Bachelor's thesis

Even Nøtland Giske
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Alternative locations of hydrogen-factory utilising surplus energy in Hellesylt

for zero-emission maritime transport in Geiranger

May 2020

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Preface

This Bachelor's thesis is submitted as a part of a three-year degree in Renewable Energy at the Norwegian University of Science and Technology. The thesis is graded from A to F and comprises 20 credits. It is written in collaboration between two persons, Even N. Giske and Stian O. Kroken. The main partner of this thesis is Kongsberg Maritime CM AS. Together with Solveig Bjørneset, Vilmar Æsøy and Joakim Kjølleberg a problem statement was developed. Solveig Bjørneset has been the main contact person from the company and Vilmar Æsøy has been our contact from NTNU throughout the whole period. They all deserve the biggest thanks from us for the great guidance and support on how to improve our thesis throughout the whole semester. Our co-partner Kongsberg Seatex with Jan Petter Høiaas provided us with excellent office space at Pirsenteret in Trondheim. Challenges due to Covid-19 prevented us from sitting at the assigned office for the last half of the semester, and it has caused challenges due to the collection of information. Despite this, we achieved a pleasing result.

The problem statement caught our interest when combining renewable energy sources, transportation issues and implementing it to the maritime sector. A fun part of the thesis was that we got a result we were not expecting from the beginning. This multidisciplinary project is highly relevant to the Renewable Energy field of study. It is part of several different subject areas, such as high voltage grids, energy production, HSE, project management, economics and different forms of energy.

We would like to thank Oddbjørn Brunstad and Clemens Kraft AS, for giving us data from Ringdal power plant and a great insight into the past and current situation in Hellesylt Hydrogen Hub -project. We would also like to thank Bjørn Gregert Halvorsen from NEL Hydrogen for information about electrolysers, and Arild Eiken from HYON for information about bunkering rate and storage. At last, thanks to Arve Ryen from Nexans, Tomas Holte from Kraftlaks AS, Morten UV from St.Olavs Hospital.

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Scope of work

The scope of work states the limitations of this thesis. Due to time limitations, the areas of focus are narrowed. The premises for this analysis are therefore set to:

- The thesis will look at the hydrogen produced from surplus energy at Ringdal hydroelectric power plant, and down to the storage tank at the quay or by doing a container switch onboard the ferry. This limitation is done after a consultation with our supervisor. However, the greatest risks are when the ship receives the hydrogen from the storage tank or dispenser. Therefore a thorough evaluation of the bunkering process should also be done.

- Factors like taxes, duties, politics, and support from pubic founds will have a significant impact on the final product. To simplify the thesis, only high voltage concession has been taken into the consideration when selection one of the cases.

- For the thesis, fixed electricity prices and gird rates are used to do the calculations. In reality, this is not the case. Electricity prices are hard to estimate and will vary a lot during the lifetime of the electrolyser. The same applies to the grid rate, which could be the deciding factor in the project if this gets reduced or removed. Therefore a new calculation should be done each year. For Case 1, 2 and 3 the thesis assumes that Ringdal power station delivers most of the power to the electrolyser with a fixed electricity price of 0.25 NOK/kWh. While Case 4 assumes import of power from the grid with a fixed price of 0.38 NOK/kWh.

- This thesis is written with with limited access to data, only open information have been used. Electrolysis and hydrogen production in this large scale is relatively new technology and gathering information can be difficult for a public bachelor thesis. Companies are usually not giving out pricing due to commercial interest without a specific project. The prices in this thesis are therefore either found on the web, similar open projects, or done by own assumptions and estimations. Therefore all the numbers used are not exact numbers and the prices and numbers calculated are either rounded up or down, or is the average values.

- The risk analysis done for this thesis have some limitations and have been simplified. Usually when doing a risk analysis a multidisciplinary group of experts comes together and discusses the risks. This can be done by using a FMEA/FMECA analysis to map out the different risks. However, due to the limitations of the thesis it was not possible to gather a larger group to discuss this, and a more simplified superior risk analysis using theory for hydrogen and electrolyser, and a discussion among the group members. The analysis is made to be a comparison between the four different cases, so the actual values may differ from the real scenario.

- The thesis uses a priority vector calculation to estimate the best solution. This is based on own assumption, thoughts and evaluated values calculated from pricing, risk analysis, transport and practical challenges. However, the limitation of access to date can affect these numbers and the calculation done. This means that the priority vectors will have uncertainty in some degree and therefore a more accurately priority vector analysis with more correct numbers should be done.

Abstract

This bachelor thesis aims to find a good solution to utilise the surplus energy in Hellesylt for hydrogen production to the ferry route Hellesylt-Geiranger. The reason for the surplus energy in Hellesylt is due to the electrical grid being undersized. This lead to a lot of heat and power loss at the grid. To reduce the losses and utilise the surplus energy, the idea is to build a hydrogen factory in Hellesylt.

The main focus of this thesis will be to find the best solution for the location of the electrolyser with focus on safety, pricing, hydrogen transport, visual pollution and practical execution. Furthermore, the thesis will look at opportunities for the sale and usage of the bi-products, oxygen and heat. The reason for this is to achieve better efficiency in the overall energy picture and to make the hydrogen competitive against marine diesel.

Four different cases are taken into consideration. Case 1 is about placing the factory at Ringdal power plant and then transporting the hydrogen through a gas pipe to the quay. Case 2 also has the factory located at Ringdal power plant, but transports the hydrogen by a truck. Case 3 has the factory located at the quay in Hellesylt centre, power is transferred using a high voltage cable that goes from Ringdal power plant through the bedrock down to the city centre. Case 4 also deals with placing the factory at the quay, but are transporting the power by expanding the existing power grid and by purchasing power.

For the gas pipe solution in Case 1, the total cost will be 75 MNOK for the ten-year period. This gives a hydrogen price of 40 NOK/kg. For the truck solution in Case 2, the total cost is 71 MNOK for a ten-years period. The hydrogen price will then be 38 NOK/kg. For the solution with a high voltage cable in a pipe, Case 3, the total cost for the ten-years period will then be 109 MNOK. This gives a hydrogen price of 58 NOK/kg. The last solution with connection to the existing grid in Case 4 gives a total cost of 114 MNOK, and a hydrogen price of 60 NOK/kg.

Safety has the highest priority when choosing one of the cases, while the economy comes second. Transport solution with truck and hydrogen plant located at Ringdal in Case 2 gives the lowest cost and hydrogen price, while transport by pipeline and the same location in Case 1 gives the second-lowest. The difference at 2 NOK/kg between the cases might be caused by the uncertainties in the calculations, so safety will be the deciding factor. Case 1 scores better on safety than Case 2 and is therefore higher valued than Case 2. High-voltage cable from Ringdal in Case 3 gives the second-highest cost and hydrogen price, while connection to existing grid in Case 4 gives the highest cost and hydrogen price. This also have the same difference at 2 NOK/kg, which could also be caused by uncertainties in the calculations. Furthermore, Case 3 and 4 have the lowest scores on safety.

Oxygen transport and sales to nearby land-based fish farms are proved to be possible. Oxygen sales can yield a net income of 1.9 MNOK. This will give a 17-20 % lower hydrogen price for all the cases. Regarding heat as one of the bi-products, it is only for Case 3 and 4 were it could serve any purpose, due to the location of the electrolysis plant. The usable heat after losses in equipment and transportation is 1.400 MWh.

It is therefore concluded that Case 1, transport via pipeline, is the best solution overall in terms of safety and economy. This gives a low hydrogen price, while the safety is high. Another good alternative would also be Case 2, truck transport, with an even better price, but lower safety. Case 3 and 4 present high costs and challenges related to concession and grid-rates. These are therefore considered not to be as competitive.

Norwegian abstract

Denne bacheloroppgaven har som mål å finne en god løsning for å utnytte overskuddsenergi i Hellesylt til produksjon av Hydrogen til ferjeruten Hellesylt - Geiranger. Overskuddsenergien i Hellesylt skyldes at strømnettet er underdimensjonert. Dette fører til mye varmgang og tap i nettet. For å redusere tapene er derfor ideen å sette opp en lokal hydrogen fabrikk i Hellesylt.

Hovedfokuset i denne oppgaven vil være å gjøre rede for den beste plasseringen av hydrogen-fabrikken med tanke på sikkerhet, pris, transport til lagringstank, visuell forurensning og praktisk utførelse. I tillegg vil oppgaven undersøke salg av bi-produktene, oksygen og varme. Dette for å oppnå en bedre virkningsgrad i det totale energibildet, og for å gjøre hydrogenet konkurransedyktig mot marine diesel.

Fire ulike caser har blitt tatt i betraktning. Case 1 handler om å plassere fabrikken hos Ringdal kraftverk, for å så transportere hydrogenet gjennom gassrør til kaien. Case 2 har også fabrikken plassert hos Ringdal kraftverk, men transporterer hydrogenet ved hjelp av lastebil. Case 3 har fabrikken plassert ved kaien i Hellesylt sentrum, kraft overføres ved hjelp av høyspentkabler som går fra Ringdal kraftverk gjennom berggrunnen ned til sentrum. Case 4 omhandler også å plassere fabrikken ved kaien, men transporterer kraften ved hjelp av utvidelse av det eksisterende kraftnettet og ved fullstendig kjøp av kraft.

For gassrør-løsningen i Case 1 er totalkostnaden 75 MNOK for tiårsperioden, med en hydrogenpris på 40 NOK/kg. For lastebil-løsningen i Case 2 er totalkostnaden på 71 MNOK for tiårsperioden, med en hydrogenpris på 38 NOK/kg. For løsningen med høyspentkabel i rør, Case 3, er totalkostnaden for tiårsperioden 109 MNOK. Dette gir en hydrogenpris på 58 NOK/kg. Siste løsningen med tilkobling til eksisterende nett i Case 4, gir en totalkostnad på 114 MNOK og en hydrogenpris på 60 NOK/kg.

For valg av case har sikkerhet høyest prioritering, etterfulgt av pris. Transportløsning med lastebil og hydrogenfabrikken plassert på Ringdal i Case 2 gir lavest kostnad og hydrogenpris, mens transport ved rørledning og samme plassering i Case 1 gir nest lavest. Forskjellen på 2 NOK/kg mellom casene kan være forårsaket av usikkerheter i beregningene, dermed vil sikkerheten være den avgjørende faktoren. Case 1 scorer bedre på sikkerhet enn Case 2 og scorer derfor best av alle totalt. Case 1 blir derfor vurdert over Case 2 på grunn av dette. Høyspentkabel fra Ringdal i Case 3 gir nest høyest kostnad og hydrogenpris, mens tilkobling til eksisterende nett i Case 4 gir høyest kostnad og hydrogenpris. Det skiller også 2 NOK mellom Case 3 og 4. I tillegg kommer både Case 3 og 4 dårligst ut på sikkerhet.

Salg og transport av oksygen til nærliggende landbaserte oppdrettsanlegg viser seg å være mulig. Salg av oksygen kan gi en bi-inntekt på 1.9 MNOK netto. Dette vil gi en 17-20 % lavere hydrogen pris for alle Casene. Varme som bi-produkt, er det kun for Case 3 og 4 som har formål med å utnytte dette, grunnet den sentrumsnære plasseringen av elektrolysefabrikken. Det vil også produseres varme tilsvarende 1 400 MWh som vil kunne benyttes som oppvarming etter tap i transport og utstyr.

Case 1, transport via rørledning er den beste løsningen totalt sett med tanke på sikkerhet og økonomi. Denne gir en lav hydrogenpris, samtidig som sikkerheten er høy. Et annet godt alternativ vil være Case 2, transport med lastebil. Denne gir en enda lavere pris, men en lavere sikkerhet enn Case 1. Case 3 og 4 gir høye kostnader og utfordringer knyttet til konsesjon og nett-tariffer. Disse er derfor vurdert til å ikke være like konkurransedyktige.

Abbreviations

Abridgement:	**Name:**	**Description:**
NOK/KR	Norwegian Kroner	Norwegian currency
HHH	Hellesylt Hydrogen Hub	Public pre-study report
kWh	Kilo watts per hour	Unit to amount of energy
LCC	Life Cycle Cost	Total cost estimate
LHV	Lower heating value	-
NVE	The Norwegian Water Resources and Energy Directorate	-
AC	Alternating current	Electric current
DC	Direct current	Electric current
NT3	Nett-Tariff 3	Tariff Area for Hellesylt
CapEx	Capital expenses	Costs
OpEx	Operational expenses	Costs
WE	Water electrolysis	-
EC	Electrolysis cell	-
HV	High Voltage	-
STP	Standard temperature and pressure	Industry standard value
PEMWE	Proten Exchange Membrane water electrolysis	Type of electrolyser
AWE	Alkaline water electrolysis	Type of electrolyser
SSB	Statistics Norway	Norwegian statistics bureau
VAT	Value Added Tax	Tax for goods and services
TSO	Transmission system operator	Electrical grid operator
DSO	Distribution system operator	Electrical grid operator
RPN	Risk potential number	Sort the risks from highest to lowest

List of Tables

List of Figures

List of symbols

Symbol	**Unit**	**Description**
Nm^3	m^3	Volumetric flow at 1 atm and 0 $°C$
kWh	Watt	Energy
I	A	Current
H_2	Chemical compound	Hydrogen gas
CH_2	Chemical compound	Compressed hydrogen gas
CO_2	Chemical compound	Carbon dioxide
OH^-	Chemical compound	Hydroxide
m	kg	Mass
O_2	-	Oxygen gas
p	Pa, bar	Pressure
Q	Joules [J]	Heat
mJ	MilliJoules [J]	Energy
T	K	Temperature
$\bar{R}$	J/Kmol	Universal gas constant

Contents

1 Introduction

Hellesylt is a village located at the far end of the fjord in Sunnylsfjorden in Stranda, Møre og Romsdal. This is a fjord at the entrance to the Geiranger fjord. The Geiranger fjord is one of the UNESCO world heritage fjords and is also one of the most visited fjords in Norway. Today two ferries are operating the route Hellesylt to Geiranger from April 1st to October 31st. The ferries are among the oldest vessels in Fjord1 portfolio., which means they are not pollution-free.

In the summer season, there are also cruise ships entering the Sunnylvsfjord and Geirangerfjord with thousands of passengers daily. These ships use fuel that leaves a large environmental footprint. Therefore the problem with local pollution in the fjord occurs. Today 80 % of the ships run on heavy oil and therefore emit a lot of NOx and SOx, which is bad for the local communities.

The Norwegian Parliament agreed that the world heritage fjords are going to be pollution-free as soon as possible or by 2026 the latest (might be delayed to 2030). This would make Geiranger one of the world's first pollution-free fjords. This is why it is urgent to find a solution to the local pollution from ferries and cruise ships [25]. Different ideas have come up on how to solve the pollution challenges. One of the solutions for vessels at this size would be to use hydrogen as fuel.

Today the use of hydrogen in the maritime transport sector is minimal, but an increasing interest is apparent. Figure 1.1 from a DNV-GL report in 2018 shows an estimation of the total hydrogen demand in 2030. The figure shows that 7 % of the total hydrogen demand needed in 2030 for Norway is for the maritime sector, which is a total of 17 900 tonnes hydrogen per year. Out of the 17900 tonnes, 10 000 tonnes hydrogen is estimated to be for ferries [8].

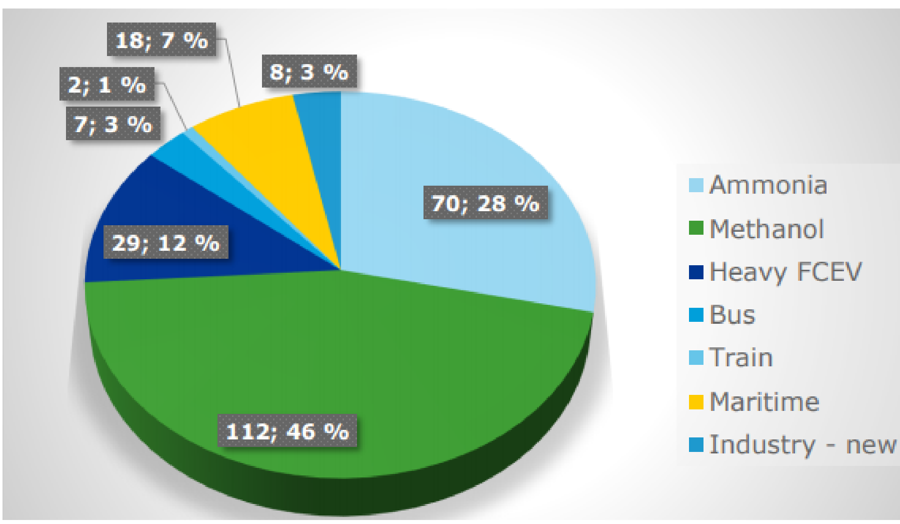


Figure 1.1: *Estimated hydrogen demand in Norway in 2030 (In thousand tonnes/year and percentage of total demand) [8]*

To produce hydrogen, electrical power is required. Hellesylt is in a unique position due to its surplus energy from the local hydroelectric power plants. Geiranger is therefore in an excellent position to be one of the first pollution-free fjords.

1.1 Structure of the thesis

The second chapter contains information about Ringdal hydroelectric power plant and how the stranded energy affects the situation, and a base of information regarding the ferries operating in the area at the moment.

The third chapter is introducing hydrogen and electrolysis technology. This chapter includes production, storage, compression and chemical data about hydrogen. At the end of this chapter, it is explained which costs are related to production, LCC-cycle and how the sale price for hydrogen is set.

Chapter four presents a general risk analysis for the whole situation. Different incidents are described together with risk-reducing measurements. The risk-scale is introduced and explained to value incidents easily.

In chapters five, six, seven and eight, all the cases with relevant information that could affect the project is listed. It mainly includes concepts, practical challenges, safety and economics.

In chapter nine, usage and sales of residues has been accounted for. Different clients, different ways of use, transportation and economic income are calculated.

Chapter ten sums up the results and discusses the findings for each case. A comparison between the different cases is done, as well as an overall economic calculation.

Chapter eleven holds the conclusion of the report. It contains a small summary with essential conclusions made from the results and discussion.

1.2 Problem to be addressed

The problem this thesis will look into is divided into two parts:

1. ***What is the most convenient, economical and safest way of producing and transporting hydrogen to the quay in Hellesylt.***
2. ***Utilisation of the residue from electrolysis to improve the total energy efficiency and the economy in the value chain.***

Today the ferries in Hellesylt run on fossil fuel, while there is a need for utilisation of the excessive power in the area. It is desirable to replace the current ferries with hydrogen ferries. Hellesylt is a small town with many tourists during the high season. The location of a hydrogen factory will have a large impact on the community. The new ferry is to be in a size of 1000 kW. This value will be used as a basis for the calculations. The focus will be on having the production either at Ringdal power plant and then transporting it down to the quay, or by having the whole production site at the quay. The second part of the problem will be to look at the usage of residue from the electrolyser.

2 The situation in Hellesylt today

Hellesylt is a small community located at the far end of the fjord in Sunnylvsfjorden in Stranda. The terrain around Hellesylt is mainly steep mountains and deep fjords. This can raise many challenges when building comprehensive infrastructure. This chapter will elaborate on the current energy and ferry situation in Hellesylt, and the energy and hydrogen needed for the new ferries.

2.1 Hydroelectric power plants and stranded energy

The source of power in Hellesylt is generated from three hydroelectric power plants. These power plants, which are named Ringdal, Litlebø and Stadhem, are three run-of-the-river hydroelectric power plants which are connected to the grid from a 22 kV high voltage cable which comes from Tomsgaard transformer. The location of the different hydroelectric power plants and the closest transformer is shown in Figure 2.1.

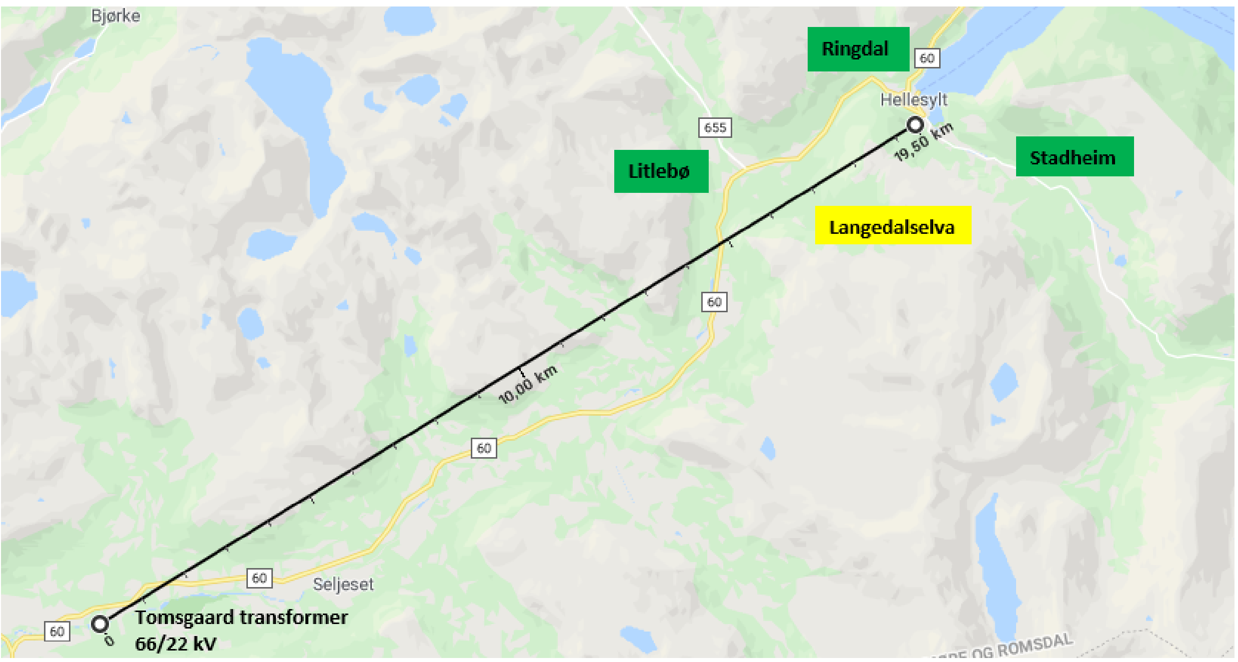


Figure 2.1: *Hydroelectric power plants and closest transformer in Hellesylt*

The Ringdal power plant is located closest to Hellesylt city centre just by the fjord. Ringdal utilises a head of 150 m and has a rated power of 5.85 MW, according to Norwegian Energy Regulatory Authority - NVE. The estimated power production is 17.8 GWh/year. In 2018 the power production was 15.89 GWh/year, a little under average [23]. Figure 2.2 shows the production data for 2019 and the mean value from 2012-2019 in kWh each month for Ringdal. The figure shows that the highest mean production is from May to August and the lowest production is during the winter months. However, in 2019 the production was almost zero both in May and December. It is assumed that the new hydrogen factory will receive most of the power from Ringdal power station. So the amount of power produced from Ringdal will have a larger impact on the hydrogen factory.

