Assessing the Feasibility of Hydrogen Plants Powered by Floating Photovoltaics

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Preface

This bachelor thesis is written by three students studying Energy Technology at the Department of Mechanical and Marine Engineering (IMM) at Western Norway University of Applied Scienes (WNUAS). In this thesis, knowledge from previous courses has been required.

Internal supervisor from WNUAS is Dr. Velaug Myrseth Oltedal, assistant head of department at IMM. Project description is provided by external supervisor Dr. Alan Henry from Solar Marine Energy Ltd.

We would like to extend a special thanks to all the people who has helped along the way. Dr. Velaug Myrseth Oltedal (IMM), Dr. Alan Henry (Solar Marine Energy Ltd), Dr. Paul Leahy (UCC), Trond Strømgren (Hub for Ocean), Bjørn Gregert Halvorsen (NEL), and all the people we met at the MaREI center in Cork. Last but not least we would like to thank Stord Rotaryklubb and Sunnhordland Kraftlag for the financial support.

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SOLARMARINE ENERGY

Abstract

The world needs to transition from a fossil fuel based energy sector into a more sustainable one. Hydrogen can serve as a low-carbon option to conventional fuels across several sectors, as long as the production, storage and distribution comes with a low carbon footprint. When used as an energy carrier, hydrogen can help decarbonise industry, transport, power generation, and buildings. However, in order to scale up hydrogen production from renewable sources, increased electrolyser capacity is needed. This thesis assessed the feasibility of hydrogen production powered by floating photovoltaics (FPV).

A literature study assessing the maturity of FPV and hydrogen technology was undertaken. An assessment of projected market demand of hydrogen across different sectors was also carried out. Several reports assessing the future demand of hydrogen, strategies for uptake, and scenarios under which hydrogen is likely to see growth were reviewed. Three case studies were carried out in order to get a more in-depth and detailed examination of the feasibility of FPV powered hydrogen plants at several locations around the globe exhibiting various degrees of solar radiation.

In the literature studies, it was found that both FPV and hydrogen technology is maturing, and that their industries are ready to help enabling the energy transition to a net-zero world. It was found that there are several advantages to installing a hydrogen plant powered by FPV located in close proximity to ports and harbours. It is also found that hydrogen demand across several sectors is projected to increase, but the degree of which is dependent on policy support, demand creation and increased investment.

In Case Study 1, an energy system for off-grid facility running entirely on renewable energy, with excess energy stored in the form of hydrogen was designed. The hydrogen supplied the energy system with electricity at times with scarce output from the renewables. It was found that a 650 kW FPV array and a 100 kW wind turbine would have to be installed in order to cover the demand of 361.2 MWh/yr. In Case Study 2, a hydrogen plant was sized so that it could produce enough hydrogen to replace UCCs natural gas consumption. It was found that an FPV array would not be able to supply the plant with enough energy. It was found that a 40 MW FPV array and a 2 MW wind turbine was able to sufficiently supply UCC with the required energy demand of 14.7 GWh/yr with help from the grid. Case Study 3 showcased the possibility of supplying the worlds first liquid hydrogen carrier with hydrogen produced from FPV. It was found that a 36 MW FPV array would single-handedly be able to sufficiently supply the hydrogen plant with electricity.

Lastly, it was concluded that the feasibility of a FPV powered hydrogen plant is dependent on its application, as well as the location of the plant. At locations with great solar resources, it is more feasible. Whereas plants located at locations with limited solar output would need to connect to the grid or install other types of renewables, such as wind energy.

Samandrag

Verda behøver eit skifte frå ein energisektor basert på fossile brennstoff, til ein som er meir berekraftig. Hydrogen kan fungere som eit lav-karbon alternativ til konvensjonelle brennstoff i fleire sektorar, så lenge produksjon, lagring og distribusjon kjem med eit lavt karbonavtrykk. Ved bruk av hydrogen som ein energiberar kan det bidra til å dekarbonisere industri, transport, kraftproduksjon, og bygg. For å kunne auke hydrogenproduksjonen frå fornybare kjelder, er det naudsynt å auke elektrolysørkapasiteten. Denne rapporten tek for seg gjennomførbarheita av hydrogenproduksjon frå flytande sol (FPV).

Det vart gjennomførd eit litteraturstudie som tok for seg modenheita til dagens FPV- og hydrogenteknologi, og ei vurdering av framtidig marknadsbehov av hydrogen i fleire sektorar. Fleire rapportar som tok for seg framtidig etterspurnad av hydrogen, strategiar for opptak, og scenario der hydrogen sannsynlegvis ser ei vekst vart gjennomgått. Tre kasusstudiar vart gjennomførd for å få ei djupare og meir detaljert forståing av gjennomførbarheita av hydrogenproduksjon frå FPV. Det vart sett på fleire lokasjonar i verda, der det var forskjellig solinnstråling.

I litteraturstudiane vart det funnet at både FPV- og hydrogenteknologiane modnast, og at industrien er klar for å hjelpe til å mogleggjere ein overgang til ei null-utslepps verd. Det kom og fram at det er fleire fordelar ved å installere eit hydrogenproduksjonsanlegg med straum frå FPV i havnar og viker. I studiet kom det og fram at etterspurnaden i fleire sektorar er forventa å auke, men at det er svært avhengig av politisk stønad, å skape etterspurnad, og aukt investeringar.

I kasusstudie 1 vart det utforma eit energisystem for eit off-grid anlegg som eksklusivt vart driven av fornybar energi, der overskotsenergi vart lagra i form av hydrogen. Når det ikkje vart produsert nok energi frå dei fornybare kjeldene vart hydrogenet brukt til å produsere elektrisitet. Det var funne at eit FPV-system med ein kapasitet på 650 kW og ei vindturbin med ein kapasitet på 100 kW var det som var behovet for å dekke behovet på 361.2 MWh/år.

I kasusstudie 2 vart det utforma eit hydrogenproduksjonsanlegg som kunne produsere nok hydrogen til å erstatte UCC sitt forbruk av naturgass. Det var funne at eit FPV-system ikkje var tilstrekkelig. Eit anlegg drifta av eit FPV-system med ein kapasitet på 40 MW, og ei vindturbin med kapasitet på 2 MW vart funne å være tilstrekkeleg for å dekke UCC sitt behov på 14.7 GWh/år ved hjelp frå straumnettet.

I kasusstudie 3 vart moglegheita for å forsyne verdas første transportbåt, som fraktar flytande hydrogen, med hydrogen produsert frå FPV. Det var funne at eit FPV-system med ein kapasitet på 36 MW var tilstrekkelig for å kunne forsyne hydrogenproduksjonen med straum.

