (DNV GL, 2015a). This is due to the fact that the growing process of the plants captures the same amount of CO_2 from the atmosphere as the biomass emits during combustion (Holtsmark, 2010).

However, in practice, fossil energy sources are used in the production of biodiesel or raw materials for the production. Thus, when considering the whole cycle from production to consumption, biodiesel can only reduce emissions by 30-60% compared to traditional diesel, depending on the production method and raw material used (NPRA, 2015b). Moreover, biofuels can in some cases lead to higher NO_x emissions when used in traditional engines (Opdal & Hojem, 2007).

Flexibility

Ferries fueled by biodiesel are more flexible than electric ferries because they do not need the same land infrastructure, and can operate on any ferry route, whether it is short or long. As mentioned earlier, a biodiesel fueled ferry is planned on the route Tjøtta-Forvik, which is 17.4 km long and takes about 45 minutes to cross. In addition, biodiesel is commercially available in the Norwegian market, though at a higher price than MGO. Biogas is still in the establishment phase, but as liquid biogas is compatible with LNG, this could in the future be used as substitute for each other (DNV GL, 2015a).

Nonetheless, even though biofuels are considered a zero-emission alternative when derived from renewable material, the use of hydrocarbons in a combustion engine will always cause emissions of some sort. The amount of emissions reduced also depends on how the biofuel is produced and will generally cause emissions from production to consumption (Opdal & Hojem, 2007). Continuing, this paper will focus on hydrogen, which when produced from renewable energy, can achieve zero emissions from production to consumption.

3. Hydrogen

The implementation of hydrogen in the Norwegian ferry fleet is interesting because the technology application has some merit when considering the geopolitical situation of Norway. Batteries have proven to be part of the solution to solving the oil dependency issue in the maritime sector, as they could potentially replace many of the ferries on the shorter routes. However, at this stage, batteries cannot provide enough energy to operate the longer distance routes without the need of big battery packs. Biofuel is an option on the longer routes, but its potential to reduce CO_2 emissions depends heavily on the production method, and in some cases the NO_x emissions would actually increase. In this chapter, we will see that hydrogen has the potential to achieve zero emissions from production to consumption, and doing so with a range that is comparable to conventional fuels. In addition, Norway's increasing power surplus and the government's position on green energy solution in the maritime sector could make it a suitable place to pilot the technology. In this chapter, we will give an overview of the many attributes hydrogen has and the road it has had to be where it is today. Finally, we will discuss the main reason why it has the potential to play an important role in the future of green transportation, and take a look at existing and future planned projects using hydrogen in the maritime sector.

3.1 What is hydrogen?

Hydrogen is energy in the form of gas. It is the lightest element on the periodic table and is the most abundant in the universe. Hydrogen is the by-product of many industrial processes and can be produced from a wide range of energy sources or electricity from the grid. It can also be converted back to electricity through a fuel cell. In this way, hydrogen is an energy carrier, one that has become more attractive recently due to improvements in fuel cell technology.

At regular temperature and pressure, hydrogen is a highly combustible gas with molecular formula H_2 (Patnaik, 2007). The combustion of hydrogen has a temperature of 500 degrees Celsius and provides a very clean reaction:

$$2\ H_2 + O_2 \rightarrow 2\ H_2O + 572\ \text{kJ}\ (286\ \text{kJ/molecule})$$

The product of this reaction being pure water and energy, we can understand how hydrogen combustion engine has been a topic of conversation, in the past. This concept never flourished because the energy efficiency of vehicles using a hydrogen combustion engine was too low due to the heat dissipation, which also occurs in traditional gasoline cars. Fuel cell technology, however, has a higher efficiency, and is increasing in popularity for use in transportation. We will come back to fuel cell technology in chapter 3.5.

Hydrogen has a higher heating value (HHV[4]) of 142 MJ/kg, which translates to an energy content of 39.44 kWh/kg. This is about three times higher than other conventional hydrocarbon fuels, meaning that hydrogen has a high energy content per unit of weight. However, the volumetric energy density is very low. For comparison, a 50-liter gasoline tank contains the same amount of energy as a 460-liter tank of compressed hydrogen at 350 bars (Tzimas, Filiou, & Peteves, 2003).

3.2 Hydrogen's slow growth

Even though hydrogen has many benefits as an energy carrier and many potential applications, it has had a slow start. The barriers have mainly been related to high costs, low energy efficiency and lacking infrastructure. Meanwhile, batteries have had somewhat of a revolution in recent times, making them cheaper and more efficient, and are now the first choice in many applications as energy storage. The cost of water electrolysis using electricity to produce hydrogen is still not competitive with other forms of power generation such as coal-fired power plants. However, the cost of electrolysis dropping, and the increasing need for backup capacity, could be enough to see hydrogen become a big part of tomorrow's energy system. Below we will first give an introduction to why batteries are often chosen over hydrogen as an energy carrier, before we take a look at some new applications that makes hydrogen interesting for future use.

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[4] The higher heating value (also known gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products (U.S. Department of Energy, 2015a).

3.2.1 Batteries vs. hydrogen

Hydrogen as an energy carrier has had one major competitor, especially in recent years: lithium-ion batteries. The advances in hydrogen technology have been somewhat hindered by the focus given to batteries. In this way, all investments towards other technologies only delay hydrogen from becoming a major part in cutting greenhouse gas emissions. Tesla has been an important player in the development of batteries, not only in electric vehicles but also for use in homes with their recently unveiled "Power wall" (Tesla, 2015). This battery pack is designed to allow consumers to store electricity from their solar panels in order to be self-sustainable. This is a very simple solution, which is becoming cheaper to implement as time goes by. Hydrogen systems have not yet seen such a dramatic cut in prices.

However, costs are not the only obstacle hydrogen faces. Storing electricity in batteries is significantly more efficient than storing it in the form of hydrogen. This is due to the fact the electricity must first be converted into hydrogen via electrolysis, compressed to a certain pressure for storage, and then converted back to electricity through a fuel cell. Each of the steps taken has a certain efficiency ratio, which varies according to the different methods chosen. Figure 3.1 shows a graphical illustration of these steps:

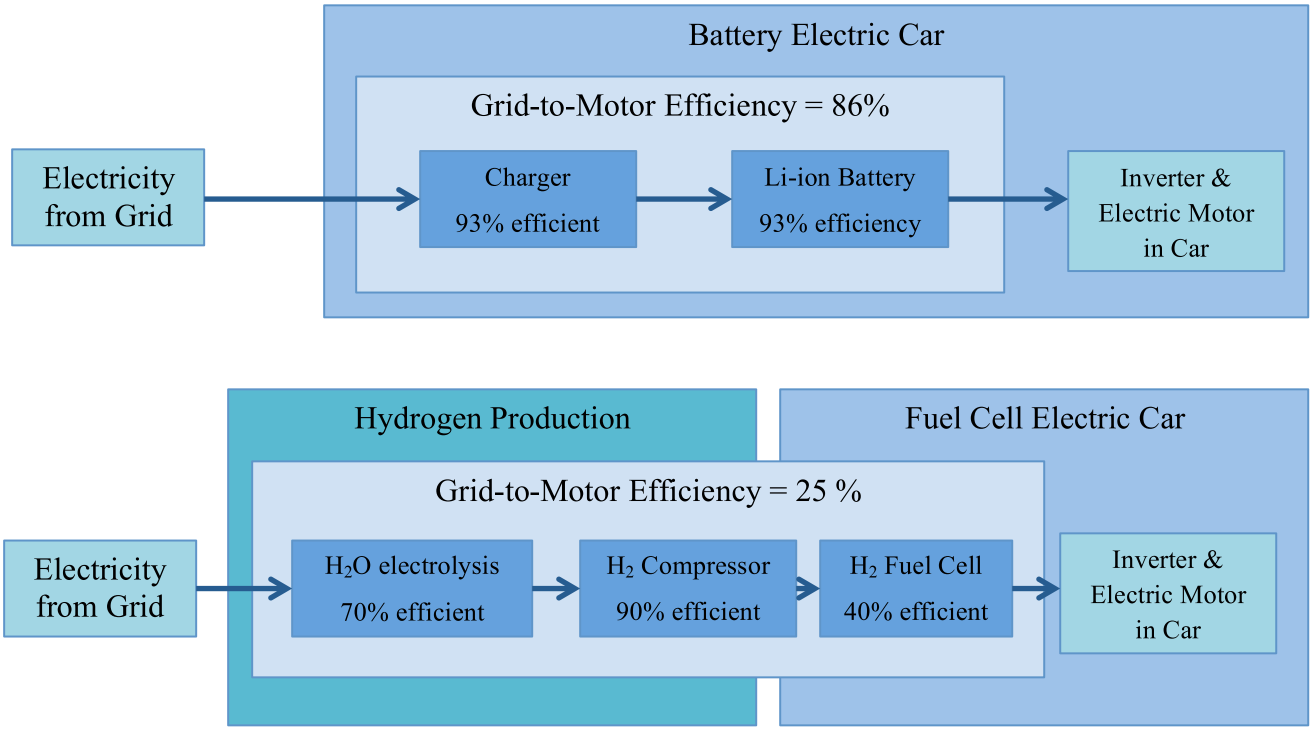

Figure 3.1: Battery and hydrogen system efficiency. Based on (Hubpages, 2015).

Even though the lithium-ion batteries have some advantages over hydrogen when it comes to energy efficiency, the batteries also have well known limitations concerning range, refueling time and weight, which hydrogen does not. Most likely, the two energy carriers will coexist in the future, serving different purposes. In fact, most hydrogen systems require some sort of chemical energy storage, i.e., batteries, in order to perform optimally.

3.2.2 Hydrogen applications

Historically, hydrogen has been used to a great extent in the chemical industry, during oil refining process and in aerospace applications. The last couple of years, however, hydrogen has become more attractive, both as a possibility of balancing the grid as more intermittent renewable energy is entering the market, and as a substitution for fossil fuel in transportation and other operations.

The advances in renewable resources in recent years have shed light on the issue of intermittency. In the more developed countries, windmills and solar panels produce an increasing amount of electricity. Wind and solar energy are intermittent energy sources as they are not continuously available, which makes it difficult to predict how much electricity will be produced. The use of more intermittent energy sources thus makes balancing the grid difficult, and requires not only expanding the transmission capacity on the grid, but also developing a more robust energy storage technology than that which is available today. Large-scale fuel cell and hydrogen storage facilities could harness the excess electricity from renewables and transfer it back to the grid in peak demand periods.

In the transport sector, hydrogen could be used as fuel in a fuel cell, substituting fossil fuels and reducing CO_2 emissions. Fuel cell electric vehicles (FCEV) have just entered the market with Toyota Mirai and Hyundai ix35 as the first cars commercially available. The car manufacturers report driving ranges of up to 600 km on one tank, refueling time of about 3-5 minutes and a fuel cell lifetime of about 10 years (Norwegian Hydrogen Forum, 2015).[5] Toyota reports a suggested retail price for Mirai of about USD 57,500, or about 450,000 NOK in Europe (Toyota Motor Sales, 2015). In addition, hydrogen fuel cell buses have also been implemented in several cities around the world, including Oslo. Fuel cell technology is

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[5] A FCEV can drive 100km on 1 kg hydrogen.

now also being discussed for use in the maritime sector. We will take a closer look at different fuel cell technologies in chapter 3.5.

Another recent example of substituting fossil fuels with hydrogen is the Tizir project. The iron and titanium producer Tizir in Tyssedal has signed an initiative agreement with Greenstat, where Greenstat will supply hydrogen from a large-scale hydrogen production facility. In practice, they are looking to replace their use of coal with hydrogen from electrolysis, both being suitable ingredients in the process of iron production. The hydrogen production facility would be fueled by electricity from the grid and produce about 30 tons of hydrogen per day (Hirth, 2015c).

3.3 The hydrogen market

The current global hydrogen production is 65 million tons per year, mostly produced by large industrial companies, satisfying their own demand (Bertuccioli et al., 2014). Thus, a competitive hydrogen market is not yet established. The current price for hydrogen delivered at refueling stations in Norway is rather high, at about 90 NOK/kg (Norwegian Hydrogen Forum, 2013). This is due to the fact that production costs have yet to come down and the current infrastructure is still small scale. The production cost of hydrogen produced from the grid in different countries in Europe was on average 5.3 EUR/kg in 2012, which is around 48 NOK/kg, and is expected to decrease (Bertuccioli et al., 2014). According to a feasibility study done by the technology group Hellenes AS, hydrogen could be produced locally and delivered at a price of 50 NOK/kg today, including investment costs, transport costs and grid tariffs (Valle, 2015). We will discuss the price of hydrogen further in chapter 4.

3.3.1 Availability and infrastructure in Norway

In Norway, industrial actors have produced and utilized hydrogen since 1927, and Hydro has developed their own electrolyser technology (Norwegian Hydrogen Forum, 2014). NEL Hydrogen continues to develop this technology, and new companies within electrolyser manufacturing and integration are being established.

It was Hydro and Statoil, together with Raufoss Fuel Systems (now Hexagon Composites), and Norwegian research institutes, that brought hydrogen from the industrial and research areas to the transport arena in 2000, through the HyNor project. The project aimed to demonstrate the readiness of hydrogen as an alternative fuel for cars, and several refueling stations were opened in the period 2006-2009. The world's first dedicated hydrogen station operation company, HYOP AS, is now operating the stations. With FCEVs entering the market, Norwegian industrial actors have the technology and the competence to supply products and services in the entire value chain (Norwegian Hydrogen Forum, 2014).

In Norway, the hydrogen supplied at the refueling stations is mainly produced on site using electrolyser technology. In this way, the cost of transporting the hydrogen is avoided. However, HyNor Lillestrøm is testing a new technology of steam methane reforming, which also includes CO_2 separation at their hydrogen station in Akershus EnergiPark. In addition, the hydrogen refueling station in Porsgrunn is supplied by hydrogen produced as a byproduct from a local chlorine plant.

The number of consumers will ultimately set the demand for hydrogen in Norway. There are currently six hydrogen refueling stations in Norway as shown in Figure 3.2, which is just enough to supply the five hydrogen buses and 30 or so prototype FCEVs currently in the country (Dalløkken, 2015).

Figure 3.2: Overview of existing hydrogen stations in Norway (Dalløkken, 2015).

With the launch of the Toyota Mirai in Norway next year, Figure 3.2 illustrates the lack of infrastructure present today. On the other hand, the rest of Europe, in particular Germany, has planned a more extensive network for hydrogen stations as seen in Figure 3.3.

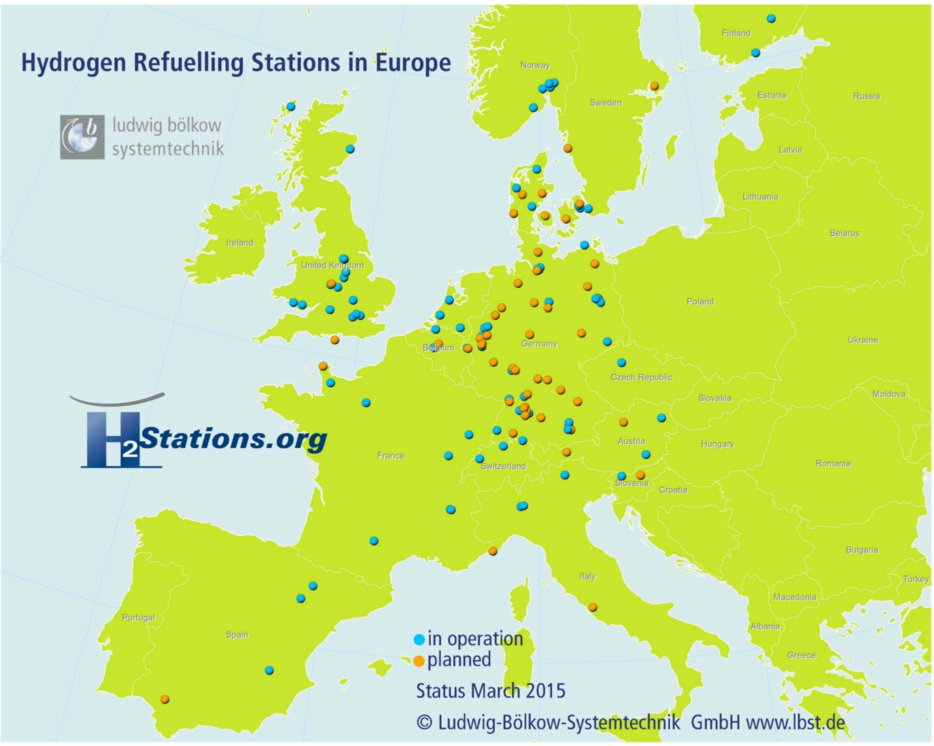

Figure 3.3: European planned hydrogen stations (H2stations.org, 2015).

Nevertheless, national plans for hydrogen infrastructure buildup in Norway have been made, and Akershus County, together with the city of Oslo, developed a joint strategy for hydrogen toward 2025, including both infrastructure and analysis of the potential value creation from taking a leading role within hydrogen (Norwegian Hydrogen Forum, 2014). Furthermore, NEL Hydrogen has just signed an initiative agreement with the Uno-X Group to build 20 new hydrogen stations in the biggest cities in Norway by 2020 (Ramsdal, 2015). Although the infrastructure is mainly focused on powering cars, having more hydrogen available in the market would be beneficial for the implementation of hydrogen in the maritime sector.

3.4 Production of hydrogen

As mentioned earlier, the global production of hydrogen is 65 million tons per year. Most of the hydrogen produced today, about 48%, comes from the process of steam methane reforming (SMR). The rest is produced from oil (30%), coal (18%) and electrolysis (4%) (IEA, 2015). However, hydrogen is in Norway produced almost entirely acquired by the means of electrolysis (Norwegian Hydrogen Forum, 2013). This process can in comparison to the other methods provide high-purity hydrogen directly, without any emissions. Production of hydrogen is not the focus in this paper. Nonetheless, we will in this section give a brief introduction to how hydrogen can be produced from water electrolysis.

3.4.1 Water electrolysis

As mentioned above, water electrolysis provides high-purity hydrogen (99.99%), which cannot be directly achieved from SMR, an aspect that is relevant when the hydrogen's purpose is to be used in a fuel cell. Using lower grade hydrogen in fuel cells require them to be replaced more often, adding costs which could be otherwise saved (IEA, 2007).

Water electrolysis occurs when a current passes through a substance called an electrolyte, from a cathode (-) to an anode (+), releasing hydrogen and oxygen, as illustrated in Figure 3.4. Electrolysis can be performed either by using electricity from the grid or by directly using electricity from renewable energy sources, which would provide zero emissions from production to consumption. Hydrogen produced from electrolysis is currently more expensive than from SMR, but the cost of electrolysers is expected to decrease. In addition, the cost of producing hydrogen can be lowered if hydrogen is produced in periods with low electricity prices. The most common forms of electrolysis are alkaline, proton exchange membrane and solid oxide, although alkaline electrolysis is the most mature technology in Norway.

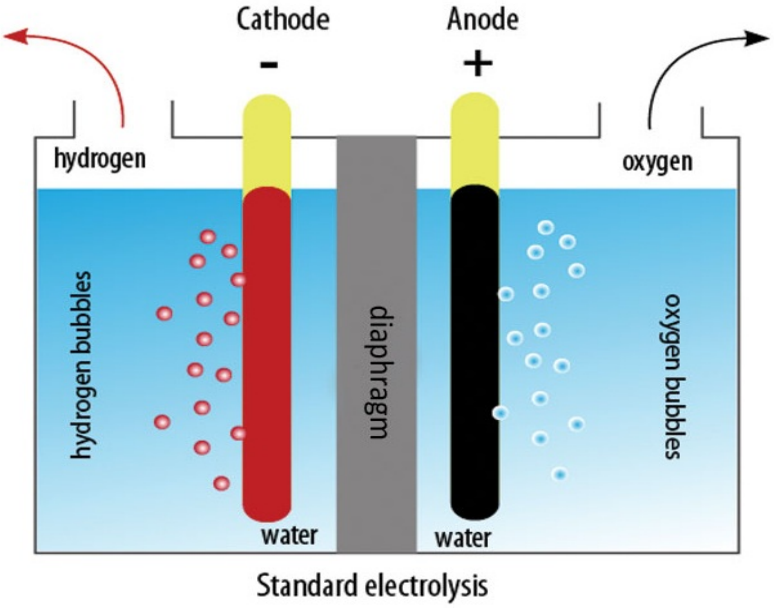

Figure 3.4: Water electrolysis (Hydrox Systems, 2015).

3.5 Fuel cell technology and storage of hydrogen

Hydrogen has proven to be useful in several applications in the past and is a very versatile energy carrier. Contrarily to gasoline or diesel, it is not an energy source; it is merely a state in which energy can be stored for future use. In this sense, we can regard hydrogen as a fuel with the stipulation that the correct infrastructure and technology needs to be present. In this part, we will provide an introduction to different fuel cell technologies and methods for storage, and evaluate which of these are the most applicable to the maritime sector.

3.5.1 Different fuel cell technologies

Since its original design in 1839 by William Grove, the fuel cell technology has been greatly improved upon. In recent years, the advances in this technology have been more pronounced as it is becoming more commercially viable. In fact, 22,000 fuel cell units were sold in 2009, a 40% increase from the 2008 figures (DNV, 2011).

There are several types of fuel cells, each with different chemical reactions, their own specific purposes and attributes. Fuel cells are electrochemical devices that use hydrogen, or hydrogen-rich fuels, together with oxygen from the air, to produce electricity and heat (IEA, 2007). Figure 3.5 shows an overview of the various types of fuel cells available today and their respective chemical reaction.

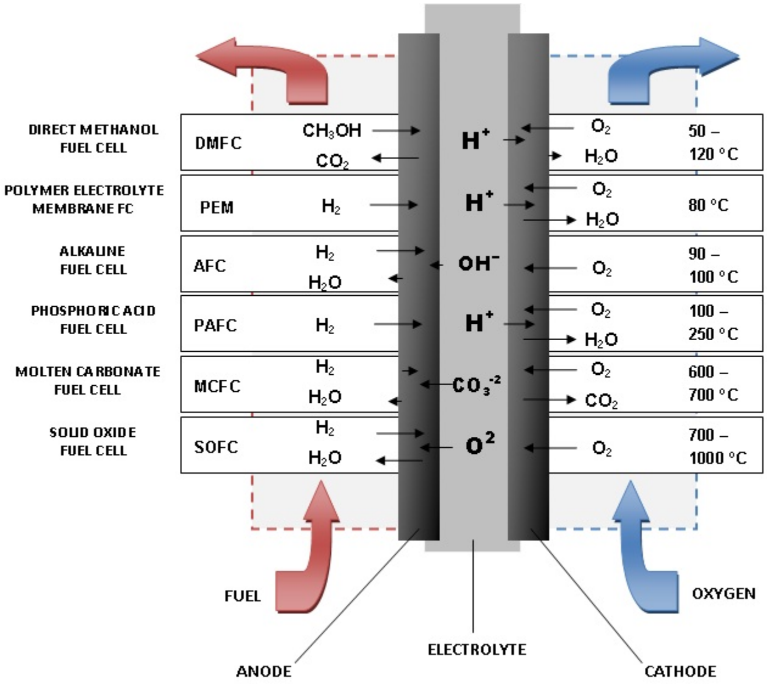

Figure 3.5: Different fuel cell technologies (Fuel Cells 2000, 2015).