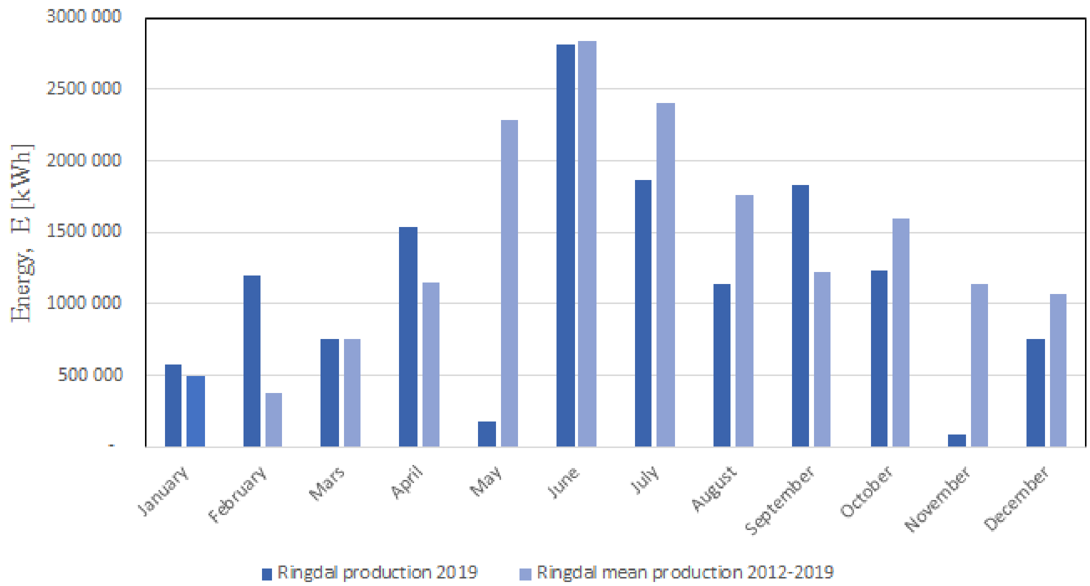


Figure 2.2: *Ringdal power plant production data for 2019 and the mean production from 2012-2019 in kWh*

The Litlebø power plant is located 5 km from Hellesylt and consists of two rivers, Langedalen and Nibbedalen. Langedalen has two Francis turbines with a rated power of 1,5 MW and 3 MW, and exploits a head of 82 m. Nibbedalen has only one Francis turbine and exploits a head of 62 m. These combined has a fixed power production of 27 GWh/year. [24]

Stadheim power plant is located east of Hellesylt and it is owned and operated by Tafjord power production AS. It utilises a head of 64 meters and has two Francis turbines with an installed capacity of 5.5 MW. The power production per year is around 25,4 GWh/year. [21]

Figure 2.1 shows that the closest transformer is Tomsgaard and is 19.50 km in air distance from Hellesylt. This is where the grid goes from 66 kV to 22 kV, and is the only import/export cable into Hellesylt. The 22 kV cable is what causes the main problem in Hellesylt, which is stranded energy.

Stranded energy means that the power plants can not produce the amount it is licensed to do, and have to run at a lower rate. Both Litlebø and Ringdal can be adjusted down as much as 3000 kW [3]. This is because the grid around this area has become undersized due to Hellesylt previously being an importing area, but has now become an export area of power.

When power is transferred on the undersized 22 kV cable grid it generates a lot of heat. This is called the marginal losses and is directly loss in power. For Ringdal, 2.5 GWh of a yearly production of 18 GWh could be exposed for 20 % marginal losses, which is a loss of 500 MWh. By establishing a hydrogen factory at around 2 MW, this loss can be reduced to half at 250 MWh. Larger factory could also possibly reduced the losses even more. Tomsgaard transformer where the 66 kV grid comes in is also recently upgraded from 15 kVA to 25 kVA. With this increased input the marginal losses in the grid will be even larger.

NVE has approved to upgrade the grid, on the condition that a total of 8.4 MW increase of power production is done. However, due to complaints regarding the impact it would have on nature, the Oil and energy department has decided to revoke the license for the new hydroelectric power plant in Langedalselva. Therefore the condition from NVE will not be fulfilled, and the current issue with stranded energy would still be there [26].

By establishing a local hydrogen factory the marginal losses can therefore be reduced. The idea is to use this surplus energy to make green hydrogen to use on the ferry as well as other vehicles like buses and cars when they become available. The electrolyser also produces oxygen and heat as residue. Utilising this residue has the potential to increase the total energy efficiency of the system and also generate more income.

A local hydrogen factory would also benefit the local town Hellesylt, as well as the owners of the power plants since today's situation is reducing the economy of the companies. Also, as mentioned Geiranger is one of the UNESCO World Heritage Fjords, so the need for a zero-emission ferry is high. The goal is to have zero-emission within 2026. Therefore a hydrogen factory in Hellesylt could help solve two problems.

2.2 Current ferries in Hellesylt

In the summer season, there are two more or less identical ferries shipping cars and passengers from Hellesylt to Geiranger through the Geiranger fjord. The ferries are called MF Veøy which was built in 1974, and MF Bolsøy which was built in 1971. This makes the ferries the eldest in the Fjord 1 portfolio. Therefore replacing these ferries in the near future is not unlikely. This ferry route is currently the most efficient way of getting to Geiranger and is therefore a vital route to operate. Figure 2.3 shows a picture of the current ferry MF Veøy and

Figure 2.3: *MF Veøy [34]*

The ferries operate from April 1st to October 31st. In the months April and October, the ferries operate a total of three times a day from Hellesylt. From May 1th to May 20st and September 11th to September 30th, the ferries operates four times a day from Hellesylt. In the summer season from May 20st to September 10st the ferries operates a total of eight times a day from Hellesylt. The trip typically has a duration of around 1,5 hours. This results in docking every one and a half hours, with about 25 minutes of laytime in the summer season [35]. Figure 2.4 shows the seagoing distance at 20.7 km with the crossing time of 65 minutes.

Figure 2.4: *Ferry route and distance from Hellesylt to Geiranger*

During wintertime, both of the ferries are generally at a layup. However, they can be used as a backup if other distances get technical problems or other issues [36] [3]. The two ferries are currently using marine diesel. These ferries have a consumption of roughly 300 000 liters/year, which corresponds to approximately 798 tonnes of CO_2 emission per year [3]. Each of the ferries have a fuel cost of roughly 3.4 MNOK every year, which is 6.8 MNOK each year in total.

2.3 Energy and hydrogen needed for the new ferries

The size of the new ferries in Hellesylt is assumed to be 1000 kW, with the same travelling time and interval as the current ferries. The travel time from Hellesylt to Geiranger is approximately 65 minutes. The laytime at each port is 25 minutes. The total travel time for a round-trip, including laytime at each port, then becomes 3 hours or 180 minutes. This means that the energy needed per ferry trip will be approximately 3000 kWh. The hydrogen stored onboard must therefore be enough to deliver energy equal to this amount.

To get hydrogen on board the it must first be produced by the electrolyser, then transferred to storage tanks, and then converted to back to electricity by a fuel cell. During this process there will be different energy losses. Figure 2.5 shows the expected energy demand and losses for each part of the hydrogen process.

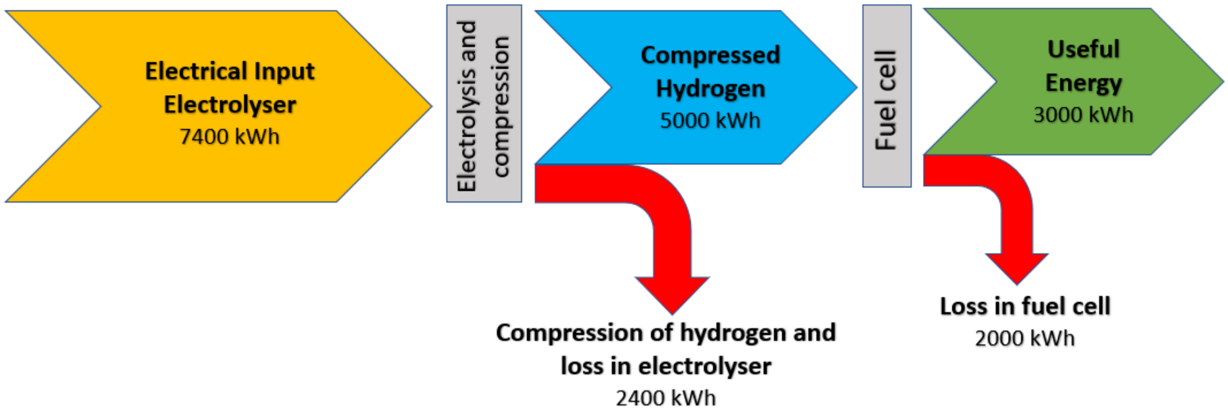


Figure 2.5: *Estimated energy need each trip for the new 1000 kW ferry*

The fuel cell have a efficiency of 60 %, which means that 2000 kWh will be lost in the fuel cell. The fuel cell therefore needs a input of 5000 kWh. The efficiency of the electrolyser is set to be 70 %, which means the loss in the electrolyser will be 2100 kWh. Additionally 300 kWh for compression to 350 bar is required. Therefore a total of 2400 kWh will be lost through electrolysis and compression of hydrogen. The total electrical input to the electrolyser for each ferry ride will therefore have to be approximately 7400 kWh to to overcome all losses and to obtain 3000 kWh output for the ferry.

The hydrogen demand can be calculated from the specific energy of hydrogen at 33 kWh/kg, and the energy needed per ferry round trip at 3000 kWh. This means the ferry needs approximately 90 kg hydrogen each round trip. Since the fuel cell can convert approximately 60 % of the energy content of the hydrogen into electrical energy the fuel cell needs an input of 150 kg of hydrogen each round trip.

There are eight departures from Hellesylt in the high season from May 20th to September 10th. The total hydrogen demand each day in the high season then becomes a total of 1200 kg/day. That means the electrolyser has to deliver 1.2 tonnes each day during this period. For the midseason from May 1st to May 20th and September 11th to September 30th the hydrogen demand is reduced to half at 600 kg/day. For the low season in April and October, the daily round trips are reduced to three and the hydrogen demand is reduced to 450 kg/day. Table 2.1 gives an overview of the total hydrogen needed each part of the season, each year and in a 10-year perspective for the new ferries. The total hydrogen demand after ten years is calculated from adding up the production each season.

Table 2.1: *Hydrogen demand for the different seasons and each year for the new ferries*

Season	Days	Hydrogen	Unit
Low season	60	450	kg/day
Mid season	40	600	kg/day
High season	113	1200	kg/day
Total hydrogen demand each year	213	187 000	kg
Total hydrogen demand in 10 year	2130	1 870 000	kg

Table 2.1 shows that the ferries will use a total of 187 000 kg each year and 1 870 000 kg hydrogen in a 10-years perspective. However, as mentioned in chapter 2.2 the ferries are normally at layup during winter time. This means that the new hydrogen factory could loose its biggest costumer during the winter time. There is still plenty of energy that could be used for hydrogen production for the rest of the year as Figure 2.2 shows. One possibility is to sell the hydrogen to other costumers and transport it with trucks or ships. There could also be other users or bigger storage facilities to store the extra hydrogen produced. It depends on the demand and costumers nearby. If the hydrogen can be sold at a competitive price it could be profitable to transport it over long distances as well. To be able to sell hydrogen all year around would increase the income and make the project more profitable.

3 Hydrogen and electrolysis technology

Hydrogen in the shipping industry is relatively new. The technology is there, but the price is still the main concern together with safety. This chapter will first explain hydrogen and its challenges before it goes into the theory of different electrolysers, explanation of the additional equipment needed, and ends with economics of electrolysis.

3.1 Hydrogen

Hydrogen is a chemical element listed as number 1 in the periodic table, which means its the lightest element in the world with an atomic weight of 2.016 kg/kmol. Also, relative to its mass, hydrogen is the element most strongly bound to oxygen. It is estimated that a total of 90% of the observable universe is hydrogen. In natural form, hydrogen is bound to water H_2O due to the strong affinity between the elements. Oxygen, on the other hand, is in its elemental form. That means it is not combined with other elements to form compounds. Therefore if this gets onboard a vehicle we would have the lightest energy source available [13].

Standard temperature and pressure is usually used to define the standard conditions. Usually STP refers to a temperature at 0 $°C$ and a pressure at 1 ATM or 10^5 bar. At this condition, 1 mole of a gas is 22.4 liters/mol [50], which can also be written as 22.4 $Nm^3/kmol$. These conditions are usually the most common to define the volume term Nm^3 which is normally what companies states for products. At this pressure and temperature the hydrogen has a density of 0.09 kg/m^3 which is quite low compared to diesel and gasoline. That is the reason why it is difficult to store. However, hydrogen has a decent energy density at 33 kWh/kg (LHV), which makes it good as an energy source [18]. A overview of the hydrogen properties is given in Table 3.1.

Table 3.1: *Hydrogen properties*

Description	Value	Unit
Specific energy	33	kWh/kg
Density (15$°C$, 350 bar)	24	kg/m^3
Molar mass Hydrogen	2.016	kg/kmol
Volume of 1 mole gas at STP	22.4	$Nm^3/kmol$

3.1.1 Hydrogen safety

Hydrogen has different properties which can cause some safety concerns. Hydrogen is both highly flammable and gets easily ignited. When hydrogen burns in air, it burns with a pale blue colour which is almost invisible. This increases the risk of injuries. Also, only a 0.017 mJ ignition energy is required for hydrogen-air mixtures to ignite compare to 0.25 mJ for hydrocarbons. This means that hydrogen-air mixtures is extremely easy to ignite. The hydrogen is especially vulnerable for auto-ignition from leaks and atmospheric vents compared to any other flammable gas due to its low ignition energy. Hydrogen is also different from most gases since it increases in temperature when it expands from a higher to lower pressure. Because of the auto-ignition and an almost invisible flame, even small leaks become a potential risk for the personnel [9].

3.1.2 Green hydrogen production

There are different ways of producing hydrogen. The preferred way is using electrolysis with power from renewable energy sources. This is called green hydrogen. Today only 1% of the hydrogen production in the world comes from electrolysis [30]. The National Renewable Energy Laboratory (NREL) has estimated that it theoretically requires 39 kWh of electricity and 8.9 liters of water is required to produce 1 kg of hydrogen from electrolysis [30]. In practice this value will be higher. Figure 3.1 shows a process diagram for production of green compressed hydrogen using electrolysis from clean energy.

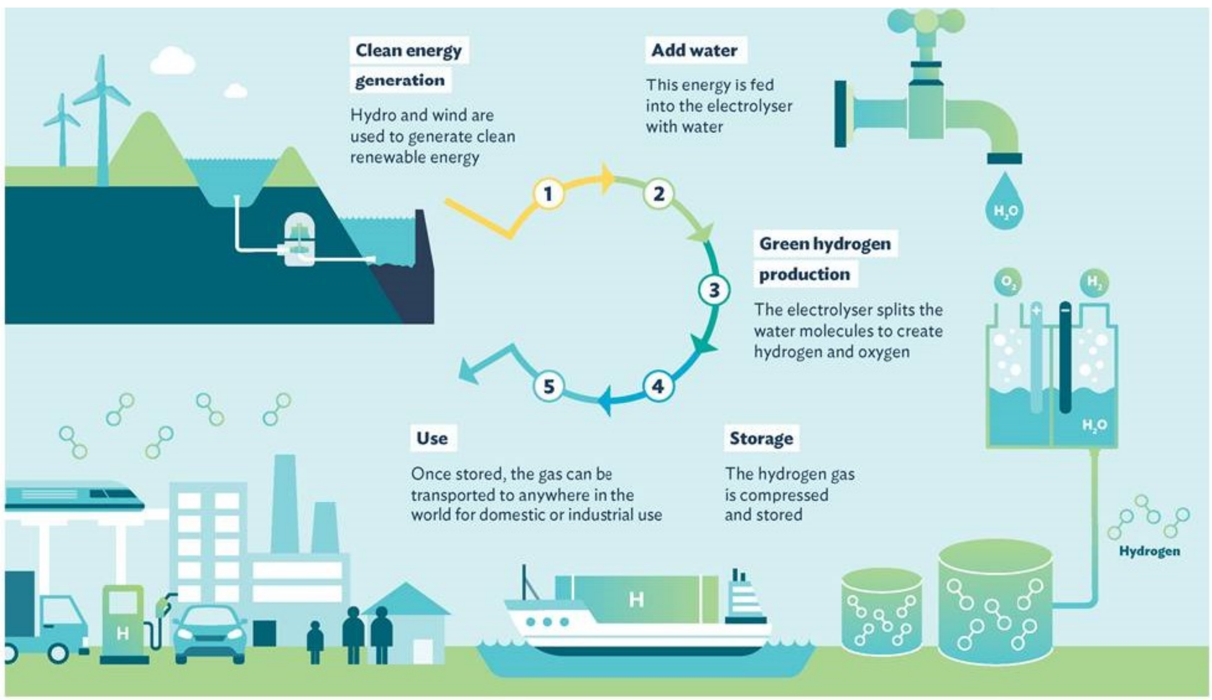


Figure 3.1: *Green hydrogen produced from clean energy through water electrolysis [53]*

One other way to produce hydrogen is by reforming natural gas where the CO_2 is captured and stored underground. This is called blue hydrogen. The last option is hydrogen produced from fossil fuels like coal and oil. This is called grey hydrogen, which is the most common way of producing hydrogen today [30].

When looking at hydrogen as an energy source, it needs to overcome three challenges. First, get hydrogen in pure elemental form. Second, getting it to a form that makes it possible to store on a vehicle. Third, convert it efficiently into power for vehicles and other appliances [13].

Table 3.2 shows the estimated prices for hydrogen per kg with different electrolysis technologies for 2020 and 2030. The green colour is the investment cost of electrolysis and the light blue is the cost of buying electricity. The figure shows that Alkaline electrolysis can be as low as 22 NOK/kg and as high as 44 NOK/kg in 2020, while proton exchange membrane electrolysis has a slightly higher price in 2020. The kilo price for hydrogen from PEM are expected to decrease in the future since this is a newer technology, and research is still ongoing to improve the efficiency.

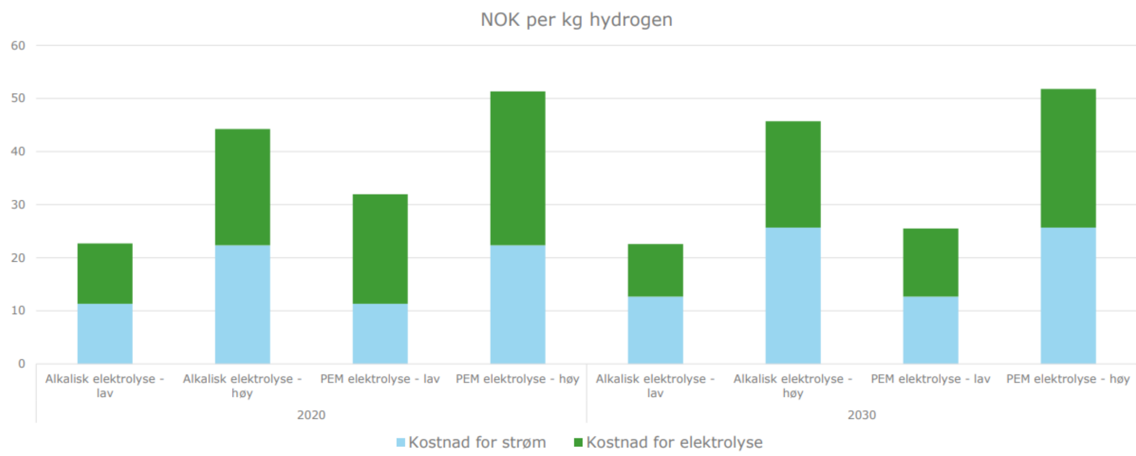


Figure 3.2: *Estimated hydrogen price per kg for different electrolysis technologies for 2020 and 2030 [8]*

3.1.3 Hydrogen as a storage medium

As mentioned earlier, one of the challenges with hydrogen is storing it. A hydrogen storage system requires three things. First, hydrogen production from electrolysis. Second, a storage and distribution system. Then third, reuse from the fuel cell. Hydrogen can also come from other sources, from reforming natural gas or coal. The benefits of hydrogen as a storage medium can be seen from comparing it to different energy storage mediums. Figure 3.3 shows the volumetric energy vs. specific energy.

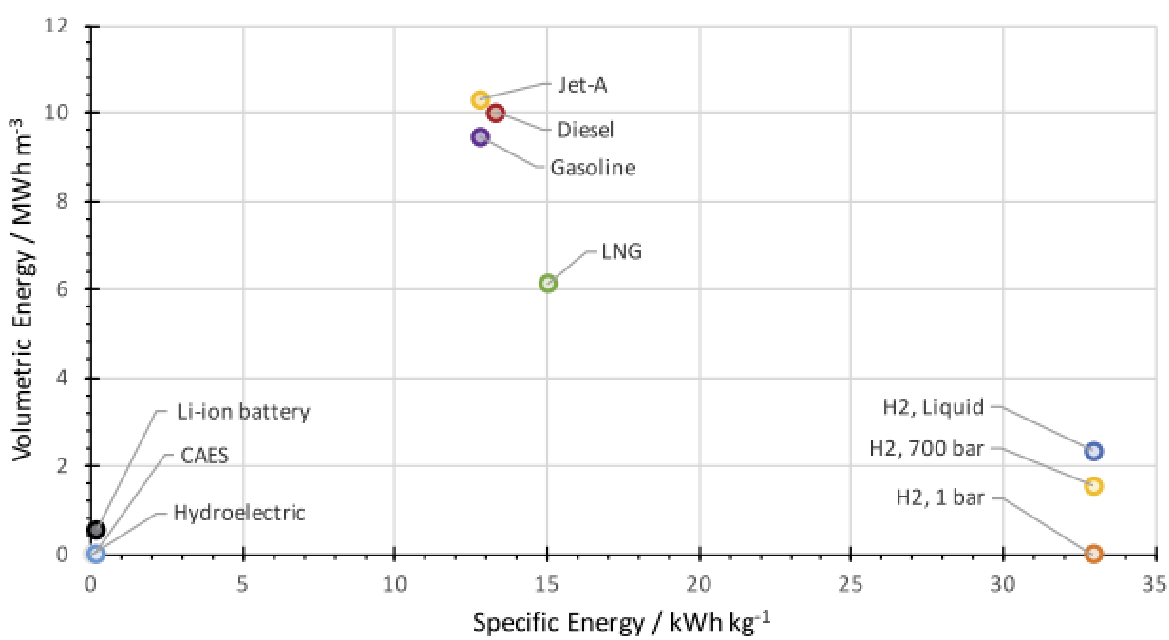


Figure 3.3: *Graphical overview of different energy storage mediums [13]*

From the graphical overview it is easy to see that the traditional Jet-A, diesel and gasoline fuel has the highest volumetric energy which makes this so good for storing in moving vehicles. LNG is also a good option for transport like we see in a lot of marine vessels. It is also worth to notice that the Li-ion battery is placed far down on the specific energy axis but a little bit higher at the volumetric energy than hydrogen. Hydrogen on the other hand, has a relatively low volumetric energy but high specific energy, around 33 kWh/kg. This shows the problem when storing hydrogen. At standard pressure and temperature (STP) hydrogen has a density of around 0.090 kg/m^3. At this density with 1 kg of hydrogen it would require a storage tank at 11 m3, which is equivalent to 100 km of driving a regular car. So to make hydrogen usable for storage it is necessary to increase the density. There are three options, either increase the pressure to gaseous form, cool it down to liquid form or in solid form metal hybrid. [28]

When in pressurised form the hydrogen is usually at 700 bar. Reaching this pressure the hydrogen's density increases to around 42 kg/m^3. At this level of density, 5 kg of hydrogen can be stored in a 125 liters tank. This solution is mostly used when storing hydrogen for vehicles. With 5 kg of hydrogen the range for a regular car goes up to about 500-600 km. For the maritime industry, a pressure around 200-350 bars would be more likely.