Til slutt vart det konkludert med at gjennomførbarheita til eit hydrogenproduksjonsanlegg drevet av FPV er avhengig bruksområde samt kvar i verda det er lokalisert. På lokasjonar med høg solinnstråling vil det vere mogleg, medan stader der solinnstrålinga er låg vil det vere behov for tilkobling til straumnettet eller installasjon av andre fornybare kjelder, som vindenergi.

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1. Introduction

1.1 Background

In December 2015 at the Conference of Parties (COP) 21 in Paris, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) consented to a historic agreement to combat climate change and adapt to its effects. The resulting Paris agreement aims to keep global temperature rise well below 2 ˚C above pre-industrial levels [1]. Implicit in the Paris Agreement`s goals is the need for a transition from an energy sector dominated by fossil fuels to a more sustainable energy sector, where renewable energy plays a much more substantial role [2]. Examples of renewable energy sources include solar energy, wind energy and hydropower [3].

Solar photovoltaics (PV) and wind power are the types of renewables that have seen the greatest expansion in recent years. However, the availability of these intermittent and non-dispatchable sources of electricity is not consistent over time. Simultaneously, supplying electricity necessitates a constant balancing of supply and demand. Furthermore, electricity has its disadvantages as well, it can generally only be directly stored for a short period of time and in small amounts, also its transportation is mostly grid-based. Longer-term storage of larger amounts of electrical energy call for new types of storage, for instance, chemical energy storage via hydrogen [4].

Provided that the production, storage and distribution comes with a low carbon footprint, hydrogen can support decarbonisation of industry, transport, power generation, and heat in buildings when used as an energy carrier [5]. According to The International Renewable Energy Agency (IRENA), close to 19 exajoules of global energy demand could be met by hydrogen produced from renewable sources. To make that happen, the world would have to add nearly 1 TW of electrolyser capacity by the year 2050 [6].

Floating solar photovoltaic (FPV) installations are a promising alternative for upscaling solar generating capacity. During the past decade, this technology has seen substantial developments in cumulative installed capacities and number of installations [7]. FPV is capable of doubling the existing installed capacity of solar PV. Under very conservative assumptions, the World Bank estimates that FPV has a global potential of 400 GW [8].

Solarmarine Energy Ltd. is developing a green hydrogen production plant which is powered by a floating solar array (FPV). The hydrogen is produced through water electrolysis. The project is concerned with researching various elements of hydrogen plant design, such as safety standards and plant sizing, as well as developing a numerical model to predict design loads and responses of the floating solar array to environmental loading.

This thesis will investige hydrogen production powered by FPV, at different locations around the globe exhibiting various degrees of solar radiation. General information regarding the maturity of FPV and hydrogen technology will be outlined, before current and future hydrogen demand will be investigated at various locations. Three different case studies will be carried out in order to get an in-depth and detailed examination of hydrogen production at dissimilar locations.

Norway, Ireland and Australia was selected as the countries of focus when assessing present and future hydrogen demand. In regards to chosing the locations of the case studies, Norway was deemed an area of interest because hydrogen is a hot topic in the nation’s energy sector. Ireland was chosen because the thesis is written in collaboration with an Irish company. Australia was selected because the worlds first liquid hydrogen carrier is set to transport hydrogen from Australia to Japan in the near future, as well as because it is one of the countries in the world with the best solar resources.

1.2 Aims and Objectives

The aim of this thesis is:

To assess the feasibility of green hydrogen production powered by floating photovoltaics at different locations around the world.

The high level objectives can be broken down as follows:

- Assess the current state of the FPV market and technology, as well as the future potential.
- Evaluate the hydrogen technology available today, in regards to production, fuel cells and storage
- Investigate the current hydrogen market in Norway, Ireland and Australia, as well as the projected future demand
- Carry out a case study assessing the feasibility of implementing a renewable energy system using hydrogen for energy storage, to power an off-grid facility located on the west coast of Norway.
- Carry out a case study investigating the feasibility of replacing University College Cork’s (UCC) natural gas consumption with hydrogen from FPV.
- Carry out a case study investigating the feasibility of supplying the worlds first liquid hydrogen carrier with hydrogen produced from FPV.

1.3 Literature Review

Hydrogen can be produced from electricity generated from various renewable energy sources, both grid assisted and off-grid. Solar energy is quite possibly the most abundant renewable energy source available on earth and hydrogen production from solar energy is considered by many to be the ultimate solution for sustainable energy [9]. Implicit in the global energy transition is the need for new and innovative solutions to deal with the many challenges regarding implementation of RES, PVs in combination with hydrogen is a promising technology. Several studies on green hydrogen production from solar PV has been conducted in the past, but only a few have been conducted on hydrogen production from FPV.

A study by Frano Barbir [10] concluded that PEM electrolysis is a feasible alternative for green hydrogen production in conjunction with solar PV. The study also addressed various issues regarding the use of PEM electrolysers in renewable energy systems that need to be tackled, such as sizing of electrolyser, intermittent operation, output pressure, oxygen generation, water consumption and efficiency. According to Hosseini and Wahid [11], the most important barriers for widespread development of solar-based hydrogen production are the low efficiency of the solar to hydrogen system as well as the high cost of a photovoltaic cell. However, this report is from 2016 and the cost of PV has decreased significantly in recent years.

Dahbi et al. [12] developed a power management strategy that organizes the energy flow for hydrogen production by controlling the flow of water. This was found to increase the quantity of hydrogen output in a grid integrated PV system. An experimental supporting study held in Iran for hydrogen production from a PV power station compared experimental findings with simulation. The study found that the region is capable of producing hydrogen with electricity generated from PV, but the economic analysis of the station found it not to be economically feasible [13]. The report proposed that future studies should investigate using a hybrid wind-solar system.

A study by Omer, Fardoun and Alameri [14] aimed to compare a conventional renewable energy system consisting of PVs and battery storage with a second system combining PVs and a fuel cell where hydrogen is produced via electrolysis. Safari camps in remote rural areas in the United Arab States desert has no access to a grid power supply, therefore the two systems were explored as they are both examples of off-grid sustainable energy systems. This economic and feasibility study used HOMER software to compare the performance of both systems and found the cost of the fuel cell system to be approximately 50% higher than the PV/battery alternative. However, the batteries assumed in the study can pose environmental risks if not discarded in a sustainable way, furthermore they have a low life span.

In a study by Temiz and Javani, the designing and modelling of an FPV system supplying electrical energy for a small community was conducted [15]. In order to compensate electric load when solar energy is unavailable, electrolyser produced hydrogen was employed in a fuel cell generator. By looking at simulation results from PvSyst software and HOMER Pro software, the study concluded that the electricity demand was reasonably satisfied, and that the whole system could be regarded as feasible. The concept of producing hydrogen from FPV is still in its initial stage, however large technological advancements are expected soon.