The fuel, mostly hydrogen, enters the fuel cell at the anode. The hydrogen molecules are stripped of their electrons, forming ionized H^+ atoms. These electrons pass through a wire towards the cathode, creating the current, and are then picked up by the oxygen at the cathode. The oxygen and H^+ atoms are combined into water as the sole waste of the reaction.

What differentiate the fuel cells are mostly the fuel used and its operating temperature. Because of their internal components, some fuel cells are more suitable for certain applications than others. In this section, we will be focusing on the most common fuel cells: molten carbonate (MCFC), solid oxide (SOFC), alkaline (AFC) and proton exchange membrane (PEMFC). MCFC and SOFC operate at high temperatures, can run on hydrocarbons (fossil fuels), and are generally used for large-scale electricity and heat generation. AFC operate at lower temperatures, but are also more suitable for large-scale stationary electricity generation as they cannot be moved around due to their rigid and liquid internal parts. PEMFC on the other hand, tolerates to be a part of a moving system and runs exclusively on high purity hydrogen (IEA, 2007).

3.5.2 PEM fuel cell in the maritime sector

PEMFCs are known to be the number one contender to lithium-ion batteries, and with good merit. In comparison with their counterparts, they are most suited for on-demand power situations where flexibility and weight are important. They have short startup times and high energy density, meaning they weigh the least for any given power output. Although the other types of fuel cells may have higher efficiencies, they are much larger installations that are only suitable for stationary power generation. PEMFCs are commercially viable and can be delivered in a number of sizes depending on the application (IEA, 2007). According to our research, PEMFCs ranging from 100-200 kW seems to be the most common power output per stack for fuel cells, and can be delivered from Ballard, a well-established global fuel cell manufacturer. Not unlike batteries, PEMFCs can be stacked endlessly in order to obtain the desired power generation. This makes them very applicable in our case, with ferries ranging from 368 to 12,380 kW of installed capacity. The price of fuel cell modules for use in bigger vessels, like buses or boats, have not yet seen as drastic price reductions as the fuel cell stacks used in FCEVs. Today, the price is around 1,300 EUR/kW[6], but is expected to decrease substantially with economies of scale and commercialization. The current price

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[6] Personal Communications: Tjalve Magnusson Svendsen, CMR Prototech.

level of PEM fuel cell stacks used in FCEVs is around 450 EUR/kW, and the fuel cell stacks for the maritime sector is expected to reach these levels (IEA, 2015).

3.5.3 Storage

There are several ways to store hydrogen and each method is used for particular applications. Hydrogen can be stored in solid state in metal hydrides, in liquid form at extremely low temperatures, or in compressed tanks at 350 or 700 bars. Although storing hydrogen in metal hydrides is very space efficient, the related energy density by weight is relatively low. Liquid hydrogen involves tremendous amount of energy and, much like LNG, is most suitable for long distance transportation of the gas. In addition, a system running on liquid hydrogen has a higher degree of complexity given that the gas must be kept at -253 degrees Celsius (IEA, 2007). Compressed hydrogen is therefore the most suitable for vehicles. The FCEVs available on the market today are equipped with 700-bar tanks, whereas hydrogen buses have 350-bar tanks (Norwegian Hydrogen Forum, 2013). Since space is not as important in a ferry as it is in a car, this study will assume the most appropriate method of storing hydrogen to be 350-bar tanks, as upping the pressure to 700 bars requires even more energy.

3.6 Existing and planned projects in the maritime sector

There are today several projects where fuel cells are being used for maritime applications. The main focus has been on fuel cells using LNG or other fossil fuels. In addition, the fuel cells have mainly been used as auxiliary machinery and not as the main propulsion system. This has mainly been the case due to high cost of fuel cell systems. However, there have also been some smaller projects testing the use of hydrogen and fuel cells. Below follows a short description of some of the most important projects.

3.6.1 Existing projects

Viking Lady

The supply vessel, Viking Lady, is the first larger ship where a fuel cell system has been developed, and is operating in the North Sea. The project is a result of a big industrial cooperation that was initiated in 2003 by DNV, Eidesvik, Wärtsilä and MTU (DNV, 2011).

A 330 kW fuel cell was successfully installed, demonstrating smooth operation for more than 18,500 hours, and an electrical efficiency of over 52% at full load, which proved that fuel cells can be adapted for stable, high-efficiency, low-emission onboard operation. It was installed with a MCFC as auxiliary machinery and a combustion engine, both fueled by LNG (DNV, 2012). The MCFC does not need pure hydrogen as the high temperatures at which the fuel cell operates converts LNG into hydrogen within the fuel cell itself by a process called internal reforming (U.S. Department of Energy, 2015b). The next phase of the project is installing a battery pack for energy storage to create a true hybrid propulsion system.

Type 212 submarines

It is in submarines the use of hydrogen in fuel cells has been developed the most. Howaldtsweke Deutche Werft AG (HDW) Germany has built submarines using PEMFCs for the German marine. Siemens delivers the fuel cell stacks of 120 kW and the hydrogen is stored in metal hydride. The development started in 1987 and with today's technology the submarine can be underwater for more than 14 days (Fuel Cell Today, 2012).

MF Vågen

In 2010, MF Vågen was the first Norwegian passenger ferry equipped with a hydrogen fuel cell system for propulsion. It was a demonstration project led by CMR Prototech, and the boat was equipped with a 12 kW fuel cell with a system efficiency of up to 57%. The hydrogen was stored as metal hydride. The project was a success and the conclusion was that the technology works and is commercially available. Also, the system would be a suitable zero-emission technology with high efficiency for ships with longer range. Unfortunately, Norwegian Maritime Authority would not allow the boat to have passengers while it was fueled by hydrogen, due to uncertainties about external factors (Transnova, 2010).

ZEMship

ZEMship (Zero Emission Ship) in Hamburg was the first project in the world to integrate a hydrogen fuel cell system on board a passenger vessel. It is run by two 48 kW PEMFCs and can store up to 50 kg of hydrogen gas in 350-bar tanks on board the vessel. Typical refueling frequency is every 2 to 3 days (DNV, 2011).

3.6.2 Future planned projects

High-speed hydrogen ferry in San Francisco

Sandia National Laboratories and the Red and White Fleet ferry company are working on a project named SF-BREEZE, short for San Francisco Bay Renewable Energy Electric vessel with Zero Emissions. The aim is to design, build and operate a high-speed hydrogen fuel cell ferryboat in the San Francisco Bay Area. The ferry would use about 1,000 kgH_2/day, and the project also plans on building the world's largest hydrogen refueling station. A feasibility study is funded by the U.S. Department of Transportation's Maritime Administration to examine the technical, regulatory and economic aspects of the project (Sandia, 2015).

The Osterøy ferry project

Osterøy ferry company, who owns the ferry MF Ole Bull, operating the route Breistein-Valestrand, has agreed to participate in a demonstration project, with CMR Prototech, testing a hydrogen and fuel cell energy system in full scale. CMR Prototech has just received monetary support, from Hordaland County, to do a test project to, among other things, plan the dimensions of the power system onboard, evaluate safety concerns, and consider systems for production and storage of hydrogen. After the test project is completed, a plan for the main project will be developed and apply for funding from Enova, Innovation Norway or other incentive programs.

A key factor for the demonstration project is to get approval from the Norwegian Maritime Authority. There currently does not exist any regulations for the use of hydrogen and fuel cells on ships. To get approval, CMR Prototech will have to show that a hydrogen fuel system is at least as safe as conventional technology by performing risk analysis and tests. The plan is to install a fuel cell system in a container, which can be tested on land, and do further testing onboard the ferry during the night when there are no passengers. Frydenbø Power, Solund Verft and Greenstat are also participating in the project. Suppliers of battery technology and hydrogen tanks are also likely to join.[7]

Zero-emission ferry linking Germany and Denmark

FutureShip designed in 2012 a zero-emission ferry for Scandlines' Vogelfluglinie that would link Puttgarden in Germany to Rødby in Denmark, which could be deployed by 2017. Power generation is essentially based on liquid hydrogen. The zero-emission ferry has 8.3 MW high-temperature fuel cells and the hydrogen is stored in 140 cubic meter (m^3) C-type tanks on deck, sufficient for a passage of 48 hours. The high-temperature fuel cells are efficient, but slow responders for changing loads, thus a battery system of 2.4 MWh is installed to

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[7] Personal Communications: Tjalve Magnusson Svendsen, CMR Prototech.

store excess electricity from the fuel cells and supply power rapidly when needed (FutureShip, 2012). The ferry will operate at a speed of 17 knots, but can accelerate up to 18 knots by drawing additional power from the batteries (GL Group, 2012). The hydrogen will be supplied from nearby wind power plants using excess electricity (FutureShip, 2012). FutureShip estimates that the ferry would cost only about 25% more than a conventional design and that the technology is available (GL Group, 2012).

4. Literature review

In this section we review previous literature regarding hydrogen. We will first take a look at cost-benefits analysis of introducing hydrogen in the transport sector. As costs seem to be the biggest barrier for the implementation of hydrogen, we review some reports regarding expected price decrease in hydrogen production. Finally, we look at two studies evaluating the feasibility of using hydrogen in Norwegian ferries. Based on the literature review we give a brief discussion on how we utilize earlier research in our thesis.

4.1 Cost-benefit analysis of hydrogen in the transport sector

When considering the implementation of hydrogen in the transport sector, several cost-benefits analysis has evaluated the possible positive and negative effects of hydrogen. The European Commission published a Hydrogen roadmap in 2008, analyzing the potential impacts on the EU economy, society and environment of a large-scale introduction of hydrogen in the short and long term (European Commission, 2008). According to the study hydrogen can become a cost-effective option to reduce CO_2 emissions by 2050. Implementing hydrogen in road transport will significantly improve the air quality in city centers, and the diversification of energy leads to improved security of supply and less vulnerability to shocks and structural high oil prices. The project also highlights that hydrogen offers the opportunity to increase the utilization of renewable energy in Europe. The two major barriers of introducing hydrogen into the energy system are cost reduction for end-use applications and the lack of policy support such as, support schemes for hydrogen end-use technologies and infrastructure build-up.

Another cost-benefit analysis, comparing diesel, compressed natural gas and hydrogen for use in the Perth bus fleet, finds that despite its significant environmental benefits in operation, the high initial cost of the hydrogen fuel cell bus is not competitive with the fossil fuel technologies (Cockroft & Owen, 2007). According to the study, the major economic impediment to the competitiveness of the hydrogen fuel cell bus is the cost of hydrogen. However, this will be mitigated if fossil fuel prices increase due to, for example, stricter environmental policies. Hydrogen is favored when considering pollutants emitted, due to long operating periods of buses in populated areas. Cockroft and Owen (2007) also agree that substituting away from fossil fuels would improve energy security and avoid fuel price volatility. However, such benefits would only be significant if a substantial part of the transport sector relied upon non-fossil fueled based technologies. The study concludes that the societal benefits arising from the introduction of hydrogen fuel cell buses rely heavily on their environmental benefits to offset their private cost disadvantages. Unfortunately, the precision of such benefits is difficult to determine. Justification of energy subsidies to developing technologies may be based upon the desire of a government to achieve certain environmental goals.

It seems that implementing hydrogen in the energy sector can provide many benefits. The biggest being reduced CO_2 emissions, improved air quality and less vulnerability to volatile oil prices, which are all relevant for the ferry sector as well. However, the high cost of hydrogen makes it less competitive with fossil fuels. Thus, if hydrogen is to be implemented in the Norwegian ferry fleet, it is likely that it would depend on subsidies or that the price would have to decrease in the near future. This study will provide an overview over CO_2 and NO_x emissions on the relevant ferry routes, and thus give a picture of the potential environmental benefits that could be achieved. The cost of reducing emissions will be presented as abatement cost, NOK/tCO_2.

4.2 Production cost and price

Hydrogen prices are among other things dependent on production costs. Water electrolysis has the possibility to provide emission free hydrogen from production to consumption. The production cost of electrolysis is currently higher than production cost from using fossil fuels, but the costs are expected to decrease. A report by Fuel Cells and Hydrogen Joint Undertaking (2014) consider the possible cost reductions in electrolyser technology. Though industrially mature in some senses, the electrolyser industry is small and fragmented, and costs have yet to be driven down through mass production or supply chain optimization, and thus the room for technology improvement is still significant. Two different types of electrolyser technology are currently available as commercial products, namely conventional alkaline electrolysers and proton exchange membrane (PEM) electrolysers. Today, the indicative system costs are in the range of 1,000-1,200 and 1,900-2,300 EUR/kW, respectively. In 2020, the report suggests that these cost can come down to 370-900 and 700-1,300 EUR/kW, respectively, and as low as 370-800 and 250-1,270 EUR/kW in 2030. Since the alkaline technology is more mature, the PEM electrolyser is expected to have a higher potential for cost reductions.

With these cost reductions, the production cost of electrolytic hydrogen at mainstream grid prices in different countries in Europe, is shown to be on average 5.3 EUR/kg in 2012 and as low as 3.74 EUR/kg in 2030, which is 48 and 34 NOK/kg.[8] Even with cost reductions, taking advantage of further support mechanisms, such as green certificates or carbon taxes, is needed to bring additional revenue streams and allow electrolytic hydrogen to compete with hydrogen from other sources.

Løland (2015) provides a case study of producing hydrogen from excess wind power from the wind farm, Raggovidda, in Finnmark. The study finds that by using the mature alkaline technology and optimizing hydrogen production to minimize production costs, the cost can currently come down to 4.23 EUR/kg, i.e., around 38 NOK/kg. The production cost includes liquefaction of hydrogen for storage and transportation by ship, and is based on a hypothetical expansion of the wind farm (Løland, 2015). Another study done by Hellenes AS in 2015 looks at a case of an already existing value chain, where they use energy from the power plant Brulandsfossen, owned by Sunnfjord Energi, to produce the hydrogen. They find a production cost, including transportation, compression and grid tariffs, of 50 NOK/kg. Excluding the grid tariff the hydrogen could be delivered at a price of 40 NOK/kg (Valle, 2015).

In our thesis we assume hydrogen is produced from water electrolysis to achieve zero emission production. Even though production method is not a focus in our study, the hydrogen price depends on the production costs. In these studies it is shown that the hydrogen production is 48 NOK/kg in Europe, and is expected to come down to 34 NOK/kg in 2030. Taking advantage of excess energy, the production cost in Norway can become as low as 38 NOK/kg today. However, as the study by Hellenes AS evaluates compressed gas and an already existing value chain, the price of 50 NOK/kg seems more realistic and suitable for the purpose of this study. With the expected price decrease in alkaline electrolysers, the hydrogen price in Norway could become even lower.

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[8] Exchange rate: 9.0 NOK/EUR.

4.3 Feasibility of hydrogen as fuel in Norwegian ferries

There are two main reports discussing the feasibility of implementing hydrogen as a zero-emission alternative fuel in the Norwegian ferry fleet. The first study was carried out by the environmental organization, ZERO, in 2008. They did a case study of implementing hydrogen as fuel on the ferry MF Svelviksund, operating the route Svelvik-Verket. In contrast to our study, the report analyzed only one short route and compared two propulsion systems: hydrogen combustion engine, and a hybrid battery and fuel cell system with conventional diesel engines as back up. As discussed in chapter 3, the hydrogen combustion engine is not very efficient, thus we have chosen to focus only on the fuel cell system with battery packs to help with energy need in acceleration. The report concludes that there are no technical barriers for using hydrogen as fuel in ferries, as the technology already has been proven in buses, cars and offshore operations. Not surprisingly, they find that the hybrid battery and fuel cell system has twice as high of an efficiency as the combustion engine. However, the capital costs are somewhat higher.

Another report performed by Det Norske Veritas (2011), now DNV GL, evaluates MGO, LNG, biogas, hydrogen and batteries as alternative technologies for ferries that could be relevant to introduce more environmentally friendly ferries in Hordaland County in the time frame 2016-2019. In this study, biogas and hydrogen are quickly regarded as not applicable due to lacking infrastructure and low availability. Hydrogen would have to be transported on trailers from production facilities located in the east part of Norway. LNG and electricity are the most interesting in terms of emissions and costs compared to MGO. However, research done for the report, and conversations with suppliers, indicates that an all-electric battery solution on crossings over 20 min would not be suitable. With increasing mileage, the batteries cannot provide the sufficient amount of sustained energy needed.

Both the studies highlight that the biggest challenges related to hydrogen are due to safety concerns and lacking regulations. The existing regulatory and security challenges makes approving solutions that entail storage of larger volumes of hydrogen in ships difficult. In addition, there are no regulations or classification rules for the use of hydrogen in the maritime sector.

DNV concludes that LNG and electricity are the most interesting alternative technologies for ferries in Hordaland County. However, DNV also states that batteries are not a suitable option for routes with a crossing time of over 20 min. This indicates that LNG is the only feasible option to MGO on the longer routes, and thus there exist no feasible zero-emission option. Other reports, studying the implementation of electric ferries in Norway, also disregard the longer routes, e.g. Siemens (2015) and DNV GL (2015), but conclude that batteries are a very interesting option on shorter routes. Based on this, our study will provide an overview of the potential implementation of hydrogen as a zero-emissions option on all the long ferry routes in Norway. Unlike the report by DNV GL, we do not discourage hydrogen, but evaluate the costs of implementing hydrogen as a zero-emission technology compared to the alternatives, MGO and LNG.

4.4 Main takeaway

Based on the literature above, the high cost of hydrogen is the main barrier related to the use of hydrogen in the transport sector. However, taking advantage of the low electricity prices in Norway, the price of hydrogen could be as low as 50 NOK/kg, including transportation costs. We will therefore in this thesis use this estimate as the base price for hydrogen. The European production cost is today 48 NOK/kg. However, this price does not include transportation costs. The expected cost in 2030, including expected price reductions in electrolyser technology, is 33 NOK/kg, a 15 NOK/kg decrease. Considering that this decrease could be expected in Norway as well, we assume a 15 NOK/kg decrease in Norwegian prices. This gives a future price of 35 NOK/kg, all else equal, which will later be used as a low estimate price.

For ferries, hydrogen has no technical barriers, but batteries and LNG is concluded as the best alternative fuels because of the high costs of hydrogen. Many reports have shown that batteries can be both a feasible and a profitable zero-emission option. However, these reports also disregard the use of all-electric ferries on the longer ferry routes, as batteries cannot provide the energy needed for routes with bigger dimensions. Thus, for the longer routes LNG seems to be the only feasible option. ZERO (2008) is the only study that has actually evaluated hydrogen on a ferry route in Norway, but the study was done on one of the shortest routes in Norway. In our thesis we want to further evaluate the potential hydrogen has as a zero-emission option on all the longer routes in Norway, assuming infrastructure exists and the hydrogen price found above. Since hydrogen is more expensive than the other options, it relies on its social benefits to offset the high cost, as highlighted by Cockroft & Owen (2007). As seen above, substituting away from fossil fuel can lead to a diversification in the energy sector, and have significant environmental effects. To evaluate this, we will look at the cost of implementing hydrogen in terms of abatement costs, in NOK/tCO_2. Subsidies to developing technologies, like hydrogen, or higher taxation on emissions, could be justified by the governments desire to achieve their environmental goals and their requirement of implementing low- and zero-emission technology on all the ferry routes in Norway.

Nevertheless, for use in the maritime sector there are difficulties regarding the implementation of hydrogen, as there are no regulatory framework or classification rules set in place. It would, however, be necessary to develop these when the first hydrogen fueled ship is planned, and an option could be built on existing work with LNG and other rules regarding the use of hydrogen, e.g. the International Code of Safety for ships using gases and other Low-flash point fuels.[9] However, we will not focus further on rules and regulations in our thesis.

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[9] Mail correspondence with Alvar Mjelde, DNV GL Maritime.

5. Data

The required data for this study is an overview of all the Norwegian ferry routes and their respective ferries, including information about distance, traffic, installed capacity on the ferries and their respective operating speed. As there is currently no such database available, this chapter will explain how the data we use have been collected, and which assumptions have been made before using the data to produce results. We will give an overview over the characteristics for the routes found most interesting for hydrogen, and the ferries operating on these routes. All data for this study have been collected from publicly accessible sources.

5.1 Collecting the data

Data surrounding all the existing ferry routes in Norway, and their respective length and crossing time, have been collected from a publically available ferry database, provided by NPRA (NPRA, 2015c). The dataset included information about crossing connections, distance and approximate crossing time. We used information from the operators' websites to update information that was outdated, and to include information that was lacking in the dataset, e.g. how many times the distance is being crossed each day. A summary of the relevant information is shown in Table 5.1.

5.1.1 The relevant group of routes

The relevant ferry routes in this thesis are the routes with longer trajectories. As mentioned earlier, previous studies evaluating zero-emission technology in ferries have mainly focused on battery technology on shorter routes. Most of the time the longer routes are excluded, or only discussed with the possibility of a hybrid solution. Because we, in this thesis, want to study the possibility of implementing hydrogen fueled ferries as a possible zero-emission option on the longer routes, we focus on the routes that ***involve at least one crossing over 10 km and have a crossing time of more than 30 minutes.*** However, we want to stress that this is not because we consider hydrogen inadequate for shorter routes, but because there have been several studies showing that using batteries is a feasible and profitable solution for these types of routes.

From the roughly 110 ferry routes from the database, 37 routes are considered relevant by these criteria. In addition, two shorter routes have been included, namely Hanøy-Kalfjord and Øksfjord-Tverrfjord, because they are operated by the same ferry as Digermulen-Hanøy/Finnvik and Øksfjord-Hasvik, respectively. These routes have been included because we want to evaluate how much hydrogen the ferries would need to maintain the same service level they have today. The specifications about the relevant routes are shown in Table 5.1.