To obtain a liquid form of hydrogen it needs to be cooled down to -252.87 $°C$ at 1.013 bar. At this pressure and temperature hydrogen has a density of close to 71 kg/m^3. With this solution 5 kg of hydrogen can be stored in a 75 liters tank. This gives almost the same characteristics as regular gasoline and diesel tanks on cars. However, this requires a perfect isolated tank and almost 1/3 of the original amount of energy goes to cool it down. [28]

3.1.4 Hydrogen onboard ships

Today there are no large-scaled vessels using hydrogen. The technology is still under development and a standardisation have to be made. There are also safety concerns when storing hydrogen that have to be evaluated before it can become a commercial standard. There are several benefits of using hydrogen onboard ships. The challenge with charging and range would be less of an issue. Some ships operating at shorter distances have started using batteries. However, today's battery technology is not suitable for larger ships going over longer distances due to the weight, charging time and energy density. Hydrogen could therefore be the solution for larger ships in the future.

3.2 Electrolysis technology

Water electrolysis is the preferred method to produce hydrogen. This is because of it is pollution-free as long as the electricity comes from renewable sources. This process only requires water and electricity. Water is split into H_2, O_2-gas and some heat. There are different types of technologies available, and the next subsections will cover some of the most promising ones.

3.2.1 Proton Exchange Membrane water electrolysis

The Proton Exchange Membrane water electrolysis, PEMWE, consists of a Membrane electrode assembly, MEA. This membrane is the core and where the protons of H^+ ions are exchanged. Figure 3.4 shows the operation of a PEMWE.[13]

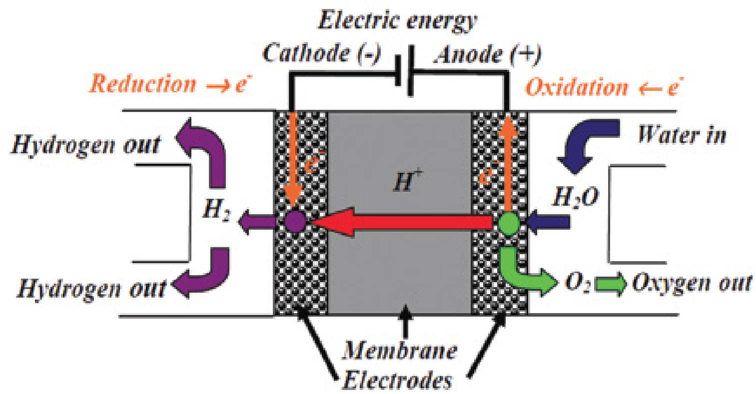


Figure 3.4: *Operation of a Proton Exchange Membrane Water electrolysis [20]*

Water enters the anode side and reacts on the electrode. This reaction sends out an H^+ proton through the membrane while retaining the O^{-2}, and electrons are transferred in the external circuit. The anode reaction is given in equation 3.1.

$$H_2O(l) \rightarrow H_2 + \tfrac{1}{2}O_2(g) \tag{3.1}$$

The H^+ proton then reacts with the electron to make H_2 at the cathode side from the reaction given in equation 3.2.

$$2H^+ + 2e^- \Leftrightarrow H_2(g) \tag{3.2}$$

The actual hydrogen production will therefore be on the cathode side. Using these equations the overall reaction then becomes equation 3.3.[13]

$$H_2 + \frac{1}{2}O_2 \Leftrightarrow H_2O \tag{3.3}$$

There are many advantages by using a PEM electrolysis. Some of these advantages are: produces high purity hydrogen, high-pressure operations, high current densities (above 2 A/cm^2), high efficiency (80-90%), fast response time, compact design and a small footprint [17].

However, there are some disadvantages. PEM electrolysis is sensitive to impurities in the water and the hydrogen. It also uses platinum electrodes which results in a higher cost. The main challenge with PEMWE is therefore to reduce costs[17] and is why the hydrogen price is higher as shown in Figure 3.2.

3.2.2 Alkaline water electrolysis

Alkaline electrolysers (AWE) have been used for a long time and is a well-established technology. In this type of electrolysis the reaction occurs in a solution that is composed of water and 30 % KOH, which is the electrolyte. To get the reaction going a voltage has to be applied between the two electrodes that are dipped in the solution.

When the voltage is applied the water molecule will take electrons and make OH^- ions and H_2 molecules at the cathode as equation 3.4 shows [13].

$$2H_2O(l) + 2e^- \Leftrightarrow H_2(g) + 2OH^- \tag{3.4}$$

The OH^- ions then travel through the electrolyte towards the anode side where they oxidise and give up an electron to make H_2O and O_2. To avoid recombination of the hydrogen and oxygen at the anode a diaphragm is usually used. The anode reaction is given in equation 3.5.

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O(l) + 2e^- \tag{3.5}$$

Combining equation 3.4 and equation 3.5 the overall reaction for the alkaline electrolysis then becomes equation 3.6.

$$H_2 + \frac{1}{2}O_2 \Leftrightarrow H_2O \tag{3.6}$$

The operation temperature of an alkaline electrolyser is usually in the 30-80° range. The electrical power consumption for the production of hydrogen depends on the current density. At 0.45 A/m^2 current density the power consumption vary around 4.1 to 4.5 kWh/Nm^3H_2 [13]. An illustration of an alkaline water electrolysis is shown in Figure 3.5.

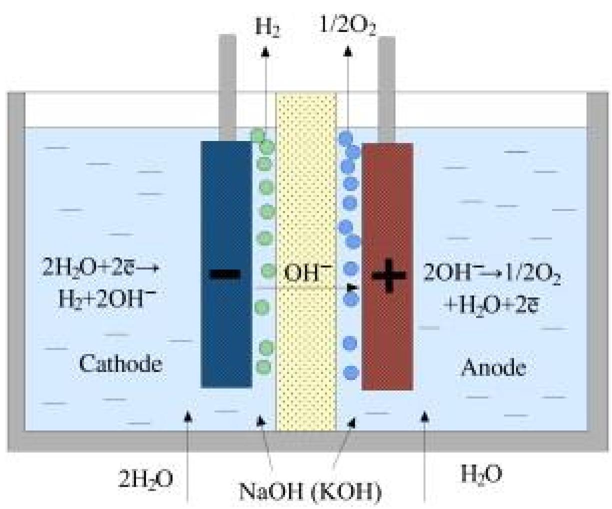


Figure 3.5: *Operation of an Alkaline Water Electrolysis*

Advantages with AWE is that it is a well-established technology, non-noble catalyst, lower costs, good efficiency (70-80%) and commercialised. However, the disadvantages with AWE is that it has limited current densities, below 400 mA/cm^2, low operation pressure, low energy efficiency, the formation of carbons at the electrode and low dynamic operation. However, a new approach to the AWE is under development and is called the Anion Exchange Membrane [17].

3.2.3 Future electrolysis technology

The Anion Exchange Membrane (AEM), known as Alkaline PEM is a promising technology. This technology utilises the benefits of both alkaline and PEM electrolysis. One of the advantages is that the noble metal in the electrocatalyst is replaced with a low cost transition metal catalyst. This technology can reduce the cost of hydrogen production and make hydrogen more competitive to traditional fuel.

3.3 Electrolyser models

NEL Hydrogen is a leading electrolyser manufacturer. The company was founded in 1927 with a small electrolyser a Norsk Hydro in Notodden. They produce both Proton Exchange Membrane Electrolysers and Atmospheric Alkaline Electrolysers. Most of the electrolysis manufacturers state the production capacity in Nm^3 which is the normal cubic meters. For the NEL models this refers to a pressure of 1 atm and temperature at 0 $^\circ C$. To calculate the m^3 at different conditions one can use the factor 22.4136 $Nm^3/kmol$.

3.3.1 NEL Proton Exchange Membrane electrolyser

The flexible Proton PEM Electrolyser M-Series from NEL hydrogen are shown in Figure 3.6. The Proton PEM electrolyser M-Series can produce 400 Nm^3/h or 892 kg/24h with a delivering pressure at 300 barg and 99.9998% purity on-demand.

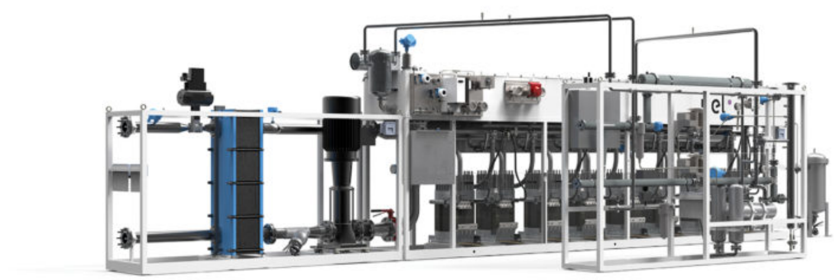


Figure 3.6: *NEL Proton PEM electrolyser M-Series [31]*

The M-Series is well suited for fuelling and can be scaled to a larger system if the need for hydrogen increases. It also has a fast response time and is very flexible, making it ideal to combine with renewable energy sources. The average power consumption per stack is 4.53 kWh/Nm^3. The M400 version would be the most reasonable choice to use with the power plant.

3.3.2 NEL Atmospheric Alkaline electrolyser

One other product from NEL is the Atmospheric Alkaline Electrolyser A-Series and is shown in Figure 3.7. This electrolyser can produce from 150 to 3880 Nm^3H_2/h. The A-series is more efficient compared to PEM and has a power consumption from 3.8 to 4.4 kWh/Nm^3. The delivering pressure is from 1-200 barg.

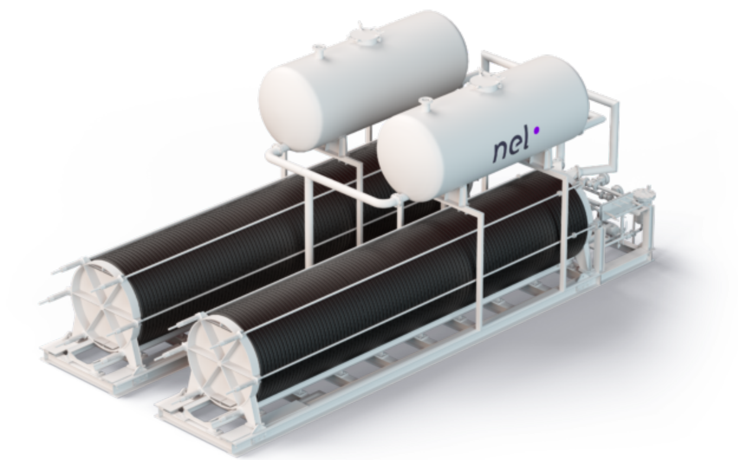


Figure 3.7: *NEL Atmospheric Alkaline Electrolyser A-Series [31]*

For this project the A1000 would be the production rate range. The A1000 has a net production rate of 600-970 Nm^3/h [31]. The advantage of choosing the Alkaline electrolyser according to NEL is that they are 20-30 % cheaper than the PEM electrolyser. Also, the Alkaline electrolysers are Norwegian while the PEM electrolysers are American.

3.4 Equipment needed for electrolysis

To get hydrogen onboard a marine vessel a good infrastructure is needed. It starts with the water in the power plant and needs to end up on the driveshaft to the vessel. The infrastructure needed in addition to the electrolyser are pipes, high voltage cables, electrical systems, safety systems, monitoring and maintenance. The electrolysis system usually consists of the electrolyser, compressor og electrical equipment. In addition storage tanks and one or more dispensers are required. In this specific project there are two different ideas for locations to the electrolyser. The location can either be at the dock close to the ferry or the building plot of Ringdal power plant. Both of these have up and downsides which will be elaborated later in the thesis. This section will elaborate on what these locations would need.

3.4.1 Compressor

When hydrogen is produced from electrolysis it is usually at a lower pressure. As mentioned earlier, low-pressure hydrogen has a low density which makes it less suitable for storing and transportation. To get hydrogen to a higher pressure and increase the density a compressor is required. The compression of hydrogen is a high energy-demanding process. It is estimated that compression of hydrogen to 70 MPa requires around 6 kWh/kg or 3 kWh/kg for 35 MPa. However, this energy is relatively low compared to what it would take to liquefy hydrogen. Compressed hydrogen needs only one-third of the energy that condensed hydrogen needs [12].

3.4.2 Storage tank

From the electrolyser the hydrogen can either be stored or used right away. The most convenient way is to store it in a tank. This tank must be able to handle the compressed hydrogen. There are different types of manufactures of hydrogen storage tanks. The company Hexagon Composite offers solutions for storing and transporting hydrogen, and are one of the leading suppliers. Hexagon Purus, which is a part of the Hexagon group, offers the X-STORE system. This system is a container-based storage system that is delivered in either 250, 300, or 500 bar pressure. Figure 3.8 shows the X-Store Hydrogen storage tank. [32]

Figure 3.8: *Hexagon X-Store Hydrogen storage [32]*

3.4.3 Fuelling station

If the ferry has a fixed tank on board, it needs a fuelling station at the quay to refill the tank. This fuelling station would need a high capacity since the ferry demands a large amount of hydrogen. The bunkering process can either be done with tubes or by swapping containers. The H_2-station in Figure 3.9 from NEL hydrogen can be used to deliver hydrogen to the ferry.

Figure 3.9: *NEL H2station for hydrogen fuelling*

This fuelling station has a capacity of 120 kg/h at 350 MPa or 350 bar. However, the bunkering rate can be much higher than the anticipated value of 120 kg/h according to NEL. The reason for this is that it can be more than one connection point with bigger diameters per bunkering line, which can reduce the filling time. With today's technology it can take around 45 minutes to tank 450 kg hydrogen.

3.4.4 Transformer and rectifier

The electrolyser would also require some electrical equipment like transformers, rectifiers and a main switch. The transformer would be needed to get the right voltage for the electrolyser, and the rectifier to get direct current (DCV). Also the main switch is important to isolate all the electrical equipment if necessary.

3.4.5 Fuel cell

To convert the hydrogen produced from electrolysis into electrical energy a fuel cell will have to be used. It exists both PEM fuel cell and alkaline fuel cell which is working on the same principle as the electrolysers, just reversed. They have an efficiency of around 60 %. Which means they can convert 60 % of the energy content of hydrogen into electrical energy.

3.5 Economics of electrolyser

This financial section will cover the capital expenditure of buying the electrolyser as well as building out the infrastructure needed. It will also look at the hydrogen price and grid rates. Like every other project there must be a reasonable economic basis for implementation. If not, financial support from public funds would be required. The total hydrogen price is mainly depending on three factors as shown in Figure 3.10.

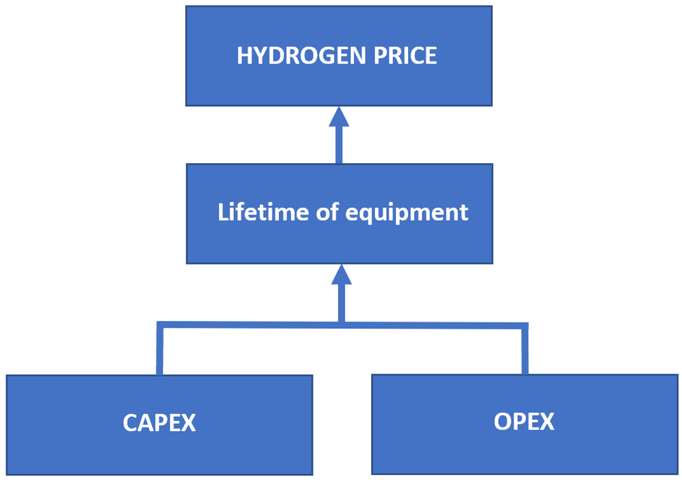


Figure 3.10: *Factors that directly affect the hydrogen price*

To explain the figure it would be natural to start with the investment cost -category. Investment costs are a wide-ranging category that can be broken down into smaller work-packages easily. It includes all materials and working hours needed to get the finalised product available on the dock. A work process or a project is normally being broken down into five different principles. It could be either physical, functional, department, business, or geographical hierarchical decomposition. For this project a natural choice would be either or both functional and geographical.

3.5.1 Capital expenses (CapEx)

The capital expenses are the main investment costs. For this project it is assumed an investment cost at about 12.5 MNOK/MW for the electrolyser including the compressor and electrical equipment, and a fixed price of 1.65 MNOK for installation, transport, and training. For the storage tank a price around 4500 NOK/kg is normal [11].

3.5.2 Operating expense (OpEx)

After commissioning there will be some expenses related to the operation and maintenance of the equipment. The electrolyser would be the equipment that requires most maintenance and follow-up. The operational costs caused by the electrolyser will mainly come from electricity. Since the price of electricity will vary, the operation cost will also vary. Additional OpEx for the electrolyser without the electricity is set to be 4.5 % of capital expenses for the electrolyser. For the storage tank the OpEx is set to be 0.5 % of CapEx of the storage tank [11].

3.5.3 Life cycle cost analysis

A life cycle costs (LCC) analysis has the advantage of doing an estimate of the total cost that will accrue over the lifetime of a component. Various reasons can be either advantages or disadvantages associated with investment costs or operating costs. Which resolution is best for the individual project can clearly be shown using the analysis [14]. The equipment has a restricted lifetime, therefore a payment often has to be completed during this period to be economical proficient. Figure 3.11 is a standard layout of an LCC. An electrolyser typically has a length of life at ten years. Financial calculations and prices will be based on this life cycle. Cost blackout and advanced estimates of ongoing unforeseen and unexpected costs in a project are not taken into account. The deeper into a project, the more the unexpected costs are revealed.

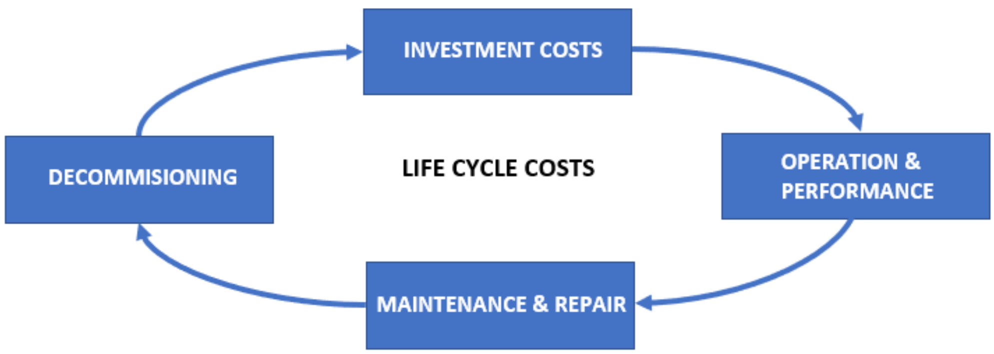


Figure 3.11: *Life cycle costs for the electrolyser and general equipment [14]*

4 Electrolyser calculations

This chapter shows the calculations done for the electrolyser and compressor. It is assumed that the new electrolyser will be an alkaline electrolyser.

4.1 Electrolyser size and production rate

The size of the electrolyser will depend upon the required fuelling speed in kg/h of hydrogen. The hydrogen needed for the new ferries is calculated in Table 2.1 and are 1200 kg, 600 kg and 450 kg for the high, mid, and low season. The calculated hydrogen demand includes losses and the energy needed for compression.

The electrolyser have to be designed after the high season demand. In the high season the time between the ferries is 1 hour and 30 minutes. With constant production on demand during this time the electrolyser would have to produce 98 kg/h of hydrogen to be able to deliver 150 kg every 1.5 hours. This would be very energy demanding, and would result in an large and more expensive electrolyser.

To reduce the production rate its possible to have a storage tank on the dock and also produce hydrogen overnight, which spreads the production over more hours and reduces the required production rate. The ferry operates a total of 12 hours per day, which means there are an additional 12 hours the electrolyser can produce and store hydrogen. This hydrogen can then be stored during the night and can fill the ferry before it starts operating 08:00 in the morning. With this solution it is possible to reduce the fuelling demand to 55 kg/h as Figure 4.1 shows.

Figure 4.1: *Daily production, storage and usage of hydrogen in the high season*

Figure 4.1 is based on production and consumption through a typical 24-hour day in the high season. It is assumed that the new ferry will have a tank big enough for one round trip, which is equal to 150 kg H2. The hourly hydrogen production is 55 kg/h and is continuously added, and consumption at 150 kg/trip for each departure from Hellesylt is subtracted. This figure illustrates the amount of hydrogen that needs to be produced daily not to get short.

On the last trip of the day 83 kg of hydrogen remains as a buffer. The graph starts at zero production at 19:00, the remaining value when time goes to 18:30 is the buffer. The storage capacity has to be at least above 710 kg to maintain a positive value for the amount of hydrogen. With the buffer added it should be slightly larger.

The manufactures of electrolyser usually states the the production rate in Nm^3. Using the fuelling demand at 55 kg/h and the parameters for hydrogen given in Table 3.1 the total production rate becomes 611 Nm^3/h. Multiplying the estimated production rate with the estimated energy need for the NEL alkaline electrolyser at 3.85 kWh/Nm^3 for a output of 20 barg, the electrolyser size becomes 2350 kW or 2.35 MW, without the compressor.

The size of the compressor is calculated from the production rate of the electrolyser and the increase of pressure. The calculated production rate from the electrolyser is 611 Nm^3/h and the outlet pressure is 20 barg. The output of the compressor is set to be 350 barg. This gives a compressor size of 114 kW. The electrolyser size including the compressor then becomes 2.5 MW. However, to prevent the electrolyser to run at constant full capacity in the high season and for future expanding, the size will be set a little higher to 2.7 MW. Table 4.1 shows the calculated values for the electrolyser for the high season.

Table 4.1: *Electrolyser calculations for the high season demand*

Description	**Value**	**Unit**
Fuelling demand in the high season	55	kg/h
Production rate in the high season	611	Nm^3/h
Energy demand for the Alkaline electrolyser	3.85	kWh/Nm^3
Electrolyser size including compressor	2.7	MW

4.2 Electrolyser energy demand

Table 4.2 shows the estimate energy need for 24 hour continuously production of hydrogen and compression, as shown in Figure 4.1, for the different seasons. The total energy demand then becomes 60 000 kWh each day for the high season, 30 000 kWh each day for the mid season and 22 000 kWh each day for the low season. Using the number of days in each season and the energy demand each year and in a ten-year perspective can be found. The total energy need each year is 9 300 000 kWh and 93 000 000 kWh in 10 years. The total energy demand includes losses and compression of hydrogen. However, it do not include wear and tear on the electrolyser, which can reduce the efficiency and increase the energy need.