2. Methodology

This section describes the methodology used in this thesis. A literature study assessing the maturity of FPV and hydrogen technology was undertaken. An assessment of projected market demand of hydrogen across different sectors was also carried out. Several reports assessing the future demand of hydrogen, strategies for uptake, and scenarios under which hydrogen is likely to see growth were reviewed. Three case studies were carried out in order to get a more in-depth and detailed examination of the feasibility of FPV powered hydrogen plants at various locations.

The methodology consists of literature studies, market analysis, interviews, data collection and energy calculations. The thesis is mainly based on a quantative research method, in which data is collected and analysed in order to address the aims and objectives. Various reports, data sheets, information from producers and calculations based on numbers from these sources are the main resources of information used in this thesis. Some qualitative research methods, such as interviews and document analysis, were used in order to gain information about certain elements of the thesis. Calculations using variables collected from different sources can sometimes give inaccurate results, but for the purpose of this thesis it was considered to be adequate. The deviation in the results were marginal, and to a certain extent neglectable.

All data and information used to develop the thesis has been carefully considered against the principle of impartiality, which means that the writers should not be biased towards certain persons, companies nor industries. All partial sources have been assessed in order to keep the analyses as neutral and non-political as possible. The thesis aims to be relevant in the long therm, therefore the focus was on sustainable solutions. When developing figures, pipeline and instrument diagram and various tables, software such as Microsoft Word, Microsoft Paint and AutoCAD Plant 3D were utilized in order to graphically present data and information.

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2.1 Qualitative Methods

Interviews

In order to gain a broader technical understanding and knowledge about electrolysers, an interview with Bjørn Gregert Halvorsen from NEL was conducted [16]. The interview mainly focused on costs, lifespan, efficiency, and advantages/disadvantages regarding electrolysers. The information retrieved was instrumental in gaining insight on how electrolysers are operated.

Documentation review

Other types of qualitative data, such as technical information was collected through surveying existing organisational documents, forms and reports, as well as by reviewing published research reports, websites and books.

2.2 Quantitative Methods

Simulations

In order to carry out the case studies, it was decided that energy calculations should be made by running simulations based on data retrieved from credible sources. At first, software packages such as Homer Pro, RETScreen, EnergyPLAN, SAM were tested. These programs are being used world-wide and they are renowned for their capabilities. However, some of the software packages were found to be difficult to operate for untrained users. The rest were either unsufficient for the needs of the thesis, or requiring too many unknown factors and variables deemed too difficult to retrieve. Subsequently, it was decided that it would be better to carry out simulations and calculations in Microsoft Excel. This made it easier to control the parameters defining the conditions of the simulations, allowing us to gain deep insight into the process. All of the coding was written by the authors of the thesis, assisted by Dr. Alan Henry.

Solar Data

The hourly solar data used in the case studies were obtained from the Ninja Automator. This is a software that allows Microsoft Excel to scrape solar and wind data from the Renewables.ninja website into a spreadsheet for easy access [17]. The user has to specify parameters such as latitude, longitude, year and source of the dataset, capacity of the PV system, system loss and tilt of the solar panels. The database chosen for all of the case studies was Merra-2, a database created by the National Aeronautics and Space Administration (NASA) [18]. Data from 2018 were selected for Case Study 1, as this is the most recent year in the dataset, and it has a complete data series for the given location. In Case Studies 2 and 3, data from 2016 was chosen as this was the most recent year with a complete dataset for the stated locations. When deciding on the optimal solar panel tilt for a given location, the power outputs from a collection of various tilts were compared, and the optimal tilt which gave the maximum power output was used.

Wind Data

When calculating the wind output, hourly wind speed data were used. The wind data series were chosen to correspond with the year for the solar data used in each of the case studies. By using the log law, the wind speeds are extrapolated to the height of the wind turbine. The log law can be seen below in Equation 1, where z_1 = height of the weather station above sea level, z_2 = height of the turbine from bottom to top, v_1 = wind speed at weather station, and v_2 = wind speed at turbine height. The constant surface roughness length, z_0 = surface roughness, is approximately one-tenth of the surface roughness elements. The surface roughness length is a constant that characterises the surface of the ground surrounding the wind turbine (see Table 1).

$$v_2 = v_1 \times \left(\frac{\ln\left(\frac{z_2}{z_0}\right)}{ln\left(\frac{z_1}{z_0}\right)} \right)$$

Equation 1 - Log law [19].

Table 1 was used to select the appropriate z_0 for each of the relevant case studies. After obtaining the new wind speeds (v_2), they are interpolated with the values from a given power curve to get the exact power output from a given wind turbine.

Table 1 - Surface roughness length [20].

Terrain Description	**Surface lengths (m)**
Very smooth, ice or mud	0.00001
Calm open sea	0.0002
Blown surface	0.0005
Snow surface	0.003
Lawn grass	0.008
Rough pasture	0.01
Fallow field	0.03
Crops	0.05
Few Trees	0.1
Many trees, few buildings	0.25
Forest and woodlands	0.5
Suburbs	1.5
City center, tall Buildings	3

3. Floating Photovoltaics

Floating photovoltaics (FPV) is a PV module or array of modules that is installed floating on water. The FPV system is quite similar to a land-based PV system in the way that it is set up, but there are some differences due to the fact that FPVs are floating on water. On a larger scale FPV system, the inverter is often placed next to the FPV array, but when it comes to smaller scale FPV installations, the inverters can sometimes be placed onshore. Smaller FPV installations are usually situated closer to land, due to the fact that they are less resistant to rough weather. These factors do not necessarily apply to inland FPV, but mainly to offshore FPV [8].

3.1 The Case for FPV

According to the UN, some of the biggest global challenges for the near future will be the depletion of freshwater resources, energy shortages and over population. An increasing population requires an increase in access to land area, fresh water and energy. Resources like water and electricity are already scarce in many parts of the world, and this is not set to change if the development continues at the pace it does now. Not only does the consumption of fossil fuels harm the planet; it also directly affects people's health by polluting the air and water. This calls for more environmentally friendly solutions [21].

Nearly 40 % of the world's population live within 100 km of the coast [22]. Increasing urbanisation and the increased need for renewable energy is forcing the technology to develop previously unexplored solutions. FPV is a technology that can take advantage of previous unused water areas. This is especially useful in highly populated areas where land is at a premium and it is increasingly difficult to find space to install solar arrays of significant size [8].