Route	Distance (km)	Estimated time (min)	Crossings per day	Ferry	# of ferries	Passenger car units (PCU)	Installed capacity (kW)	Operating speed (knots)	Year built	End of tender
Rysjedalsvika-Rutledal-Krakhella	20.2	58	18	MF Nordfjord	1	54	2,080	13.0	2002	2025
Askvoll-Fure-Værlandet	24.6	70	16	MF Eid	2	34	1,134	13.0	1978	2025
Smørhamn-Kjelkenes	12.5	35	18	MF Dalsfjord	1	27	746	13.0	2002	2016
Horn-Igerøy	13.5	41	12	MF Torgtind	1	50	1,760	12.0	1999	2017
Igerøy-Tjøtta	21.8	63	4	-	1	-	-	-	-	2017
Tjøtta-Forvik	17.4	51	14	MF Godfjord	1	28	735	12.0	1987	2017
Stokkvågen-Onøy-Sleneset-Lovund	43.1	120	14	MF Lovund	2	50	2,125	13.0	2013	2021
Træna-Onøy-Stokkvågen	47.8	127	4	MF Husøy	1	50	2,125	13.0	2013	2021
Mosjøen-Hundåla-Dagsvik	28.2	91	6	MF Rana	1	22	1011	11.0	1977	n/a
Solfjellsjøen-Vandve	13.0	42	10	MF Vandve	1	12	368	11.0	2015	n/a
Bodø-Værøy-Røst-Værøy-Moskenes**	301.0	562	6	MF Landegode	3	120	5,250	18.0	2012	2023
Bognes-Lødingen**	23.3	56	22	MF Lødingen	2	120	2,430	14.5	2012	2023
Kjøpsvik-Drag	13.6	41	18	MF Vardehorn	1	120	2,560	12.0	1999	2017
Jektvik-Kilboghamn	18.5	47	10	MF Rødøy	1	69	1,771	14.0	1991	2015
Rødøybassenget	39.6	149	4	MF Fykan	1	28	920	10.0	2000	n/a
Sund-Horsdal-Sørarnøy	11.0	44	10	MF Gildeskål	2	28	930	10.0	2000	n/a
Ørnes-Vassdalsvik-Meløysund-Bolga	27.1	100	10	MF Ørnes	1	28	960	10.0	2000	n/a
Digermulen-Hanøy/Finnvik	22.3	68	12	MS Lofotferje I	1	18	582	12.0	1981	n/a
Hanøy-Kalfjord	8.5	27	2	-	1	-	-	-	-	n/a
Lyngseidet-Olderdalen	12.6	33	18	MF Goalsevarre	1	57	1,517	14.0	2011	2019
Sørrollnes-Stangnes	13.9	42	18	MF Ibestad	1	74	1,492	12.0	2014	2019
Hansnes-Karlsøy-Vannøy-Hansnes	33.3	80	15	MF Malangen	1	62	2,692	16.0	2001	2020
Rotsund-Havnnes-Klauvnes	33.2	102	10	MF Uløytind	1	16	749	12.0	2011	2019
Sør-Tverrfjord-Bergsfjord-Øksfjord	39.1	114	4	MF Hasfjord	1	20	728	12.0	1975	2025
Øksfjord-Tverrfjord	3.0	12	4	MF Åfjord	1	35	2,238	12.0	2000	2025
Øksfjord-Hasvik	28.0	80	6	-	1	-	-	-	-	2025
Stavanger-Tau**	14.5	33	64	MF Ryfylke	3	165	4,000	16.0	2013	n/a
Fogn-Jelsa	54.3	188	22	MF Stjernarøy	2	48	2,160	12.0	1999	2019
Mekjarvik-Kvitsøy	13.3	37	20	MS Fjordveien	1	79	4,320	13.0	2001	2017
Våge-Halhjem**	12.5	35	26	MF Selbjørnsfjord	1	120	2,686	13.0	2010	n/a
Hufthamar-Krokeide	13.0	39	38	MF Trondheim	1	124	3,000	12.0	1992	2016
Ranavik-Skjersholmane	14.3	35	46	MF Hardingen	2	86	2,432	15.0	1993	2018
Utbjoa-Sydnes-Fjelbergøy-Borgundøy	13.5	49	14	MF Sveio	1	26	835	12.0	1996	2018
Sandvikvåg-Halhjem**	21.7	38	70	MF Raunefjord	3	212	12,380	21.0	2007	2016
Brattvåg-Dryna-Fjørtofta-Harøya	34.1	101	27	MF Dryna	2	35	1,616	13.0	2005	2018
Geiranger-Hellesylt	19.9	54	16	MF Bolsøy	2	35	1,544	13.0	1983	n/a
Molde-Sekken	11.5	38	16	MF Ørsta	1	25	1,066	11.0	1964	2019
Molde-Vestnes**	11.5	33	45	MF Romsdalsfjord	3	120	1,800	13.0	2010	2019
Moss-Horten	10.5	30	102	MF Bastø 1	3	200	3,960	13.0	1997	2026
Average						***83***	***2,738***	***13.5***	***1999***	

** Routes currently operated by LNG ferry

Table 5.1: Relevant group of ferry routes and ferries.

5.2 Characteristics of the relevant routes

The relevant group of routes varies in terms of traffic, number of stops and capacity of the ferries operating. From the route operators' websites, we have obtained information regarding which ferries are operating the routes. Some of the routes have only two stops and one ferry going back and forth, other routes have more than two stops and are operated by two or three ferries. Figure 5.1 provides an overview of the characteristics of the chosen routes.

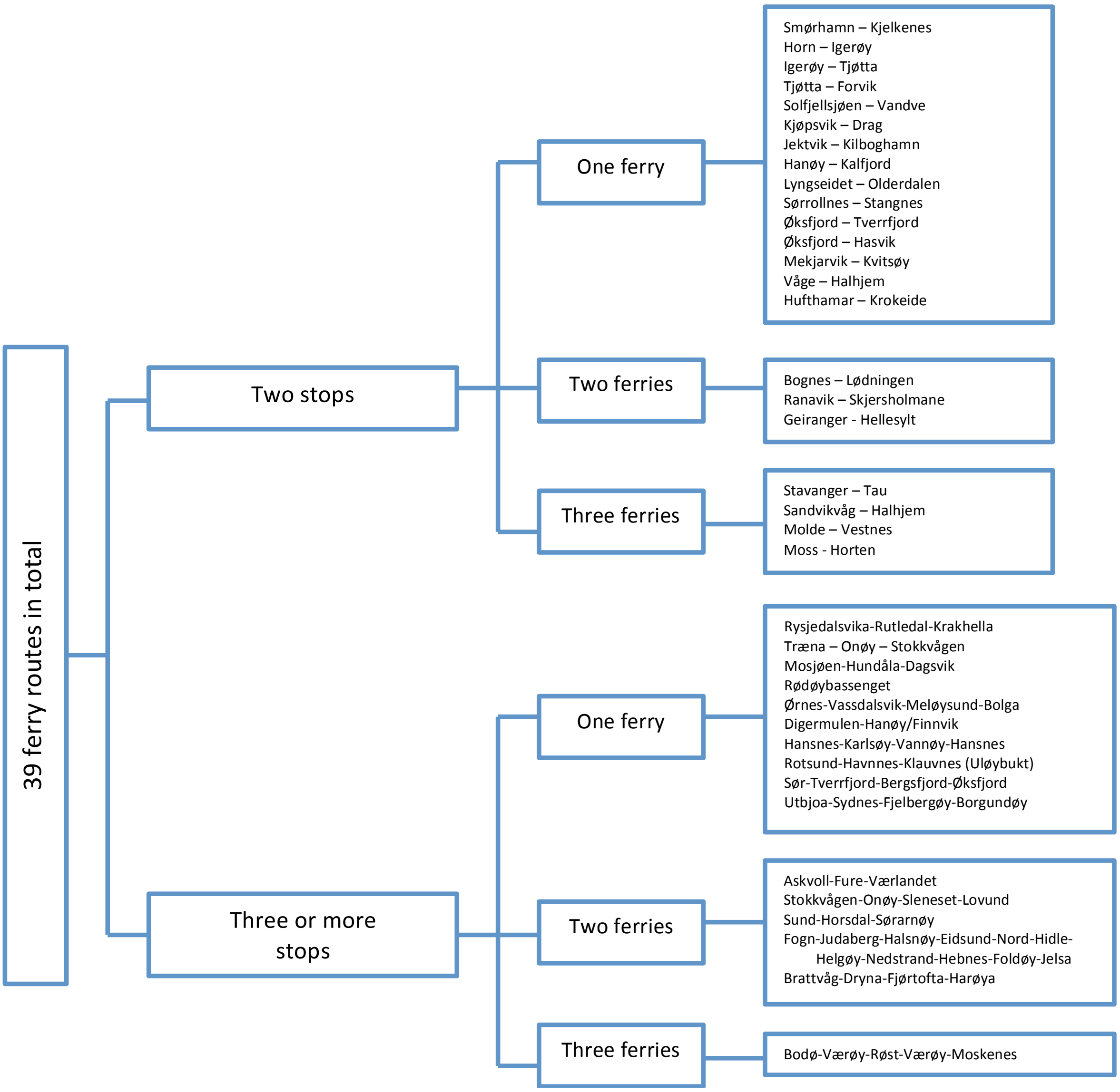

Figure 5.1: Overview of the relevant routes.

5.2.1 Distance

The length of the crossing varies significantly among the routes and is an important parameter as it determines the total energy need for the route. The distance between two connecting harbors within a route vary from 1 km to 94 km. The average distance among all the connecting points in the selected routes is 14.5 km and the average length of an entire route is 28 km.

5.2.2 Crossings per day

Using the timetables for the different routes, we found how many crossings per day ferries currently perform. Crossings per day refers to how many times the distance within the route is being crossed during one day, regardless of how many ferries operates the route. We used the most common routes, which usually run from Monday to Friday, as an approximation for number of crossings per day. To find crossings per year we assumed this route goes six days a week because there is usually less traffic on the routes during the weekends. The final estimates for each route can be found in Table 5.1.

5.3 Characteristics of the relevant ferries

There are 54 different ferries operating the 39 routes today. This is also illustrated in Figure 5.1, where we see that some routes are operated by more than one ferry. For the routes operated by more than one ferry we assume all the ferries to have identical characteristics as the ferry that is most commonly used on the route in terms of installed capacity, PCU capacity and operating speed. This is a fair assumption as the ferries operating within the same route often have identical or similar characteristics. For instance, for the two ferries operating on the route Fogn-Jelsa with an installed capacity of 2,160 and 2,088 kW, we use 2,160 kW as MF Stjernarøy is the ferry most commonly used. The number of ferries and the most common ferry for each route is shown in Table 5.1. To find information about installed capacity and operating speed on the different ferries, we mainly used two websites: a German online ferry register, *Fährenregister Norwegen*, and the website skipsrevyen.no.

We distinguish between MGO and LNG fueled ferries, and diesel and gas engines, as six of the relevant routes are currently operated by LNG fueled ferries. However, we do not distinguish between a mechanical and an electric propulsion system. We will present an overview over the characteristics of the relevant ferries that can be found in Table 5.1.

5.3.1 Installed capacity and passenger car units

The data behind the installed capacity in the different ferries was given in both HP and kW. As we are interested in how much energy the ferries use, we converted the installed capacity found in HP to kW. The installed capacity and PCU capacity on the ferries vary. For example, the ferry MF Uløytind, operating the route Rotsund-Havnnes-Klauvnes, has an installed capacity of 749 kW and 16 PCU. In contrast, the ferry MF Raunefjord, operating the route Halhjem-Sandvikvåg, has an installed capacity of 12,380 kW and 212 PCU. Figure 5.2 show that there is some correlation between PCU and installed capacity. The average capacity of the ferries we are looking at is 2,738 kW and has a PCU of 83, when considering that there is more than one ferry operating some of the routes.

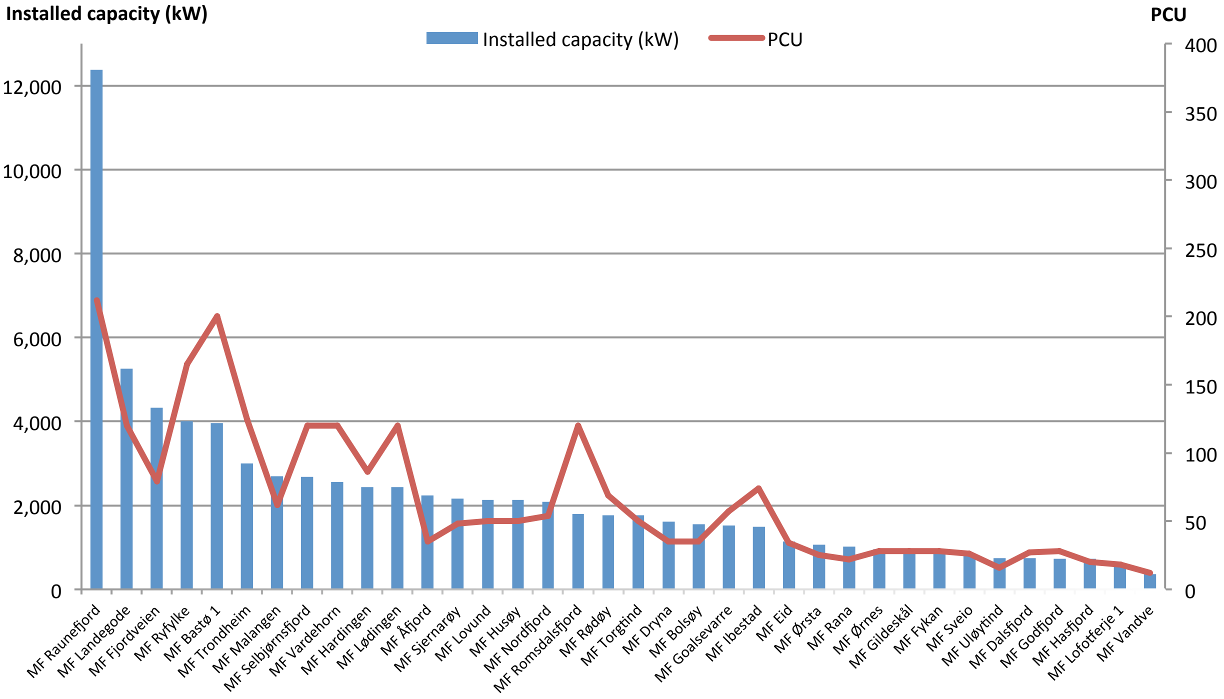

Figure 5.2: Installed capacity and PCU.

In some of the ferries, the installed capacity and PCU capacity seem to be less correlated. For instance in the ferries MF Ryfylke, MF Bastø I, MF Romsdalsfjord and MF Ibestad, the PCU capacity is relatively high in relation to installed capacity compared to the other routes. These ferries operate relatively short routes, around 13 km more or less, but with a significant amount of traffic.

5.3.2 Operating speed

The ferries also have different operating speeds. MF Uløytind operates at 12 knots, and MF Raunefjord at 21 knots. The average speed of the group is 13.5 knots. In the calculations, we use the speed the ferries are currently operating with. However, the speed only affects the estimated crossing time and indirectly the energy usage.

5.3.3 Age distribution

Generally, the ferries in Norway are relatively old. The lifetime of a ship varies with type, operation area, maintenance and the owners' willingness to replace it. Regulations for ship classification and approval are based on an expected lifetime of 25-30 years. However, there are older ferries than this in operation in Norway today. Figure 5.3 displays the age distribution of the relevant ferries. The average age is 16 years. The older ferries generally have higher installed capacity per PCU than the newer ferries.

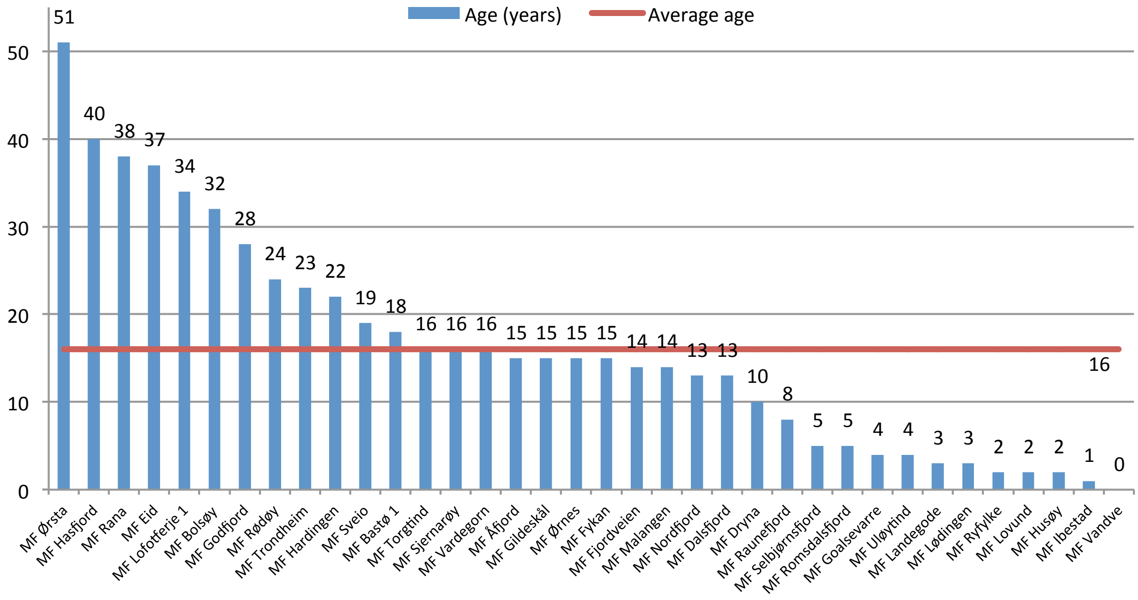

Figure 5.3: Age distribution of the relevant ferries.

5.4 Uncertainties in the data

It is difficult to find completely accurate data, as many of the ferry routes are complex. It would have been preferable to get data from one database, containing all the information about the routes and ferries. However, as this currently does not exist, we have been thorough when collecting the data to make it is as accurate as possible. We have also taken assumptions about certain parameters, which will make our results differ somewhat from the reality. A parameter with extra uncertainty is crossings per day as it might change depending on the season, which will affect the energy need for the route.

We have not considered exposure to harsh weather. Many of the ferries in Norway operate on the open sea and might use more energy on the route, or bad weather may force ferries to take detours. However, this is difficult to consider, as we do not know how often and where this occurs.

6. Model

The goal of the study is to determine under which conditions hydrogen could be an efficient fuel in the maritime sector. In this chapter, a description of the model employed will be presented, as well as a set of necessary assumptions that have been made throughout the calculations. Working with a predetermined group of ferry routes, we evaluate which are the most and least suitable for hydrogen, based on their characteristics. Using a generic model, we first estimate the energy consumption of every route. We then proceed to calculate the different costs related to LNG and hydrogen ferry operation. Lastly, combining this with the potential emissions reductions, we find the abatement costs related to transitioning from MGO to hydrogen or LNG.

6.1 Energy need

When reviewing the benefits and drawbacks of a new fuel source, it is important to base the calculations on the energy consumption. In order to estimate the various energy needs for the given routes, we applied the data described in the previous chapter to a dynamic model that responds to changes in speed, installed capacity and crossing distance.

6.1.1 Generic operation profile

In general, ferries have very similar navigating operation, regardless of size and location. They all use some sort of propulsion system, accelerating at the start of the journey and braking before entering port. What truly differentiates the ferries' operation is their engine size, speed, PCU capacity and how far they travel. In practice, each ferry may have slightly different operation from start to finish, but a general power output in each phase of navigation can be set to compare them through changes in other variables. A generic operation profile for car passenger ferries generates different navigation profiles based on different inputs. The variables which are used for input are mostly ferry characteristics gathered from research, as was shown in Table 5.1.

The generic operation profile used in this study is based on factors retrieved from the DNV GL report on electric ferries (DNV GL, 2015c). These factors are based on the all-electric ferry Ampere that, regardless of its advanced technology, still operates in a similar fashion as that of a traditional ferry. Some values remain unchanged throughout our entire calculations such as *time in port*, whereas others change for every route because they depend on factors like *overall distance*. There are six phases in the operation of a ferry from point A to point B, which we have called:

- *Maneuvering*: The ferry leaves port and gets into position to start accelerating
- *Acceleration*: Optimal motor output to reach service speed
- *Cruising*: Locks in a cruise at service speed
- *Retardation*: Shuts off most of its power and uses momentum before braking
- *Braking*: Increases output to steer into port
- *In port*: Motors stay on to keep the ferry in place and supply power onboard

The service speed changes from ferry to ferry due to its design, installed capacity and overall desired crossing time. The average speeds in the different phases of operation are all a function of the service speed. For example, if a ferry has a cruising speed of 12 knots, its average speed during acceleration and retardation would be 6 knots, 2 knots during maneuvering and 2.5 knots while braking. The calculations in this study assume that the different speeds change in the same manner in correlation with the service speed.

The power output is the percentage of overall motor capacity installed, often found in kW. These factors differ by operation phase, but remain constant throughout the study. In practice, ferries are operated at different power outputs for a given phase but the variations are not significant. When comparing various routes and ferries, it is crucial for the output percentages to remain constant in order to obtain consistent results.

The distance travelled in every phase is determined by time and speed. As illustrated in Table 6.1, the ferries travel most of the distance at service speed. Nevertheless, it was important to first calculate the distances travelled in the other phases so as to calculate an accurate energy need for the entire crossing.

	Maneuvering	**Acceleration**	**Crossing**	**Retardation**	**Braking**	**In Port**	**Moss-Horten example**	
Time in phase (s)	45	90	1406	185	90	300	30	*min*
Average speed (knots)	2.17	6.50	13	6.50	2.71	0	13	*service speed*
Power output (%)	75%	80%	42%	7%	56%	14%	3,960	*total output*
Distance travelled (m)	50	301	9,405	619	125	0	10,500	*m*
Energy consumption (kWh)	37.13	79.20	649.70	14.25	55.44	46.20	881.91	*kWh*

Table 6.1: Variables and constants in the generic operations profile. Values in red are constants.

The highlighted values in this table are held constant for all the calculations to come. The distance travelled in each phase is calculated with the speed and time values, except for the cruising distance, which is determined by the total distance minus the distance for all other phases. These values allow us to calculate the last variable, which is the duration of the cruising phase. The energy consumption formula is the simple multiplication of total output for the specific ferry, power output percentage and time elapsed. This unit of energy is expressed in kilowatt hours (kWh). In this example, we are displaying the Moss-Horten route with a service speed of 13 knots, installed capacity of 3,960 kW and overall distance of 10.5 km. The resulting energy consumption for this route is 881.91 kWh. It should be noted that this is a route containing only one crossing, meaning it only has two ports. As seen in Table 6.1, there is some energy consumption in port, and this must be accounted for when ferries have more than two ports. A five-minute port time is taken into account for every stop the ferries encounter, as several stops require more time in acceleration and braking than if we were to only look at the overall route distance. Figure 6.1 shows a graphical illustration of the variations in speed and motor output for the entire crossing of the ferry MF Bastø I from Moss to Horten.