Table 4.2: *Electrolyser daily and yearly energy demand*

Description	**Value**	**Unit**
Total energy consumption for 1200kg CH_2	60 000	kWh/day
Total energy consumption for 600 kg CH_2	30 000	kWh/day
Total energy consumption for 450 kg CH_2	22 000	kWh/day
Total energy consumption each year	9 300 000	kWh
Total energy consumption in 10 years	93 000 000	kWh

The values from Table 4.2 is then compared with Figure 4.2, which shows the production from Ringdal from 2019 and the mean value of the production from 2012-2019. It is assumed the Ringdal will deliver most of the power to the electrolyser.

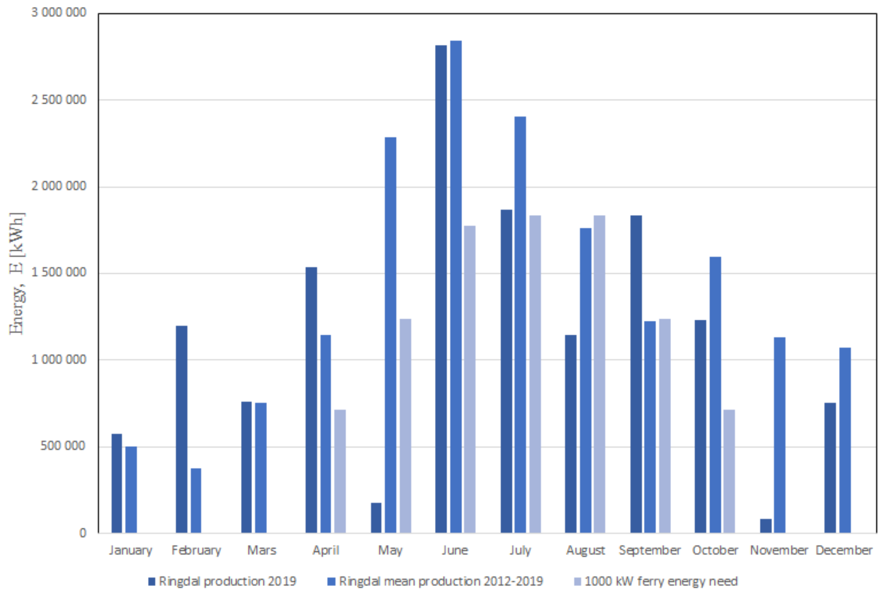


Figure 4.2: *Energy production from Ringdal per month with energy consumption from the electrolyser*

Looking at the mean production value from 2012-2019 it is expected that the production will follow the same path in the future, and therefore Ringdal should be able to deliver enough energy to the electrolyser most of the time. However, there might be periods where the production is too low from Ringdal. In May 2019 the production was only 179 000 kWh and the demand from the electrolyser is 1 200 000 kWh. This means the electrolyser would have to import energy from the grid or other nearby power stations. Also for August and September the energy from the 5 electrolyser is higher than the mean production from 2012-2019, which means that these months might always require to purchase energy from the grid or other plants.

5 Risk analysis

In this section, an analysis to identify the risks associated with a commissioned hydrogen system is described.

5.1 Introduction

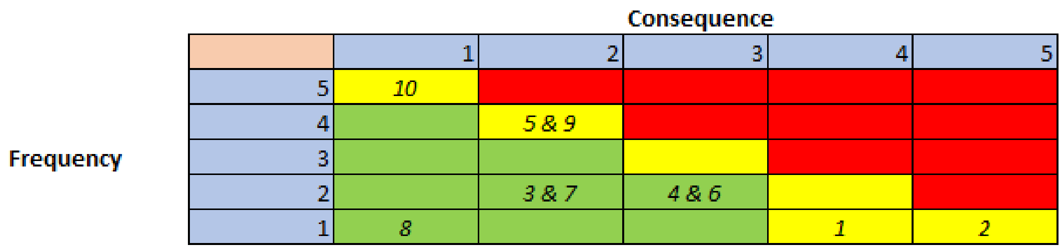
Hydrogen is highly flammable and can represent a great risk. Before the realisation of any project, a risk assessment should be implemented. The evaluations below include production, storage and offloading. Risk is a description of probability times consequences [Risk (Priority Number) = Probability · Consequences]. In the following analysis the scales are rated from 1 to 5, where 1 are the lowest and 5 are the highest. To get an indication of where the highest risks are located, an RPN-number is calculated. [15] Frequency is the definition of how likely it is that the incident will occur and the consequences are the result or effects of an unpleasant incident. Often is large experience data is used and needed for calculating this. Table 5.1 and Figure 5.1 is made mainly to explain the procedure and the function of the analysis.

The evaluation of the electrolyser is based on theory (hydrogen are highly inflammable, safety concerns from electrolyser) and real previous incidents. Risk concerned to flood and tide is estimated data received from Clemens Kraft AS. The remaining incidents are based on discussion, experience and consideration between group members.

Table 5.1: *RPN calculation*

Incident number	Incident	Frequency	Consequence	RPN
1	Damage fire	1	4	4
2	Damage explosion	1	5	5
3	Damage by a leak in electrolyser	2	2	4
4	Damage by a leak in storage tank	2	3	6
5	Damage / leak while transport	4	2	8
6	Crash in infrastructure	2	3	6
7	Weather	2	2	4
8	Tide	1	1	1
9	External fire	2	4	8
10	Tsunami	1	5	5

The values from the RPN Table 5.1 are to be placed in the desired box in Figure 5.1. In that way, each risk is being identified in the degree of the risk level. The values inserted are concluded after risk-reducing initiatives has been implemented. The red boxes symbolise High-, yellow Moderate- and green Low- risk. An incident after implementing risk-reducing measurement located in the red area should be avoided.



	Consequence				
Frequency	1	2	3	4	5
5	10				
4		5 & 9			
3					
2		3 & 7	4 & 6		
1	8			1	2

Figure 5.1: *Risk analysis table*

Table 5.2: *Valuation frequency [16]*

5	Extreme - Incident occurs often
4	High - Incident occurs
3	Considerable - Incident occurs from time to time
2	Moderate - Incident occurs rarely
1	Low - Incident occurs more or less never

Table 5.2 is the description behind the numbers of scaling for the frequency. Evaluations are based on a typical general matter.

Table 5.3: *Valuation consequences [16]*

5	Catastrophic - (equipment becomes totally inoperative and multiple possible deaths)
4	Severe loss - (causes a loss of primary function. Loss of all safety margins, may result in complete unsafe operation, severe damage, severe injuries, max 1 possible death)
3	Damage - (affects the system) low damage, no deaths, hospital admission
2	Minor damage - (affects very little of the system) low damage, light injuries
1	Insignificant - No damage or injuries

Table 5.3 is the description behind the numbers of scaling for the consequences.

5.2 Description of the incidents

Incident number 1: [Damage fire]
How much fire would affect the equipment, nearby infrastructure, buildings, persons, nature etc. A fire caused by a combination of heat and leakages, or not. Hot surfaces, leaks or failure of mechanical and electrical equipment.
Risk-reducing:
Heat- and smoke detectors. Fire extinguishing equipment such as fog, handheld, inert gases, foam and ventilation.

Incident number 2: [Damage explosion]
How much an explosion would affect the equipment, nearby infrastructure, buildings, persons, nature etc. En explosion caused by a combination of a leak and flames or hot surfaces. Often caused by ignition in concentrated areas of gas. Constant ventilation should be implemented.

Risk-reducing:
Gas leakage detectors, heat- and smoke detectors. EX- equipment, restricted areas and explosive-proof walls. Walls that will not create projectiles if an explosion occurs.

Incident number 3: [Damage by a leak in electrolyser]
The potential damage caused by a leakage in the electrolyser. The pressure in the electrolyser is not as high as the rest of the system. Most of the chemical activities happen here and could affect the probability. A leak in the electrolyser would result in less consequences. [40]

Risk-reducing:
Flameproof non-return valve which prevents the flammable gas from spreading to the storage tanks.

Incident number 4: [Damage by a leak in storage tank]
The potential damage caused by a leakage in the storage tank. The hydrogen is stored under relatively high pressure in the storage tanks. A leak in the high-pressure storage tank would result in a large spread of flammable fluids. [40]

Risk-reducing:
Flameproof non-return valve which prevents the flammable gas from returning to the electrolyser. Protective casing.

Incident number 5: [Damage / Leak while transport]
Potential risks involved in transport. The probability of leakages while transporting, loading and offloading is relatively high. This function has a high operation frequency and is done by personnel onboard the ferries. This could add human errors and wear to the equipment which can cause incidents.

Risk-reducing:
Preventive maintenance and safe working routines.

Incident number 6: [Crash in infrastructure]
Crash and collision in infrastructure caused by vehicles. An incident that may be caused intentionally or not.

Risk-reducing:
Road-blocks and positioning of the equipment aside from all-roads.

Incident number 7: [Weather]
Weather that causes either flood or tear the building / equipment apart, also protection against moving projectiles caused by wind. Including the more severe hurricanes that normally occurs every decade.

Risk-reducing:
High-quality buildings to withstand the weather.

Incident number 8: [Tide / Flood]
Tide from the ocean or high water level from rivers. Tide or flood that could flood and short-circuit equipment.

Risk-reducing:
Wave and tide-walls to prevent a flood.

Incident number 9: [External fire]
External fire in nearby buildings or equipment that could spread and ignite the hydrogen building or equipment.

Risk-reducing:
Distance and non-flammable blocks between nearby buildings that could potentially ignite and production-equipment.

Incident number 10: [Tsunami]
This incident is quite relevant to this area. A tsunami from the Åkerneset mountain would be a disaster for the whole community. Since this affects the community at this certain degree, it is therefore necessary to add in the risk analysis. It would also affect Geiranger, Stranda and several other communities for longer periods. Vessels would be useless.

Risk-reducing:
Hard or almost impossible to reduce risk. Placement of electrolyser at Ringdal power plant would be above the estimated height of an eventual tsunami. Nevertheless, it would be below the evacuation zone. Placement at harbour would only have evacuation measures.

6 Case 1: Production facility at Ringdal with hydrogen pipeline

Pipeline as gas transportation has been used for decades. Norway, which is a large natural gas supplier, has long experience with gas transportation in the oil industries. Hydrogen in gas form can also use the same natural gas pipes as transportation. Case 1 looks into hydrogen transportation from Ringdal power station using gas lines.

6.1 Concept

In Hellesylt one of the options is to have the production facility at Ringdal power plant plot. Since the power plant is located approximately 1 km away from the quay in air distance, hydrogen transportation down to the ferry quay will be required. Hydrogen transportation through gas lines is therefore one possible option. The value chain for this solution is illustrated in Figure 6.1. The rectifier, transformer and compressor are not taken into the chart but are included in the electrolysis station.

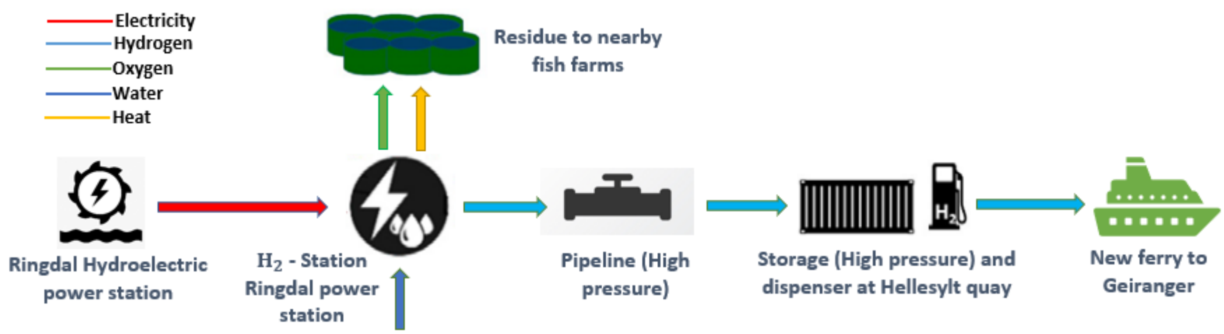


Figure 6.1: *Value chain from production to costumer for Case 1*

6.2 Distribution system

From Ringdal power station it is possible to build a tunnel for a pipe through the ground down to the quay. A map over Hellesylt area with the intended pipeline length is given in Figure 6.2. The map shows that approximately 920 meters (from point A to point C) of pipe would be required without taking the height different into account. However, laying the pipe raises some practical challenges.

First of all, when a metal is exposed to hydrogen it can create both hydrogen embitterment and corrosion. Hydrogen embitterment is a complex process and could damage the metal. Corrosion can be handled by using different types of metal, for example by using stainless steel pipes. However, stainless steel is not cheap so there will be an additional cost. The reason for hydrogen embitterment and corrosion is that the hydrogen has an active electron and behaves like a halogen, and electrons can easily migrate into the crystal structures of metals [33].

Figure 6.2: *Map over Hellesylt with the pipe solution*

Underground pipes must also be protected with a specific coating to prevent soil corrosion. The pipe should also be adequately buried to prevent frost damage and casual surface construction. Hydrogen pipes located underground are also vulnerable to lightning strikes or earth faults. These can cause a rupture in the pipe material. Therefore the hydrogen pipeline should be isolated or not connected to any other overground metal structures to reduce the chance of electrical continuity [9].

Hydrogen pipelines require both maintenance and monitoring. Maintenance can be cleaning, checking for leaks by pressure testing or repairing apparent damages. A good solution could be pressure testing by using air overnight. To prevent leaks underground it is recommended not to have any flanges or joint mechanical points if possible. In situations where this is not possible the amount should be limited. It should also be installed in a way that makes it possible to install an inspection hatch for maintenance and repairs. In this case the pipeline would follow a straight line down to Hellesylt, but it would need some mechanical joints or flanges due to the height change, direction change, and connection to fuelling/storage as the map shows. When the pipe comes out from the bedrock in Hellesylt it is also possible to place it above ground [9].

One of the most frequent leaks after mechanical damage is due to corrosion. This happens because a difference in electrical potential between the pipe and soil sets up an electrochemical cell, which takes metal from the pipe to the soil, eventually it makes a hole. To prevent this sacrificial anode or impressed current is used in combination with a coating [9]. It is therefore important to analyse the ground conditions before choosing the pipe. The pipe-route to Hellesylt through the bedrock consists mostly of mountain and rocks, frost and soil issues would be minimal.

There are different types of stainless steel. One of them is Austenitic (300 series) stainless steel, this is recommended for gaseous hydrogen in pipes. The 300-series are chromium-nickel alloys and are non-magnetic steel. The reason for the chromium-nickel composition is that it enhances the corrosion resistance and the structure gets modified from the ferry to Austenitic steel [9].

A criterion when sizing a pipeline is often a compromise between allowed pressure drop and velocity of the gas. The delivered pressure from the electrolyser is 20 bar. From the electorlyser the pressure gets increased to 350 bar, which gives a density of 24 kg/m^3.

The diameter of the pipe can be found from using the maximum production from the electrolyser. As mentioned there are a lot of challenges when sizing a pipeline. The pressure drop can be too high and the speed of the substance can be too high. Hydrogen can handle to be transported at high speed due to its high sonic velocity. However, high speed can cause turbulent flow and damage to the pipe.

To find the diameter for the pipe the volume flow equation $\dot{V} = vA$ can be used. Here is v the velocity [m/s] and A is the area of the pipe $[m^2]$. From Table 4.1 the maximum volume flow is set to be 611 Nm^3/h. Using the volume flow and assuming a velocity at 15 m/s, which is normal for natural gas lines, the diameter for the pipe can be calculated. The calculated values are given in Table 6.1 [19]. Data for the 316L steel weight and properties are obtained from Sverdrup steel [46].

Table 6.1: *Parameters for the hydrogen pipeline*

Pipeline case parameter	**Value**	**Unit**
Pipeline length	920	m
Fluid velocity	15	m/s
Inner diameter pipe	124	mm
Outer diameter pipe	141,3	mm
Wall thickness	17	mm
Density 316L Stainless steel	26,7	kg/m
Weight steel	24700	kg

From the table the diameter of the pipe becomes 141 mm with a thickness of 17 mm. With a weight of around 26,7 kg/m the total weight for 920 m becomes 24 700 kg. Flanges, fittings and mechanical joints are not taken into the calculations. This would add some additional kilograms of steal to the construction. So the total amount of stainless steel might be higher. However, it is small compared to the pipe weight.

6.3 Storage and dispenser

In this case it is most convenient to have the fuelling station or storage located at Hellesylt quay. From the quay high pressurised hydrogen can be transported onboard the ferry either from tubes that fill a tank, or with modular containers that can be switched.

The storage/fuelling pressure is desired to be around 350 bar. The higher the pressure the more energy we need for the compressor. The output pressure of the electrolyser is around 20 bar. It is estimated that compression from 20 bar to 350 bar would require a compressor of around 114 kW [48].

6.4 Pipeline costs

This section will elaborate on the additional costs a pipeline will bring to the project. The values are gathered from similar projects and might not reflect the exact pricing, but it gives an indication on what the price of a steel pipe will be.

Stainless steel pipe

Table 6.2 shows the estimated investment cost for 24 700 kg stainless steel pipe and transport and installation. The European price for stainless steel hot rolled peeled bar 316 is 34 NOK/kg [49]. For transport, installation and additional costs it is assumed a price of 11 NOK/kg. This gives a total price of 45 NOK/kg for the stainless steel.

Table 6.2: *Pipeline costs*

Cost parameter	Value	Unit
Stainless steel cost	34	NOK/kg
Transport and installation	11	NOK/kg
Total pipeline cost	1.1	MNOK

It is difficult to get the exact price of stainless steel. The price differ from place to place. All piping systems are different, with different diameter, type of steel and length. A customised piping system would have to be made for this project. However, the calculated price gives an estimation on how much the pipeline could cost.

Tunnel and trench

NVE guidelines for tunnel drilling for hydroelectric power plants are used to estimate the tunnel and trench costs due to its similarities. This gives an estimate for a given diameter. From Figure 6.2 the pipe length is 750 m to point B. For pipe length over 500 meter directional drilling can be an option. Directional drilling is a new technology and can be used on distances up to 1.5 km. This technology also has less impact on nature since the technology dig from beneath and upwards. Some rough estimates indicate that this would cost around 10 000 NOK/m for a 700 mm diameter tunnel. With this technology it also delivers special equipment for leading the steel pipe through the tunnel. The additional 168 meter to the dock does not require drilling, but a trench has to be made to lay the pipe to the quay. The price for digging per consecutive meter with 1.5 meter width is given in Table 6.3.

Table 6.3: *NOK per consecutive meter for trench digging [10]*

Total trench depth:	1,5	2	3	4
Soil trench	1380	2000	3570	5600
Mountain trench or combination	2030	2680	4116	5880

Depending on the depth length required the price will be from 1380 NOK to 5600 NOK per consecutive meter. The 1.5 m width is also much more than needed for the pipe, but it gives an estimation of what the price will be. Table 6.4 shows the estimated total cost of the tunnel, trench and the total cost. The gives a tunnel cost of 7.5 MNOK, a trench cost of 340 000 NOK, and a total cost of 8 MNOK.

Table 6.4: *Calculated tunnel and trench cost from Ringdal to the quay*

Digging cost parameter	**Value**	**Unit**
Tunnel	750	m
Trench	170	m
Tunnel cost	10 000	NOK/m
Trench cost	2000	NOK/m
Total cost tunnel	7.50	MNOK
Total cost trench	340 000	NOK
Total cost from Ringdal to quay	**8**	**MNOK**

6.5 Safety

There are different safety measures to take into consideration for the pipe solution. Table 6.5 shows the incidents that can occur, with the frequency, consequence and risk potential number RPN. The frequency and consequence use scales from 1-5, where 5 is the highest. The higher RPN, number the greater the risk.

Table 6.5: *RPN calculations Case 1*

Incident number	Incident	Frequency	Consequence	RPN
1	Fire from equipment	2	3	6
2	Damage explosion	1	4	4
3	Damage by leak in electrolyser	1	2	2
4	Damage leak in storage tank	1	3	3
5	Damage / Leak while transport	2	2	4
6	Crash in infrastructure	1	1	1
7	Weather	4	2	8
8	Tide / Flood	2	2	4
9	External fire	1	3	3
10	Tsunami	1	2	2
Summation				**37**

These results are illustrated in Figure 6.3. The figure shows the frequency on the vertical axis and the consequence on the horizontal axis. Red symbolises high risk, yellow moderate risk and green low risk.

		Consequence				
	Risk Analysis	1	2	3	4	5
Frequency	5					
	4		7			
	3					
	2		5 & 8	1		
	1	6	3 &10	4 & 9	2	

Figure 6.3: *Risk analysis for Case 1*

Safety in this section are dedicated to the location of the equipment. As well method of transport. It is desirable to have the lowest overall RPN value as possible.

Incident number 1: [Damage fire]
Fire hazards are directed at how much it can affect nearby constructions. If a fire should occur in the production equipment, what other nearby constructions, nature and infrastructure could be affected. Hydrogen in combination with oxygen is highly flammable and creates an almost transparent flame. This makes it hard to spot and increases the danger level. A constant ventilation to prevent high leakage concentrations and gas-detecting is required.

The location for this case has the electrolyser placed near Ringdal power plant. This is far away from any urban area and any other buildings. A lot of forests is around the area which could result in a forest fire. Forest fire is comprehensive, but normally not in any direct risks of lives. Material damages to the production site may be a fact.

Incident number 2: [Damage explosion]
An explosion could affect nearby constructions, users, or passengers. The hydrogen in a combination with oxygen is as mentioned highly flammable, but not as explosive. In this case there would be a relatively small amount of people around the production site. No people are normally travelling or passing the production site, neither are there any nearby buildings. Personnel working on the power plant or at the hydrogen fabric are the only expected activities.

Incident number 3: [Damage by leak in electrolyser]
The electrolyser produces hydrogen under low pressure. A leak in this unit could result a fire to occur. A jetfire would be minor due to the pressure. The same potential of fire as in Incident 1 also occurs here. Ventilation, gas detecting and Ex-equipment should be implemented.

Incident number 4: [Damage leak in storage tank]
Storage tanks are storing hydrogen under high pressure. If these are located at the power plant it could result in a larger and more serious jetfire. If not, the pressure could do serious flammable blowout damage to personnel. Good working routines, frequent testing and inspections are required to prevent situations that could damage the storage tank while under operation.

Incident number 5: [Damage / Leak while transport]
Transportation is done through a suitable pipe. This pipe could potentially leak and penetrate through the bedrock and up to the urban areas. This would most likely happen if the pipes go through a tough treatment over time. Corrosion, voltage potentials and wear could create flammable leakages.

Incident number 6: [Collision in infrastructure]
There is a main road just above the factory. Any accident here could result in a collision in infrastructure. The main road and the exit down to the facilities are separated with collision barriers. The low frequency of traffic and incidents here reduces the overall total risk of Incident 6.

Incident number 7: [Weather]
Ringdal power plant are located in a valley, well shielded from the weather. The weather conditions are relatively bad quite often, but most often not extreme enough to cause any considerable damages. Due to hilly terrain a snow avalanche is set to unlikely.

Incident number 8: [Tide / Flood]
Ringdal power plant is located in a valley. In heavy rainfall or ice melting the river could potentially flood. This could result in water seeping into the power plants. Due to previous experience, Ringdal power plant has build higher walls as protection if the river floods again. Tide created by the ocean is not applicable.

Incident number 9: [External fire]
Potential external fires could be caused by nearby industries or urban areas. At Ringdal power plant, the only nearby hazard is the power plant itself. No other nearby buildings, only high voltage transmission lines. The frequency is low, but the consequences to the production site are high.