Some of the advantages of installing FPV over regular land-based PV are:

- Reduced efficiency-loss from thermal loss.
- More space available.
- Reduced water evaporation loss when used on reservoirs.
- Potentially easy access to existing power grid.
- Can potentially reduce the growth of harmful algae [23].
- No need to purchase/use land that could be used for housing or agriculture.
- No need for costly civil engineering works – simple float out modules and connect.
- Increased packing density of solar panel. Greater output per square metre.

FPV technology is versatile and allows for both in-land, fresh water and sea water installations. There are many different FPV designs available or in development, depending on location, size and climate conditions. Apart from design and location, the tilt of the panels could be considered the most important aspect. Optimal panel tilt varies greatly depending on the location and is a key factor in securing the highest possible efficiency of a system [8]. In some locations the tilt would have to be reduced, in order to be able to withstand extreme wind speeds, especially in areas exposed to hurricanes and typhoons.

Studies show that FPV can have an increase in yearly energy yield of around 10 % due to the reduction in thermal losses which represents a significant increase in efficiency [24]. Nevertheless, the price will vary from project to project due to the cost of buying land. If the land price is low, the FPV could be more expensive than land based PV, but if the land price is high, FPV could be a cheaper solution. However, the difference in price is expected to drop as new technologies are developed.

The utilization of space available on water could turn out to be a good way to save land space, as well as the potential to reduce growth of algae and water evaporation on reservoirs. This could turn out to be especially important in areas with high water evaporation and low access to clean water. When placing a FPV array on water, it screens the water from the sun, which reduces the photosynthesis in the water and helps keep the water clean from algae. When utilizing the space available on the water in highly urbanised cities and locations with a high population density it can be vital to take advantage of every possible area available. This is due to the lack of space and increasing demand for electricity [24].

Figure 1 - Upsolar/SolarMarine Energy FPV array in Singapore

3.2 FPV Market Overview

The market for FPV is reflected in the global need for green, renewable energy and the increasing demand due to population rise and development/modernisation. In places where land is scarce or expansive bodies of water can be utilized in the same way as land for the FPV, without displacing housing or agriculture. This means that the market for FPV will not necessarily be affected in the same way as land-based PV in overall project costs. According to the World Bank, China currently sits on around 73 % of the world’s capacity of FPV. The rest of the capacity is mainly split between Japan, Korea, Taiwan and UK. As of December 2018, there was over 300 ongoing projects around the world accumulationg to over 1300 MWp of FPV [8].

According to data collected from the Food and Agriculture Organization of the United Nations (FAO) by ourworldindata.org and the growth in the global population, we can see that there is an increased need for land. This means that potential space for land based PVS is decreasing. With 71 % of the surface area of the Earth consisting of ocean this represents a potential space for FPVS that is currently not taken fully advantage of. This indicates that FPV has a huge market growth potential [25].

In order for the FPV to reach the same GWp installed capacity as all the conventional solar PV systems combined (400 GWp) at the end of 2017, only 1 % of the total man-made surfaces needs to be utilized. If 10 % of the worlds man-made reservoir surface was potentially covered with FPV, a total output of 5,211,086 GWh/year would be possible [8]. According to Statista, 5,211 TWh/year would be approximately 234 times the electricity consumtption of the world in 2017, which was 22.3 TWh [26].

3.3 The Case for FPV Powered Hydrogen Plants

The marine sector is a sector with growth potential for the FPV to hydrogen industry, due to the increased focus on environmental friendly solutions. Several hydrogen powered boats and ships are already in development. A hydrogen plant powered by FPV located in close proximity to ports and harbours, would have the advantage of providing a localized supply of hydrogen, which reduces the cost of infrastructure regarding transportation. Additional advantages such as calm waters and close proximity to potential hydrogen and electricity consumers makes ports and harbours an ideal environment for FPV. Installing FPV in such an environment also provides good accessibility for maintenance and upgrades. One of the downsides of installing FPV too far offshore is the costs and challenges related to maintenance. Performing maintenance related tasks offshore in rough weather can be challenging [27].

Because of the reasons outlined in this section it can be concluded that FPV technology is maturing. Most countries do not have an infrastructure in place for supplying, transporting, and storing hydrogen. In order for hydrogen to be a viable low-carbon fuel alternative, it has to become cost competitive [28]. And it can also be concluded that FPV powered hydrogen plants have the potential to become an integral part of the hydrogen industry, because of the reasons outlined in the preceding paragraph.

4. Hydrogen

Hydrogen is the first element in the periodic table, and it is also the lightest, smallest atom. Even though it is the most abundant element in the universe, it rarely exists in its pure form on Earth. In most cases, hydrogen is found chemically bonded to oxygen in the form of water [4]. Hydrogen is an energy carrier. When produced it is extracted from its compound by using energy from primary energy sources. An energy carrier is a substance (fuel) used to move, store, and deliver energy produced from primary energy sources. Hydrogen can help decarbonise industry, transport, power generation and heating of buildings, provided that the production, storage and distribution of hydrogen comes with a low carbon footprint [5]. Out of all common fuels, hydrogen has the highest energy content by weight, but the lowest by volume, as can be seen in Table 2 [29].

Table 2 - Energy density for Hydrogen and other fuels

Energy carrier	**Mass density [kg/m3]**	**Gravimetric density [kWh/kg]**	**Volumentric density [kWh/m3]**
LNG (-162˚C)	450	13.5	6075
Hydrogen (300 bar)	20	33.33	666.6
Liquified H_2 (-273˚C)	71	33.33	2366.43
Gasoline	750	12.06	9045

The value chain, from production to consumption of hydrogen, includes several energy losses along the way. This is know as round trip efficiency [30]. When converting electricity to hydrogen and back to electricity, there would be energy losses in the form of heat. In Figure 2 a hypothetical round trip efficicency for a hydrogen system are simply displayed.

Figure 2 – Round trip efficiency hydrogen

Hydrogen	Efficiency [%]		100%		70.00%		90%		50%
		Power Source	-->	Electrolyser	-->	H2 stored	-->	El from FC	
	Effect in [kW]		100		70		63		31.5

4.1 Hydrogen Production

Hydrogen can be produced from a large amount of primary energy sources, and there are several production processes available and in use today. Most of the global hydrogen production is based on fossil energy sources. Hydrogen produced based on conventional fossil methods is popularly termed “grey hydrogen”, whereas hydrogen produced from fossil fuels with Carbon Capture and Storage (CCS) or Carbon Capture and Utilization (CCU) is referred to as “blue hydrogen”. “Green hydrogen” is produced from renewable energy sources, usually through electrolysis [31]. Roughly 95 % of all hydrogen produced today is generated from fossil fuels [32]. Consequently, global hydrogen production is responsible for the emission of 830 MtCO_2 per year [33]. The energy sector must strive to produce more green hydrogen, as it has a substantially lower carbon footprint than grey hydrogen [34]. Various production methods will be outlined in more detail below.