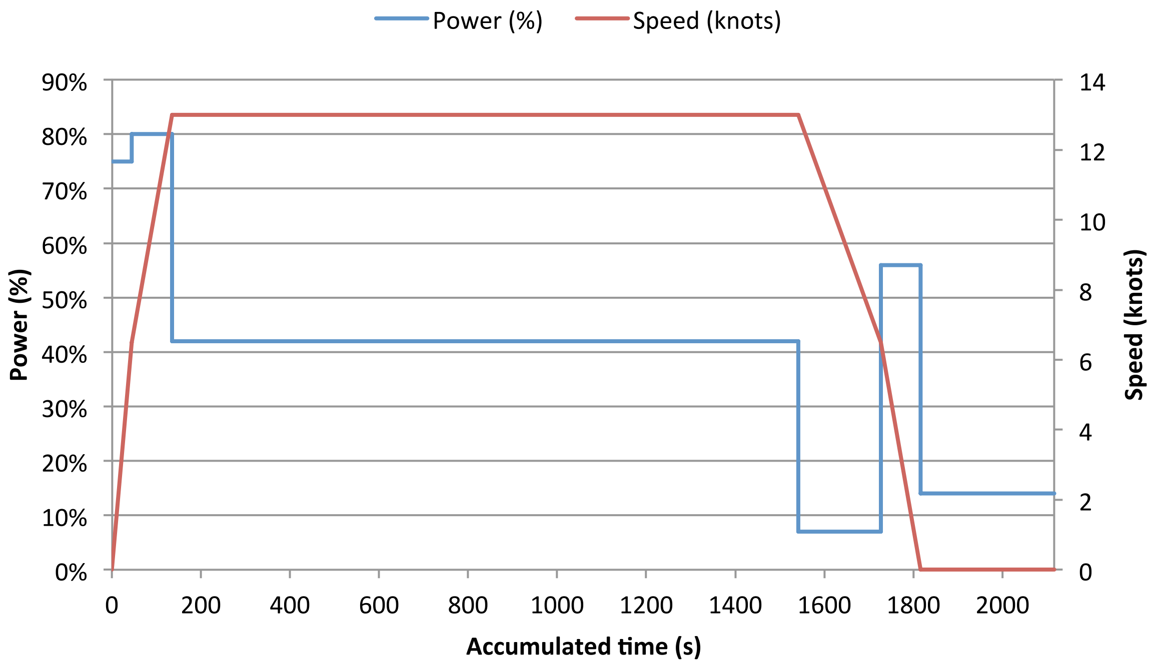

Figure 6.1: Generic operation profile, Moss-Horten.

The energy consumption per crossing is ultimately what is retrieved from this model and later combined with the number of crossings per day to calculate the overall daily energy consumption. To check the robustness of this model, we look at the well-documented Ampere route from Lavik to Oppedal (Fjellstrand, 2014). When we input 5.1 km, 900 kW and 11 knots in the model, we find a total energy consumption of 130.21 kWh. It has been publically stated that Ampere consumes around 150 kWh per crossing; this includes the energy consumed onboard to power the electrical equipment and appliances (Stensvold, 2015). We therefore conclude that the model gives a good approximation of the actual energy required to operate the ferry's engines.

6.1.2 Fossil fuel demand

The fossil fuel demand for the chosen route can be calculated per crossing, per day or as the total amount required to operate per year. As we mentioned earlier, we are looking at the two most common fuels, MGO and LNG. To translate consumed energy into fuel demand for the various ferries, we utilize the energy content in the fuels and the typical energy efficiency of the engines. Diesel and gas engines cannot use 100% of the energy contained in the fuel, as some of that energy is lost inside the combustion chamber and some outside of the system by heat dissipation and transmission losses. The following equation shows our approach to calculating the fuel demands, based on each route energy need:

$$\text{tFuel}/\text{year}_{\text{(tons)}} = \frac{\text{energy consumption}_{\text{(GWh/year)}}}{\text{energy content}_{\text{(kWh/kg)}} \times \text{engine efficiency}_{(\%)}} \times 10^3$$

Here, we use the following factors:

- MGO energy content = 11.861 kWh/kg
- Diesel engine efficiency = 40%
- LNG energy content = 15.417 kWh/kg
- Gas engine efficiency = 48%

So as to calculate the total amount of fuel required to operate the ferries for one year, we assume six working days per week with 52 weeks, as explained in chapter 5.2.2. For example, given that the route Moss-Horten consumes 89,956 kWh per day and thus 28.07

GWh per year, we find that it would need 5,915 tons of MGO every year.[10] The same calculations apply when it comes to the amount of LNG used, only using the relative factors for this fuel instead. It is important to estimate the annual energy consumption at this stage, as it will determine the annual fuel costs. The reason behind this is that fuel costs will later be used in conjunction with annual investment costs of the different propulsion systems.

6.1.3 Emissions reduction

Gradually implementing hydrogen technology into the Norwegian ferry fleet has one major benefit: that of reducing the emissions from the maritime sector. Depending on which fuel we substitute, CO_2 and NO_x emission would be reduced by different amounts.

Reduction in CO_2 was also estimated on a yearly basis by multiplying the amount of fuel used with its CO_2 combustion factor from Table 6.2: 3.2 $tCO_2/tMGO$ and 2.75 $tCO_2/tLNG$ (DNV, 2011).[11] We assume in this study that using hydrogen as fuel, does not emit CO_2, which is a reasonable assumption given the energy mix in Norway, having 99% of electricity originating from hydro power, if we disregard any effects on the net export of electricity.

The differences in NO_x reduction are even more pronounced, as LNG is a much cleaner fuel than MGO with regard to emitting NO_x. As we mentioned in chapter 2, the 2011 standards for ships (built after the year 2000) in the IMO tier II is 7.7 gNOx/kWh. Reducing NO_x emissions is a relevant factor for ferry operators as their projects can be partially funded by the NO_x fund. In this way, capital costs can be greatly reduced and turn the profitability of certain projects. To estimate the total amount of NO_x emissions per route we used the following formula:

$$ {}^{tNO_x}\!/_{year}\ {\scriptstyle (tons)} = \text{energy consumption}\ {\scriptstyle (GWh/year)} \times NO_x\ \text{fuel factor}\ {\scriptstyle (gNO_x/kWh)} $$

Where: 1 kWh = 7.7 gNO_x for MGO and 1.16 gNO_x for LNG given an 85% reduction in emissions.

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[10] 28.07 / (11.861x0.4) x 1000 = 5,915 tons MGO.

[11] 1 ton of MGO releases 3.2 tons of CO_2. LNG releases 2.75 tons.

6.2 Hydrogen implementation

Implementing hydrogen entails large investments in relatively new technology. In this section, the assumptions taken to simplify our calculations will be explained, as well as a description of the different components needed to power a hydrogen ferry.

6.2.1 Proton exchange membrane fuel cell requirements

As mentioned previously, running a PEMFC at its rated capacity without interruptions or variations will result in longer lifetime. We could install enough fuel cell stacks to provide the entire installed capacity output, however this would be inefficient and lead to increased investment costs. Using batteries when high output is required and charging them when in phases of low output results in better system synergy, and reduces the overall weight and cost of the system. This is very similar to the so-called hybrid solution we find in cars nowadays. In this fashion, the fuel cell stacks would constantly provide the energy required to navigate at service speed, in our case 42% of total output. Figure 6.2 shows a variation of the generic operation profile previously utilized, taking into account the PEMFC. The PEMFC operates at constant effect, managing 42% of the total power output, while the batteries supply the necessary power when the blue line is above the green line, meaning in *acceleration* and *braking*.

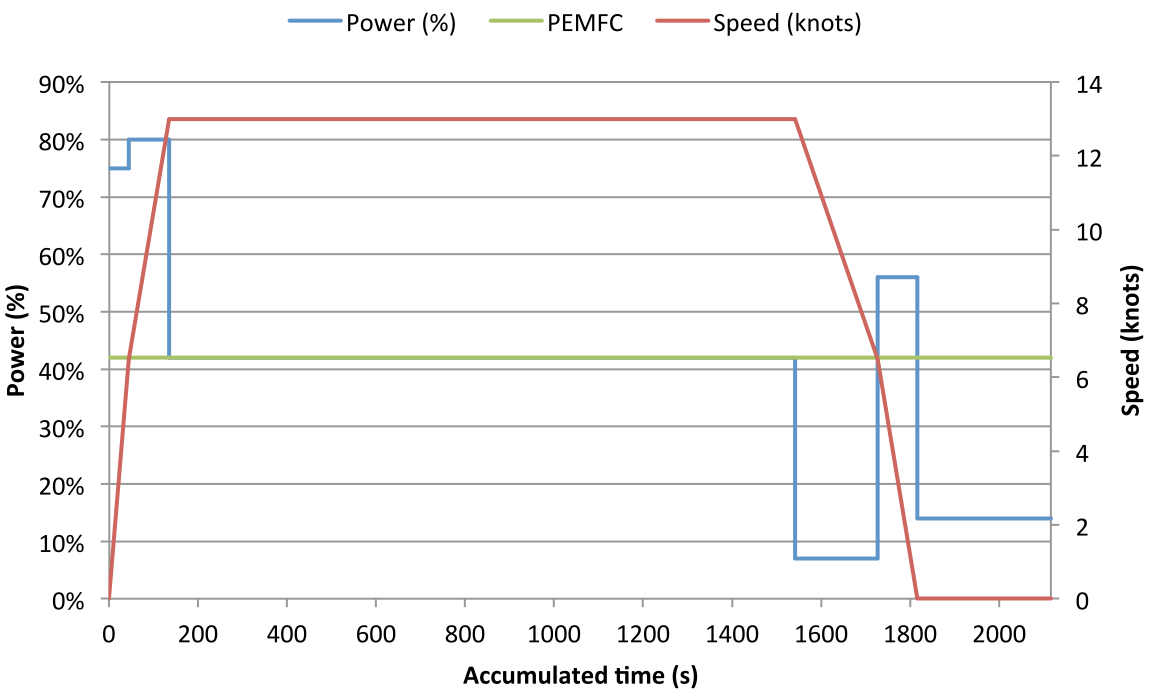

Figure 6.2: Generic operation profile with PEMFC.

One drawback of using hydrogen as fuel is that one needs more energy per crossing than if we were to use traditional fossil fuels. Figure 6.2 provides a good graphical illustration of this issue. The area under the green line, which is the energy used by the fuel cells, is greater than the area under the blue line, which is the energy a traditional engine would use. This is unavoidable and necessary, as batteries need more time in charging mode than in discharging mode. Our calculations show that the overall energy used by the relevant group of ferry is about 278 GWh/year. In contrast, the aggregation of all the fuel cells would amount to an energy need of 299 GWh/year, an increase of about 7.87%.

The model behind the operation profile, illustrated in Table 6.1, is also designed to estimate total navigation time (excluding port time of 5 minutes). The values in estimated time provided by the model show consistent results when compared to the real time found by the route tables available online. Using this, the known installed capacity and the number of crossings per day, we can determine how much energy the PEMFC systems would need. The following equation demonstrates our approach to calculating the PEMFC energy need[12]:

$$\text{FC energy}\big/\text{year}_{\ (\text{GWh})} = \frac{\frac{((\text{estimated time} + 5\text{min} \times \#\text{stops}) \times \text{yearly crossings})}{60\text{min}} \times \text{installed capacity}_{\ (\text{kW})} \times 42\%}{10^6}$$

To calculate the operating hours in a year, we add five minutes of port time to each crossing's estimated time with regard to how many stops the route includes, and thereafter divide by 60. Multiply this number by the PEMFC effect of 42% and the installed capacity on the ferry, the resulting value is the fuel cell's annual energy use expressed in kWh. It is divided by a factor of 10^6 in order to obtain a result in GWh.

6.2.2 Hydrogen usage

Once we have the total amount of energy need, we can translate this into the required hydrogen by using the energy content of hydrogen and an assumed fuel cell efficiency rate. As we discussed earlier, the energy content of hydrogen is 39.44 kWh/kg and the average efficiency of a PEMFC is currently about 50% (Bertuccioli et al., 2014). The Moss-Horten

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[12] The product of the time elapsed and the PEMFC capacity is the energy consumed expressed in kWh.

route's fuel cell stack would figuratively use 31.11 GWh/year, which is equivalent to about 1,578 metric tons of hydrogen.[13]

6.2.3 Battery requirements

The batteries installed on the ferries would provide the energy required during maneuvering, acceleration and braking. The fuel cells would charge the batteries during retardation and port time. During the cruising phase, there is no charge or discharge occurring, the PEMFC provide just enough to power the engines. As can be observed in Figure 6.2, the phases when the system is in power deficiency (blue line above the green line) account for a smaller area than when the system has power to spare (blue line below the green line). This means that the batteries have ample amount of time to charge and serve their purpose. In order to calculate energy need in these peaks, we looked at every route's energy use per crossing in the power deficient phases, and subtract the power provided by the fuel cell. The result is the power capacity of the battery pack needed for every ferry. We have taken into account the fact that the same ferry can be used for several routes and also that there are several ferries operating the same route. As an example, the Moss-Horten ferries Bastø I, II and III would each need a battery pack of 81.38 kWh.[14] This is a similar sized battery as that of the Tesla, which has a battery pack of 80 kWh.

6.2.4 Storage capacity

Storing hydrogen on ships is very similar to storing LNG. Depending on the pressure and temperature used, it is in fact safer than using natural gas as source for fuel. Most ships running on natural gas utilize the liquid format, which is more complex than using 350-bar tanks. PEMFC systems are usually accompanied by these types of tanks so as to remain safe without having the additional complexity involved with maintaining the gas in liquid form.

In our study, we have assumed that every ferry should have enough fuel onboard to satisfy the energy need of an entire day in operation. As storage costs for LNG are low, LNG ferries usually have several days' worth of fuel onboard. Hydrogen storage being such a costly investment, the ferries would have to be refueled at least once daily, but have the necessary capacity for an entire day's operation. The refueling time of hydrogen being relatively short, it is possible for operators to cut storage cost by having better logistics. However, we have

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[13] (31.11 x 1000) / (39.44 x 0.50) = 1,577.66 tH_2.

[14] We have used a 20% margin on the battery pack to ensure they have abundant power capacity.

made these assumptions so as to not underestimate the storage costs. With this in mind, the capacity of hydrogen storage onshore has been set to two times the onboard capacity. If and when a hydrogen market forms, more frequent transportation can be arranged, thus decreasing the need for capacity onshore. The tank capacity for every ferry has been calculated in m^3, which is a standard unit of measurement for pressurized tanks. Using the amount of hydrogen each ferry needs per day and the density of hydrogen at 350 bars, of 25 g/l, we used the following formula (Vehicle Projects LLC, 2007):

$$H_2 \text{ storage/day/ferry}_{\text{(tons)}} = tH_2\text{/day/ferry} \times 10^3 \times 25_{\text{(g/l)}}$$

Moss-Horten has a daily hydrogen consumption of 1.69 tons per ferry, which means each ferry would subsequently need tanks of about 67.42 m^3.[15] These results are comparable to the size of LNG tanks on other ferries, which currently host tanks of up to 250 m^3. The resulting onshore capacity required for Moss-Horten is 404.42 m^3.

6.3 Costs

Having established the energy consumption and technical requirements for the various routes, this section will focus on the costs related to the implementation of hydrogen on ferries. The variables and fixed costs will first be explained for all fuel types, followed by the calculations of the costs in regard to carbon emissions reduction.

6.3.1 Fuel costs

The reduction in fuel costs when moving towards a greener ferry fleet is one of the most important aspects of the overall picture. We estimate the total savings in fuel costs for every route using the amount of fossil fuel used. As discussed in chapter 2, MGO has a price of about 6.2 NOK/kg, while LNG is priced at 3.55 NOK/kg. The overall cost for Moss-Horten then amounts to 37 MNOK, given annual MGO consumption of 5,915 tons.

Hydrogen pricing is a big topic of debate nowadays, which makes it challenging to estimate the hydrogen variable costs. Although, hydrogen production costs are expected to drop significantly by 2030, we have applied a hydrogen price based on contemporary technology

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[15] (1.686 x 1,000) / 25 = 67.42 m^3.

and electricity prices, as seen in chapter 4. Under these assumptions, hydrogen is priced at 50 NOK/kg. The price might be higher, but as there is no established market for hydrogen today, we assume the hydrogen can be delivered at this price. As we mentioned previously, Moss-Horten uses about 1,578 tons of hydrogen in a year, resulting in a total cost of 78.9 MNOK. The net effect of introducing hydrogen as a fuel, when it comes to variable costs, is in all cases negative due to the high price of hydrogen.

6.3.2 PEMFC and LNG system costs

There are two major components in a PEMFC system: a stack of fuel cells and a battery pack. As we have concluded from part 3 of the paper, PEMFC stacks are the most suitable for application in ferries. With this in mind, the most commercially available fuel cell on the market at the moment has a size of 100 kW, which one can stack in order to have the desired installed capacity. An example of this type of PEMFC is the Ballard FCVelocity HD7. The projected costs for such a system are set at 1,300 EUR/kW, as discussed in chapter 3.5.2, and represent what is available in the Norwegian market today. An exchange rate of 9.0 NOK/EUR was used during the calculations, which has been the average rate so far in 2015. However, it is worth mentioning that the exchange rates have been very volatile this past year. Given Moss-Horten's installed capacity of 3,960 kW, we find an investment cost for the fuel cell stacks of about 70.5 MNOK.[16] The LNG motors for new ferries have an estimated cost for 13,000-26,000 NOK/kW (DNV, 2011). We have chosen the lowest estimate for calculating the LNG motors costs since we are comparing hydrogen to the alternative and do not want to overestimate the LNG investment costs.

Fortunately, the costs related to battery requirements in a PEMFC system are not as large as for all-electric ferries. As described in 6.2.3, the battery packs installed on each ferry are rather small. DNV GL (2015a) has estimated a cost of 16,000 NOK/kWh related to the batteries, including installation and maintenance. In the example of Moss-Horten, with a battery requirement of 81.38 kWh and a total of three ferries in operation, this route's investment in batteries amounts to 3.9 MNOK.[17]

The investment costs in pressurized hydrogen tanks are more straightforward as they are closely related to the well-known costs for storing other gases. A report by Hexagon Lincoln

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[16] 3,960 x 42% x 1,570 x 9.0 (EUR/NOK) = 70,503,048 NOK.

[17] 81.38 x 16,000 x 3 = 3,906,144 NOK.

(2015) stated that storing hydrogen at 350 bars costs about 500 USD/kg of stored hydrogen. An exchange rate of 8.0 NOK/USD was used during the calculations, which has been the average rate in 2015. Again, this rate has also been very volatile recently. Given Moss-Horten's daily hydrogen usage, the total investment in hydrogen onboard tanks for the route is of 20 MNOK.[18] LNG tanks are much more affordable at 3,000 USD/m^3 (GL group, 2013). Given the density of LNG of 456 kg/m^3, this results in a storage cost of about 7 USD/kg (U.S. Department of Energy, 2005).[19]

6.3.3 Abatement cost

Abatement costs are defined as costs related to the removal of unwanted nuisances in businesses. In our case, we are looking at abatement cost as the sum of all costs related to the implementation of hydrogen in the Norwegian ferry fleet per unit of CO_2 removed. The lifetime of PEMFC systems (fuel cell stacks and batteries) is approximately 10 years with today's technology. The discount rate used may vary depending on the project's lifetime and risk, but is by default set to 4% according to the Norwegian Ministry of Finance report R-109/2014 (Ministry of Finance, 2014). The equivalent annual cost (EAC) formula was used to calculate the amount of yearly fixed investment costs, which are part of the equation for the abatement cost calculation (Investopedia, 2015).

$$\text{EAC} = \frac{\text{Asset Price} \times \text{Discount Rate}}{1 - (1 + \text{Discount Rate})^{-\,\#\text{periods}}}$$

The investment is discounted over the period of 10 years with a 4% discount rate, resulting in an annual cost the operator incurs to payback the investment. The investment costs for the implementation of hydrogen in the Moss-Horten route sum up to about 135 MNOK.[20] The resulting EAC for such an investment is of 16.7 MNOK.[21] Calculating the overall annual cost divided by the CO_2 reduced for each of the routes in this study allows us to compare the various projects without looking at financial profitability as the only measurement. The abatement cost (AC) formula used in our calculation is as follows (NVE, 2010):

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[18] 1.686 x 1,000 x 500 x 8 (USD/NOK) = 20,226,422 NOK.

[19] 3,000 / 456 (LNG density in kg/m^3) = 6.58 \$/kg.

[20] 20,226,422 (tank onboard) + 70,503,048 (PEMFC) + 40,452,843 (tank onshore) + 3,906,144 (batteries) = 135,088,457 NOK.

[21] 135,088,457 x (0.04 / (1 - (1.04^{-10})) = 16,655,183 NOK.

$$\text{AC}_{\ (\text{NOK/tCO}_2)} = \frac{\text{EAC+ H}_2 \text{ cost/year} - \text{Fossil Fuel cost/year}}{\text{tCO}_2/\text{year}}$$

The abatement cost is simply the sum of the annual costs related to the implementation of hydrogen divided by the total amount of CO_2 reduced. The annual costs are defined as the sum of the annual investments and the hydrogen fuel costs minus the fuel costs of the original fuel. Using this formula we find that the abatement cost for Moss-Horten is 3,109 NOK/tCO_2.[22] To put this into perspective, theoretically, if the CO_2 price was as high as this figure, the implementation of hydrogen on this specific route would come at no extra cost. To calculate the additional abatement cost for reducing to remain CO_2 emissions from LNG to hydrogen, we use an incremental abatement cost formula (IAC). This takes into account investment costs for both technologies.

$$\text{IAC}_{\ (\text{NOK/tCO}_2)} = \frac{\text{EAC}(\text{H}_2) - \text{EAC}(\text{LNG}) + \text{H}_2 \text{ cost/year} - \text{Fossil Fuel cost/year}}{\text{tCO}_2/\text{year}_{\ (\text{LNG to H}_2)}}$$

In this variation of the abatement cost formula, the fuel costs calculations remain identical, while the investment part of the formula only accounts for the additional cost hydrogen represents. This is then divided by the CO_2 emissions remaining for going from LNG to hydrogen. Table 6.2 is a brief overview of the factors and assumptions utilized in this study for further reference.

	Calorific value (MJ/kg)	**Energy content (kWh/kg)**	**Engine efficiency**	**CO_2 factor (tCO_2/tFuel)**	**NO_x factor (gNO_x/kWh)**	**Price (NOK/kg)**	**Price (NOK/kWh)**	**Engine/PEMFC cost (NOK/kW)**	**Storage cost (USD/kg)**
MGO	42.70	11.86	40%	3.20	7.70	6.20	0.52	-	-
LNG	55.50	15.42	48%	2.75	1.16	3.55	0.23	13,000	7.00
Hydrogen	142.00	39.44	50%	0.00	0.00	50.00	1.27	11,700	500.00

Table 6.2: Model factors and assumptions. [23]

Based on the factors and assumptions provided in this chapter, hydrogen seems to have some positive attributes despite being rather expensive. Nevertheless, this new technology has to be comparable to the current standards for ferry propulsion if hydrogen is to be deemed an efficient fuel. In the next chapter, the generic operation profile and formulas presented above will be the basis for all the calculations, which will in turn justify or discourage the use of hydrogen on the various routes.

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[22] (16,655,183 (EAC) + 78,883,045 (H_2) – 36,676,309 (MGO)) / 18,929.17 = 3,109.50 NOK/tCO_2.

[23] Exchange rates: 8.0 NOK/USD and 9.0 NOK/EUR. Battery costs in the fuel cell system of 16,000 NOK/kWh are not included in the table.