Incident number 10: [Tsunami]
This location is placed above the expected tsunami height. But it is below evacuation height. If personnel are at the site, they would need to evacuate to higher ground. The construction would probably not be affected. The total risk is set to low. [41]

7 Case 2: Production facility at Ringdal with daily truck transport

Gas transportation using trucks is also a well-established solution. Most of the fuel and gas used today are transported by trucks. Case 2 looks into the transportation of hydrogen using trucks.

7.1 Concept

The value chain for Case 2 is shown in Figure 7.1. The production facility is located at Ringdal power stations building plot. From Ringdal power station trucks will shuttle back and forth from Hellesylt ferry quay with containers filled with hydrogen. This solution would not require any big infrastructure to be built other than the electrolysis station. The rectifier, transformer and compressor are not taken into the figure but are included in the electrolysis station.

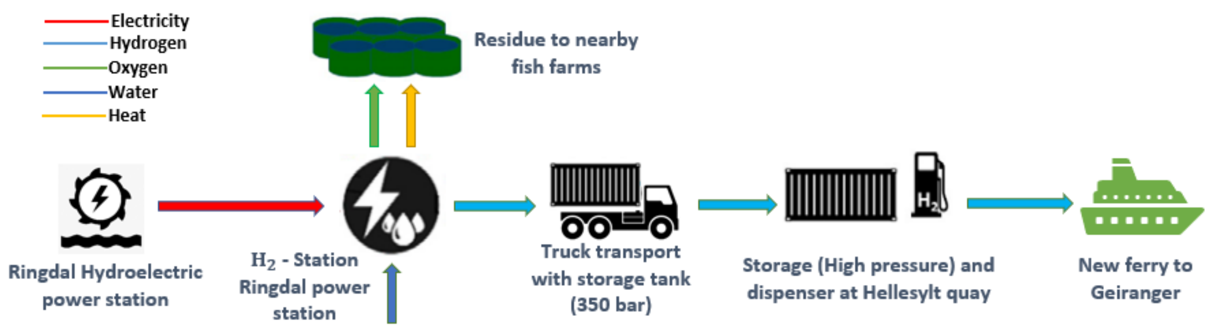


Figure 7.1: *Value chain from production to customer for Case 2*

7.2 Distribution system

The distance that the truck will have to cover each time is 2.1 km from the production facility at Ringdal to Hellesylt ferry quay. The map in Figure 7.2 gives an overview of the truck route in Hellesylt.

The map shows that the truck has to drive through Hellesylt city centre to get to the quay. The roads in this area are narrow and it is steep down from Ringdal power plant. Also in the summer season there is a lot of traffic and pedestrians in the area which can lead to traffic jams. This can cause the truck to get delayed or not make it to the quay in time for the ferry. Also for the locals it can be an inconvenience having the truck drive through the town up to eight times a day. One solution would be to have the truck drive straight down instead of through the town, but due to the steepness from the mountains it is hard or almost impossible to build a road straight down.

This solution would require an investment in trucks that can transport hydrogen. Most of the trucks today are using diesel as fuel. Since the goal of the project is to reduce emissions, the trucks that operate the route between the production facility and the dock should ideally also use hydrogen or a zero-emission type of fuel if possible. However, due to the short distance the fuel consumption would be minimal.

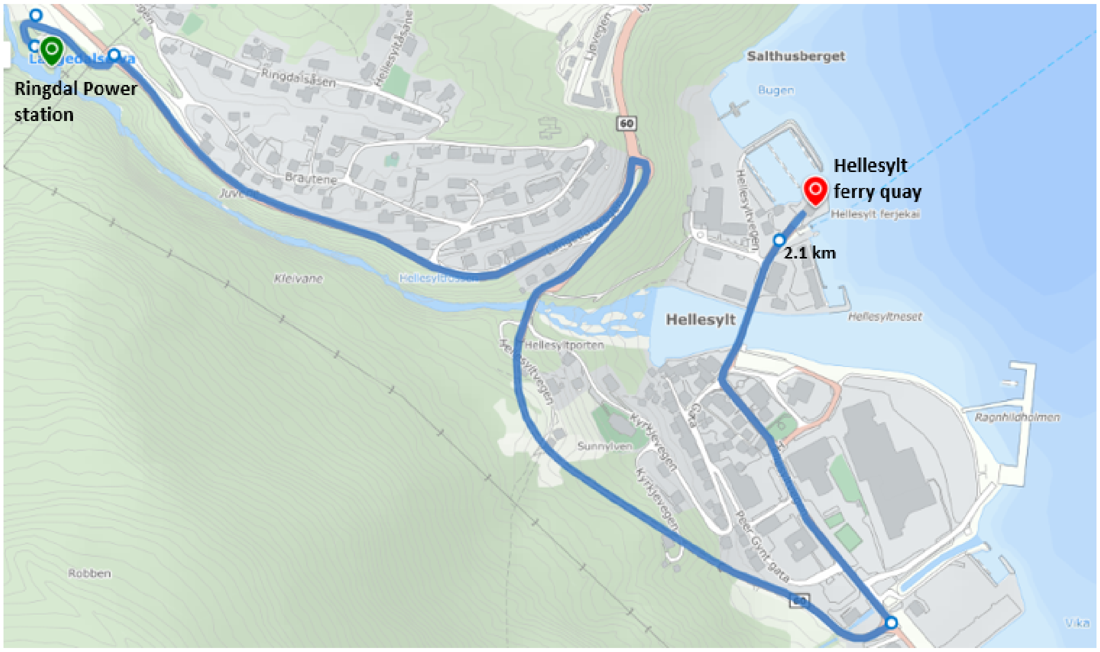


Figure 7.2: *Map over Hellesylt with the truck solution*

Compressed hydrogen in gas cylinders can be transported by trucks from 200-500 bar pressure. The tank is usually bundled to modules in 20' and 40' which is mounted on the trailer. The weight of the hydrogen cylinders is the main factor that limits the amount of hydrogen that can be transported as well as fuel consumption. Steel cylinders can typically store up to 25.000 liters or 420 kg hydrogen at 200 bar. There is also another type of composite cylinders under development that can transport hydrogen at a higher pressure, which reduces the weight of the tank [39]. A storage trailer from the company UMOE with 350 bar storage pressure is shown in Figure 7.3.

Figure 7.3: *UMOE Advanced Composites container that can be lifted on top of the truck [11]*

The size of the tank will determine how many times the truck needs to operate between Ringdal and the quay. Larger storage tanks would reduce the number of times the truck have to refill the tank at the quay. However, a bigger tank size will increase the filling time per tank, so one solution could be to have a backup tank with hydrogen.

7.3 Storage and dispenser

There are two options to refill from the container when the ferry arrives. Swapping of containers is one option. Since the hydrogen already is pressurised in the transportation-container, it could be switched directly when the truck arrives at the quay. If so, the ferry will not need a fixed tank. This reduces the filling time and can be more efficient due to the low laying time. However, this would require a crane to lift the container on board, or that the truck drives on board and places the container on the car deck. Due to all the cars and passengers on board, it can be a safety risk having the container stored close to people. One other option, has a fixed tank onboard. This has a dispenser connected to the container, filling the hydrogen onboard the ferry when it arrives. If the tank size on the ferry is limited to 1-2 trips to reduce weight, then this could be a solution.

7.4 Truck costs

Truck investment and drivers

These trucks would also need drivers which is an extra cost that would need to be taken into the calculations. Numbers from Statistics Norway indicate that the monthly average salary for a truck driver is around 37 540 NOK in 2019 [38]. The ferry operates seven months a year from April 1st to October 31st. If one person was hired to drive the truck it would cost around 260 000 NOK each year in salaries.

There is also the cost of buying the trucks that need to be taken into consideration. A new truck could typically cost between 1-3 MNOK. Nevertheless, this is a one-time investment that could operate for many years. One other option is to lease the truck instead of buying. This reduced the CapEx, but can increase the OpEx over time.

There will also be some maintenance costs for the truck. The truck will only drive from 10-20 km per day due to the short distance between Ringdal power station and the ferry quay. The truck operates seven times a week and a total of 28 weeks per year. Using a truck maintenance cost calculator the estimated maintenance cost per year with a labour cost of 1000 NOK/hour and default pricing on parts are 61 000 NOK/year [47]. However, this pricing is for a regular diesel truck, if this gets replaced with an electric truck or hydrogen truck the maintenance costs will be different.

Trailer with storage tank

It is estimated that storage cost for steel tanks lies between 3900 NOK - 10 000 NOK, depending on the size of the tank, and the investment cost depends upon the price of steel. Composite tanks with storage options up to 350 bars have shown to be cost-competitive. In this project it is assumed that the tank onboard the ferry will use pressure around 350 bar CH_2. A price of around 4500 NOK/kg would be reasonable.

7.5 Safety

There are also some safety concerns by using the truck as transportation. In the risk analysis it would be incident number 6 that is the most relevant for this solution. Since the vehicle operates daily back and forth, a collision could happen. Especially in the summer season when there is much traffic in the area. Table 7.1 shows the calculated risk from frequency and consequence for the different incidents.

Table 7.1: *RPN calculations Case 2*

Incident number	Incident	Frequency	Consequence	RPN
1	Damage fire	2	3	6
2	Damage explosion	1	4	4
3	Damage by leak in electrolyser	1	2	2
4	Damage leak in storage tank	1	3	3
5	Damage / Leak while transport	3	4	12
6	Crash in infrastructure	2	1	2
7	Weather	4	2	8
8	Tide / Flood	2	2	4
9	External fire	1	3	3
10	Tsunami	1	2	2
Summation				**46**

Figure 7.4 shows the results of RPN calculation from frequency and consequence. Green is representing low risk, yellow is medium, and red is high risk.

Consequence

Frequency	Risk Analysis	1	2	3	4	5
	5					
	4		*7*			
	3	*9*			*5*	
	2	*6*	*8*	*1*		
	1		*3 & 10*	*4*	*2*	

Figure 7.4: *Risk analysis for Case 2*

Incident number 1: [Damage fire]
Fire hazards are defined by how much it can affect nearby constructions. If a fire should occur, what other nearby constructions, nature and infrastructure could be affected. Hydrogen in combination with oxygen is highly flammable and creates an almost transparent flame. This makes it hard to spot and increases the danger level. Constant ventilation to prevent high leakage concentrations and gas-detecting is required.

The location for the case has the electrolyser placed near Ringdal power plant. This is far away from any urban area and any other buildings. A lot of forests are around this area which could result in a forest fire. Forest fire is comprehensive, but normally not in any direct risks of human lives. Material damage to the production site may be a fact.

Incident number 2: [Damage explosion]
An explosion could affect nearby constructions, users or passengers. The hydrogen in combination with oxygen are as mentioned highly flammable, but not as explosive. In this case there would be a relatively small number of people around the production components. No people are normally travelling around or passing by the production site, and there are not any nearby buildings. Personnel working on the power plant or at the hydrogen fabric are the only expected activities.

Incident number 3: [Damage by a leak in electrolyser]
The electrolyser produces hydrogen under low pressure. Jetfires could occur but under the following circumstances is at such a low energy level that there is no significant danger to either persons or constructions. The same potential of fire as in incident number 1 also occurs here. Ventilation, gas detecting and Ex-equipment should be implemented.

Incident number 4: [Damage by a leak in the storage tank]
Storage tanks are storing hydrogen under high pressure. Jetfire could occur and be fatal. If this component is located at power plant the risk is set to low due to a small number of people and short stays. The risk of storage on the truck is considered in incident number 5.

Incident number 5: [Damage / Leak while transport]
Transportation is done by loading and offloading a truck. An accident in or near the city centre could expose a large area of potentially dangerous gas. Hydrogen is a light weighted gas that will quickly arise to the sky if released. The gas is non-toxic but can become serious concerning the danger of inflammation. In a high-speed collision a large fire could be a fact.

Incident number 6: [Collision in infrastructure]
There is a main road just above the factory. Any accident here could result in collision in infrastructure. The main road and the exit down to the facilities are separated with collision barriers. The low frequency reduces the overall total risk of Incident 6. In this case it is also considered that a truck is loading and offloading often. That is why the consequence is set to be considerable.

Incident number 7: [Weather]
Ringdal power plant is located in a valley, well shielded from the weather. As in Case 1 the weather conditions are bad relatively often, but most often not extreme enough to cause any considerable damages. Any severe damage would be unlikely.

Incident number 8: [Tide / Flood]
Ringdal power plant is located in a valley. In heavy rainfall or ice melting the river could potentially flood. This could result in water seeping into the power plants. After experiences Ringdal power plant has build higher walls as protection if the river floods again. Tide created by the ocean is not applicable.

Incident number 9: [External fire]
Nearby industries or urban areas could cause potential external fires. At Ringdal power plant, the only nearby hazard is the power plant itself. No other nearby buildings, only high voltage transmission lines. The frequency is low, but the consequences to the production site are high.

Incident number 10: [Tsunami]
This location is placed above the expected tsunami height. Nevertheless, it is below evacuation height. If personnel are at the site, they would need to evacuate to higher ground. The construction would probably not be affected. The absolute risk is set to low. [41]

8 Case 3: Production facility at the quay with cable from Ringdal

The Case 3 looks into the possibility of transporting electricity to the quay instead of the hydrogen. The whole production facility would then be located at the quay close to the ferry.

8.1 Concept

The value chain for Case 3 is illustrated in Figure 8.1. From Ringdal power station a high voltage cable would go down to the quay either above or underground. The cable would then be connected to the electrolyser station at the quay. From the electrolyser station high pressurised hydrogen would go into a storage tank or directly to a dispenser that can fill the ferry. The rectifier, transformer and compressor are not taken into the chart but are included in the electrolysis station.

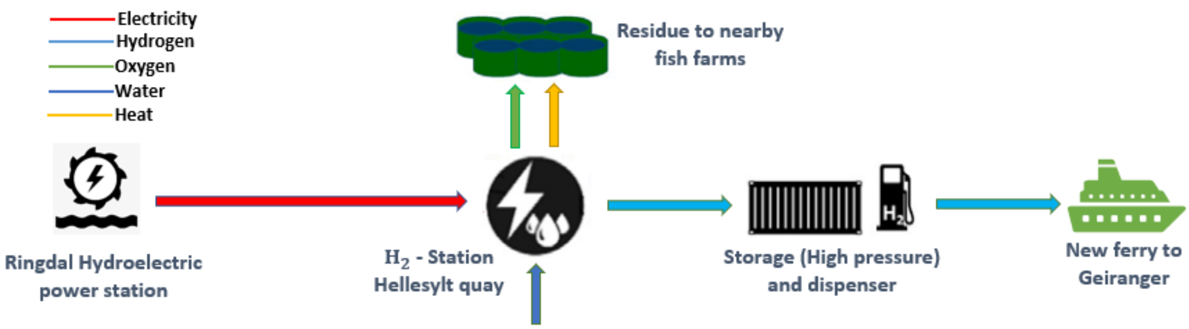


Figure 8.1: *Value chain from production to costumer for Case 3*

This case will require space to build out the production facility at the quay. The space around the ferry quay consists mostly of some unused houses, which makes it practical to use as a location for the hydrogen factory. Figure 8.2 shows a map of Hellesylt with the intended high voltage cable to the ferry quay.

Figure 8.2: *Map over Hellesylt with the high voltage solution*

Depending on the size, point C would be an ideal place to put the hydrogen factory. The electrolyser requires around 350 m^2. Quick measurement in google maps gives around 625 m^2, which means there is plenty of space for the hydrogen factory and storage. This is without taking any safety distance requirements under consideration, which can increase the area required for the hydrogen factory. There is also already a house beside the dock which could be a possible housing for the factory.

8.2 High voltage cable

The cable conductance is found from the power of the electrolyser and the transportation-voltage. This is done by calculating the current I = $\frac{2700*10^3 W}{22*10^3 V}$ = 123A. A dialogue with Nexans has been established to estimate the correct cable dimension and pricing. Looking in the Nexans Cable Book a single line cable named TSLF 24kV 1x50A would be within limits. The capacity of a three-phase transmission line would then be 3*50A = 150A in total. This includes corrections for transportation in a non-ventilated pipe [4].

TSLF 24 kV enleder

Betegnelse	Leder diam.	Isolasjons-tykkelse	Diam. over isolasjon	Kappe-tykkelse	Ytre diam.	Vekt	El. nr.
	mm	mm	mm	mm	mm	Kg/km	
TSLF 24 kV 1x50A/16	8,0	5,5	19,3	2,1	27,2	696	10 671 13

Figure 8.3: *Cable dimensions [4]*

These three-phase cables are to be placed through a pipe in the bedrock in a symmetrical trefoil formation as shown in Figure 8.4. This will minimize the inner diameter of the pipe. Using pipe dimension of 2 1/2¨ equivalent to 65,5mm inner diameter. This pipe would most likely be in a PVC material [42].

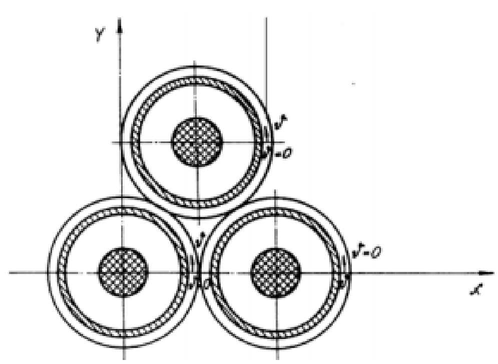


Figure 8.4: *Trefoil cable formation [43]*

From Ringdal power station a tunnel of around 750 m would have to be made using the same directional drilling technique as for the pipeline case down to point B.

The high voltage cable could then go through the tunnel using a PVC pipe. From point B to the electrolyser station at point C a trench of around 168 m for the high voltage cable would have to be made.

One other possibility is placing the new transmission line above ground. This would eliminate the need for a tunnel and pipe. However, high voltage-fee is not possible to avoid when transporting high voltage. The transmission would have to go a different path as the blue line in Figure 8.2 shows.

8.3 Concession

When building transmission lines above 1000V a concession from NVE is required. The new high voltage line in Case 4 would therefore require a concession before building starts. Concession bound projects are considered after then Norwegian Energy Law or the waterway legislation. Concession is usually granted if it has a positive value for the public society, and that other environmental and public interest has been taken into consideration [51].

The grid is divided into two different operators, transmission system operator, TSO, and distribution system operator, DSO. TSO has the system responsibility and is Statnett in Norway. They are responsible for continuously balance between production and consumption, which is usually for the 132-420 kV range. The DSO is the local power companies. Stranda Energy is a local power company and owns and operate the grid in Hellesylt area. Norway is divided into area concession. This gives the grid owners , such as Stranda Energy, right to build and operate the grid with voltages up to 22 kV in the area [51].

The concession for the hydrogen factory in Hellesylt has recently been discussed. The previous member of the energy- and environment committee, now oil and energy minister, Tina Bru, was contacted regarding the possibility to evaluate the grid-solution to better the economy for hydrogen projects. The short answer is that the government will propose a general strategy for hydrogen initiatives and research [52].

Hydrogen production through electrolysis requires large amounts of energy, which result in large expenses in grid rates. Therefore it would be convenient to have own grid-rates, or have it removed to increase the interest for green hydrogen production. Hydrogen storage can be a part of the total grid solution to utilise power when the production is larger than the demand. There are therefore several benefits of re-evaluation the grid solution which can have a large impact on the economy of hydrogen projects.

8.4 High voltage transfer cost

As mentioned above transferring large amount of power on the existing grid or laying a new high voltage cable will have large expenses in grid-rates. In contact with the power company Stranda Energi it was possible to get an insight and estimate of what the high voltage transfer would cost. At Stranda Energi's homepage there are listed documents with an overview of previous and current grid-charges [5]. For industrial use the NT3 charge is the correct one, this is listed in the document referred to. The calculations below is completed together with Stranda Energi. The values are based on a continuous consumption of 2.7 MW. However, the real consumption will probably be lower than this. This gives a worst-case scenario regarding the costs by using the grid. Calculations received from Stranda Energi are given in Table 8.1. The table shows that the total monthly costs would be 290 000 NOK. Both if the cable goes through the bedrock or above ground, a high voltage-fee would still need to be paid. Note that the prices in Figure 8.1 are excluded VAT.

Table 8.1: *High voltage transfer cost*

	Power	Cost	Monthly cost
	200 kW	44 NOK/kW	8 800 NOK
	300 kW	41 NOK/kW	12 300 NOK
	2200 kW	38 NOK/kW	83 600 NOK
Total Power	2700 kW	67.68 NOK/kW	182 700 NOK
Fee	12000 NOK	0.083	1 000 NOK
Consumption fee	182700 NOK	0.0050	923 NOK
Monthly cost			**290 000 NOK**
Yearly cost			**3.5 MNOK**

8.5 Safety

Table 8.2 shows the calculated values for the different incidents that can occur. RPN is calculated by the values from frequency and consequence.

Table 8.2: *RPN calculations Case 3 & 4*

Incident number	Incident	Frequency	Consequence	RPN
1	Damage fire	2	4	8
2	Damage explosion	1	5	5
3	Damage by leak in electrolyser	1	3	3
4	Damage leak in storage tank	1	4	4
5	Damage / Leak while transport	1	1	1
6	Crash in infrastructure	3	1	3
7	Weather	4	3	12
8	Tide / Flood	2	3	6
9	External fire	2	3	6
10	Tsunami	1	5	5
Summation				**53**

Figure 8.5 shows the frequency on the vertical axis and consequence on the horizontal axis. The colour indicates the different types of risks. Green represents a low risk, yellow is medium and red is high risk.

		Consequence				
	Risk Analysis	1	2	3	4	5
	5					
	4			7		
Frequency	3	6				
	2			8 & 9	1	
	1	5		3	4	2 & 10

Figure 8.5: *Risk analysis Case 3 & 4*

Incident number 1: [Damage fire]
Fire hazards are directed at how much it can affect nearby constructions. If a fire should occur, what other nearby constructions, nature and infrastructure could be affected. Hydrogen in combination with oxygen is highly flammable and creates an almost transparent flame. This makes it hard to spot and increases the danger level. Constant ventilation to prevent high leakage concentrations and gas-detecting is required. The location for Case 3 and 4 has the electrolyser placed near Hellesylt city centre. This is in an urban area and close to other buildings. A potential fire could spread to the city centre and do serious damages.

Incident number 2: [Damage explosion]
An explosion could affect nearby constructions, users, or passengers. Hydrogen in combination with oxygen is as mentioned highly flammable, but not as explosive. The area for the construction would be in a populated area, with several nearby buildings, ferry-quay and people passing by.

Incident number 3: [Damage by a leak in the electrolyser]
The electrolyser produces hydrogen under low pressure. A leak in this unit could result in a fire to occur. A jetfire would be minor due to the pressure. Constant ventilation to prevent high leakage concentrations and gas-detecting is required.

Incident number 4: [Damage a leak in storage tank]
A leak in the storage tank could cause a jetfire which could be fatal in exposure for humans. A safety distance should be set to maintain safety for civilians. An constant ventilation to prevent high concentrated leakages and gas-detection is required.

Incident number 5: [Damage / Leak while transporting]
In this case, the transport is done through the high voltage line. The conclusion of this incident is set to be minor. Frequency and consequence for any damage caused by the transport are unlikely since the high voltage lines are stable.