4.1.1 Reforming of Natural Gas

Steam Methane Reforming

Steam methane reforming (SMR) is a widely used method of converting natural gas, mostly methane, into hydrogen. The process typically consist of four basic steps:

1. To remove sulfur compounds, natural gas is treated catalytically with hydrogen.
2. The desulfurized gas is then reformed by mixing it with steam and passing it over a catalyst to produce CO and hydrogen.
3. In the next step CO is converted into CO_2 and hydrogen. This reaction is called the water-gas shift reaction.
4. In the final step, the hydrogen gas is purified.

The reaction is highly endothermic and requires a large amount of heat [35]. A module in a large-scale SMR facilitiy can be up to 30 m high and produce around 5-10 tonnes of hydrogen per hour. The CO_2-emission rate from SMR is usually at roughly 9 kg CO_2/kg H_2 [34].

Partial Oxidation

Another way of converting natural gas into hydrogen is through partial oxidation (POX). In this process the first step is similar to that of steam reforming, where sulfur compounds are removed from the gas. The desulfurized gas is then combined with oxygen or air before the partial oxidation reaction takes place to produce CO and hydrogen. The reaction is carried out in a high-pressure, refractory-lined reactor and the process generates a large amount of heat. Because heat is released the process is exothermic [35].

Autothermal Reforming

Autothermal reforming (ATR) is a combination of steam reforming and partial oxidation. It operates with a mixture of air and water vapour. The required process heat is supplied internally by the partial oxidation step, whereas the high hydrogen yield is determined by the steam reforming step. The fact that the reaction is not dependent on an external heat supply is an advantage. However, this advantage is more or less offset by the high operating expenses (OPEX) and capital expenditures (CAPEX) of the air separation unit and the complicated flue gas purification process [4].

4.1.2 Electrolysis

Electrolysis splits water into hydrogen and oxygen by using electricity. Electrolysers consist of two noble-metal-coated electrodes separated by an electrolyte, as well as a DC source. The DC power source drives the electrochemical reactions, as electrical energy is converted into chemical energy. Electrolysers can be adapted to match the desired production capacity by combining electrolytic cells and stacks. Today, the efficiency of an electrolyser is in the region of 60 - 80 %, depending on the technology used. There are several types of electrolysers such as Proton Exchange Membrane (PEM) Electrolysers, Alkaline Electrolysers (AE), Anion Exchange Membrane Electrolysers and Solid Oxide Electrolysers. They are differentiated by their operation temperature and by the electrolyte materials [4]. PEM and AE will be investigated further, as they are the most common types utilised today. The principle of electrolysis is shown in Figure 3 below.

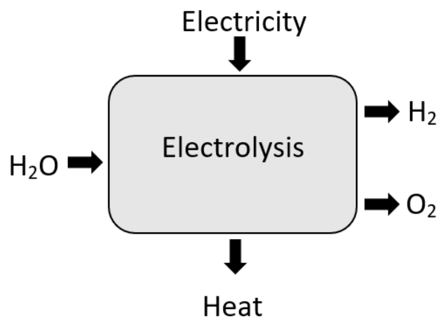

Figure 3 - Principle of electrolysis

Proton Exchange Membrane Electrolysis (PEM)

Proton Exchange Membrane electrolysis uses a polymer as the electrolyte and operates at a temperature around 60-80 ˚C. The hydrogen produced will have a purity of at least 99.9 %. The efficiency of the electrolysers typically range from 65-78 %, and the lifespan varies from 20 000-60 000 hours [4]. PEM electrolysers work at a high current density, which may end up reducing operating costs, particularly when dynamic energy sources such as wind and solar is utilized. This has recently led to an increase in the use of PEM. Other advantagesof using PEM are that it requires less space, and it is easier to compress the hydrogen. The latter advantage could help reduce the cost of transport and storage [31].

The central component of a PEM cell is a membrane made out of a proton-conductive polymer, as it is used for double purposes. The membrane is both carrying ionic charges (protons) and separating the products of the electrolysis (oxygen and hydrogen). This prevents their spontaneous recombination into water. At the anode the water reacts and splits into oxygen and H^+. The proton is transported through the membrane to the cathode, where it reacts and produces molecular hydrogen [36].

Alkaline Electrolysis (AE)

Alkaline Electrolysis is a mature technology that has been commercially used in industry for over a 100 years. It is currently the clear market leader, as it accounts for the majority of the installed capacity worldwide [4]. The electrolyte is a highly concentrated alkaline aqueous solution. The electrodes are immersed in the electrolyte and a porous solid material is placed between the anode and cathode to effectively separate the produced gases, and to let hydroxyl ions (OH^-) transport between the electrodes. At the cathode the water reacts and splits into hydrogen and hydroxyl ions. The hydroxyl ion is carried over to the anode where they form oxygen and water by oxidation [37]. Alkaline electrolysers operate with similar efficiency, purity and in the same temperature range as PEM electrolysers [4]. Key features of PEM and AE electrolysers is presented in Table 3.

Table 3 - PEM and Alkaline electrolyser key features [4]

	Temperature [˚C]	**Size [kW]**	**System cost [€/kW]**	**Efficiency [%]**	**Hydrogen purity**	**Lifespan [h]**
PEM	60-80	0.2 - 1150	1900 – 2300	65 – 78	99.9 - 99.9999 %	20000-60000
Alkaline	60-80	1.8 - 5300	1000 – 1200	65 - 82	99.5 - 99.9998 %	60000-90000

4.2 Hydrogen Storage

The physical and chemical properties of hydrogen makes it a challenging substance to contain. It is a colourless and odourless gas. The high diffusibility of hydrogen requires the use of special materials for storage and transport. It is the lightest gas and can therefore pass through airtight spaces, porous materials, and even metals. Another reason why hydrogen has to be handled with care, is because its most characteristic chemical property is its excellent flammability. It is combustible in a very broad concentration spectrum, and its ignition range is correspondingly large [4]. Hydrogen gas is highly flammable in concentrations between 4-75 % mixed with air, and it is explosive in the range of 18-59 % [38].

Hydrogen gas has a very low mass density under standard conditions; therefore it is usually stored under pressure. The mass density for compressed hydrogen increases proportionally with pressure. When compressed to 300 bar, the mass density is approximately 20 kg/m^3, while at 700 bar it has a mass density of approximately 40 kg/m^3. Liquefaction also play an important role in the transport and storage of hydrogen, as it increases the density by a factor of roughly 800. When cooled below -253 ℃, hydrogen becomes liquid and the mass density increases to 71 kg/m^3 [4]. Containers holding liquid hydrogen (LH_2) has more components than the ones holding compressed hydrogen, such as valves, regulators, added insulating capacity in double layer containers to keep the temperature low, and more. This is required to keep the hydrogen liquified [39].