7. Results

In this chapter we will present our main results. First, we provide an overview over the results found using the model presented in chapter 6 regarding energy need, and the related fuel consumption and CO_2 emissions. We focus our reflections on the results of hydrogen, but use LNG as an alternative for comparison. We go on to discuss fuel cost, investment costs and CO_2 emissions on the different routes. Thereafter, we present the abatement costs for each route related to three options: switching from MGO to hydrogen, MGO to LNG, and the incremental cost of reducing additional emissions by going from LNG to hydrogen. We compare our results to relevant costs put on CO_2 emissions. Finally, we present a sensitivity analysis regarding changes in hydrogen and fuel cell prices.

7.1 Main findings

The results shown in Table 7.1 are based on the idea that hydrogen ferries would replace the ferries operating the route today, maintaining the same installed capacity and traffic. The first part of the table shows the energy need, fuel consumption and possible CO_2 emissions for the conventional fuels, MGO and LNG, while the last part of the table shows the potential energy need using fuel cell technology and the respective hydrogen consumption.

The first column in Table 7.1 displays the annual energy need of the conventional ferries for each route, based on the operating profile shown in chapter 6.1.1. The energy need is the basis for how much fuel is needed to operate the route for one year. Consequently, the following columns show the annual fuel consumption of MGO and LNG in tons, based on the annual energy need, the energy content of the respective fuels, and the efficiency of the respective engines, as explained in chapter 6.1.2. Six of the relevant routes are today operated by LNG fueled ferries; these routes are marked by ** in the table and the results based on LNG factors are marked with *. Diesel ferries fueled by MGO operate the rest of the routes.[24] However, we have also included the potential fuel consumption for LNG on the routes that are currently fueled by MGO. Even though the Norwegian Parliament has

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[24] We assume all diesel fueled ferries to be fueled by MGO because this is the most common type of diesel used on ferries today. In addition, it has lower emissions compared to other diesel types, which makes for a conservative estimate.

established that pure LNG ferries should not be considered a low-emission alternative for new ferry tenders, it is today the most realistic alternative to hydrogen as a substitute for diesel on the longer ferry routes (Committee on Energy and the Environment, 2015). The CO_2 emissions displayed in column four are the estimated emissions from the ferries operating the routes today, given the CO_2 factors shown in Table 6.2, and consequently show the potential amount of emissions that could be reduced by implementing hydrogen ferries. The last two columns display the energy need in GWh based on the operating profile using PEMFC technology shown in chapter 6.2, and the hydrogen consumption given the energy need, the energy content of hydrogen and the fuel cell efficiency.

Route	Energy/year (GWh)	Annual fuel consumption (tMGO)	Annual fuel consumption (tLNG)	Annual CO_2 emissions (tCO_2)	Annual NO_x emissions (tNO_x)	Energy/year fuel cell (GWh)	Annual fuel consumption (tH_2)
Rysjedalsvika-Rutledal-Krakhella	5.03	1,060	680	3,392	39	5.59	284
Askvoll-Fure-Værlandet	2.88	606	389	1,940	22	3.15	160
Smørhamn-Kjelkenes	1.08	227	146	728	8	1.18	60
Horn-Igerøy	1.94	409	262	1,310	15	2.10	107
Igerøy-Tjøtta	0.99	209	134	668	8	1.04	53
Tjøtta-Forvik	1.18	249	160	798	9	1.26	64
Stokkvågen-Onøy-Sleneset-Lovund	8.09	1,705	1,093	5,455	62	8.76	444
Træna-Onøy-Stokkvågen	2.42	511	327	1,634	19	2.55	129
Mosjøen-Hundåla-Dagsvik	1.25	263	169	843	10	1.34	68
Solfjellsjøen-Vandve	0.35	74	48	238	3	0.38	19
Bodø-Værøy-Røst-Værøy-Moskenes**	39.21	-	5,299	14,573*	45*	40.40	2,049
Bognes-Lødingen**	6.74	-	910	2,504*	8*	7.14	362
Kjøpsvik-Drag	4.26	899	576	2,876	33	4.61	234
Jektvik-Kilboghamn	1.87	395	253	1,264	14	2.01	102
Rødøybassenget	1.26	265	170	849	10	1.40	71
Sund-Horsdal-Sørarnøy	0.95	201	129	642	7	1.09	55
Ørnes-Vassdalsvik-Meløysund-Bolga	2.20	463	297	1,482	17	2.41	122
Digermulen-Hanøy/Finnvik	0.33	70	45	224	3	0.39	20
Hanøy-Kalfjord	0.07	15	10	49	1	0.08	4
Lyngseidet-Olderdalen	2.08	438	281	1,400	16	2.28	116
Sørrollnes-Stangnes	2.53	534	342	1,708	19	2.74	139
Hansnes-Karlsøy-Vannøy-Hansnes	5.33	1,123	720	3,593	41	5.96	302
Rotsund-Havnnes-Klauvnes	0.65	137	88	437	5	0.74	37
Sør-Tverrfjord-Bergsfjord-Øksfjord	0.74	157	100	501	6	0.79	40
Øksfjord-Tverrfjord	0.27	57	36	181	2	0.34	17
Øksfjord-Hasvik	2.38	502	322	1,607	18	2.48	126
Stavanger-Tau**	19.52	-	2,637	7,253*	23*	21.45	1,088
Fogn-Jelsa	9.00	1,896	1,216	6,069	69	11.09	563
Mekjarvik-Kvitsøy	7.32	1,543	989	4,937	56	7.97	404
Våge-Halhjem**	5.60	-	756	2,080*	6*	6.12	311
Hufthamar-Krokeide	10.17	2,144	1,375	6,860	78	11.03	559
Ranavik-Skjersholmane	8.92	1,880	1,205	6,016	69	9.76	495
Utbjoa-Sydnes-Fjelbergøy-Borgundøy	1.36	287	184	920	10	1.63	83
Sandvikvåg-Halhjem**	74.05	-	10,007	27,519*	86*	80.59	4,086
Brattvåg-Dryna-Fjørtofta-Harøya	5.06	1,067	684	3,415	39	5.78	293
Geiranger-Hellesylt	2.99	629	403	2,014	23	3.17	161
Molde-Sekken	1.47	310	199	993	11	1.60	81
Molde-Vestnes**	6.08	-	821	2,259*	7*	6.69	339
Moss-Horten	28.07	5,916	3,793	18,930	216	31.11	1,578
Total	***275.70***	***46,673***	***33,463***	***140,160***	***1,133***	***300.25***	***15,224***

** Routes operated by LNG-fueled ferry

* Calculated with LNG factors

Table 7.1: Annual fuel consumption and emissions from each route.

As seen from Table 7.1, there are big variations within the routes in terms of hydrogen consumption and possible savings in CO_2 emissions by substituting hydrogen with MGO or LNG. The variations are due to differences in length, traffic, fuel type, installed capacity and number of ferries operating the route. From Table 7.1 we see that when considering the fuel used on the routes today, there is a potential to reduce 140,160 tons of CO_2 and 1,133 tons of NO_x. This means 13% less CO_2 emissions and 7% less NO_x emissions compared to the emissions from passenger boats we saw in chapter 2. The reduction is equivalent to replacing over 60,000 conventional cars with electric or fuel cell vehicles.[25]

7.2 Fuel consumption and cost

Hydrogen consumption is directly related to the energy required to operate the route, the energy content of hydrogen and the fuel cell efficiency. It also depends on how much daily traffic there is on the route. As the total fuel cost depends on how much hydrogen is consumed, these factors will also affect the fuel cost on each route, and we will thus focus on hydrogen consumption before comparing fuel costs to the different alternatives.

7.2.1 Fuel efficiency

By looking at the fuel efficiency of each route we get a more comparable picture of how much fuel the different routes need than by just looking at the total fuel consumption. By fuel efficiency, we mean how much fuel is needed to transport one PCU one kilometer. In Figure 7.1, the routes are arranged by the amount of hydrogen consumed per km per PCU. For reference, we also include the total hydrogen consumption on the right axis.

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[25] Calculation is based on cars driving on average 13,500 km a year and an emission factor of 0.17 kgCO_2 /km.

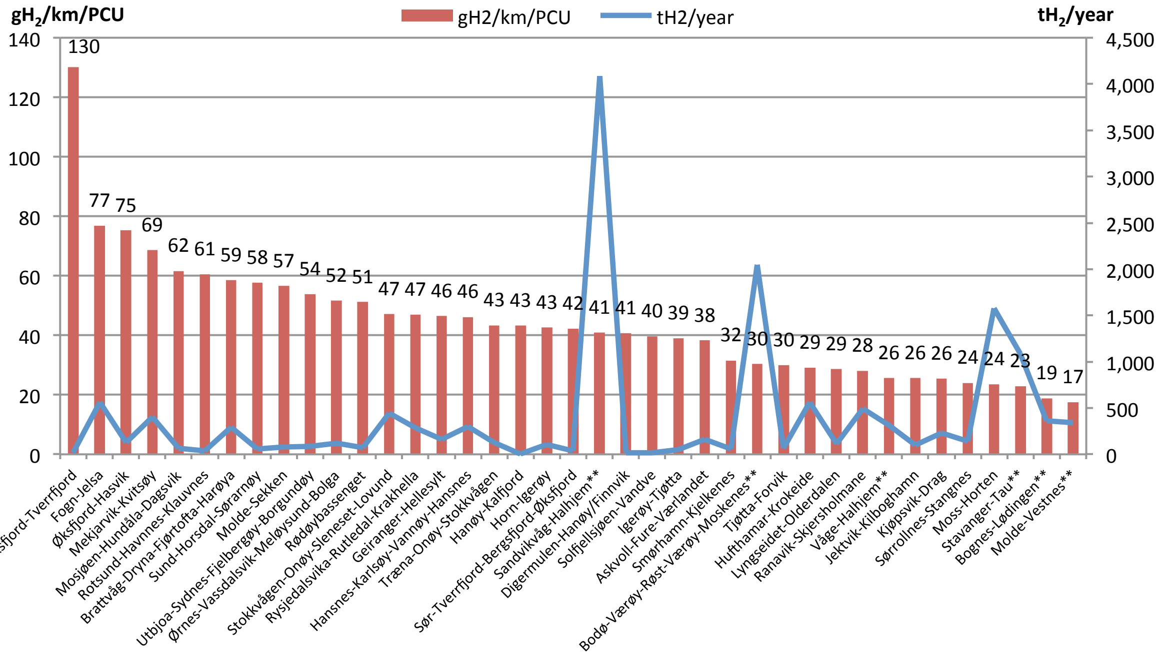

Figure 7.1: Fuel efficiency and total fuel consumption.

The fuel efficiency depends on the length of the route and the PCU capacity of the ferries. The routes with low fuel efficiency are generally the routes with low PCU capacity, few crossings per day and relatively short trajectories. The routes with higher fuel efficiency are generally the routes with high PCU capacity and many crossings per day. However, it seems that the fuel efficiency depends more on PCU capacity than length and traffic of the route.

As seen in Figure 7.1, Molde-Vestnes consumes only 17 $gH_2/km/PCU$ and is the most fuel-efficient route; as a comparison, a FCEV consumes 10 gH_2/km. In contrast, the route Øksfjord-Tverrfjord consumes 130 $gH_2/km/PCU$, or 13 times what a FCEV would use on the same distance. The fuel efficiency on this route is very low due to the fact that it is a very short route, only three kilometers, operated by MF Åfjord, with a capacity of 35 PCU that only has four crossings per day. Even though Øksfjord-Tverrfjord has very low total fuel consumption, it uses a lot more fuel to transport one PCU per kilometer than the other ferries.

Molde-Vestnes, on the other hand, has three ferries with a capacity of 120 PCU, and does in total 45 crossings per day. However, the route itself is also relatively short at only 11.5 km. In fact, the route Mosjøen-Hundåla-Dagsvik, located to the left in Figure 7.1, uses 40% less hydrogen per km than Molde-Vestnes, but because Mosjøen-Hundåla-Dagvisk has a PCU capacity of only 22 it ends up consuming a lot more hydrogen per km per PCU than Molde-Vestnes. The peaks in total hydrogen consumption are related to routes with high installed capacity, longer trajectories or many crossings per day, and have more than one ferry operating.

As fuel costs are directly related to hydrogen consumption, the graph above also compares the fuel costs for the different routes. Nevertheless, below we compare the fuel cost of hydrogen to that of MGO and LNG.

7.2.2 Fuel cost comparison

Hydrogen has a higher fuel cost than both MGO and LNG. The fuel cost per kg being 50, 6.2, and 3.55 NOK/kg for hydrogen, MGO and LNG, respectively. However, this is a bit misleading as hydrogen has a much higher energy content than both MGO and LNG. Consequently, even though the price is higher the amount of fuel needed in tons would be lower, given the same energy need (see Table 7.1). It is therefore more interesting to compare the price in terms of energy content. The resulting prices in NOK/kWh are 1.27, 0.52 and 0.23 for hydrogen, MGO and LNG, respectively. Hydrogen is still more expensive, but this approach gives a more realistic price comparison. In Table 7.2, the total fuel costs for the different routes are shown in million NOK.

Route	Annual MGO fuel cost (MNOK)	Annual LNG fuel cost (MNOK)	Annual H_2 fuel cost (MNOK)	Route	Annual MGO fuel cost (MNOK)	Annual LNG fuel cost (MNOK)	Annual H_2 fuel cost (MNOK)
Rysjedalsvika-Rutledal-Krakhella	6.57	2.41	14.18	Sørrollnes-Stangnes	3.31	1.21	6.93
Askvoll-Fure-Værlandet	3.76	1.38	7.99	Hansnes-Karlsøy-Vannøy-Hansnes	6.96	2.55	15.10
Smørhamn-Kjelkenes	1.41	0.52	2.99	Rotsund-Havnnes-Klauvnes	0.85	0.31	1.87
Horn-Igerøy	2.54	0.93	5.33	Sør-Tverrfjord-Bergsfjord-Øksfjord	0.97	0.36	2.00
Igerøy-Tjøtta	1.29	0.47	2.64	Øksfjord-Tverrfjord	0.35	0.13	0.85
Tjøtta-Forvik	1.55	0.57	3.20	Øksfjord-Hasvik	3.11	1.14	6.30
Stokkvågen-Onøy-Sleneset-Lovund	10.57	3.88	22.21	Stavanger-Tau**	-	9.35	54.38
Træna-Onøy-Stokkvågen	3.17	1.16	6.47	Fogn-Jelsa	11.76	4.31	28.13
Mosjøen-Hundåla-Dagsvik	1.63	0.60	3.40	Mekjarvik-Kvitsøy	9.57	3.51	20.21
Solfjellsjøen-Vandve	0.46	0.17	0.97	Våge-Halhjem**	-	2.68	15.53
Bodø-Værøy-Røst-Værøy-Moskenes**	-	18.79	102.43	Hufthamar-Krokeide	13.29	4.87	27.97
Bognes-Lødingen**	-	3.23	18.10	Ranavik-Skjersholmane	11.66	4.27	24.75
Kjøpsvik-Drag	5.57	2.04	11.69	Utbjoa-Sydnes-Fjelbergøy-Borgundøy	1.78	0.65	4.13
Jektvik-Kilboghamn	2.45	0.90	5.09	Sandvikvåg-Halhjem**	-	35.48	204.32
Rødøybassenget	1.65	0.60	3.54	Brattvåg-Dryna-Fjørtofta-Harøya	6.62	2.43	14.66
Sund-Horsdal-Sørarnøy	1.24	0.46	2.77	Geiranger-Hellesylt	3.90	1.43	8.04
Ørnes-Vassdalsvik-Meløysund-Bolga	2.87	1.05	6.12	Molde-Sekken	1.92	0.71	4.06
Digermulen-Hanøy/Finnvik	0.43	0.16	1.00	Molde-Vestnes**	-	2.91	16.96
Hanøy-Kalfjord	0.09	0.03	0.21	Moss-Horten	36.68	13.45	78.88
Lyngseidet-Olderdalen	2.71	0.99	5.79	***Total***	***162.70***	***132.10***	***761.19***

Table 7.2: Total MGO, LNG and hydrogen fuel costs.

The extra cost of hydrogen is 0.75 and 1.04 NOK/kWh compared to MGO and LNG, respectively. LNG is cheaper than both MGO and hydrogen, and if we were to consider LNG as a low-emission option for the routes, it would actually save 0.29 NOK/kWh in fuel cost by switching from MGO to LNG. Choosing hydrogen instead would cost 1.04 NOK/kWh as you would miss out on the fuel cost savings you could have achieved from using LNG. Figure 7.2 below gives an overview of the extra fuel cost of hydrogen with respect to MGO and LNG, and the fuel cost savings by switching from MGO to LNG.

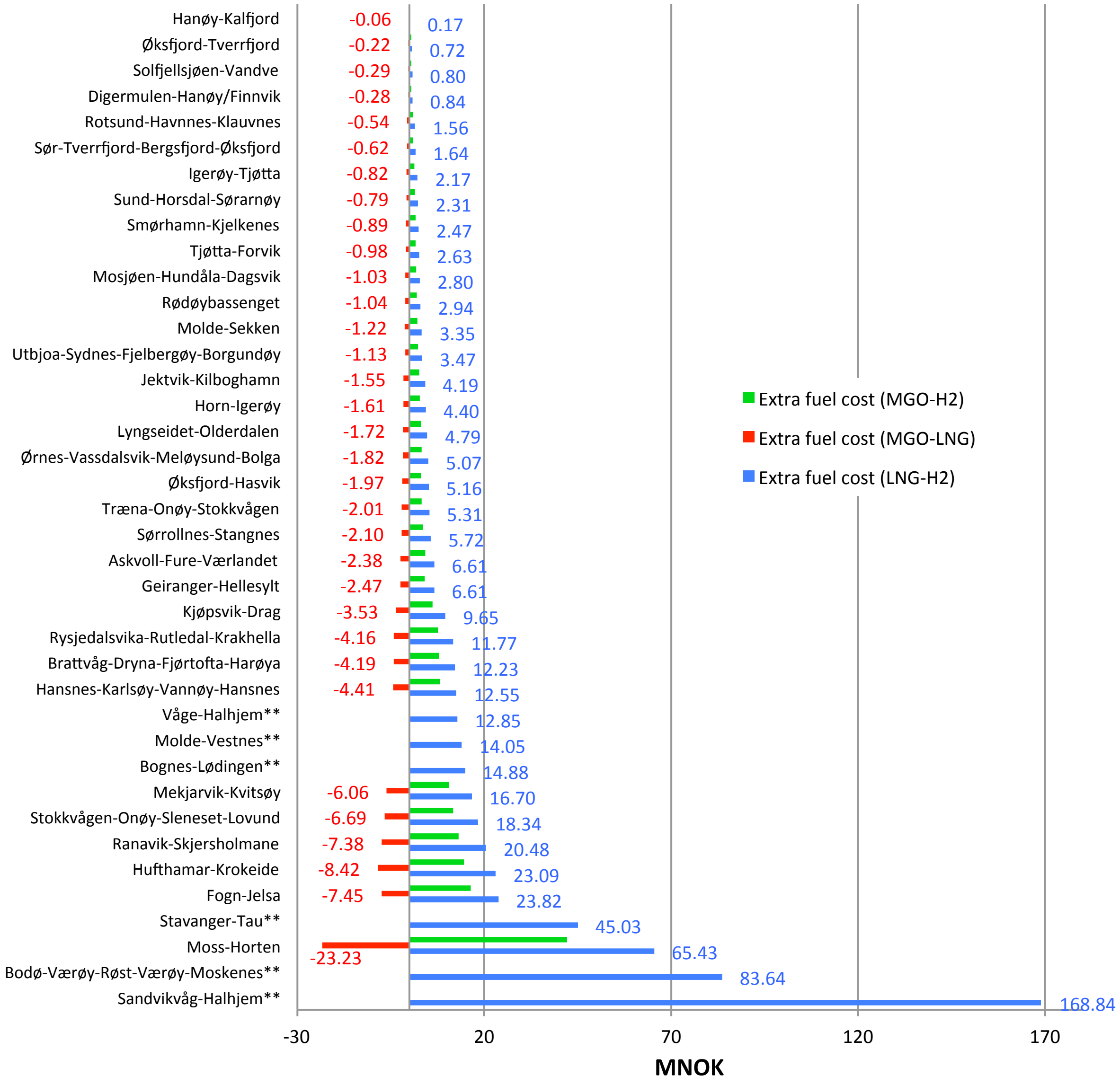

Figure 7.2: Comparison of extra fuel cost in million NOK.

The extra cost of switching from MGO to hydrogen, illustrated by the green bar, equals the extra cost of switching from LNG to hydrogen, the blue bar, plus the savings you get from switching from MGO to LNG, the red bar.

7.3 Investment costs: Ferry

In this study, we assume that the investments required for the implementation of low- and zero-emission ferries are only related to the extra costs of installing LNG or hydrogen in new ferries. In this way, the investment costs account only for the different components needed to power a traditional ferry. The actual cost of the ship is not included as we assume it would be the same regardless of the machinery used to power it.

7.3.1 Hydrogen propulsion system

There are three main cost drivers if we were to use hydrogen as fuel on a ferry: batteries, PEMFCs and onboard tanks. Figure 7.3 shows the average share each cost represents for the total investment in the ferries.

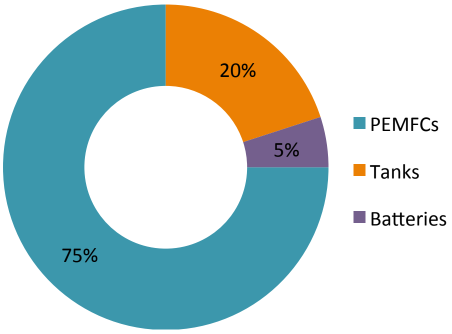

Figure 7.3: Share of investment costs, hydrogen ferry.

As seen in Figure 7.3, the fuel cell stacks account for 75% of the overall extra investment in the ferry, while tanks and batteries represent 20% and 5%, respectively. The results for the various costs associated to each route will be displayed in Table 7.3, in section 7.3.3.

7.3.2 LNG propulsion system

In comparison, investing in an LNG propulsion system requires only two components: gas powered engines and LNG tanks. The LNG tank costs are only a fraction of the costs for the LNG motors, which is understandable given the low price of LNG storage in conjunction to the relatively high price of new gas engines. Our calculations show that the tank costs are only 0.2% of the total investment for LNG ferries. On the other hand, the LNG motors account for 99.8% of the investments.

7.3.3 Cost comparison and Equivalent Annual Cost (EAC)

As we have mentioned, the investments related to using hydrogen or LNG on the various routes have different cost drivers. Table 7.3 gives an overview of all the onboard investment costs for hydrogen and LNG for all the routes based on the costs found in Table 6.2. The first part of the table shows the investment costs for a hydrogen ferry, including batteries, PEMFCs and storage tanks. The investment in batteries is based on the battery requirements explained in section 6.2.3, the investment in PEMFC is based on 42% of the installed capacity of the ferries as explained in section 6.2.1, while the tank storage costs depend on the fuel consumption per day per ferry and the density of hydrogen as explained in section 6.2.4. The investment cost in LNG engines is based on installed capacity on the ferries, and the investments in storage tanks are based on the fuel consumption and density of LNG, as explained in section 6.3.2. We also display the total investment costs and the EACs for both technologies, showing the overall annual investment costs based on a lifetime of 10 years.