Incident number 6: [Collision in infrastructure]
The electrolyser station is exposed to traffic in and out of the ferry. There is a relatively high risk of a collision if not any risk-reducing measurements are implemented. Roadblocks and fences could easily be built at a low cost to protect the electrolysis station at the quay.

Incident number 7: [Weather]

The city centre close to the ocean is one of the most exposed areas in Hellesylt. Extreme weather that only occurs every few years could affect or tear constructions apart. The buildings must maintain high standards and be built with high quality. Risk-reducing factors as quality could prevent severe damage and remove the incident from the red areas in the risk analysis.

Incident number 8: [Tide / Flood]

Tide could cause a flood that could damage the equipment. This is an incident that could be drastically reduced by Risk-reducing measurements. By putting up either walls or a water-block.

Incident number 9: [External fire]

If any fire should occur in the area it may spread to the construction. Buildings and vegetation are near enough to make a fire spread. On the northern part of the river there are no production-industries, but some public buildings and a harbour for smaller vessels.

Incident number 10: [Tsunami]

A tsunami is a well-spoken incident that could occur. A tsunami from the Åkerneset would ruin the whole city centre. The frequency is therefore set to 1, and the consequence is set to 5.

9 Case 4: Production facility at the quay using the grid

Case 4 looks into the use of the current electrical grid in Hellesylt. This could be an option if Ringdal can not produce the power needed for the electrolyser. Reasons for this can be a low flow of water in the river, or a technical fault at the power plant.

9.1 Concept

The electrical grid will then be connected to the electrolyser station at the quay. From the electrolyser high pressurised hydrogen will be stored on a tank or fed directly to a dispenser to fill the ferry on demand. Figure 9.1 shows the value chain for Case 4. The rectifier, transformer and compressor are not taken into the chart but are included in the electrolysis station.

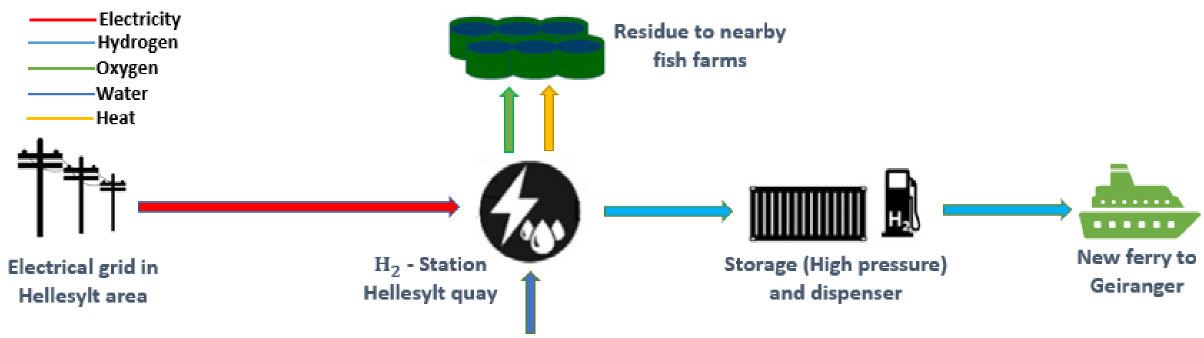


Figure 9.1: *Value chain from production to the costumer for Case 4*

To use the grid a high voltage cable has to build out from the existing electrical grid in Hellesylt. Figure 9.2 shows a map from NVE with three new options for building out a high voltage line. The green lines are the existing electrical grid and the red ones are the possible new high voltage lines.

Option A is almost the same as Case 3 at 920 m. The only difference would be that the electrolyser would use the grid as power supply and not Hellesylt power station directly. This would require the same distance with high voltage cable and digging tunnel and trench.

Option B has the shortest distance at 450 m from the connection point to the electrolyser. However, there are not any connection points where this cable would start so a new junction point has to be made. Since this option is about placing a new high voltage transmission line from the existing grid to the quay, it has to go through some challenging wooden terrain and cross the river. It would not be an issue, but require some work in more or less untouched areas and some urban areas.

Option C is 530 meters away from the electrolyser. This cable would have to go through the town above or underground. At this location there might already be a junction point to connect to, so less work would have to be done. However, there might be some challenges with setting up a new high voltage line through the town as the current high voltage lines are outside the city centre. Either by digging a trench to lay a cable or by placing a new overhead line. A trench would cause a lot of work due to existing streets and roads.

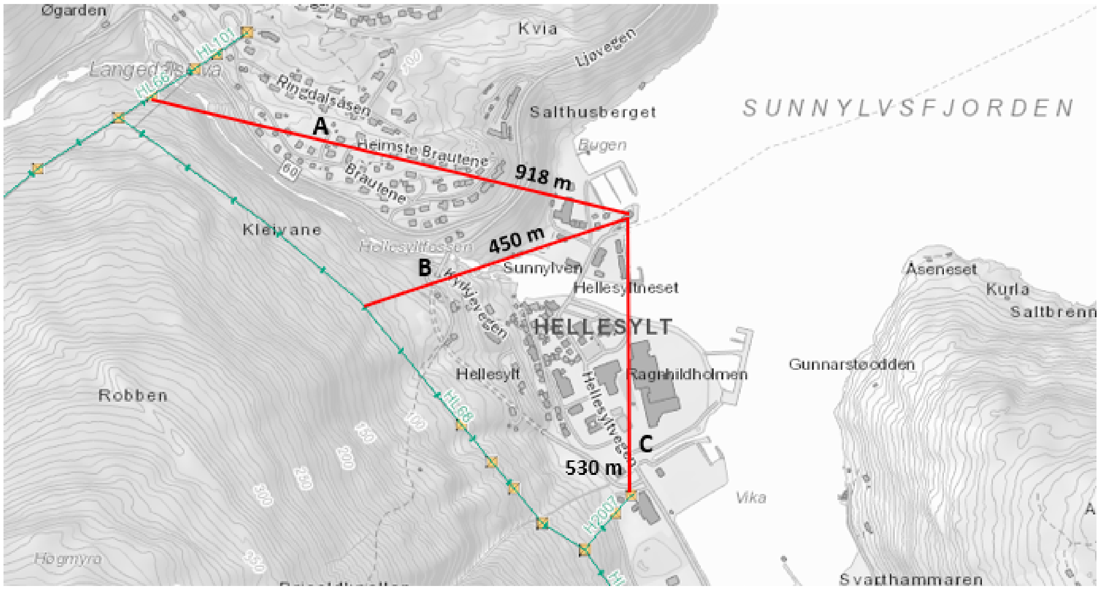


Figure 9.2: *Possible grid connection for the production facility in Case 4*

Since the options above are an expansion of the current grid, a concession from NVE would be required before the building starts. This concession would be similar to the concession for the high voltage cable in Case 3.

9.2 Grid costs

The main expense of Case 4 is the cost of buying electricity. The price of electricity is not fixed and will vary. For 2019 the average price from Nordpool was 0.38 NOK/kWh. For the 1000 kW system in the high season with 59 200 kWh/day this would result in a cost of around 22 500 NOK/day and 675 000 NOK per month. If the electrolysis station is using the current power-grid, the calculated cost from Stranda Energi is roughly 700 000 - 800 000 NOK to do the electrical upgrades. Those are costs related to laying cable and building a power-substation, and includes materials and working hours. The total amount is dependent on the exact position of the electrolyser. The same grid rate would also apply for this solution as shown in Table 8.1.

9.3 Safety

Case 3 and Case 4 have the same possible location, only different methods from the external grid separate them. That is why the same risk analysis can be done. As seen in Figure 8.5 there is only one incident located in the red area. This is the most critical and common incident that could occur. A combination of high frequency and consequence places this incident in the red area. In Table 8.2 a summation of the risk factors is listed to indicate the overall risk tied up to the location and method.

The only risk that is not mentioned is related to the stability of the grid. When connection 2.7 MW to the current grid, voltage drop or unstable frequency could occur. This can be an inconvenience for the local consumers. Also if the high voltage cable is placed above the ground in option B and C, extra safety distances will be required. This is because the cable is 22 kV and it would go close or through the city centre.

10 Usage and sales of residue

Residues from production will increase the financial income if they have value to the correct customer. It is inevitable to prevent the production of the residues. These could go to waste if no solutions are available. Nevertheless, if an income from the sale would be possible it would be very lucrative for the project.

10.1 Oxygen

Clean oxygen will be produced as a residue in the electrolyser process. It seems difficult to find any local usage of this residue, due to Hellesylt and Geiranger's small scale of industry. The biggest local industries are tourism and meat production. In some industries, oxygen could be used in combination with acetylene for welding and cutting metals. Hospitals could also be a possibility, but the closest one is located in Aalesund.

Normally fish-farms will have a great advantage of using this. They add oxygen in the water to replace the oxygen which the fish consumes. By doing this it is possible to reduce the amount of water needed if they were only using the natural oxygen from water. By reducing the water level it becomes easier and cheaper to do maintenance and water purification for discharge. Currently it is unlikely to have fish-farms in or nearby Hellesylt centre due to the visual pollution. The oxygen would need to be transported to the preferred area.

There are several nearby fish-farms in the districts, the four closest ones are listed in Table 10.1. Google Maps found distances and times. Time consumption at sea is calculated by using 10 knots = $39\frac{km}{h}$. These values are also filled in Table 10.1. Prices listed includes transport, and all of them are onshore production sites.

Table 10.1: *Overview of nearby fish-farms*

Name	Kraft Laks AS	Marine Harvest AS	Urke Fiskeoppdrett AS	Aqua Farms AS
Location	Dalsbygda	Ytre Standal	Urke	Vartdal
Type	Hatchery	Broodstock	Hatchery	Hatchery
Distance vehichle[km]	83	45	30	89
Time vehicle	1h 20m	1h 25m	0h 35m	1h 25m
Distance sea [km]	121	81	95	90
Time sea	3h 5m	2h 5m	2h 20m	1h 25m
Capacity [tonnes]	12	12	40	N/A
Consumption [kg]	250	40 - 50	360	6
Price [NOK/kg]	2,9	3	2-3	2,75 - 3,0

The following companies informed us that they pay about 3,0 NOK/kg oxygen, where freight costs vary from 25-45% of the total costs. This is mostly transported over long distances by trucks. One of the companies from Table 10.1 informed us that their oxygen is transported from Rjukan, which is located more than 500 km away, resulting in a 8 hours 30 minutes drive. Contracts are controlled by competitive prices, but the most important factor when choosing a supplier is mainly determined by the predictability throughout the whole year. It is expected that the quality from the electrolyser would be accepted at the fish farms.

Another possible customer is the Hospital in Aalesund. The hospitals require medical oxygen. This oxygen requires high purity of a minimum 99,5 % [6]. In contact with the technical department at St. Olavs Hospital in Trondheim a usage of around 600 kg/day is normal. Still, there are some uncertainties if the quality from the electrolyser is sufficient enough for this use. If the quality is not met, it would require a process that would probably lead to a high cost. Either way, the medical oxygen would require way more quality control and data sheets which would affect the price.

To calculate the amount of oxygen produced from the Electrolysis in Hellesylt, it is possible to take a basis in the kg hydrogen produced. It requires nine times the amount of water to produce 1 kg hydrogen. Which means for 1200 kg H_2 it requires 11 000 kg H_2O. The amount of oxygen produced can be found from the stoichiometric calculations and the total reaction for alkaline electrolysis given in equation 3.6. The calculated values are given in Table 10.2.

Table 10.2: *Oxygen production during high season*

Note: Descriptions marked with <*> are data based on estimation and assumption.

Description	Value	Unit
Molar mass water	0.018	kg/mol
Molar mass oxygen	0.032	kg/mol
Kilograms of water	11 000	kg
Number of moles water each day	600 000	mole
Number of moles oxygen each/day	300 000	mole
Oxygen produced in the high season	9600	kg
Oxygen produced in the mid season	4800	kg
Oxygen produced in the low season	3600	kg
Oxygen produced each year	1 500 000	kg
Market price oxygen	2.90	NOK/kg
Oxygen freight cost	20	%
Liquefying oxygen and storage cost *	1/3	
Gross income from oxygen	4 200 000	NOK
Liquefying oxygen cost*	1 400 000	NOK
Total freight cost per year	850 000	NOK
Net income from oxygen each year	**1 900 000**	**NOK**

Table 10.2 shows that by producing 1200 kg H_2, the amount of O_2 produced is 9600 kg/day in the high season, 4800 kg in the mid season and 3600 kg in the low season. This gives a total of 1 500 000 kg or 1500 tonnes each year. With a market price of 2.90 NOK/kg the gross income becomes 4.2 MNOK. However, to find the net income, both the freight cost and liquefying cost have to be subtracted. The cost is set to 20% of the gross income, which is equal to 850 000 NOK.

Similar to hydrogen, oxygen must either be compressed or liquefied to increase the density. Oxygen is often stored as liquid in bulk in specially insulated tanks. The reason for this is that 1 liter of liquefied oxygen is equal to 840 liters of gaseous oxygen. For this case it is assumed the 1/3 of the gross income will go to liquefying and storing the oxygen. Therefore a total cost of 1.4 MNOK will go to the liquefying and storage system. The net income from the oxygen then becomes 1.9 MNOK.

10.2 Heat

The electrolyser will also produce heat as residue due to the electrical input being larger than the enthalpy change of the reaction. To cool the electrolyser, water is usually used. The increased temperature of the water can then be used to heat buildings. Utilising thermal energy can increase the overall efficiency of the electrolyser. Electrolysers usually produce heat in the form of low quality due to Ohmic resistance and friction on the cathode and anode. Therefore the heat generated can only be used for heating and not the production of electricity. Increasing the temperature of the water to a higher level can make it more usable, but additional energy would have to be added to increase the temperature. The heat can be calculated using the efficiency of the electrolyser, which is around 70 %, and the calculated energy need in Figure 4.2. Table 10.3 shows the calculated heat loss in kWh for the electrolyser.

Table 10.3: *Heat generated from the electrolyser*

Season	Days	Heat loss	Unit
Heat loss each day high season	113	18	MWh
Heat loss each day mid season	40	9	MWh
Heat loss each day low season	60	7	MWh
Total heat loss each year	213	2 800	MWh
Usable heat loss each year	213	1 400	MWh

The table shows that the heat loss from the electrolyser is 18 MWh each day in the high season, 9 MWh/day in the mid season, and 7 MWh/day in the low season. Using the number of days in each season the total heat loss becomes 2 800 MWh. After losses in transportation, heating pumps and other equipment it is assumed that around 50 % of the heat generated will be usable for heating. This means that a total of 1 400 MWh will be usable each year. Table 10.4 shows the heating demand for different buildings and the area the amount of heat from the electrolyser can heat [7].

Table 10.4: *Heating demand for different buildings*

Building type	Heat demand [kWh/m2 year]	Usable heat [kWh/year]	Area [m2]
Skoler	170	1 400 000	8200
Hoteller	240	1 400 000	5800
Idrettsbygg	235	1 400 000	6000
Kulturbygg	245	1 400 000	5700
Lett Industri	255	1 400 000	5500

The table shows that a school up to 8200 m^2 can be heated from the amount of heat generated. Hotel, sports facilities, cultural buildings and smaller industries can also use the heat in buildings from to 5500 to 6000 m^2.

11 Results and discussion

This chapter shows the results and discussion for the thesis. The CapEx for all cases is based on the Life Cycle Cost method in Figure 3.11, while the hydrogen price is based on the CapEx, OpEx and lifetime of equipment as shown in Figure 3.10. The result shows the main findings. All numbers used and a more detailed calculation for the priority vectors and the costs are given in Appendix A and B.

11.1 Case 1: Production facility at Ringdal with hydrogen pipeline

Table 11.1 shows the total cost, hydrogen demand, hydrogen price and hydrogen fuel costs for Case 1. The total CapEx and OpEx are calculated from the economic values given in Table B.1 in Appendix B. The CapEx needed are a total of 50 MNOK, and the OpEx are 25 MNOK in a ten-years perspective. By summing up the total values from CapEx and OpEx, the total price in a ten-year perspective is 75 MNOK. The estimated hydrogen needed for the new ferries in ten years are calculated from Table 2.1 and are a total of 1 870 000 kg. Dividing the estimated total cost on the total hydrogen produced in ten years, the price per kg hydrogen then becomes 40 NOK/kg.

Table 11.1: *Total costs and hydrogen price for Case 1*

Description	Value	Unit
Total CapEx	50	MNOK
Total OpEx	25	MNOK
Total Price 10 years	75	MNOK
Hydrogen price	40	NOK/kg
Hydrogen fuel cost each year	7.5	MNOK

Table 11.1 shows the price of hydrogen at 40 NOK/kg. The market price for hydrogen from alkaline water electrolysis in 2020 is around 23-44 NOK/kg as Figure 3.2 shows. So the price from Case 1 is around the expected market price. However, this price can vary a lot due to varying electrical prices. With a price of 40 NOK/kg, and assuming the ferry has a tank of 150 kg, a filled tank for the ferry would cost about 6 000 NOK. This gives a total cost of 7.5 MNOK each year. The current marine diesel fuel-cost for the ferries are 6.8 MNOK. This gives an increase of 700 000 NOK for hydrogen fuel costs. Nevertheless, this extra cost might be covered by different support founds to make the transition to hydrogen more competitive.

The total CapEx and OpEx consist of different expenses. Figure 11.1 shows capital expenses divided into parts in the percentage of total CapEx, while Figure 11.2 shows the operational expenses divided into parts in the percentage of total OpEx.

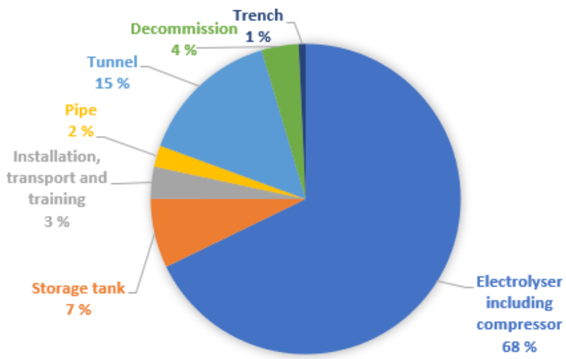


Figure 11.1: *Capital expenses for Case 1 in percentage*

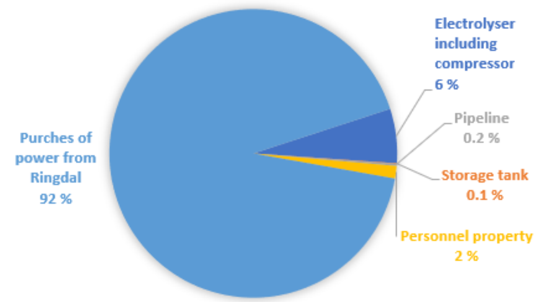


Figure 11.2: *Operational expenses for Case 1 in percentage*

The different capital expenses in Figure 11.1 show that 75 % of the total CapEx is for the cost of buying the electrolyser, including compressor and electrical equipment and storage tank. The last 15 % is for the tunnel and pipeline costs as well as installation, transport, training and decommissioning. The tunnel and trench are based on the cost of drilling tunnels for hydropower from the NVE guidelines. The price for the tunnel is set to 10 000 NOK/m for a 700 mm diameter size, which is much larger than needed for the pipe which is only 141 mm in outer diameter. However, the installation of the pipe might require additional space in the tunnel and also space for maintenance. The trench which are 1.5 m deep and 1.5 m wide would cost about 2000 NOK/m. The pipeline costs are based on a steel price of 45 NOK/kg, which is based on the current stainless steel price and from assumptions. The market price of steel will also vary and a larger amount of steel can give larger discounts. This can impact the CapEx from Case 1.

The different operational expenses in Figure 11.2 show that 92 % of the total operational costs are caused by purchasing power for the electrolyser and compressor. The additional 6 % is extra maintenance cost during the lifetime of the electrolyser, which includes electrical equipment and compressor. The remaining 1-2 % is for a pipeline, storage tank and property maintenance. The operational cost for the electrolyser depends upon the price of electricity, which means it can vary during the season. This can impact the hydrogen price.

Case 1 assumes that the power comes directly from Ringdal power station and that the price of electricity can be lower than the market price due to the electricity being produced locally, and the loss in transportation and the marginal losses are much lower. For the current model the price of electricity is set to 0.25 NOK/kWh, which gives a total operational cost of close to 23 MNOK in a ten-year perspective. Note that this price is not fixed and can both increase and decrease as the price of electricity and the water level in Ringdal changes over the years.

11.1.1 Pipeline

The advantage of having a pipeline as hydrogen transport is that the high voltage cable fee and concession are avoided. The hydrogen factory would be located at Ringdal power station which eliminates visual pollution. It would also reduce exposure of noise from production and operations. The short distance between Ringdal power station and the production facility would also reduce the transfer losses for the electricity to the electrolyser.

However, there are some disadvantages of having a pipeline with hydrogen. First of all, it requires a tunnel and trench for the pipe from Ringdal power station and down to the quay, this represents 18 % of the total capital expenses.

The total distance is 920 m, where the last 200 m are in a trench buried underground. This requires a lot of working hours from the entrepreneur. Since the tunnel is over 500 m, directional drilling needs to be used. This is also more expensive than traditional drilling. The pipeline would also have to be made out of stainless steel, which is expensive. The pipeline can also get leaks or be damaged. Corrosion can be a problem with hydrogen due to it being a halogen. However, chances of corrosion can be reduced by using Austenitic (300 series) stainless steel which is recommended for gaseous hydrogen and this enhances the corrosion resistance.

One other challenge is leaking. Hydrogen leaks can be difficult to detect and would require pressure testing overnight. Due to the constant production of hydrogen it can be difficult to find time to do pressure tests and do maintenance during the season. It is also often recommended that flanges and joints are kept to a minimum because this is where the leaks usually start. Transferring fluid also raises some challenges. Higher speed can cause vibrations and turbulent flow in the pipe. High pressure in the pipe can also be challenging to keep constant.

However, if the pipeline is correctly installed it can be a strong infrastructure that can last many years. The pipeline would also be protected underground which is a great risk reducing factor for hydrogen transport.

11.1.2 Risk analysis

The result from the risk analysis for Case 1 is shown in Table 6.5. The incidents that give the highest RPN is: Incident 1, fire from equipment with 6 in RPN, and Incident 8 weather with 8 in RPN. Incident 1 is fire from equipment, the frequency is set to 2, and the consequence is set to 3. The production facility is located at Ringdal which is far away from the city centre or any urban areas. Due to being placed close to a forest, a forest fire could occur. Therefore the consequence is set to 3. The weather-incident has a lower consequence at 2. The weather changes quite often and therefore the frequency is set to 4.

Incident 2 is damage by explosion. An explosion could occur in the production facility, which could cause larger material damages on Ringdal power station, which is why the consequence is set to 4. However, the chances for this happening is quite low, and therefore frequency is set to 1. With the same RPN at 4 is Incident 5, damage from leak in transportation. As mentioned before leakage in the pipe could occur. The frequency is therefore set to 2. However, the consequence from the leakage is lower and is set to 2. A leakage is mostly a risk for personnel repairing the damages, as a leakage of hydrogen can again cause a fire due to it being easily ignited with oxygen.

The higher RPN, the greater the risk. By summing all the incidents in Table 6.5 together the total RPN becomes 37 for Case 1.