It is also possible to store hydrogen chemically in temporary hydrogen carriers, such as ammonia (NH_3) or methanol (CH_3OH_2). Liquid ammonia has a hydrogen mass density of 121 kg/m^3, but there are several energy losses during the synthesis and dehydrogenation processes, which again decreases the total efficiency of the process [34]. It is also possible to store hydrogen underground in salt caverns and exhausted oil and gas fields, but this is not widely used and would be more suited for large scale industrial purposes [40].

4.3 Fuel Cells

The fuel cell process is the reverse of the electrolysis process. Instead of using water and electricity to produce hydrogen and oxygen, hydrogen and oxygen is used to produce electricity and water. The fuel cell is built in a similar way as an electrolyser, with two electrodes separated by an electrolyte. The hydrogen splits into protons and electrons at the anode. The protons will travel through the electrolyte, and the electrons will travel through a circuit, thus producing electricity. At the cathode the protons and electrons will reunite and react with oxygen, thus producing water. A single fuel cell will theoretically produce electricity with a voltage of 1.23 V. To achieve higher voltages, several fuel cells are combined in series to create "fuel cell stacks" [41]. Fuel cells are categorised by operating temperature and the type of electrolyser. The most important types are Alkaline fuel cell (AFC), Proton exchange membrane fuel cell (PEMFC), Phosphoric acid fuel cell (PAFC), Molten carbonate fuel cell (MCFC) and Solid oxide fuel cell (SOFC) [4]. The principle of fuel cell operation is shown in Figure 4.

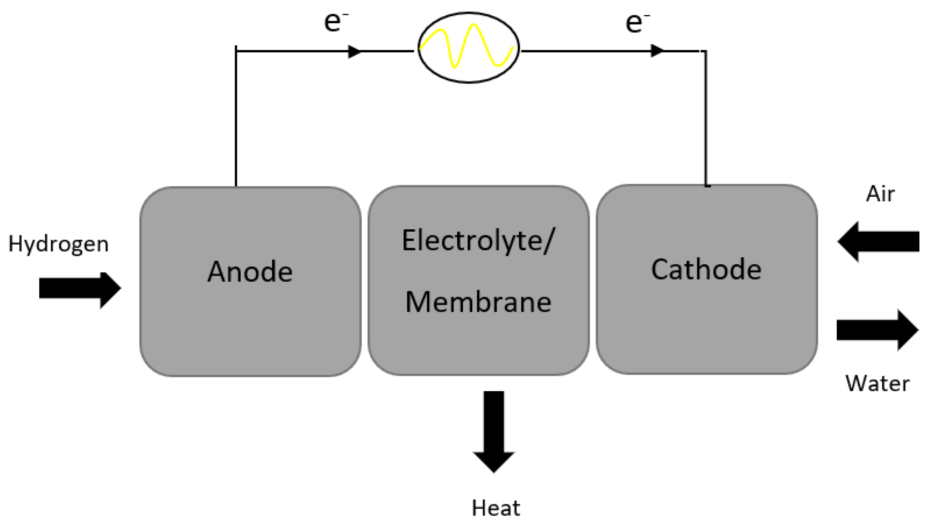

Figure 4 - Principle of fuel cell operation

Alkaline Fuel Cell

Alkaline fuel cells (AFC) has been utilized for a long time and was used by NASA in some of their spaceships during the 1960s. The AFC is a low temperature fuel cell, operating at temperatures ranging from 60-90 °C. The electrolyte is typically a potassium hydroxide solution and the catalyst are low-cost base metals, which leads to low investment cost. AFCs are vulnerable to carbon dioxide, therefore it needs to run on high purity hydrogen in order to operate for a long time [4].

Proton Exchange Membrane Fuel Cell

The PEM fuel cell is also a low temperature fuel cell as it operates at around 50-90 °C. The electrolyte is a solid polymer membrane, and the catalyst typically platinum. The platinum leads to high construction costs and the hydrogen must be clean to prevent catalyst poisoning. The PEM fuel cell has, according to Shell, a high cost reduction potential, with regards to production volume, and could be the leading fuel cell technology for the future [4]. Key features of the most important types of fuel cells is presented in Table 4 below.

Table 4 - Fuel Cell key features [4]

Fuel Cell	**Electrical Performance [kW]**	**Efficiency [%]**	**Lifespan [h]**	**Application**
AFC	Up to 250 kW	50 - 60	5000-8000	Space travel, submarine
PEMFC	0.5 - 400 kW	30 - 60	60000 (stationar) 5000 (mobile)	Vehicle drivetrains, Space travel, Backup power
PAFC	Up to several 10 MW	30 - 40	30000 - 60000	Decentralised power generation
MCFC	From a few 100 kW to several MW	55 - 60	20000 - 40000	Power plants, CHP
SOFC	From a couple of kW to several MW	50 - 70	Up to 90000	Power plants, CHP

4.4 Cost of Hydrogen

The price of hydrogen is dependent on the production method. Hydrogen is currently not the best fuel option avaliable cost-wise. This is due to the fact that the price per kg produced is conciderably higher than that of other fuels like LNG and gasoline. Green hydrogen is, according to the Hydrogen Council, currently priced at approximately USD 6 per kg [42]. In a recently published report by The Hydrogen Council, they claim that a production cost of USD 2.5 per kg would unlock approximately 8 % of the total global energy demand, while a producton cost of USD 1.8 per kg would unlock roughly 15 %. They also claim that by 2030, hydrogen can cover almost 15 % of the transport sectors energy demand with a production cost of USD 6 per kg. If the price of hydrogen after production, distribution and retail was at USD 4 per kg it could cover more than 50 % of the mobility sectors energy demand [42].

4.5 Overview of the Current Hydrogen Market

Approximately 120 million tonnes of hydrogen is produced each year, two-thirds of which is pure hydrogen and one-third is in mixture with other gases. The overwhelming majority is produced and utilized on-site in industry [32]. Over 50 % of global hydrogen production is used to produce ammonia for various fertilizers. Around 30 % is utilized in numerous refining processes, whilst 10 % is used for methanol production [43]. Beyond these traditional applications, hydrogen use is very modest, and there is no significant production from renewable sources. Roughly 95 % of all hydrogen produced today is generated from fossil fuels [32]. Consequently, global hydrogen production is responsible for emissions of 830 MtCO_2 per year [33].