Route	Investment cost hydrogen ferry					Investment cost LNG ferry			
	Batteries (MNOK)	PEMFCs (MNOK)	Tanks (MNOK)	Total investment (MNOK)	Equivalent Annual Cost (MNOK)	LNG engines (MNOK)	Tanks (MNOK)	Total investment (MNOK)	Equivalent Annual Cost (MNOK)
Rysjedalsvika-Rutledal-Krakhella	0.68	10.22	3.64	14.54	1.79	27.04	0.115	27.15	3.35
Askvoll-Fure-Værlandet	0.75	11.14	2.05	13.94	1.72	29.48	0.033	29.52	3.64
Smørhamn-Kjelkenes	0.25	3.66	0.77	4.68	0.58	9.69	0.025	9.72	1.20
Horn-Igerøy	0.58	8.65	2.04	11.27	1.39	22.88	0.067	22.95	2.83
Igerøy-Tjøtta	-	-	-	-	-	-	-	-	-
Tjøtta-Forvik	0.24	3.61	0.82	4.67	0.58	9.56	0.027	9.58	1.18
Stokkvågen-Onøy-Sleneset-Lovund	1.40	20.89	5.70	27.98	3.45	55.26	0.092	55.35	6.82
Træna-Onøy-Stokkvågen	0.70	10.44	1.66	12.80	1.58	27.63	0.055	27.68	3.41
Mosjøen-Hundåla-Dagsvik	0.33	4.97	0.87	6.17	0.76	13.14	0.028	13.17	1.62
Solfjellsjøen-Vandve	0.12	1.81	0.25	2.18	0.27	4.78	0.008	4.79	0.59
Bodø-Værøy-Røst-Værøy-Moskenes**	5.18	77.40	26.26	108.84	13.42	Already LNG			
Bognes-Lødingen**	1.60	23.88	4.64	30.12	3.71	Already LNG			
Kjøpsvik-Drag	0.84	12.58	3.00	16.42	2.02	33.28	0.097	33.38	4.12
Jektvik-Kilboghamn	0.58	8.70	1.31	10.59	1.31	23.02	0.043	23.07	2.84
Rødøybassenget	0.30	4.52	0.91	5.73	0.71	11.96	0.029	11.99	1.48
Sund-Horsdal-Sørarnøy	0.61	9.14	0.71	10.46	1.29	24.18	0.011	24.19	2.98
Ørnes-Vassdalsvik-Meløysund-Bolga	0.32	4.72	1.57	6.60	0.81	12.48	0.050	12.53	1.54
Digermulen-Hanøy/Finnvik	0.19	2.86	0.31	3.36	0.41	7.56	0.009	7.57	0.93
Hanøy-Kalfjord	-	-	-	-	-	-	-	-	-
Lyngseidet-Olderdalen	0.50	7.46	1.48	9.44	1.16	19.73	0.047	19.77	2.44
Sørrollnes-Stangnes	0.49	7.33	1.78	9.60	1.18	19.40	0.058	19.45	2.40
Hansnes-Karlsøy-Vannøy-Hansnes	0.89	13.23	3.87	17.99	2.22	35.00	0.121	35.12	4.33
Rotsund-Havnnes-Klauvnes	0.25	3.68	0.48	4.41	0.54	9.74	0.015	9.75	1.20
Sør-Tverrfjord-Bergsfjord-Øksfjord	0.24	3.58	0.51	4.33	0.53	9.46	0.017	9.48	1.17
Øksfjord-Tverrfjord	0.74	11.00	1.83	13.57	1.67	29.09	0.060	29.15	3.59
Øksfjord-Hasvik	-	-	-	-	-	-	-	-	-
Stavanger-Tau**	3.95	58.97	13.94	76.86	9.48	Already LNG			
Fogn-Jelsa	1.42	21.23	7.21	29.86	3.68	56.16	0.103	56.26	6.94
Mekjarvik-Kvitsøy	1.42	21.23	5.18	27.83	3.43	56.16	0.167	56.33	6.94
Våge-Halhjem**	0.88	13.20	3.98	18.06	2.23	Already LNG			
Hufthamar-Krokeide	0.99	14.74	7.17	22.90	2.82	39.00	0.232	39.23	4.84
Ranavik-Skjersholmane	1.60	23.90	6.35	31.85	3.93	63.22	0.102	63.33	7.81
Utbjoa-Sydnes-Fjelbergøy-Borgundøy	0.27	4.10	1.06	5.44	0.67	10.86	0.031	10.89	1.34
Sandvikvåg-Halhjem**	12.21	182.51	52.39	247.11	30.47	Already LNG			
Brattvåg-Dryna-Fjørtofta-Harøya	1.06	15.88	3.76	20.70	2.55	42.02	0.058	42.07	5.19
Geiranger-Hellesylt	1.02	15.17	2.06	18.25	2.25	40.14	0.034	40.18	4.95
Molde-Sekken	0.35	5.24	1.04	6.63	0.82	13.86	0.034	13.89	1.71
Molde-Vestnes**	1.78	26.54	4.35	32.66	4.03	Already LNG			
Moss-Horten	3.91	58.38	20.23	82.51	10.17	154.44	0.213	154.65	19.07
Total	***48.61***	***726.55***	***195.18***	***970.34***		***910.22***	***1.98***	***912.20***	

Table 7.3: Overview of onboard investments, hydrogen and LNG.

Although the fuel costs for hydrogen are considerably larger than those for LNG, the onboard investments costs are less if we implement hydrogen compared to LNG. The EACs displayed in Table 7.3 will be used in the calculation of the abatement cost in part 7.6.

7.4 Investment costs: Onshore storage tanks

The onshore investments for hydrogen are substantially larger than for LNG. Small scale LNG storage can be achieved with cheap materials, whereas hydrogen storage requires high-grade pressurized tanks. In Table 7.4 we present the overall onshore investment for the routes, which will also later be used to calculate the abatement costs.

Route	H_2 Onshore tank		LNG Onshore tank		Route	H_2 Onshore tank		LNG Onshore tank	
	Tanks onshore (MNOK)	EAC (MNOK)	Tanks onshore (MNOK)	EAC (MNOK)		Tanks onshore (MNOK)	EAC (MNOK)	Tanks onshore (MNOK)	EAC (MNOK)
Rysjedalsvika-Rutledal-Krakhella	7.274	0.897	0.229	0.028	**Sørrollnes-Stangnes**	3.556	0.438	0.115	0.014
Askvoll-Fure-Værlandet	4.096	0.505	0.066	0.008	**Hansnes-Karlsøy-Vannøy-Hansnes**	7.746	0.955	0.243	0.030
Smørhamn-Kjelkenes	1.534	0.189	0.049	0.006	**Rotsund-Havnnes-Klauvnes**	0.960	0.118	0.030	0.004
Horn-Igerøy	4.088	0.504	0.134	0.016	**Sør-Tverrfjord-Bergsfjord-Øksfjord**	1.023	0.126	0.034	0.004
Igerøy-Tjøtta	-	-	-	-	**Øksfjord-Tverrfjord**	3.667	0.452	0.121	0.015
Tjøtta-Forvik	1.639	0.202	0.054	0.007	**Øksfjord-Hasvik**	-	-	-	-
Stokkvågen-Onøy-Sleneset-Lovund	11.390	1.404	0.184	0.023	**Stavanger-Tau****	27.886	3.438	Already LNG	
Træna-Onøy-Stokkvågen	3.317	0.409	0.110	0.014	**Fogn-Jelsa**	14.424	1.778	0.205	0.025
Mosjøen-Hundåla-Dagsvik	1.744	0.215	0.057	0.007	**Mekjarvik-Kvitsøy**	10.365	1.278	0.334	0.041
Solfjellsjøen-Vandve	0.495	0.061	0.016	0.002	**Våge-Halhjem****	7.963	0.982	Already LNG	
Bodø-Værøy-Røst-Værøy-Moskenes**	52.527	6.476	Already LNG		**Hufthamar-Krokeide**	14.343	1.768	0.464	0.057
Bognes-Lødingen**	9.284	1.145	Already LNG		**Ranavik-Skjersholmane**	12.695	1.565	0.203	0.025
Kjøpsvik-Drag	5.995	0.739	0.194	0.024	**Utbjoa-Sydnes-Fjelbergøy-Borgundøy**	2.117	0.261	0.062	0.008
Jektvik-Kilboghamn	2.611	0.322	0.085	0.011	**Sandvikvåg-Halhjem****	104.778	12.918	Already LNG	
Rødøybassenget	1.818	0.224	0.057	0.007	**Brattvåg-Dryna-Fjørtofta-Harøya**	7.518	0.927	0.115	0.014
Sund-Horsdal-Sørarnøy	1.420	0.175	0.022	0.003	**Geiranger-Hellesylt**	4.124	0.508	0.068	0.008
Ørnes-Vassdalsvik-Meløysund-Bolga	3.139	0.387	0.100	0.012	**Molde-Sekken**	2.081	0.257	0.067	0.008
Digermulen-Hanøy/Finnvik	0.618	0.076	0.018	0.002	**Molde-Vestnes****	8.697	1.072	Already LNG	
Hanøy-Kalfjord	-	-	-	-	**Moss-Horten**	40.453	4.987	0.427	0.053
Lyngseidet-Olderdalen	2.968	0.366	0.095	0.012	***Total***	***390.35***		***3.96***	

Table 7.4: Onshore investments, hydrogen and LNG.

7.5 Potential reduction in CO_2 emissions

The CO_2 emissions for every route depends on a number of factors, such as installed capacity, number of operating ferries, type of fuel, number of crossings per day, PCU count or distance travelled. As per Figure 7.4, we can see which routes emit the least amount of CO_2 per kilometer per car.

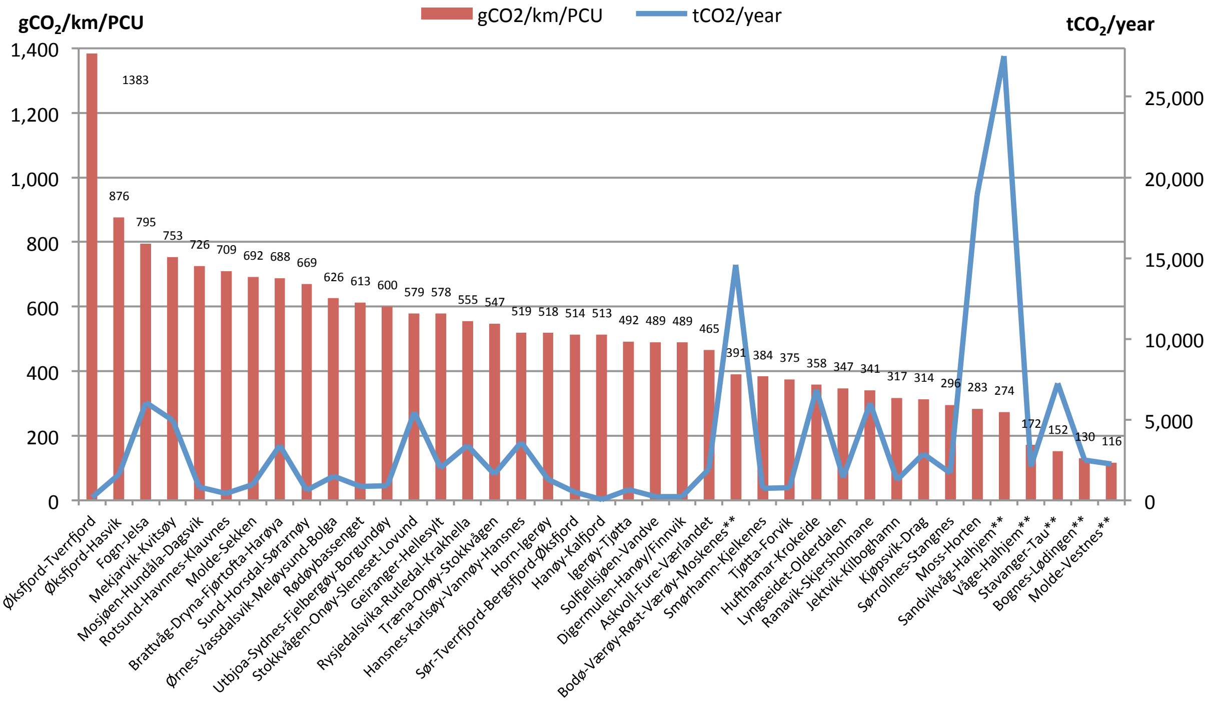

Figure 7.4: Overview of CO$_2$ emissions.

Here, we are looking at the consequences of implementing hydrogen on all suitable routes. Although the emissions per kilometer per car do not give a good understanding of which routes can reduce emissions in the most cost-efficient manner, comparing this with the total amount of CO$_2$ emitted per year does provide some background for analysis. Routes that emit little CO$_2$ per kilometer per car but emit large amounts per year have the potential of having lower abatement costs than those that do not. Most of these routes, as seen in Figure 7.4, are the ones already powered by LNG. Excluding these, we find that the routes, which present a peak on the blue line (tCO$_2$/year) and have relatively low emissions per kilometer per car (below 600 gCO$_2$/km/PCU), all have under average abatement costs.

In this study, we are attempting to establish when hydrogen could be the better alternative. With this in mind, it is important to evaluate the amount of CO$_2$ reduction the technology can bring. If we were to progressively replace the current MGO/LNG ferries with hydrogen driven ferries, a total of 140,160 tons of CO$_2$ could be reduced. Alternatively, to cut some of the CO$_2$ emissions on longer routes, i.e., above 10 km, the best option would be to implement LNG ferries. Given the carbon factor of LNG, its energy content and engine efficiency, the CO$_2$ reductions related to the introduction of LNG on MGO powered ferries is of about 45%. We are thus comparing the implications of going from MGO to LNG, MGO to Hydrogen and finally LNG to Hydrogen. Table 7.5 illustrates the potential carbon emissions reductions on the featured routes.

Route	Annual tCO_2 reduced (MGO-LNG)	Annual tCO_2 reduced ($LNG-H_2$)	Annual tCO_2 reduced ($MGO/LNG-H_2$)	Route	Annual tCO_2 reduced (MGO-LNG)	Annual tCO_2 reduced ($LNG-H_2$)	Annual tCO_2 reduced ($MGO/LNG-H_2$)
Rysjedalsvika-Rutledal-Krakhella	1,523	1,869	3,392	**Sørrollnes-Stangnes**	767	941	1,708
Askvoll-Fure-Værlandet	871	1,069	1,940	**Hansnes-Karlsøy-Vannøy-Hansnes**	1,613	1,980	3,593
Smørhamn-Kjelkenes	327	401	728	**Rotsund-Havnnes-Klauvnes**	196	241	437
Horn-Igerøy	588	722	1,310	**Sør-Tverrfjord-Bergsfjord-Øksfjord**	225	276	501
Igerøy-Tjøtta	300	368	668	**Øksfjord-Tverrfjord**	81	100	181
Tjøtta-Forvik	358	439	798	**Øksfjord-Hasvik**	722	885	1,607
Stokkvågen-Onøy-Sleneset-Lovund	2,449	3,005	5,455	**Stavanger-Tau****	-	7,253	7,253
Træna-Onøy-Stokkvågen	734	901	1,634	**Fogn-Jelsa**	2,725	3,344	6,069
Mosjøen-Hundåla-Dagsvik	379	465	843	**Mekjarvik-Kvitsøy**	2,217	2,720	4,937
Solfjellsjøen-Vandve	107	131	238	**Våge-Halhjem****	-	2,080	2,080
Bodø-Værøy-Røst-Værøy-Moskenes**	-	14,573	14,573	**Hufthamar-Krokeide**	3,080	3,780	6,860
Bognes-Lødingen**	-	2,504	2,504	**Ranavik-Skjersholmane**	2,701	3,315	6,016
Kjøpsvik-Drag	1,291	1,584	2,876	**Utbjoa-Sydnes-Fjelbergøy-Borgundøy**	413	507	920
Jektvik-Kilboghamn	568	697	1,264	**Sandvikvåg-Halhjem****	-	27,519	27,519
Rødøybassenget	381	468	849	**Brattvåg-Dryna-Fjørtofta-Harøya**	1,533	1,881	3,415
Sund-Horsdal-Sørarnøy	288	354	642	**Geiranger-Hellesylt**	904	1,110	2,014
Ørnes-Vassdalsvik-Meløysund-Bolga	665	817	1,482	**Molde-Sekken**	446	547	993
Digermulen-Hanøy/Finnvik	101	123	224	**Molde-Vestnes****	-	2,259	2,259
Hanøy-Kalfjord	22	27	49	**Moss-Horten**	8,500	10,430	18,930
Lyngseidet-Olderdalen	629	772	1,400	***Total***	***37,706***	***102,455***	***140,160***

Table 7.5: Potential CO_2 reductions.

Six of the routes in the analysis are already serviced by LNG ferries. In these instances, we have calculated to amount of CO_2 the ferries emit today and only assume we can reduce emissions by that amount by going from LNG to hydrogen.

7.6 Cost of reducing carbon emissions: Abatement costs

In this section we will be presenting the fundamental results of our study. The previous parts of this chapter have introduced the basis for the abatement cost calculation that will follow. Since implementing hydrogen is by no means a cost-saving solution, rather an emission-saving one, we have to measure its costs in relationship to its environmental impact. The abatement cost function represents the cost of implementing the alternative technology per ton CO_2 reduced. It is the most widespread application used for this kind of measurement and is therefore the tool we will use to display our results. Below, we first present the abatement costs found for switching from MGO to hydrogen before comparing it to the alternatives. Then, we go on to evaluate our results with regard to different estimates of the cost of carbon emissions.

7.6.1 Abatement cost of MGO-H_2

The cost for reducing one ton of CO_2 when implementing hydrogen on routes that were previously fueled by MGO is shown in Figure 7.5. To better understand what affects the abatement costs, we have divided the costs with regard to the sections discussed above, namely fuel costs, onboard investment costs and investments in onshore storage tanks. In general, the main cost driver in the abatement formula are the fuel costs, followed by the onboard investment costs. This is not surprising given the current price level of hydrogen.

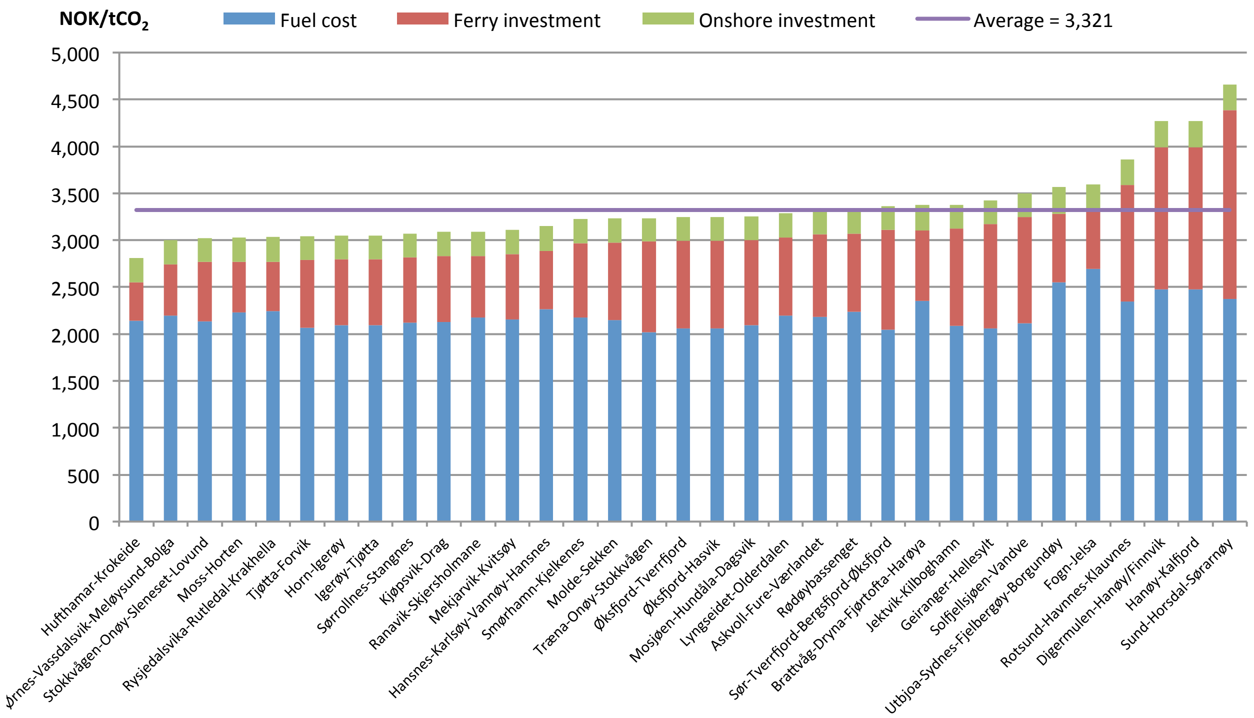

Figure 7.5: Abatement costs (NOK/tCO_2) of switching from MGO to H_2, divided into extra fuel costs, investment in hydrogen ferry and onshore storage tanks.

The average abatement cost for MGO-H_2 is about 3,321 NOK/tCO_2. These cost calculations give us a good idea of how expensive it is to actually implement hydrogen in the existing ferries with regard to emissions reductions. By our estimates, the route Hufthamar-Krokeide is the cheapest one to have run off hydrogen. Looking back at Figure 7.4, we can see that this route emits a large amount of CO_2 per year in conjunction with emitting little CO_2 per kilometer per car. The relatively low installed capacity means it does not consume a lot of energy per crossing. This translates to lower investments, as well as fuel costs.

7.6.2 Abatement cost comparison

In order to compare the abatement cost of implementing hydrogen in the current ferry fleet with the alternative, we compare it with the abatement cost of LNG. Table 7.6 is an overview of the abatement costs related to each possible fuel transition.