11.2 Case 2: Production facility at Ringdal with daily truck transport

Table 11.2 shows the total cost, hydrogen demand, hydrogen price and hydrogen fuelling costs for Case 2. The values for CapEx and Opex is obtained from the economic calculations done in Table B.4 in Appendix B. The total CapEx is 43 MNOK and the OpEx within ten years is 28 MNOK. The total cost for a ten-year operation then becomes 71 MNOK. The total hydrogen needed for the new ferries are calculated from Table 2.1 and is a total of 1 870 000 kg. Dividing the total cost after ten years by the total amount of hydrogen needed for ten years, the price per kg hydrogen then becomes 38 NOK/kg.

Table 11.2: *Total costs and hydrogen price for Case 2*

Description	Value	Unit
Total CapEx	43	MNOK
Total OpEx	28	MNOK
Total Price 10 years	71	MNOK
Hydrogen price	38	NOK/kg
Hydrogen fuel cost each year	7.1	MNOK

A hydrogen price at 38 NOK/kg is about the same estimated market price as for alkaline water electrolysis in 2020, which is around 23-44 NOK/kg according to Figure 3.2. With a price of 38 NOK/kg the price for a full tank at 150 kg for the ferry will cost around 5700 NOK. This gives a total cost of 7.1 MNOK each year. The current ferries have a fuel cost of 6.8 MNOK each year. The cost per year using hydrogen would therefore only increase the costs with 300 000 NOK. Support from different public funds can also make the price more competitive. The maintenance cost for the new ferry would most likely also be less than the current ferries.

The total CapEx and OpEx consist of different expenses. Figure 11.3 shows the capital expenses divided into parts in the percentage of the total CapEx, while Figure 11.4 shows the operational expenses divided into parts in the percentage of total OpEx.

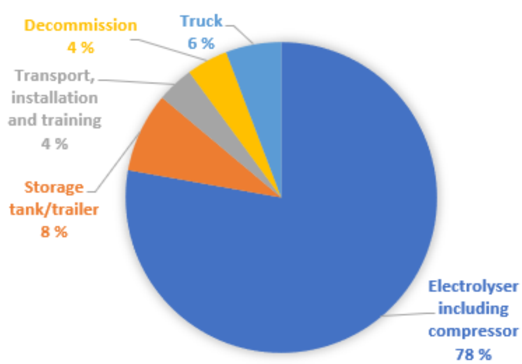


Figure 11.3: *Capital expenses for Case 2 in percentage*

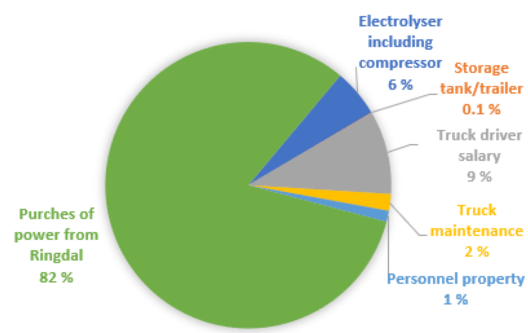


Figure 11.4: *Operational expenses for Case 2 in percentage*

The different capital expenses in Figure 11.3 show that 86 % is for buying the electrolyser system, including compressor and storage tank. The storage tank will be mounted on the truck. The same storage costs are assumed for all the cases. However, there could be some difference in the pricing due to the storage tank not being fixed. The cost of buying the truck is set to be 2.5 MNOK which is 6 % of the total CapEx and includes additional equipment like a crane or bracket for the trailer/storage tank. This price can vary depending on the truck model and the pricing on trucks in general. The truck is creating uncertainty due to the costs. The remaining 8 % is transport, installation, training, and decommissioning are the same for all cases.

The different operational expenses in Figure 11.4 show that 82 % of the total operational cost in ten years is the purchase of electricity to the electrolyser. The additional 6 % is maintenance on the electrolyser, compressor and electrical equipment.

The maintenance cost is set to 61 000 NOK each year, which is 2 % of the total OpEx. This price is for a normal diesel engine truck. However, as one of the goals of the projects is to reduce emissions, the truck could also be a hydrogen truck or other type of zero-emission truck that could change the maintenance costs. The truck driver's salary is found from SSB and is set to be 260 000 NOK each year for the period the ferry operates. This is 2.6 MNOK in salary after ten years, and is 9 % of the total OpEx. This amount does not take inflation, salary raise and other expenses of having an employee into account. The salary will therefore most likely be higher than anticipated. The remaining 2 % is for maintenance on the property and storage tank/trailer.

Case 2 also has the production facility located at Ringdal power station. Ringdal power station can then feed directly into the electrolyser minimising the transfer losses and reducing the marginal losses in the grid. The electricity price is therefore set to 0.25 NOK/kWh, which gives a total operational cost for the electrolyser at 23 MNOK in a ten-year perspective. As mentioned in Case 1 the price is not fixed and may vary a lot depending on the time of the season and water level in the river.

11.2.1 Truck transport

The advantage with the truck solution is that the additional infrastructure needed other then the electrolyser and storage tank is limited to the truck. The truck is a one-time investment that can operate the route between the production facility at Ringdal and Hellesylt quay during the lifetime of the electrolyser. During this time the truck must run on fossil-free fuel so the green hydrogen stays green.

However, one drawback is that the truck would shuttle back and forth through the town. With a normal storage tank at 450 kg, the truck would have to operate up to 3 times a day. Also, it will require two tanks since there is always one storage tank at the quay, and one on refill at the production facility.

11.2.2 Risk analysis

The risk analysis is given in Table 7.1. The table shows that the Incident 5, damage and leak while transport have the highest RPN. Since the truck drives back and forth from Ringdal to the ferry quay there is a chance for collision. The frequency for this is therefore set to 3. Due to the truck being filled with hydrogen the consequence in a collision is high, and the consequence is therefore set to 4.

Incident number 8 and Incident number 1 also have a relatively high RPN number. Incident 1, damage from fire, is fire from equipment. The electrolyser can cause a fire, which can damage Ringdal power station and since the forest is close, a forest fire could also happen in dry periods. The frequency for this is set to 2, while the consequence is set to 3. Incident 8, weather, also generate some additional risk for Case 2. The electrolyser is located at the same location as Case 1, and therefore the weather risk are the same. Additionally, due to the hydrogen being transported with a truck, icy roads and bad weather could also generate an additional risk for the truck.

The higher RPN, the greater the risk. By summing all RPN for the incidents in Table 7.1 the total RPN then becomes 46.

11.3 Case 3: Production facility at the quay with cable from Ringdal

Table 11.3 shows the total cost, hydrogen demand and hydrogen price for Case 3. The calculated CapEx and OpEx is based on economic calculations done in B.3 in Appendix B. The table shows that the total CapEx cost will be 49 MNOK and the OpEx over ten years is 60 MNOK. The total cost after ten years then becomes 108 MNOK. The total hydrogen demand for the new ferries after ten years is calculated from Table 2.1 and is 1 870 000 kg. Divided the total cost on the total amount of hydrogen in 10 years the hydrogen price becomes 58 NOK/kg.

Table 11.3: *Total costs and hydrogen price for Case 3*

Description	Value	Unit
Total CapEx	49	MNOK
Total OpEx	60	MNOK
Total cost	108	MNOK
Hydrogen price	58	NOK/kg
Hydrogen fuel cost each year	10.8	MNOK

This case gives a hydrogen price at 59 NOK/kg. This is above the estimated hydrogen price at 23-44 NOK/kg given in Figure 3.2. This means a full tank at 150 kg for the new ferry would cost 8700 NOK, and a total of 10.8 MNOK each year. The current ferry has a fuel cost of 6.8 MNOK each year, which means that this case would give 4 MNOK in increased fuel costs. The main reason for the higher price is that an extra cost for the grid rate is required.
This is because the high voltage cable would go outside of Ringdal power station building plot. This generates an extra cost to the OpEx at 34.6 MNOK in a ten-year perspective. However, this can change as the grid rates and concession has been re-evaluated to improve the economics of hydrogen projects. Hydrogen is a good for energy storage, therefore implementing this as a part of the grid can improve the stability of the grid and help shave the peaks.

The total CapEx and OpEx consist of different expenses. Figure 11.5 shows the capital expenses divided into parts in the percentage of the total CapEx, while Figure 11.6 shows the operational expenses divided into parts in the percentage of total OpEx.

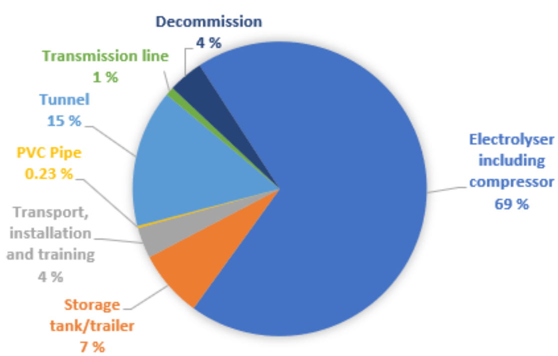


Figure 11.5: *Capital expenses for Case 3 in percentage*

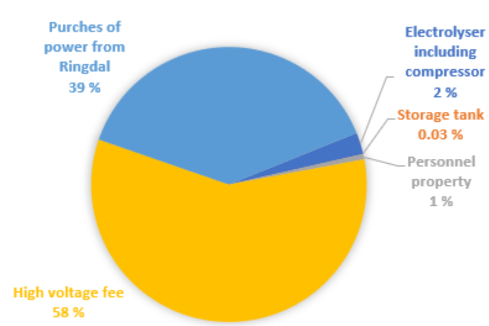


Figure 11.6: *Operational expenses for Case 3 in percentage*

The different capital expenses in Figure 11.5 show that 76 % of the total CapEx is for buying the electrolyser system, including compressor and electrical equipment, and storage tank. It is assumed that the new high voltage cable would go underground from Ringdal power station down to the ferry quay. This would require a tunnel and a pipe similar to Case 1. The cost for the tunnel and pipe is 15.23 % of the total CapEx. The PVC pipe is only 0.23 % of the cost, which is 110 000 NOK. This is without taking pipe fittings and other additional needed equipment into account. The high voltage cable is 1 % of the total CapEx which is 460 000 NOK. This is a assumed price from similar cables, it could therefore be some error in the pricing. The remaining 8 % is for transport, installation and training and decommissioning.

The different operational expenses in Figure 11.6 show that 58 % of the total OpEx in a ten-year perspective is the high voltage fee, and 39 % is purchase of electricity. The remaining 3 % is for electrolyser, compressor, electrical equipment, storage tank and personnel for the property. The figure shows that the high voltage fee costs is higher than the cost of buying electricity. The high voltage fee is approximately 34.7 MNOK and the purchase of power is 23 MNOK. This means that the high voltage fee costs 11.7 MNOK more than the purchase of power in a 10-year perspective. However, this price can vary a lot over the years. Electricity prices will depend upon the water levels in the river and how much surplus energy Ringdal can produce. The high voltage fee would also most likely increase in the future. This can impact the hydrogen price and the costs of the project.

11.3.1 High voltage cable

Case 3 considers the production facility at the ferry quay in Hellesylt. One advantage of having the production facility here is that the transportation step for hydrogen is eliminated. This means that the electrolyser can fill the storage tank or ferry directly. Having the production facility at the quay is also good for future expanding. Hydrogen fuelled cars, buses or shuttle boats could be possible customers in the future.

The main challenge with this Case is the concession for the high voltage cable and the grid rates. This is the largest expense for Case 3 and which is why the hydrogen price is higher. The concession and grid rates have been discussed in the Norwegian Parliament to re-evaluate the current grid rates to improve the economy of hydrogen projects. The result of this is not yet to be decided, but a change to the current grid system could happen that can impact the result of this Case.

11.3.2 Risk analysis

One problem with placing it close to the shore is the safety concern. Close to the intended place for the electrolyser is a facility for elderly people. This could be a security concern since the size of the electrolyser would be in the megawatt size. An explosion could cause a lot of material damage and injuries. Therefore this needs coordination with the local town and different safety measurements must be done to prevent this from happening. However, from the risk analysis in Table 8.2 the frequency is set to 1 and the consequence is set to 5. So the chances of an explosion is relatively low, but the consequence is high.

Fire is also an incident that could occur. Incident number 1 from 8.2 gives a RPN at 8. A fire could occur in the electrolyser and spread to nearby habitats. Due to the electrolyser being located at the quay closer to the city centre the consequence for the fire is set to 4, while frequency is set to 2.

Having the electrolyser at the quay also means its more vulnerable for bad weather. From Figure 8.5 the weather-incident is placed in the red areas due to its high frequency at 4 and consequence at 3. Extreme weather and tide/flood can occur and damage or tear the construction. Risk-reducing factors like extra protection for housing of the electrolyser should therefore be considered. The maintenance cost for this case could therefore be higher than anticipated. Having the electrolyser at the quay also means that the well-spoken tsunami-incident from Åkerneset would hit the facility. This would damage not only the whole production facility but also the town. However, the chances for this happening is relatively low and the frequency is therefore set to 1, but the consequence is set to 5.

The higher RPN, the greater the risk. By summing all RPN for the incidents in Table 7.1 the total RPN then becomes 53.

11.4 Case 4: Production facility at the quay using the grid

Table 11.4 shows the total cost, hydrogen demand and hydrogen price for Case 4. The CapEx and OpEx is based on economic calculations done in Table B.4 in Appendix B. The CapEx is 42 MNOK and the OpEx over ten years is 72 MNOK. This gives a total cost after ten years of 114 MNOK. The total hydrogen demand after ten years is calculated from Table 2.1 and is 1870 tonnes. Dividing the total cost on the total hydrogen demand after ten years, the hydrogen price becomes 60 NOK/kg.

Table 11.4: *Total costs and hydrogen price for Case 4*

Description	Value	Unit
Total CapEx	42	MNOK
Total OpEx	72	MNOK
Total cost	114	MNOK
Hydrogen price	60	NOK/kg
Hydrogen fuel cost each year	11.3	MNOK

Case 4 gives a hydrogen price at 62 NOK/kg. This is also above the estimated hydrogen price at 23-44 NOK/kg given in Figure 3.2. For this case a full tank of hydrogen at 150 kg would cost 9100 NOK, and a total of 11.3 MNOK each year. The current ferry have a fuel cost of 6.8 MNOK each year, which means this case gives 4.5 MNOK in increased fuel costs each year. The main reason for the higher cost in this case is both the high voltage fee and the purchase of power directly from the grid which gives a high OpEx. The average price from Nordpool in 2019 were 0.38 NOK/kWh which is higher than the other cases and therefore results in a higher OpEx. However, as all the other cases this electricity price can also vary a lot.

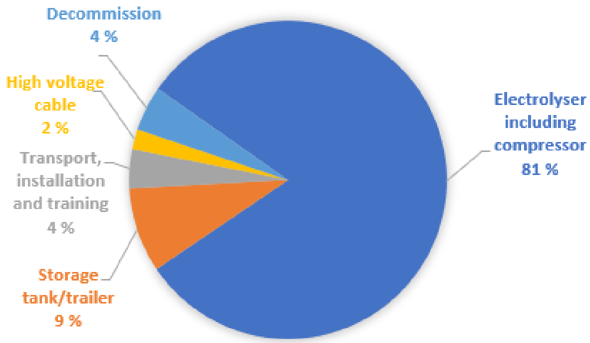


Figure 11.7: *Capital expenses for Case 4 in percentage*

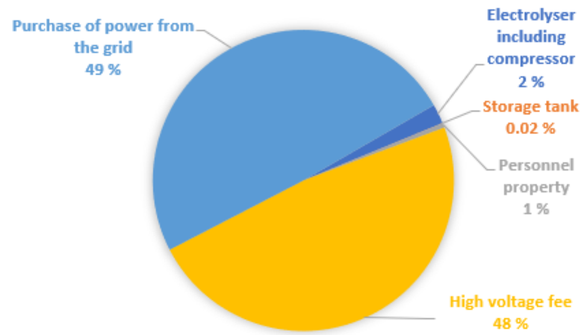


Figure 11.8: *Operational expenses for Case 4 in percentage*

Figure 11.7 shows the different capital expenses in the percentage of the total capital expenditures. This shows that 90 % of the investment cost is for the electrolyser system, including the compressor and electrical equipment, and the storage tank. 2 % of the costs is for the new high voltage cable, which is 850 000 NOK, and is based on a rough estimation done by Stranda Energi. The remaining 8 % are transport, installation, training, and decommissioning.

Figure 11.8 shows the different operation expenses in the percentage of the total operating expenses in a ten-year perspective. This shows that 49 % of the operational expenses are for purchasing power. Purchase of power is calculated from the maximum electric power consumption of the electrolyser from a 10-year perspective. As mentioned the price used to calculate the cost for electricity is 0.38 NOK/kWh, and is the average value from 2019. The grid rate is still the same as Case 3 at 34.6 MNOK which is 48 % of the total OpEx. The remaining 3 % is maintenance on the electrolyser, including compressor and electricity, storage tank, and some personnel on the property.

11.4.1 Existing grid

The estimated cost for Case 4 is dependent on where the new high voltage cable will be. Figure 9.2 shows three different options for the new high voltage cable. Option A would be similar to Case 3 and could increase the costs if a pipe would also be used in this case. Option B and C would be the more reasonable options to choose for Case 4. This is due to the distance being halved compared to option A. Option C would have to go through the town. This option causes more visual pollution if the new high voltage line is above ground. Option B would have less visual impact in the city, but would require to split the current cable and make a new junction point. However, option B have a more challenging terrain to build in. Also it will have to cross the river in Hellesylt.

The main challenge for Case 4 would be similar to Case 3, concession and grid rates. If a re-evaluation and a improved system for hydrogen projects gets approved in the Norwegian Parliament this Case might be more competitive and cost efficient.

The benefit for Case 4 is also similar to Case 3. The production facility is located at the ferry quay, which is convenient for future expanding. The transportation step for hydrogen is also removed since the storage tank is also located at the quay.

11.4.2 Risk analysis

Case 4 also considers the production facility at the ferry quay in Hellesylt. This means the advantages and disadvantages are similar to those in Case 3. The risk analysis is also similar or equal to Case 3. The main difference is where the production facility gets its power from. Case 4 assumes the import of power directly from the grid. This can generate an additional risk related to stability of the grid. The electrolyser is a large consumer of power at around 2.7 MW. This can cause voltage drop or unstable frequency in the area, which can be an inconvenience for other local customers of the electrical grid. The total RPN for Case 4 would therefore be around the same RPN as for Case 3 at around 53.

11.5 Usage of residue from hydrogen production

This subsection discusses the main findings for the bi-products oxygen and heat which will be produced by the electrolyser.

11.5.1 Oxygen as a residue

From Table 10.2 the produced oxygen each day is 9.6 tonnes for the high season, 4.8 tonnes for the mid season and 3.6 tonnes for the low season. The total oxygen produced each year then becomes 1 500 tonnes. The estimated oxygen price vary from 2-3 NOK/kg. With a price of 2.9 NOK/kg the total gross income becomes 4.2 MNOK. After freight costs and liquefying costs the total net income becomes 1.9 MNOK from the oxygen produced. Over ten years the total net income becomes 19 MNOK, assuming the oxygen price, costs and demand stays relatively the same over this period.

In Hellesylt there are no possible customers to this date, but there are some located in nearby municipalities. With the correct sales price and regularity the possibilities for the sale of the residue oxygen is competitive. Research proves that there are a large number of clients willing to buy oxygen at a reasonable price. Most of these clients are fish farms who are dependent on using the product in their production as Table 10.1 shows. Kraft Laks AS gets the oxygen delivered from Rjukan, which is a 500 km drive, which takes approximately 8 hours and 30 minutes. Hellesylt is only 83 km away from Kraft Laks AS. With this short distance it can be possible to reduce the freight costs for Oxygen. A sale to fish farms would generate a great extra income for this project, making the project more lucrative to realise. Since the Oxygen will be produced no matter what it is better to sell this than let it go to waste.

The hospital located in Aalesund could also be a possible customer of purchasing oxygen. Hospitals are rapidly using medical oxygen for patients. For medical use, there is a standard for the purity of the oxygen to make it usable for persons. The purity of the produced oxygen from the electrolyser is 99.5 %, with an uncertainty of 0.2 %. The quality standard demand for medical oxygen is minimum 99.5 %, so the produced oxygen from the electrolyser might not be used without increasing purity. However, there could be an opportunity to clean this oxygen to get it approved, but this depends upon the price and demand.

There is a market for selling this residue since there is no other nearby production site. A market for cheaper, local and more environmental oxygen has been revealed. The current oxygen is transported by trucks from Rjukan once a week for one single fish farm. Somewhere between 25-45% of the price is caused by transportation.
Additionally there are costs related to storing and liquefying oxygen that is inevitable. However, the oxygen will be produced anyway from the electrolyser and it shows that even with the costs it can be profitable for the project to sell

the oxygen. Table 11.10 shows that by selling oxygen the hydrogen price can be reduced and be more competitive. This proves that local production and sale has a potential.

In the end, the most important factor to the fish farms is the predictability of the deliveries throughout the whole year. And since the production facility in Hellesylt only produces from April through October it cant deliver all year around. Which can make the fish farms stick to the current deliveries even though the price is higher.

11.5.2 Heat as a residue

From Table 10.3 the total heat produced per year from the electrolyser is 2800 MWh. It is assumed that around 50 % could be used as heating after losses in transportation and in equipment is accounted for. Therefore the total usable heat becomes 1400 MWh.

In Table 10.4 the usable heat is compared to the heating demand in kWh/m^2year for different buildings. The table shows that it can heat up 8200 m^2 for school buildings, 7600 m^2 for hotels, 7700 m^2 for sports facilities, 7400 m^2 for cultural buildings, and 7100 m^2 for smaller industries. This shows that there are some potential for the heat produced from the electrolyser.

The local industry Ringdal meat factory is in the small-industry category and could be a possible customer. The factory is also located relatively close to the production facility at the quay if Case 3 or 4 is chosen. How much Ringdal would be willing to pay depend upon their current source of heating. The price of electricity is also low so if Ringdal gets heated up using electricity it might be hard to compete in price. Since Ringdal is a meat factory they would mostly need more cooling than heating, due to the cold rooms for food storage.

There is also a school and a cultural building that could be possible customers. They are also located in the city centre, which is not too far from the production facility for Case 3 and 4. Hellesylt is a small town and both the school and cultural building is small, which means that the heat demand is also small. Building out large infrastructure in the town for small buildings would therefore most likely not be worth it economically.

For Case 1 and 2 utilisation of the heat would be more difficult due to the production facility being located at Ringdal power station, which is a couple of kilometres away from the city centre. Transporting heat over longer distances is not efficient and building out the additional infrastructure down from Ringdal would be expensive. Therefore utilisation of the heat would manly be if the production facility is located at the quay.

11.6 Comparison of the Cases

Figure 11.9 shows the total costs after ten years for different cases with and without the sale of oxygen. Figure 11.10 shows the estimated price per kg hydrogen for different cases with and without the sale of oxygen.