4.5.1 Current Situation – Norway

In Norway, approximately 225 000 tonnes of hydrogen is produced every year. Just like globally, most of the hydrogen produced is utilized on-site in industrial processes. Examples being Equinor’s methanol plant at Tjeldbergodden and Yaras ammonia factory in Porsgrunn. Both facilities produce their hydrogen by reforming natural gas, without CCS [43].

In 2019, NEL ASA announced the establishment of Green H2 Norway, a joint venture looking to establish green hydrogen production facilities in Norway which will supply Hyundai fuel cell trucks [44]. BKK, Equinor and Air Liquide are at the forefront of an initiative that aims to develop a complete liquid hydrogen supply chain for the maritime industry. The project has received public funding and intends to make liquid hydrogen available for commercial shipping within the first quarter of 2024 [45]. There is already a demand for liquid hydrogen in Norway, as a Norled ferry fueled by liquid hydrogen is expected to launch into operation by 2021.

Currently there are several other innovative hydrogen projects underway in the Norwegian maritime sector. The ShipFC project, co-ordinated by the Norwegian cluster organization NCE Maritime CleanTech looks to install the world's first ammonia-powered fuel cell on the offshore vessel, Viking Energy [46]. A coalition of Norwegian companies are working on building a fuel cell powered cruise ship striving for zero-emission operations along parts of the Norwegian coastal route. The ship will have a 3.2 MW fuel cell installed and will run on hydrogen stored in liquid form [47].

4.5.2 Current Situation – Ireland

The Irish energy mix is dominated by fossil fuels such as oil, natural gas and peat. In 2018, fossil fuels accounted for 89 % of primary energy use. Oil stands out as the dominant energy source, maintaining a 49 % share of the total primary energy requirement. The share of renewables stood at only 10 % [48]. Ireland is not on track to meet any of its 2020 renewable energy targets, and is currently ranked 27th out of 28 EU countries for progress towards the 2020 goals [49]. There is a glaring need to increase sustainable energy solutions rapidly.

The Island of Ireland is producing hydrogen at a modest rate when compared to other European countries, and the demand is very different from that of the rest of the world. There is no widespread petrochemical sector and the manufacturing industry is limited. Nevertheless, most of the Irish hydrogen demand still does come from this area [50]. Whitegate Refinery in Cork is producing hundreds of tonnes per day for internal use, production of fuels for heating and transportation [51]. The hydrogen used at Whitegate comes from cleaning gas streams originating in the refining process.

Irelands commercially available hydrogen is either produced via an electrolyser production facility in Dublin or imported from Europe and/or the UK [50]. The electrolyser in Dublin produces 200 kg per day for aerospace, electronics, pharmaceuticals and biomedical industries [51]. The pharmaceutical and electronics sectors are the biggest commercial sectors utilizing hydrogen.

There are several projects in development that will increase the Island of Ireland's hydrogen production significantly over the next few years. Such as the electrolyser production facility planned as part of the GENCOMM project. The planned hydrogen plant will install a 500 kW electrolyser that is coupled with a wind farm and will utilize low cost curtailed electricity. The facility will produce 160 kg of hydrogen per day. Belfast is set to receive 3 FCEV buses before the end of 2020. The Office for Low Emission Vehicles (OLEV) is funding the project, and the busses will run on hydrogen from the GENCOMM project. Furthermore, Indaver has proposed installing a 9 MW electrolyser and hydrogen refueling station at Meath waste-to-energy plant [51].

4.5.3 Current Situation – Australia

Australia is in an ideal position to make hydrogen its next major export. They have a tremendous amount of natural resources available that can produce both grey, blue and green hydrogen. Some examples are coal, natural gas, wind, solar and hydro resources. They are already an established energy supplier to Asias biggest energy importers, and they have a solid track record in building large-scale energy industries. Australias single biggest current use for hydrogen is for making ammonia. More than 350 000 tonnes of hydrogen is produced per year to make ammonia. This accounts for almost three-quarters of all the hydrogen produced in the country. Like elsewhere around the world, that hydrogen is made from natural gas without CCS [52].

BOC, a subsidiary of Linde plc, has announced a hydrogen project at its production facility in Bulwer Island, Brisbane. They will install a 220 kW electrolyser supplied by ITM Power and a 100 kW solar array to produce up to 2400 kg of hydrogen per month. The hydrogen will supply industrial customers and a hydrogen refuelling station in Brisbane [53]. Australias first public hydrogen refueling station will be built in the nation's capital, Canberra, and is set to be operational in 2020 [52].

In Victoria, the Hydrogen Energy Supply Chain (HESC) Pilot Project demonstrates the worlds first fully integrated hydrogen supply chain. The pilot project contains multiple stages to produce and export hydrogen from Latrobe Valley to Japan. The hydrogen is produced from brown coal and transported in the worlds first liquid hydrogen carrier. By the 2030s, a commercial hydrogen supply chain could be in operation, pending a commercial decision by the project consortium, and a successful pilot [52].

4.6 Projected Market Demand

Hydrogen is expected to play a substantially larger role in the world's energy sector in the coming decades. The amount of nations with policies that support investment in hydrogen technologies is increasing, as well as the number of sectors they target [33]. The expected market demand is the main factor for the development of a future hydrogen value chain. It has principal implicatons for the entire value chain. Hydrogen is gaining global interest in industries such as shipping, chemical production and steel production, as it is seen as a sustainable alternative to fossil fuels in the long-term. Maritime applications might be of particular interest. The International Maritime Organization (IMO) has committed to reducing emissons by at least 50 % by 2050 [42]. Hydrogen could be the key to decarbonisation, as the shipping industry have limited low-carbon fuel options available. Hydrogen avoids the land-use and air quality impacts of biofuels, and the limited range and long recharging times associated with electric vehicles (EV) [54].

4.6.1 Projected Market Demand – Norway

Maritime Sector

The market for hydrogen in Norway can still be characterized as raw. However, a string of projects has commenced in recent years and the potential for expansion is promising. Norway is especially well positioned in the maritme sector, as there are several innovative vessels already in development. In a report exploring future value chains for liquid hydrogen in Norway, NCE Maritime Cleantech identified high speed crafts, ferries and platform supply vessels as potential key consumers of LH_2 soon. A complete shift from fossil fuels to LH_2 would lead to a daily demand of about 275 tonnes of hydrogen [43].

High speed crafts crossing distances shorter than 10 nautical miles can be operated primarily by batteries. Conversely, for vessels travelling over longer distances, hydrogen is the best non-emission solution as the alternative, fully battery-electric vessels has storage volume/weight limitations. The energy density in batteries is low compared to other energy carriers and this creates challenges regarding weight and space conditions. NCE Maritime Cleantech has estimated the necessary volume of LH_2 needed to power the vessels crossing routes over 10 nautical miles. The result can be seen in Table 5.