Route	Abatement cost (NOK/tCO_2)			Comparison
	MGO-LNG	LNG-H_2	MGO-H_2	MGO-H_2 vs. MGO-LNG
Rysjedalsvika-Rutledal-Krakhella	-516	5,932	3,037	3,553
Askvoll-Fure-Værlandet	1,453	4,851	3,325	1,872
Smørhamn-Kjelkenes	953	5,079	3,227	2,273
Horn-Igerøy	472	5,154	3,051	2,579
Igerøy-Tjøtta	-	-	-	-
Tjøtta-Forvik	584	5,048	3,044	2,460
Stokkvågen-Onøy-Sleneset-Lovund	63	5,438	3,024	2,962
Træna-Onøy-Stokkvågen	1,937	4,295	3,236	1,300
Mosjøen-Hundåla-Dagsvik	1,576	4,623	3,254	1,679
Solfjellsjøen-Vandve	2,810	4,062	3,500	690
Bodø-Værøy-Røst-Værøy-Moskenes	n/a	5,365	n/a	n/a
Bognes-Lødingen	n/a	4,759	n/a	n/a
Kjøpsvik-Drag	473	5,221	3,089	2,616
Jektvik-Kilboghamn	2,296	4,258	3,377	1,081
Rødøybassenget	1,162	5,100	3,332	2,170
Sund-Horsdal-Sørarnøy	7,622	2,241	4,657	-2,964
Ørnes-Vassdalsvik-Meløysund-Bolga	-393	5,772	3,004	3,396
Digermulen-Hanøy/Finnvik	4,897	3,756	4,268	-629
Hanøy-Kalfjord	-	-	-	-
Lyngseidet-Olderdalen	1,163	5,018	3,287	2,124
Sørrollnes-Stangnes	413	5,239	3,072	2,659
Hansnes-Karlsøy-Vannøy-Hansnes	-31	5,740	3,149	3,179
Rotsund-Havnnes-Klauvnes	3,413	4,225	3,860	448
Sør-Tverrfjord-Bergsfjord-Øksfjord	2,479	4,078	3,360	881
Øksfjord-Tverrfjord	1,762	4,460	3,249	1,487
Øksfjord-Hasvik	-	-	-	-
Stavanger-Tau	n/a	5,329	n/a	n/a
Fogn-Jelsa	-178	6,673	3,597	3,775
Mekjarvik-Kvitsøy	418	5,304	3,110	2,692
Våge-Halhjem	n/a	7,718	n/a	n/a
Hufthamar-Krokeide	-1,144	6,030	2,809	3,953
Ranavik-Skjersholmane	167	5,472	3,090	2,923
Utbjoa-Sydnes-Fjelbergøy-Borgundøy	537	6,031	3,564	3,027
Sandvikvåg-Halhjem	n/a	5,541	n/a	n/a
Brattvåg-Dryna-Fjørtofta-Harøya	660	5,587	3,375	2,715
Geiranger-Hellesylt	2,755	3,973	3,426	671
Molde-Sekken	1,128	4,947	3,232	2,104
Molde-Vestnes	n/a	4,637	n/a	n/a
Moss-Horten	-483	5,894	3,031	3,514
Average	***1,282***	***5,079***	***3,321***	-

Table 7.6: Comparison of abatement costs, MGO-LNG, LNG-H_2, MGO-H_2.

The abatement costs for implementing LNG on the existing MGO ferries are considerably lower than that of implementing hydrogen. There are only two exceptions where it would be more cost-efficient to use hydrogen compared to LNG: Sund-Horsdal-Sørarnøy and Digermulen-Hanøy/Finnvik. However, these routes have some of the highest abatement costs for pure hydrogen transition. The reason why they are even less profitable with LNG is that they have high investment costs in combination with low overall CO_2 reduction, further increasing the MGO-LNG abatement cost. Nevertheless, if a tender requiring low- or zero-emission technology were issued on these routes, similar to the tender for Anda-Lote, hydrogen would be more cost-efficient than LNG.

Shifting our focus onto the incremental abatement cost of LNG-H_2, we notice that the alternative cost of changing fuel would entail very high abatement costs. With an average incremental abatement cost of 5,079 NOK/tCO_2, switching from LNG to hydrogen is the most expensive way to reduce the remaining carbon emissions. This result is not surprising as the investments are higher than the MGO-LNG transition, the fuel cost savings are lessened, while the CO_2 reduced is only 55% of the overall annual amount. In Table 7.6, we have estimated the incremental abatement cost of reducing the additional carbon emissions with hydrogen by subtracting the LNG investments from the hydrogen investments. For example, the route Moss-Horten has an abatement cost of -483 NOK7tCO_2 for MGO-LNG and 5,894 NOK/tCO_2 for LNG-H_2. In comparison, the abatement for switching directly from MGO to hydrogen is 3,031 NOK/tCO_2. As seen in Table 7.6, it is almost always the case that the incremental abatement cost is higher than the MGO-H_2 abatement cost. If an operator switches its ferry to LNG, the resulting abatement cost for switching to hydrogen to reduce the remaining emissions in the future would be very high. The only two routes where this is not the case, are the same routes that showed lower MGO-H_2 abatement cost compared to MGO-LNG. Figure 7.6 shows a graphical illustration of the different abatement costs.

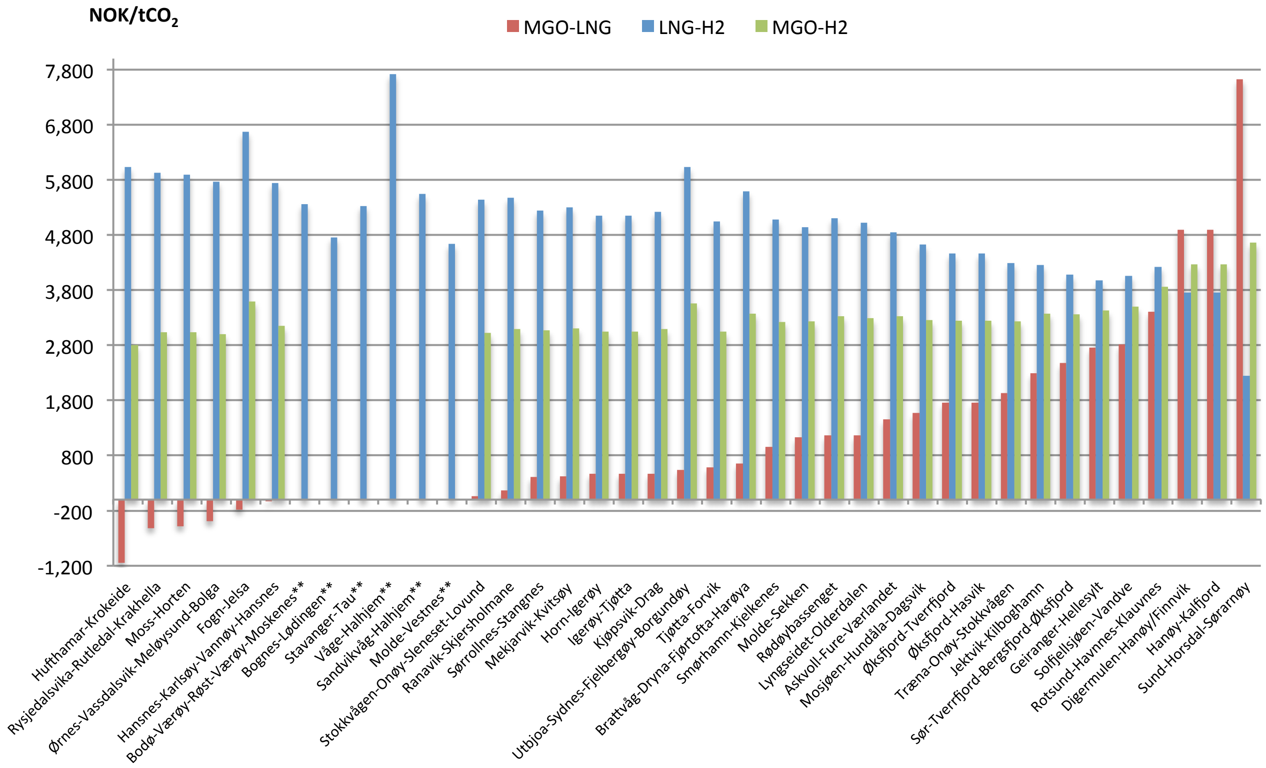

Figure 7.6: Graphical illustration of abatement costs.

Operators could take advantage of the currently competitive abatement costs for transitioning to LNG and wait for the price of hydrogen and PEMFCs to drop. In fact, as you can see in Figure 7.6, some of the abatement costs for MGO-LNG are negative, meaning it should already be profitable to switch to LNG. Having switched to LNG, the remaining CO_2 reductions could be performed if the abatement cost of LNG-H_2 comes down to a more competitive level. In today's market, one has to evaluate whether the goal is to cut as much CO_2 as possible or to do so in the most cost-efficient way. If the former is the priority, hydrogen has the potential of eliminating CO_2 emissions in operation.

7.6.3 Results weighed against carbon tax systems

Since there is no international price on CO_2 emissions, it is difficult to determine if the abatement cost is compatible with society's willingness to pay for reduced emissions. Nonetheless, it is widely believed that the true cost to society of emitting CO_2 is greater than its private cost. An increased concentration of atmospheric CO_2 and other greenhouse gases will result in unwanted climate change: higher global temperatures, greater climate variability and possible increases in sea levels. However it is difficult to estimate how much society should spend today to protect future generations against the unknown risks that emissions create. Through the European Union Emission Trading Scheme (EU ETS) and carbon taxes, policy makers have tried to put a price on carbon. Below, we compare our results to different estimates of the carbon price.

EU ETS

External costs will usually not have a market price, however, the closest we get to an international market price on CO_2 emissions is the carbon price in the EU ETS. The purpose of the scheme is to reduce emissions in a cost-efficient manner by trading climate quotas. However, since the establishment of the market, the carbon price has been very volatile. Due to an initial oversupply of quotas, effective subsidies for renewable energy and the recession in the European economy causing lower demand for energy, the price has fallen from 30 EUR/tCO_2 in 2008 to only 6-7 EUR/tCO_2 today (Norwegian Environment Agency, 2014). As previously mentioned, the average abatement cost of switching fuel from MGO to LNG is 1,282 NOK/tCO_2 and 3,321 NOK/tCO_2 from MGO to hydrogen. Compared to the current EU ETS carbon price of only 63 NOK/tCO_2, the average abatement cost of switching to hydrogen is very high. The implementation of hydrogen ferries will therefore most likely not be triggered by the quota system alone, if the quota price stays at this level. When looking at the option of switching to LNG fueled ferries instead, seven of the routes have an abatement cost lower than 63 NOK/tCO_2. Nevertheless, the low carbon price is not considered to reflect the true value of reducing CO_2 emissions, and the price is expected to increase in the future. Klimakur 2020 (2010) expects the price to increase to 40 EUR/tCO_2 in 2020, i.e., 360 NOK/tCO_2.

Norwegian Carbon tax

The current carbon tax on MGO is 0.90 NOK/l or 0.774 NOK/kg, and this is set to remain unchanged through 2016 (Ministry of Finance, 2014).[26] The abatement costs for implementing hydrogen being so high, it would be interesting to see how much the carbon tax set on the consumer would have to increase for these costs to be comparable to the future EU ETS. If we were to bring the average MGO-H_2 abatement cost down to 360 NOK/tCO_2, the carbon tax would have to be 11.92 NOK/l. This is an increase of 1,224% from the current level. Figure 7.7 gives a brief overview of the abatement costs for MGO-H_2 in this scenario.

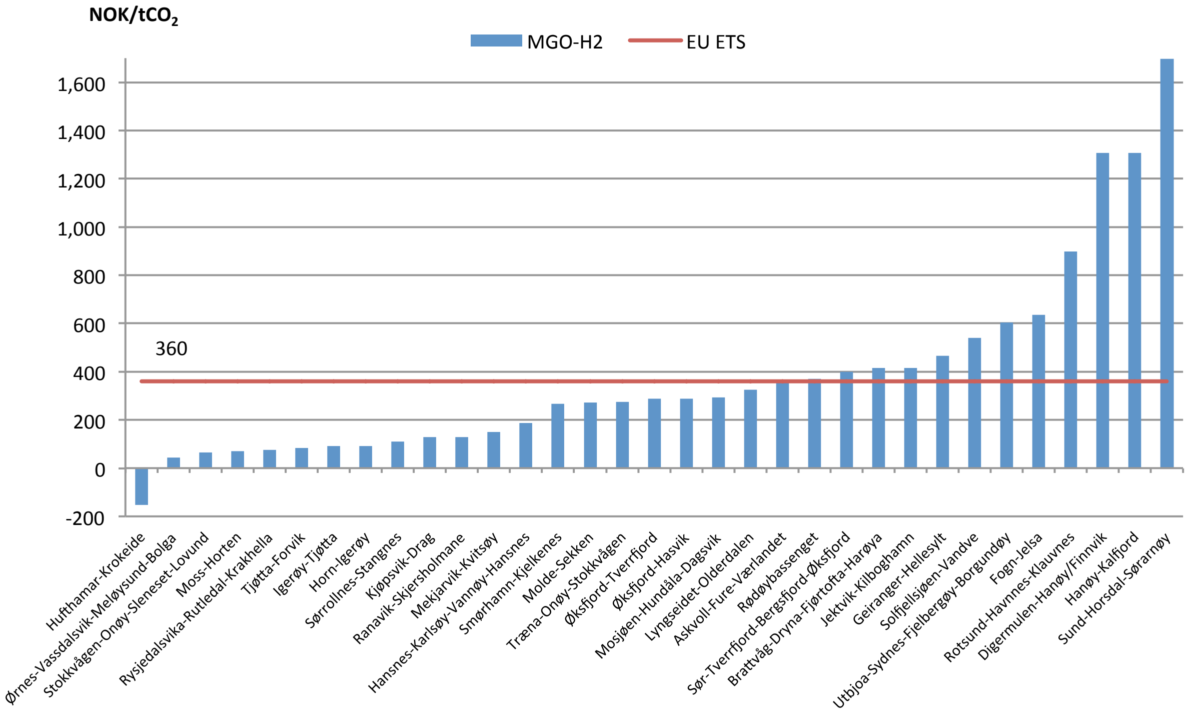

Figure 7.7: MGO-H_2 abatement costs when increasing the carbon tax to achieve an average abatement cost equal to the future EU ETS price of 360 NOK/tCO_2.

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[26] 0.9 x 0.86 (MGO density) = 0.774 NOK/kg (GEOS Group, 2014).

In the unlikely scenario described above, most of the routes would have reasonable abatement costs compared to the predicted European carbon price. However, under these assumptions, some routes still retain high abatement costs. Needless to say, the following routes should be the last to be considered for the implementation of hydrogen: Sund-Horsdal-Sørarnøy, Hanøy-Kalfjord, Digermulen-Hanøy/Finnvik, Rotsund-Havnnes-Klauvnes, Fogn-Jelsa, Utbjoa-Sydnes-Fjelbergøy-Borgundøy, Solfjellsjøen-Vandve, Geiranger-Hellesylt, Jektvik-Kilboghamn, Brattvåg-Dryna-Fjørtofta-Harøya, Sør-Tverrfjord-Bergsfjord-Øksfjord, Rødøybassenget, Askvoll-Fure-Værlandet.

Value of CO_2 emissions with regard to national reduction targets

Society's willingness to pay for reducing emissions could be related to the national target for emission reductions. According to a macroeconomic study performed by SSB, the national target of 12 million tons of CO_2 reduced can be achieved with an emission price of 1,500 NOK/tCO_2 in 2020 (SSB, 2010). This will be the price all polluters in Norway would face. Compared to the abatement cost of implementing hydrogen, the cost is still too high. However, when looking at the implementation of LNG, the average abatement cost is comparable to 1,500 NOK/tCO_2. As much as 21 routes have a lower abatement cost than 1,500 NOK/tCO_2. This amounts to a total CO_2 reduction of 40,591 tCO_2, which is about 0.3% of the total emission reduction target.

The report also considered a scenario where the quota-applicable sector is shielded from price increases beyond the quota price. Then, 9 million tons CO_2 of the national target will have to be cut in the non-quota-applicable sectors, and the related emission price is estimated to be around 3,400 NOK/tCO_2. Considering that the ferry sector is not subject to the quota, this emission price is much more comparable to the cost of implementing hydrogen ferries, with an average abatement cost of 3,321 NOK/tCO_2 and 26 of the routes have an abatement cost lower than 3,400 NOK/tCO_2. However, such a differentiated climate policy between quota-regulated and non-quota-regulated sources does not ensure that the cheapest measures are triggered and we therefore consider this carbon price as less relevant.

Compared to the carbon prices used in other reports, the abatement cost of implementing hydrogen ferries is currently very high. However, by setting the criteria of implementing low- and zero-emission ferries where it is technologically feasible, and proposing to exclude LNG as a low-emission alternative, Norway has shown signs of wanting to reduce emissions in the maritime sector. It is therefore reasonable to believe that the willingness to pay for reduced emissions is higher than the quota price. With increasing global pressure to reduce emissions, carbon prices expected to increase, and hydrogen technology becoming more affordable, the situation for hydrogen ferries might change. In addition, other projects have been carried out even though they have not been the most cost-efficient way to reduce emissions. One example is the tax exemption of electric vehicles, which we will come back to in chapter 8.

There could also be other possible gains for society by implementing hydrogen than merely cutting CO_2 emission to reach emission targets. Firstly, by reducing CO_2 emissions, NO_x emissions are generally also reduced to a high extent. NO_x emissions are one of the biggest contributors to local air pollution, which represent a significant health issue in the biggest cities in Norway, leading to respiratory and cardiovascular diseases (Høiskar, Sunvor, Tarrason, & Endregard, 2011). Reducing CO_2 and NO_x emissions on the routes close to urban areas could reduce the local pollution and thus also decrease the number of related negative health effects. It could however be argued that many of the routes in this study are located near the open sea, like for instance the route Bodø-Værøy-Røst-Moskenes, and the NO_x emissions would be carried away from inhabited areas with the wind. Nevertheless, a reduction in NO_x emissions could be beneficial for the ferry routes located in fjords and near urban areas. In Table 7.1 we have shown the current NO_x emissions for all the routes with regard to their original fuel.

Secondly, there could also be value in technology development regarding the use of hydrogen and fuel cells. As discussed in chapter 3, since hydrogen is increasing in popularity for several applications in the energy sector, developing this technology locally could increase industrial competitiveness. It could also lead to positive knowledge spillovers, meaning that other countries pick up the technology, which could in turn lead to lower global emissions. Lastly, it could create much needed work in the Norwegian shipyard industry, which has been suffering due to the oil crisis.

7.7 Sensitivity Analysis

In order to evaluate the consequences of advances in technology on the results of the study, we performed a sensitivity analysis with respect to some of the key model assumptions. In this part, we will look into the impact of a lower hydrogen price followed by reduced fuel cell costs. As these two parameters account for most of the abatement cost, and are predicted to become more affordable, they would lead to the most pronounced and logical changes in the results.

7.7.1 Hydrogen price

H_2 price = 35 NOK/kg

We first consider a hydrogen price of 35 NOK/kg to evaluate how a change in price affects our results. This is considered a low estimate and is based on future estimates for hydrogen production price in Europe, as discussed in chapter 4. The change in price has a direct impact on the fuel costs and thus, reduces the abatement cost for MGO-H_2 and LNG-H_2, while MGO-LNG remains unchanged. Figure 7.8 shows a graphical representation of the changes from a lower hydrogen price.

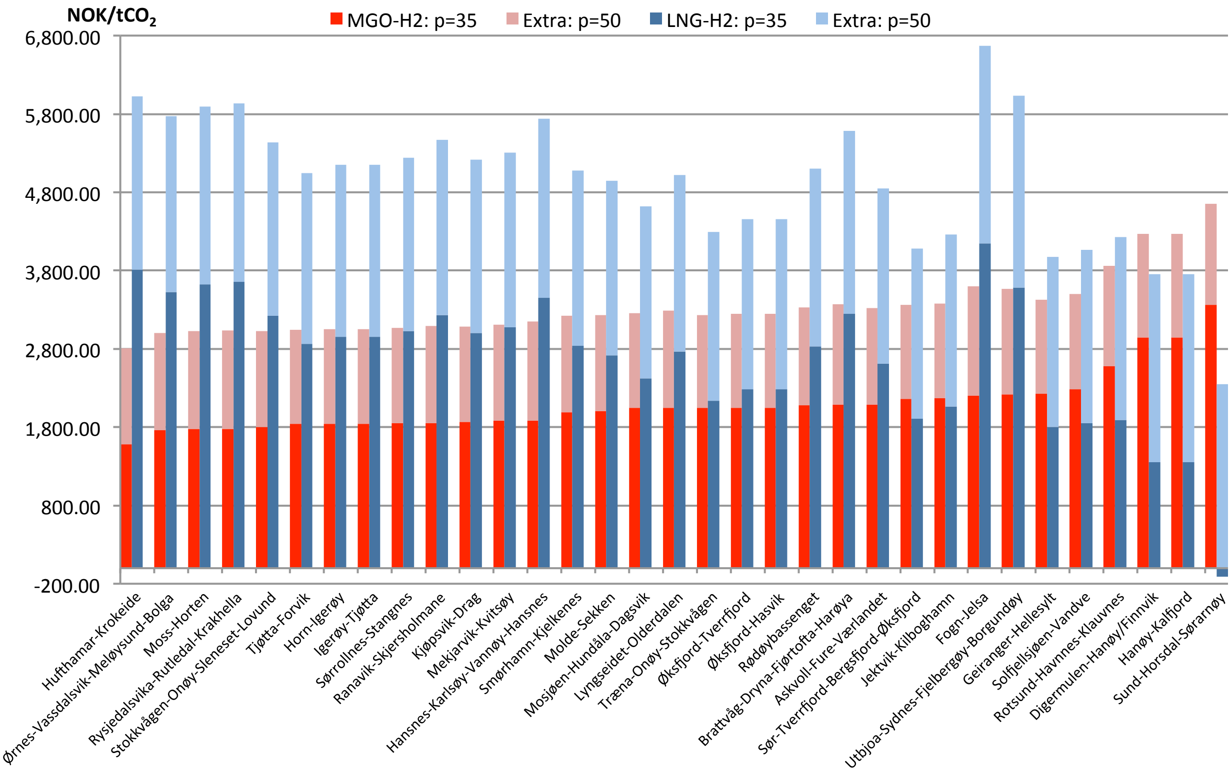

Figure 7.8: Abatement costs of MGO-H_2 and LNG-H_2, with H_2 price of 35 NOK/kg compared to 50 NOK/kg.

In Figure 7.8, the sum of the red colored bars shows the original abatement costs for MGO-H_2 with a hydrogen price of 50 NOK/kg, while the sum of the blue colored bars represents the original abatement cost for LNG-H_2. The dark colored bars are the new abatement costs calculated with a hydrogen price of 35 NOK/tCO_2. Assuming a hydrogen price of 35 NOK/kg, the abatement cost of MGO-H_2 and LNG-H_2 are reduced. Yet, when compared to the emissions cost of 360 NOK/tCO_2 and 1,500 NOK/tCO_2 discussed above, none of the routes seem to have reached an affordable MGO-H_2 abatement cost. Nevertheless, several of the routes have become less expensive for LNG-H_2 compared to the MGO-H_2 alternative, as can be seen on the right side of Figure 7.8. However, this only occurs on routes with generally high abatement costs.

Necessary H_2 price reduction

Using Excel Solver we estimated which hydrogen prices would lead to the abatement costs for MGO-H_2 and MGO-LNG to be equal, resulting in the prices illustrated in Figure 7.9.