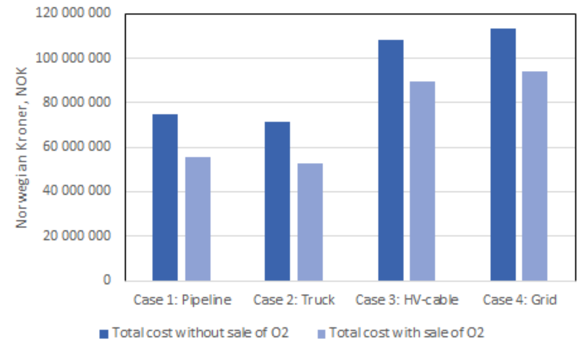


Figure 11.9: *Total cost in ten years with and without the sale of O_2*

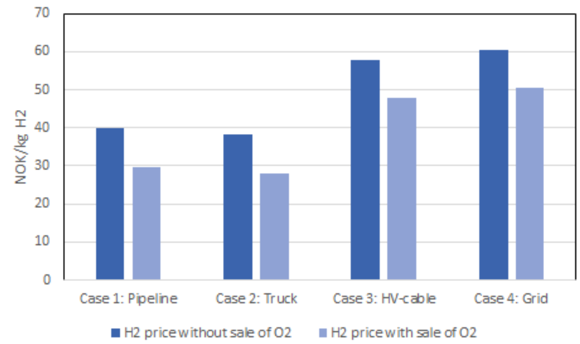


Figure 11.10: *H_2 kilo price with and without sale of O_2 for the cases*

The figures shows that Case 2 gives the lowest cost after ten years, which is 71 MNOK, and a hydrogen price at 39 NOK/kg. For Case 1 the total cost is 75 MNOK, with a hydrogen price at 41 NOK/kg. The figure also shows that cases 3 and 4 differ in price from the other cases. Case 3 has a total cost of 108 MNOK, and a hydrogen price at 59 NOK/kg. While Case 4 has a total cost of 114 MNOK, and a hydrogen price at 62 NOK/kg, which is the highest price of all cases.

Figure 11.10 also shows that if the sale of oxygen from Table 10.2 is taken into the calculations the total costs can be reduced to 56 MNOK and the hydrogen price to 30 NOK/kg for Case 1. For Case 2 the total costs can be reduced to 52 MNOK and the hydrogen price to 28 NOK/kg. For Case 3 and 4 the total costs gets reduced to 89 MNOK and 94 MNOK. The hydrogen price then becomes 48 NOK/kg and 50 NOK/kg. The total cost reduction then becomes 17-20 % for all cases. It is assumed a fixed price on the oxygen at 2.90 NOK/kg for the ten years period. However, this price can also vary a lot similar to the electricity price and also impact the hydrogen price.

The difference in hydrogen price between Case 1 and 2 are 2 NOK/kg. The same applies to Case 3 and 4. As mentioned in the scope of work, the numbers used have some uncertainties. Hence, this small difference at 2 NOK/kg between the cases can be caused by uncertainties in the calculations.

Case 1 and 2 have the production facility at Ringdal power station, while Case 3 and 4 have the production facility at the ferry quay. Table 11.5 gives a overview of the different location options for the dispenser and storage tank for the different cases. Case 1 and 2 gives more versatility of where the storage tank and dispenser can be located, while Case 3 and 4 are limited to the ferry quay due to the electrolyser being located there.

Case 1 and 2 have a lower price overall due to the production facility being located at Ringdal power station building plot. This avoids the extra cost from the high voltage fee. Also, both these cases assume that Ringdal power station delivers most of the power to the electrolyser, which is why the price of electricity is lower for these cases due to lower transfer losses. However, as seen in Figure 4.2 in August and September the average production is lower than the needed energy for the electrolyser. This means that import of electricity is necessary, which can increase the cost

Table 11.5: *Possible location of the dispenser and storage tank for the cases*

Case	Dispenser location	Storage tank location
Case 1: Pipeline	Ferry quay	Ringdal or Ferry quay
Case 2: Truck	Ringdal	Ringdal or Ferry quay
Case 3: Cable	Ferry quay	Ferry quay
Case 4: Grid	Ferry quay	Ferry quay

and hydrogen price for Case 1 and 2.

Both Case 3 and 4 have a higher OpEx. The main reason for this is the grid rates. Both of these cases require to build out new high voltage lines, and therefore grid rates will have to be paid. The grid rates stand for 58 % of the total OpEx in Case 3, and 48 % in Case 4. Also, the price of electricity is set to a higher value due to it being transferred over longer distances and might have a higher transfer loss.

Case 4 have the lowest CapEx which can be convenient for the start-up of the project. Since hydrogen production in this scale being relatively new technology, the grid rates and current system for hydrogen factories are under discussion in the Norwegian Parliament. This can have a large impact and decrease the operational costs and make Case 3 and 4 a better option. Furthermore, the location in Case 3 and 4 will be a excellent location for future expanding in Hellesylt.

It is also worth noting that the calculated prices for hydrogen do not make any room for profit. Due to the length of life of the electrolyser at ten years it would be the first bigger component that would have to be changed. Therefore a profit on every kilo sold hydrogen could be saved and reinvested in a new electrolyser after ten years. All the cases also have a assumed price of electricity. In reality this price is close or almost impossible to predict, which would also mean that the hydrogen price would also be hard to predict. Nevertheless, the prices give an estimation of what price to expect. Support from public funds are not taken into the calculations, which could reduce the CapEx and OpEx for the cases.

To get a clear overview of what is the best option overall, priority factors for all cases are analysed. These are carefully assessed against what is the importance of each structure in the project. Values set are based on the final results of the assignment and scaled from 1-10 and are calculated in Appendix A.

The different criteria are weighted on what is the most important factors for this project to succeed. The values in Figure 11.11 show that the highest summation-value is safety. This means that this factor affects the priority vector the most. A more detailed description of the categories is given in Appendix 12.

Priority factors	Sum
Price	0,41
Visual pollution	0,04
Transportation	0,05
Safety	0,45
Practical execution	0,05

Figure 11.11: *Priority factors*

The column with the highest summation value in Figure 11.12 represents the overall preferred location. Here all the different priorities have been weighted to summarise a conclusion based on the scaling of numbers. The full calculation and weighting can be found in Appendix 12.

Priority vectors	Sum
Case 1 (Pipe)	0,45
Case 2 (Truck)	0,34
Case 3 (Cable)	0,11
Case 4 (Grid)	0,1

Figure 11.12: *Final priority vectors*

The figure shows that Case 1 gives the highest overall sum at 0.45, which means this is the best option overall. Case 2 comes in second with a sum of 0.34, and Case 3 in third with a sum of 0.11. Case 4 comes last with a sum of 0.10. The main difference between Case 1 and 2 is safety. Case 1 scores higher on safety due to the hydrogen being transported in a fixed pipe underground.

Case 2 has transportation on the road which gives a greater chance of collision which reduces the safety score. Case 2 also gives the lowest cost after ten years and the best hydrogen price at 38 NOK/kg or 28 NOK/kg with the sale of O_2 of all cases. Additionally, Case 2 has a better practical execution, due to the practical challenges of building approximately 920 m pipeline from Ringdal power station.

Case 3 and 4 scores lower in almost all the categories, except the transportation category. Both cases generate extra costs due to the grid rates. They also cause visual pollution due to the production facility being located at the quay, higher safety concern due to the production facility being close to the city centre and more practical challenges due to concessions. However, the transportation category scores higher for Case 3 and 4, which is due to the production facility being located at the ferry quay.

12 Conclusion

The price per kilogram hydrogen in Case 1 is 40 NOK, and for Case 2 at 38 NOK. The difference between these Cases is 2 NOK. This is considered more or less insignificant and can be caused by uncertainties in the calculations. Case 1 scores better on safety, and are therefore a better overall choice. Case 3 has a hydrogen price at 58 NOK, and Case 4 at 60 NOK, which also gives a difference at 2 NOK.

The total evaluation shows that the production facility at Ringdal with hydrogen transport through a pipeline in Case 1, gives the best score overall. The truck solution in Case 2 comes in second-best. The high voltage cable in Case 3 gives the third-best solution and connection to the existing grid in Case 4 gives the lowest score. The thesis therefore concludes with that Case 1, production facility at Ringdal power station and hydrogen transportation by using a pipeline is the better overall solution for this project. In addition, the thesis also concludes that Case 2 is a good second choice. Due to the much higher price and lower safety, Case 3 and Case 4 are not recommended.

For the usage of residues, there is a market for selling oxygen. Nearby fish farms are willing to purchase oxygen. Hospitals and research institutes could also be possible customers, but these do not seem like the best purchasers due to low consumption and high purity requirements. As for the heat, only local customers could utilise some of the waste heat. The high voltage cable solution in Case 3, and the grid solution in Case 4 would be the only cases that could utilise the heat, due to the location of the production facility in the city centre.

The main findings show that there is an excellent opportunity to utilise the surplus energy in Hellesylt. Apart from the investment in the vessel, the fuel price is close to economically sustainable even without public funds for case 1 and 2. Including the sale of oxygen, the hydrogen price will be even more competitive to the current marine diesel.

Recommendations for further work

Since this thesis is a piece of a larger project, it is reasonable to give guidance on further work. In the beginning of this thesis, the total scope of work is described. This chapter will give an insight into areas were information was hard to gather or collect. The fact that this is a Bachelor's thesis led to restrictions due to sensitive information, offers of services and goods. To achieve accurate prices it had to be a realistic and specific order or project.

As this thesis has developed, it has become evident that it could be written separate theses about project management, HMS, the vessels, economy and more. If the thesis would be expanded, the main focus would cover the specifications for delivery and loading hydrogen from the quay to the vessels.

A more detailed look into the new ferries should also be done. This thesis mainly looks into the production of hydrogen and the transportation to the storage tank/dispenser. The new hydrogen ferries are still under development and uses new technology. Therefore, among other factors, a more detailed calculation for energy usage, safety systems and fuel cell system should be done. The greatest risk with hydrogen is when the ferry receives it. Therefore a detailed risk analysis is also recommended to be done for the ferry.

The ferries are normally at layup in the winter, solutions for the rest of the year should be looked into. For example, this could either be larger storage facilities or sale of hydrogen to other clients, also outside Hellesylt. In that way, hydrogen and the residue oxygen could be sold throughout the whole year increasing the income for the project.

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A Excel data from priority factors

Figure A.1 has the function to show which category that is highest valued and have the highest impact. In the figure, priority values are summarised to give an overview of which solution is preferred. Values are based on inputs, opinions and facts that the thesis has given. Values are summarised vertically in the first matrix, then normalised by dividing the sum to each vertical category. After this is done, the numbers are multiplied horizontally and divided on the number of categories. The final result in yellow to the right gives an overview of which category is most valued.

	Price	Visual pollution	Transportation	Safety	Practical execution
Price	1,00	10,00	8,00	1,00	7,00
Visual pollution	0,10	1,00	0,90	0,10	0,70
Transportation	0,13	1,11	1,00	0,10	1,20
Safety	1,00	10,00	10,00	1,00	9,50
Practical execution	0,14	1,43	0,83	0,11	1,00
Sum	2,37	23,54	20,73	2,31	19,40

Normalised

Priority factors	Price	Visual pollution	Transportation	Safety	Practical execution	Sum
Price	0,42	0,42	0,39	0,43	0,36	0,41
Visual pollution	0,04	0,04	0,04	0,04	0,04	0,04
Transportation	0,05	0,05	0,05	0,04	0,06	0,05
Safety	0,42	0,42	0,48	0,43	0,49	0,45
Practical execution	0,06	0,06	0,04	0,05	0,05	0,05

Figure A.1: *Priority factors calculation*

Total price: The costs in a life cycle that justifies the hydrogen price per kilograms. The hydrogen price is explained in Figure 3.10. The total price is based on the total value calculated by using the LCC Figure 3.11. It consists of four main categories: investment costs, operation, maintenance & repair and decommissioning.

Visual pollution: Normally man-made constructions or buildings that do not fit in the environment. Often this is a personal matter and are therefore hard to determine. The consideration has been evaluating if most of the equipment is either located in the city centre or outside the centre. It is clear that having all the equipment placed in the city centre would lead to more visuals. No matter what option is selected the storage tanks would have to be placed in the centre.

Transportation: This considers the practical solutions regarding transportation. It describes the extent to which transport leads to more traffic in the immediate area, activities in the area and neighbourhood, convenience, employment and environment. The three different transportation methods are explained in Figure 6.1, 7.1 and 8.1.

Safety: This includes the risk that is involved in construction work, operation and maintenance of the equipment. Also it involves the exposure of external areas and surroundings if an incident should occur. The relevant risks are explained Table 5.1 and also for each case.

Practical challenges: This category is how complicated each case is to realise. Each case have different practical challenges that must be taken into the calculations.

In Figure A.2 the different cases are considered up against each other in separate categories. The category for each valuation is noted in the top left corner. Values are summarised in the same way as Figure A.1. Summarised vertically and divided the summation on each value in the normalised matrix, then an average is calculated horizontally. The numbers will then be able to tell which case is the most suitable for each category.

Price	Case 1	Case 2	Case 3	Case 4
Case 1 (Pipe)	1,00	0,90	3,00	6,00
Case 2 (Truck)	1,11	1,00	5,00	7,00
Case 3 (Cable)	0,33	0,20	1,00	1,80
Case 4 (Grid)	0,17	0,14	0,56	1,00
Sum	2,61	2,24	9,56	15,80

Visual pollution	Case 1	Case 2	Case 3	Case 4
Case 1 (Pipe)	1,00	1,00	4,00	4,00
Case 2 (Truck)	1,00	1,00	4,00	4,00
Case 3 (Cable)	0,25	0,25	1,00	1,00
Case 4 (Grid)	0,25	0,25	1,00	1,00
Sum	2,50	2,50	10,00	10,00

Transportation	Case 1	Case 2	Case 3	Case 4
Case 1 (Pipe)	1,00	6,00	0,50	0,50
Case 2 (Truck)	0,17	1,00	0,20	0,20
Case 3 (Cable)	2,00	5,00	1,00	1,00
Case 4 (Grid)	2,00	5,00	1,00	1,00
Sum	5,17	17,00	2,70	2,70

Safety	Case 1	Case 2	Case 3	Case 4
Case 1 (Pipe)	1,00	3,00	6,00	6,00
Case 2 (Truck)	0,33	1,00	3,00	3,00
Case 3 (Cable)	0,17	0,33	1,00	1,00
Case 4 (Grid)	0,17	0,33	1,00	1,00
Sum	1,67	4,67	11,00	11,00

Practical execution	Case 1	Case 2	Case 3	Case 4
Case 1 (Pipe)	1,00	0,20	0,60	0,50
Case 2 (Truck)	5,00	1,00	4,00	5,00
Case 3 (Cable)	1,67	0,25	1,00	0,80
Case 4 (Grid)	2,00	0,20	1,25	1,00
Sum	9,67	1,65	6,85	7,30

Normalised

Price	Case 1	Case 2	Case 3	Case 4	Sum
Case 1 (Pipe)	0,38	0,40	0,31	0,38	0,37
Case 2 (Truck)	0,43	0,45	0,52	0,44	0,46
Case 3 (Cable)	0,13	0,09	0,10	0,11	0,11
Case 4 (Grid)	0,06	0,06	0,06	0,06	0,06

Visual pollution	Case 1	Case 2	Case 3	Case 4	Sum
Case 1 (Pipe)	0,40	0,40	0,40	0,40	0,40
Case 2 (Truck)	0,40	0,40	0,40	0,40	0,40
Case 3 (Cable)	0,10	0,10	0,10	0,10	0,10
Case 4 (Grid)	0,10	0,10	0,10	0,10	0,10

Transportation	Case 1	Case 2	Case 3	Case 4	Sum
Case 1 (Pipe)	0,19	0,35	0,19	0,19	0,23
Case 2 (Truck)	0,03	0,06	0,07	0,07	0,06
Case 3 (Cable)	0,39	0,29	0,37	0,37	0,36
Case 4 (Grid)	0,39	0,29	0,37	0,37	0,36

Safety	Case 1	Case 2	Case 3	Case 4	Sum
Case 1 (Pipe)	0,60	0,64	0,55	0,55	0,58
Case 2 (Truck)	0,20	0,21	0,27	0,27	0,24
Case 3 (Cable)	0,10	0,07	0,09	0,09	0,09
Case 4 (Grid)	0,10	0,07	0,09	0,09	0,09

Practical execution	Case 1	Case 2	Case 3	Case 4	Sum
Case 1 (Pipe)	0,10	0,12	0,09	0,07	0,10
Case 2 (Truck)	0,52	0,61	0,58	0,68	0,60
Case 3 (Cable)	0,17	0,15	0,15	0,11	0,14
Case 4 (Grid)	0,21	0,12	0,18	0,14	0,16

Figure A.2: *Priority vectors calculations*

Figure A.3 represents the conclusion of the priority calculations. After calculating the most important categories to the project, the different options are put together. All values used for calculations are from the normalised matrices. Values from the first matrices are just calculations to find the normalised values. For example by finding the final priority vector to Case 1. The value for Case 1 and Price-value are found in Figure A.2, this value is multiplied with the price-value from Figure A.1. The same method is used to find the value for all the categories to Case 1. In the end all the values are multiplied, and this is the final priority vectors. With this method each case focuses on its bad and good advantages, the importance of the categories is weighted.

Final result

Priority vectors	Price	Visual pollution	Transportation	Safety	Practical execution	Sum
Case 1 (Pipe)	0,15	0,02	0,01	0,26	0,00	0,45
Case 2 (Truck)	0,19	0,02	0,00	0,11	0,03	0,34
Case 3 (Cable)	0,04	0,00	0,02	0,04	0,01	0,11
Case 4 (Grid)	0,03	0,00	0,02	0,04	0,01	0,10

Figure A.3: *Final priority vectors calculations*

B Financial calculations

This appendix shows the financial calculations done for each case. The values are divided into capital expenses and operational expenses.

B.1 Case 1: Production facility at Ringdal with hydrogen pipeline

Case number one looks into the possibility of having the production facility at Ringdal power plant, and transporting the hydrogen through a pipeline. Table B.1 shows the economic calculations done for case number one.

Table B.1: *Economical calculations for Case 1*

Note: Descriptions marked with <*> are data based on estimation and assumption.

Investment:			
Description	**Value**	**Price**	**Total [NOK]**
Electrolyser incl. Compressor	2,7 MW	kr 12 500 000	kr 33 750 000
Storage tank	800 kg	4500 kr/kg	kr 3 600 000
Transport, installation, training			kr 1 650 000
Pipe	24656 kg	45 kr/kg	kr 1 110 000
Tunnel	738 meter	10000 kr/meter	kr 7 380 000
Trench	180 meter	2000 kr/meter	kr 360 000
Decommissioning	5 %	kr 38 460 000	kr 1 923 000
Total investment price			kr 49 773 000
OPEX 10 year plan:			
Electrolyser	4.5 %	kr 33 750 000	kr 1 519 000
Storage tank	0,5 %	kr 3 600 000	kr 18 000
*Pipe	0,05	1 110 000	kr 56 000
*Personnel property	350 hour	1000 kr/hour	kr 350 000
Purchase of power from Ringdal	91 900 554 kWh	0,25 kr/kWh	kr 22 975 000
Total OPEX 10 yrs			kr 24 917 000
Total price after 10 yrs			***kr 74 690 000***
Hydrogen price			***40 kr/kg***

B.2 Case 2: Production facility at Ringdal with daily truck transport

Case number two looks into the possibility of having the production facility at Ringdal power plant, and transporting hydrogen with a truck. Table B.2 shows the economic calculations done for case number two.

Table B.2: *Economical calculations for Case 2*

Note: Descriptions marked with <*> are data based on estimation and assumption.

Investment:			
Description	**Value**	**Price**	**Total [NOK]**
Electrolyser	2.7 MW	12500000 kr/MW	kr 33 750 000
Storage tank	800 kg	4500 kr/kg	kr 3 600 000
Transport, installation, training			kr 1 650 000
Truck			kr 2 500 000
Decommissioning	5 %	kr 37 350 000	kr 1 868 000
Total investment price:			kr 43 368 000
OPEX 10 year plan:			
Electrolyser	4.5 %	kr 33 750 000	kr 1 519 000
Storage tank	0.5 %	kr 3 600 000	kr 18 000
*Personnel property	350 hour	1000 kr/hour	kr 350 000
Truck driver	10 year	263000 kr/year	kr 2 630 000
*Truck maintenance	10 year	53000 kr/year	kr 530 000
Purchase of power from Ringdal	91 900 554 kWh	0,25 kr/kWh	kr 22 975 000
Total OPEX 10 years			kr 28 022 000
Total price after 10 years			***kr 71 390 000***
Hydrogen price			***38 kr/kg***

B.3 Case 3: Production facility at the quay with hv-cable from Ringdal

Case number three looks into the possibility of having the production facility at the quay with high voltage cable from Ringdal power plant. Table B.3 shows the economic calculations done for case number three.

Table B.3: *Economical calculations for Case 3*

Note: Descriptions marked with <*> are data based on estimation and assumption.

Investment:			
Description	**Value**	**Price**	**Total**
Electrolyser	2.7 MW	12 500 000 kr/MW	kr 33 750 000
Storage tank	800 kg	4500 kr/kg	kr 3 600 000
Transport, installation, training			kr 1 650 000
*Pipe	920 meter	120 kr/meter	kr 110 000
Tunnel	738 meter	10000 kr/meter	kr 7 380 000
*Cable	920 meter	500 kr/meter	kr 460 000
Decommissioning	0,05	kr 37 460 400	kr 1 873 000
Total investment price:			kr 48 820 000
OPEX 10 year plan:			
Electrolyser	4.5 %	kr 33 750 000	kr 1 519 000
Storage tank	0,5 %	kr 3 600 000	kr 18 000
*Personnel property	350 hour	1000 kr/hour	kr 350 000
High voltage fee	10 year	3468000 kr/year	kr 34 680 000
Purchase of power from Ringdal	91 900 554 kWh	0,25 kr/kWh	kr 22 975 000
Total OPEX 10 yrs			kr 59 542 000
Total price after 10 yrs			***kr 108 365 000***
Hydrogen price			***58 kr/kg***

B.4 Case 4: Production facility at the quay using the grid

Case number four looks into the possibility of having the production facility at the quay using the existing grid and purchase of power to operate the electrolyser. Table B.4 shows the economic calculations done for case number four.

Table B.4: *Economical calculations for Case 4*

Note: Descriptions marked with <*> are data based on estimation and assumption.

Investment:			
Description	**Value**	**Price**	**Total**
Electrolyser	2.7 MW	12 500 000 kr/MW	kr 33 750 000
Storage tank	800 kg	4500 kr/kg	kr 3 600 000
Transport, installation, training			kr 1 650 000
Electric mounting			kr 850 000
Decommissioning	0,05	kr 38 200 000	kr 1 910 000
Total investment price:			kr 41 760 000
OPEX 10 year plan:			
Electrolyser	4.5 %	kr 33 750 000	kr 1 520 000
Storage tank	0,5 %	kr 3 600 000	kr 18 000
*Personnel property	350 hour	1000 kr/hour	kr 350 000
High voltage fee	10 year	3468000 kr/year	kr 34 680 000
Purchase of power	91 900 55 kWh	0,38 kr/kWh	kr 34 922 000
Total OPEX 10 yrs			kr 71 490 000
Total price after 10 yrs			***kr 113 250 000***
Hydrogen price			***60 kr/kg***