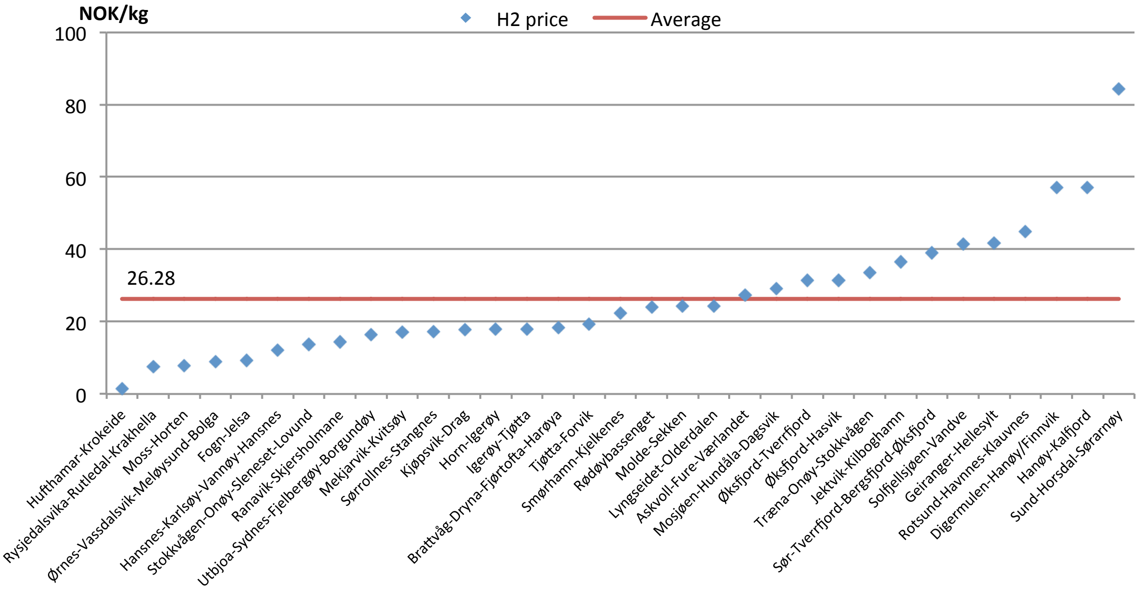

Figure 7.9: Necessary hydrogen prices for abatement costs of MGO-H_2 to equal abatement costs of MGO-LNG.

The solutions found via Solver range from 1.52 NOK/kg for Hufthamar-Krokeide to 84.36 NOK/kg for Sund-Horsdal-Sørarnøy. It is worth noticing that prices found above 50 NOK/kg are related to routes, which already are more cost-efficient with hydrogen compared to LNG. However, as seen see in Figure 7.9, with an average price of 26.28 NOK/kg, most of the routes would need a price below our low estimate of 35 NOK/kg. Maintaining a low hydrogen price, we will next estimate the investment reductions necessary to satisfy the carbon price target of 2020.

7.7.2 Hydrogen abatement costs reaching 2020 targets

If the abatement cost for the implementation of hydrogen reaches a level of 1,500 NOK/tCO_2 or lower, which was the carbon price found in the report from SSB (2010), it can be argued that this is low enough to make it a valid alternative. With this in mind, a sensitivity analysis is performed on the other most uncertain variable of the model: the price of PEMFC, which has previously been set to 1,300 EUR/kW. Figure 7.10 is a graphical illustration of the required price levels of PEMFCs for the MGO-H_2 abatement cost to be 1,500 NOK/tCO_2 given the low estimate hydrogen price of 35 NOK/kg.

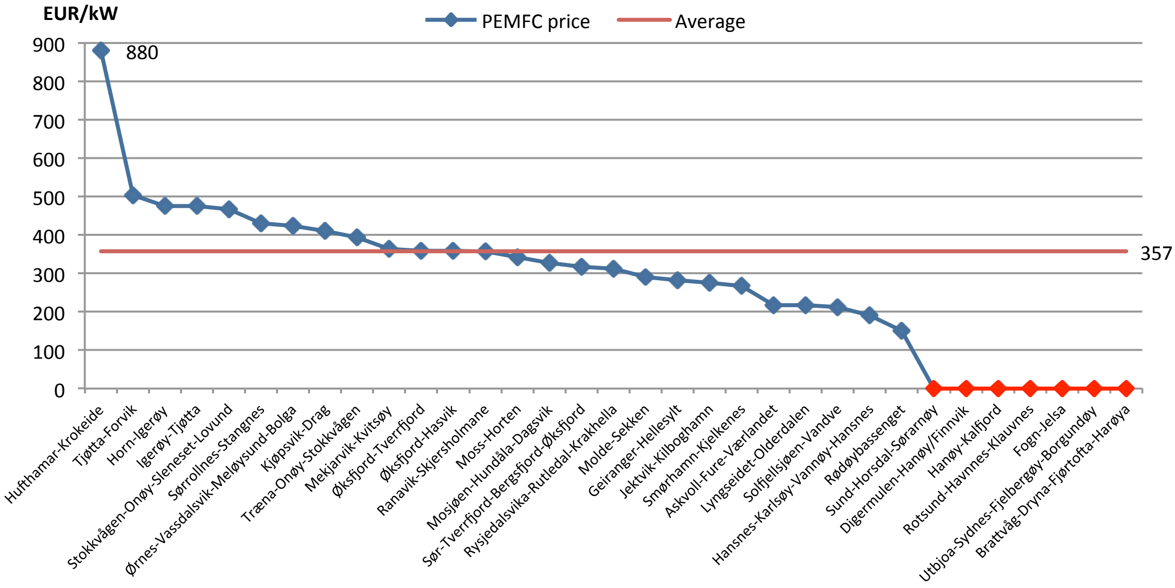

Figure 7.10: Necessary PEMFC prices for MGO-H_2 = 1,500 NOK/tCO_2 including the low estimate hydrogen price of 35 NOK/kg.

As can be observed from the red iterations on the right hand side of Figure 7.10, some of the routes cannot reach an abatement cost of 1,500 NOK/tCO_2, regardless of how low the PEMFC price becomes. On the other hand, the following routes have rather favorable results: Hufthamar-Krokeide, Tjøtta-Forvik, Horn-Igerøy, Igerøy-Tjøtta and Stokkvågen-Onøy-Sleneset-Lovund. The PEMFC prices required for these routes to be validated ranges from 880 to 466 EUR/kW. The price of maritime PEMFCs is expected to decrease to the current PEMFC price for FCEV of about 450 EUR/kW (IEA, 2015). Consequently, these routes could become some of the firsts to be competitive for CO_2 reduction purposes, if and when the technology reaches a certain point in maturity.

8. Discussion

In this chapter, we present a discussion around broader topics regarding our results. First, we briefly discuss whether or not the demand of hydrogen on the ferry routes is realistic and how it might change in the future. We then go on to looking at technology and price development, and discuss how hydrogen could be produced directly from renewable energy sources. We look at some socio-economic costs and benefits before finally discussing other possible applications in the maritime sector.

8.1 Demand and supply of hydrogen

As seen in section 3.3.1, the availability and infrastructure of hydrogen in Norway is still small scale and there is currently no large-scale supplier of hydrogen. However, it is not unfeasible that the supply of hydrogen in the Norwegian market could expand over the next decade, in which case the fuel demand in our selected group of ferries of 15,224 tons per year could be satisfied. In fact, there could be as much as to export hydrogen in liquid state to countries with scarce natural resources, like Japan, as concluded by a study performed by SINTEF (SINTEF, 2015). If we rather consider that only the best routes were to adopt the technology, the hydrogen demand could be more achievable. The aggregated demand for the routes Hufthamar-Krokeide, Tjøtta-Forvik, Horn-Igerøy, Igerøy-Tjøtta and Stokkvågen-Onøy-Sleneset-Lovund only amounts to about 1,227 tH_2/year. As we mentioned earlier, Greenstat plans to produce as much as 10,950 tons of H_2 per year, albeit not for the purpose of fueling the maritime sector. Nevertheless, it is worth mentioning the potential of such installation and their general impact in the interest of hydrogen.

Our study estimates annual hydrogen consumptions ranging from 4 to 4,086 tH_2/year, depending on the route. However, it is doubtful that new ferries would need as much to operate these routes. With new ship design and the use of lighter materials, such as Ampere built in aluminum, the fuel efficiency of ferries would most likely be significantly improved. Ampere has the capacity to transport 120 cars, as does the 1999 MF Vardehorn with an installed capacity of 2,650 kW. In contrast, Ampere is able to achieve comparable operation with only 900 kW, which is not surprising seeing that it has a contemporary design and built to be as energy efficient as possible. In our model, Ampere uses 130 kWh on the Lavik-Oppedal route. If MF Vardehorn was to navigate the same crossing of 5.1 km, it would in turn use 370 kWh, which is almost three times as much. This is the case for many of the ferries we have looked at; many have far too much installed capacity by today's standards. This deliberate overestimation on our part has two effects on the abatement cost results. Firstly, the investments we assume are necessary for the fleet will most likely be lessened since newer ships do not need as much power capacity installed. Secondly, the quantity of hydrogen needed to operate the fleet would also shrink. The hydrogen consumption is directly connected to the energy used. Consequently, the total hydrogen need might well be less than 10,000 tons per year for the featured group of ferries. The cost of storing the hydrogen are reduced threefold for every ton of hydrogen reduced, meaning there would be significant cost reduction in this area alike.

8.2 Technology development

In this study, we have assumed a price of 1,300 EUR/kW for the PEMFC system to be installed. If and when the measures start to be implemented, the price for fuel cells will most likely have dropped considerably. Not that Norway must assume an early adopter role, but rather wait for the price to be more competitive. The PEMFC costs account for a large share of the overall cost for the implementation of hydrogen. If we assume technology advances for these fuel cells and a more competitive price, the abatement cost range we presented earlier would perhaps approach the carbon price, rendering the idea profitable. Some studies predict that the cost for producing PEMFCs for FCEVs in scale could descend to 89 EUR/kW in the near future (IEA, 2007). This is only a fraction of the price we have utilized and would make the results of the study very different. However, this price is related to PEMFC for use in FCEVs and the price of PEMFCs for use in the maritime sector is not expected to decrease to these levels as rapidly.

PEMFC costs need to fall below 44 EUR/kW to compete with traditional combustion engines in cars, although they can compete at higher rates when we look at vehicles with high mileages. This is when energy efficiency makes up for the initial investment cost, which is why the first applications of fuel cells are being tried on large vehicles such as buses and forklifts. Ferries are also vehicles of the same nature, long running times make them suitable for pilot projects such as the Osterøy route ferry MF Ole Bull. In addition, the cost of diesel engines is expected to increase due to stricter regulations for NO_x emissions when the IMO Tier III takes effect in 2016. The fuel cells' lifetime is also crucial for the calculation of the abatement cost. Increased lifetime would significantly reduce the EAC of the investment and play an important role in the profitability of the projects.

Lithium-ion batteries, which are a part of the system, are as well expected to keep dropping in price. The price we have used of 16,000 NOK/kWh installed is very conservative in the sense that it includes the installation and maintenance of very large battery packs as described in DNV GL (2015a), which was a study on all-electric ferries. Given the fact that our battery packs are of much smaller sizes and that the general price is expected to drop, the cost for batteries in our study would also be considerably less. As the PEMFC and the battery packs account for most of the investment costs, we can see how reliant the profitability of projects are on the technology advances. It could therefore be argued that development contracts should be established for hydrogen ferries in the same way the first electric and LNG fueled ferries were introduced.

As per Figure 7.10, we have concluded that certain routes are more suitable for the future implementation of hydrogen. These routes require less of an advance in technology then the rest of the featured routes, and present relatively low abatement costs. With this in mind, we have plotted the end-of-tender year in combination with the abatement costs with a hydrogen price of 35 NOK/kg in Figure 8.1.

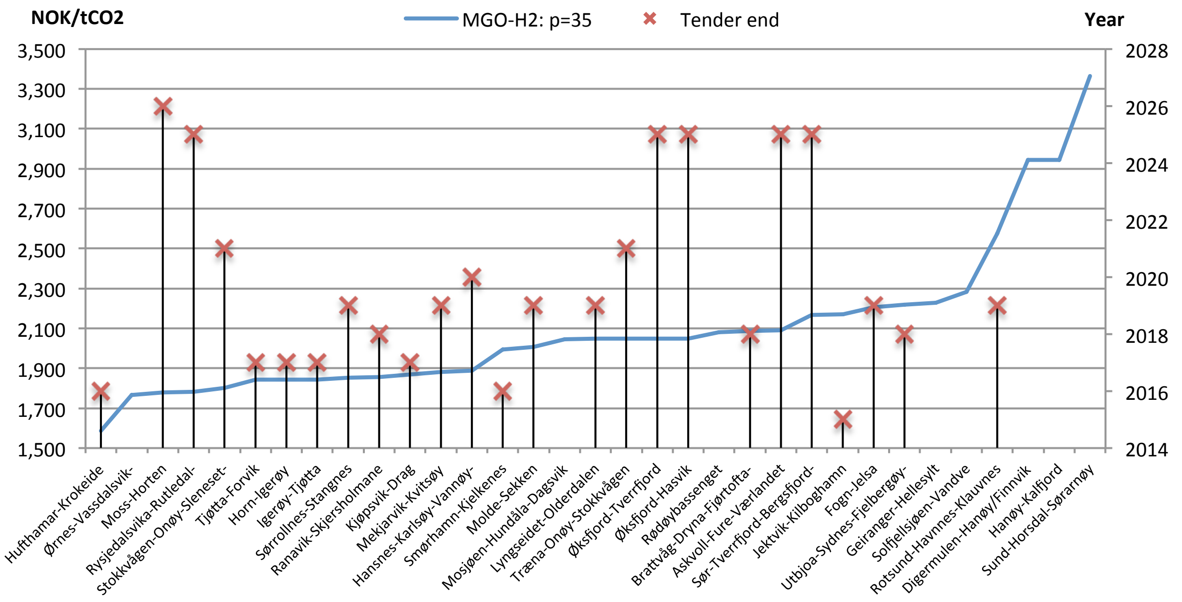

Figure 8.1: End of tender and MGO-H_2 abatement costs.

With a low hydrogen price of 35 NOK/kg, we are looking for routes whose tenders end further into the future. Although the tender for Moss-Horten ends in 2026, the results in Figure 7.10 illustrate that the route requires a dramatic reduction in PEMFC prices for its MGO-H_2 abatement cost to be reasonable. On the other hand, in the case of the route Stokkvågen-Onøy-Sleneset-Lovund, the tender ends in 2021 and the sensitivity analysis shows that its MGO-H_2 abatement cost could come down to 1,500 NOK/tCO_2, with a PEMFC price of 466 EUR/kW or lower. Consequently, by the time the tender is re-evaluated, the hydrogen and PEMFC prices might be at a level that allows the implementation of hydrogen on this route. In contrast, the routes Hufthamar-Krokeide, Tjøtta-Forvik, Horn-Igerøy and Igerøy-Tjøtta all have relatively low MGO-H_2 abatement costs and require less PEMFC price reduction than most, but their tenders end in the near future. Accordingly, if a development contract is issued and there is a willingness to pay to prove the technology, these routes could already be considered for the use of hydrogen as fuel today.

8.3 Producing hydrogen from excess energy

As discussed earlier, the high hydrogen price is one of the major barriers for the implementation of hydrogen ferries. As seen in chapter 4, hydrogen could be produced cheaper when taking advantage of excess energy. Current environmental policies like the el-certificate market, provides incentives for more renewable energy production in Norway. By 2020, 13.2 TWh of the power generation in Norway is to be produced from renewable energy sources (NVE, 2012). Even though export cables to the European continent are planned, it will take time before they are fully operational. In recent years, Norway has had a power surplus and consequently low electricity prices. With more renewable energy entering the market, and before the export cables have taken full effect, the power balance will likely remain in surplus with periods of excess renewable energy.

Electrolysers can harvest this excess energy and lower the production cost of hydrogen by using cheap electricity. This can for example be done in places where the grid capacity is restricted and there is access to intermittent energy that will not be harvested otherwise, as was the case with Raggovidda wind farm in Finnmark, or during the night when demand is low. When electricity prices are low, small renewable energy producers, e.g. hydropower producers, also have trouble selling their electricity with a profit. If a hydrogen market is established, it is possible that decentralized production of hydrogen could prove profitable.

Example: Midtfjellet wind farm

Midtfjellet wind farm is located close to the route, Sandvikvåg-Halhjem. It has 44 wind turbines with a capacity of 2.5 MW each (Midtfjellet Vindkraft, 2015). With a total yearly production of 347 GWh it has the possibility to produce around 6,160 tH_2 a year. If all the energy were used to produce hydrogen, it would generate more than enough to supply the routes located nearby: Sandvikvåg-Halhjem (4,086 tH_2/year), Halhjem-Våge (311 tH_2/year) and Husavik-Sandvikvåg (263 tH_2/year). In this way, the high costs of transporting hydrogen could be avoided. Assuming Midtfjellet wind farm could produce hydrogen using excess energy, the production cost of hydrogen could come down to 38 NOK/kg, as we saw in the case with Raggovidda wind farm in chapter 4. However, the case with Raggovidda wind farm included transportation costs, meaning that the resulting price could be even lower when produced locally. If Midtfjellet could supply Sandvikvåg-Halhjem with hydrogen at this price, the annual fuel costs for the route could be reduced by almost 50 MNOK or 2,245 NOK per crossing. Currently the route is operated by LNG fueled ferries, and with LNG being cheaper than both MGO and hydrogen, even with the low estimate price, it is unlikely that a hydrogen transition will occur in this specific case.

Nevertheless, Sogn og Fjordane County is considering using excess renewable energy to produce cheap hydrogen. In addition to having abundant energy resources and water available, they also have an infrastructure that is dependent on ferries and other maritime transportation (Valle, 2015).

8.4 Socio-economic costs and benefits

Implementing hydrogen in the Norwegian ferry fleet would have additional socio-economic benefits to consider, besides the ones discussed in chapter 4. Based on the examples given for green technology on ships, it is safe to say Norway is in the forefront when it comes to innovative ways to make ships more environmentally friendly. There are dozens of shipyards in Norway, which deliver world-class ships on a global basis. Incentivizing this industry would bring some much-needed activity to the Norwegian economy and insure that the benefits remain inside the borders. Creating competitiveness for the maritime sector could give Norway a comparative advantage and generate more employment, not only in shipbuilding but also in green technology.

In Norway, electric cars and FCEVs have tax exemptions. Electric cars are not subject to import tax or value added tax, adding up to 1.75 billion NOK for each category. Consequently, the Norwegian government has, since the rule was implemented, lost over 3.5 billion NOK in tax income by the increase in sales of these vehicles, as of May of this year (Qvale, 2015). The benefits of this measure to promote green energy solutions will not be discussed in the study, but we can see how comparable the two approaches are. In our case, the hydrogen ferries investment amounts to 1.5 billion NOK, which is less than the tax exemption cost on electric cars. Our estimates show that the CO_2 reduction related to the implementation of hydrogen would be more or less equal to the amount emitted by 61,614 traditional cars. As of May 2015, there were about 54,000 electric cars in Norway. With this in mind, the implementation of hydrogen in the Norwegian ferry fleet may not be as expensive as one might think. In fact, the CO_2 emissions reduction per NOK invested are more than double than in the case of the electric cars subsidies. In addition, given the fact that Norway does not produce its own electric cars, the profits from these subsidies fall in the hands of car producers such as Volkswagen, Tesla and Nissan. Building ferries in Norway would create industrial competitiveness and increase workplaces.

8.5 Other potential applications in the maritime sector

The domestic maritime sector emits 9% of the total emissions in Norway and has the potential of being a big contributor to reach the 2030 targets. With this in mind, car passenger ferries are not the only place where hydrogen could be used as a fuel. As we mentioned previously, the supply vessel Viking Lady was equipped with a MCFC with the intention of having it run off hydrogen. With technology improvements and the higher carbon tax applied to petroleum activity on the Norwegian continental shelf, we could see hydrogen power several supply vessels and oil platforms.

Since hydrogen fuel cell technology is still too expensive to compete with fossil fuels, but has the advantage of being more energy efficient, the first application should be in projects with high mileage that use a lot of energy. For this reason there have been discussions regarding the use of hydrogen in both fishing vessel and the express passenger ferry.

9. Conclusion

This thesis was set out to evaluate potential implementations of hydrogen in the Norwegian ferry fleet. Seeing as battery powered ferries are a suitable alternative for shorter routes, the study has assessed the effects of using hydrogen on the longer routes, both in terms of environmental impact and economic implications. Given the recent ruling on new tenders requiring ferries to run off low- or zero-emission fuel, finding a viable alternative to fossil fuels for Norwegian ferries is a pressing issue. Hydrogen is an energy carrier with many attributes, one of which is being emission free when produced from renewable resources. However, the technology is still young and not yet competitive with the current fossil fuel technology. The components one has to install on the ferries (PEMFCs, hydrogen tanks and lithium-ion batteries) are very costly. However, it is the high price of hydrogen compared to the alternatives that render the projects unprofitable. The study attempts to establish under which conditions hydrogen could be an efficient fuel in Norwegian ferries. Under the current conditions, hydrogen is not a cost-efficient alternative to fossil fuels.

Nevertheless, there are some important findings to extract from the results of this study. Among the 39 routes the study includes, some show signs of being more suitable for the use as hydrogen as fuel than others. Mainly based on lower abatement costs, we have identified the following routes as the most interesting for the implementation of hydrogen: Hufthamar-Krokeide, Tjøtta-Forvik, Horn-Igerøy, Igerøy-Tjøtta and Stokkvågen-Onøy-Sleneset-Lovund. Assuming that hydrogen prices fall to the predicted low price of 35 NOK/kg and that maritime PEMFCs reach a level of 450 EUR/kW, these routes would have the lowest abatement costs of the featured group at less than 1,500 NOK/tCO_2. However, all except Stokkvågen-Onøy-Sleneset-Lovund have tenders expiring by 2017. Given that the timeline is too short for the current prices of hydrogen and PEMFC to decrease, it seems unlikely for hydrogen implementation on these routes to be feasible at this stage. Stokkvågen-Onøy-Sleneset-Lovund has a tender expiring in 2021, by which time the technology might have become more competitive. Nevertheless, a more detailed analysis including true costs, only available to operators and other players in the industry, should be carried out to get a more realistic cost estimate of implementing hydrogen in each specific route.

The results also show that LNG is currently a better alternative on the longer routes if the goal is to reduce emissions in the most affordable way. Be that as it may, the Norwegian Parliament has stated that LNG cannot be regarded as a low-emission alternative, and that all future ferry tenders should include a requirement of low- and zero-emission technology, when technologically feasible. Given this, and the fact that batteries are not suitable on longer routes, there is a need to develop a Norwegian industry that can provide a viable alternative fuel for Norwegian ferries operating on such routes.

If hydrogen is to be used as a fuel in future ferry projects, the results show that some barriers have to be crossed. Firstly, an established hydrogen market is a requirement for the sustained delivery of the fuel at a lower price than that which is available today, and with that, the need for infrastructure arises. Secondly, the technology linked to the PEMFC system must advance at the predicted rate. Thirdly, the evolution of Norwegian electricity prices is a factor to be permanently considered, given how susceptible hydrogen production is to increases in electricity prices. Lastly, governmental support schemes can be put in place to further accelerate the timeline of a potential hydrogen implementation.

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