Table 5 - LH_2 for High Speed Crafts [43]

Route	Region	LH_2 tonnes/yr	LH_2 tonnes/day
Trondheim - Kristianssund	Trøndelag	1 371	3.8
Trondheim - Brekstad	Trøndelag	302	0.8
Namsos - Leka og Rørvik	Trøndelag	212	0.6
Total Trøndelag		**1 185**	**5.2**
Ålesund - Nordøyane	Møre og Romsdal	413	1.1
Molde - Helland - Viksebusekken	Møre og Romsdal	311	0.9
Total Møre og Romsdal		**723**	**2.0**
Bergen - Sogn - Flåm	Sogn og Fjordane	1 447	4.0
Bergen - Nordfjord	Sogn og Fjordane	1 281	3.5
Sogn - Nordfjord	Sogn og Fjordane	576	1.6
Florø - Svanøy - Askrova	Sogn og Fjordane	250	0.7
Florø - Fanøy - Barekstad	Sogn og Fjordane	154	0.4
Florø - Måløy	Sogn og Fjordane	94	0.3
Ortnevik - Vik	Sogn og Fjordane	91	0.2
Flåm - Balestrand	Sogn og Fjordane	78	0.2
Hardbakke - Mjømma	Sogn og Fjordane	44	0.1
Eivindvik - Mastrevik	Sogn og Fjordane	43	0.1
Hardbakke - Utvær	Sogn og Fjordane	31	0.1
Total Sogn og Fjordane		**4 087**	**11.2**

Sunnhordland - Austevoll - Bergen	Hordaland	1504	4.1
Rosendal - Bergen	Hordaland	311	0.9
Norheimsund - Eidfjord	Hordaland	114	0.3
Austevollruten	Hordaland	88	0.2
Reksteren - Våge - Os	Hordaland	62	0.2
Total Hordaland		**2 079**	**5.7**
Stavanger - Ryfylke	Rogaland	803	2.2
Stavanger - Hjelmeland	Rogaland	730	2.0
Stavanger - Lysebotn	Rogaland	326	0.9
Stavanger - Kvitsøy	Rogaland	110	0.3
Stavanger - Fisterøyene	Rogaland	35	0.1
Total Rogaland		**2 003**	**5.5**
Total		**10 778**	**29.5**

As it pertains to car ferries, similarly to high speed crafts, it is the longer routes that are the most relevant for hydrogen utilization. Two key ferry routes have been identified, Hjelmeland-Nesvik in Rogaland, and Halhjem-Sandvikvåg in Hordaland. The estimated LH_2 consumption for the two ferries can be seen in Table 6. In addition to the two key routes already identified, there are other routes that could end up being run by hybrid-vessels. This is for the most part relevant in areas where poor quality of the local grid prevents a fully battery-electric option.

Table 6 - LH_2 for Car Ferries

Route	Region	LH_2 tonnes/yr	LH_2 tonnes/day
Halhjem - Sandvikvåg	Hordaland	5 743	ca. 15.75
Hjelmeland - Nesvik	Rogaland	54.75	0.15
Total		**ca. 5 797**	**ca. 16**

There has also been estimated that the current fuel consumption for PSVs is equivalent to an annual LH2 demand of roughly 90 000 tonnes. The regional demand is presented in Table 7.

Table 7 - LH_2 for Platform Supply Vessels

Region	LH_2 tonnes/yr	LH_2 tonnes/day
Rogaland	23 830	65.3
Hordaland	31 617	86.6
Sogn og Fjordane	20 453	56.0
Møre og Romsdal	12 853	35.2
Trøndelag	245	0.7
Total	**88 999**	**243.8**

Land-based Transport

According to DNV-GL, it is not likely that the total cost of ownership of a fuel cell electrical vehicle (FCEV) will be competitive with electric cars in Norway. It is also assumed that limited access to refueling stations is a contributing factor to the slender increase in hydrogen cars. However, it is likely that heavier land-based transport will will be more competitive from a cost perspective, and narrow access to refuelling stations will not have as big of an impact. DNV-GL has estimated a yearly demand of 29 000 tonnes H_2/yr for trucks, and 7000 tonnes H_2/yr for long distance buses in 2030 [34].

Industry

The future demand of hydrogen in Norwegian industry has not been an area of focus in this report, as it is deemed as outside the scope of this report. However, a sector where hydrogen demand could increase in the near future is the Norwegan aquaculture industry. **The project owner of the Hydrogen Based Zero Emission Off-grid Facility Project has defined parts of this section as confidential. This is because it includes sensitive information about the project.**

4.6.2 Projected Market Demand – Ireland

Land Based Transport

A report by Hydrogen Mobility Ireland (HMI) claims that by 2030, FCEVs will be cost-competitive with Internal Combustion Engine Vehicles (ICEV) in Ireland. HMI also believes that in an ideal scenario, Ireland would have a hydrogen powered fleet of 29 000 cars, 6 800 vans, 880 buses and coaches, and 2 000 heavy goods vehicles (HGV) by 2030 [51].

Gas Grid

In 2018, Ireland's gas network delivered 30 % of the county's primary energy needs. If hydrogen were to be injected into the gas grid, it would lead to significant cuts in GHG emissions. Gas Networks Ireland's vision for Ireland's gas network is to be net zero carbon by 2050. To accomplish this, hydrogen isp planned to be injected into the gas grid after 2030 [55]. The Irish government has a policy in place vowing to deliver 70 % renewable electricity by 2030. In 2018, natural gas supplied 30 % of Irelands primary energy demand. It covered 52 % of the electricity demand, and 41 % of heat demand. The option of injecting hydrogen directly into the gas grid is currently planned to be completed by Networks Ireland (GNI) by 2030 [56].

Industry

The demand for green hydrogen is also projected to increase in industry, as GHG emissions will have to decrease in this sector as well. Whitegate refinery is currently exploring the option to increase production and could therefore be looked at a potential partner for companies producing hydrogen [51].

Maritime Sector

In 2016, Irelands established maritime industries had a turnover of €5.3 billion, whilst the emerging maritime industries had a turnover of €383 milllion [57]. Naturally this makes the maritime industry an attractive industry for hydrogen suppliers to establish themselves in. Maritime transport services contributed to 37% of the total turnover in the established marine industries as shown in Figure 5. If this sector were to focus on sustainable energy solutions, hydrogen could play a huge role. As mentioned in Section 3.3, ports and harbours makes for great locations for FPV. The availability of this techonogy can contribute to the growth of LH_2 powered ships and boats.

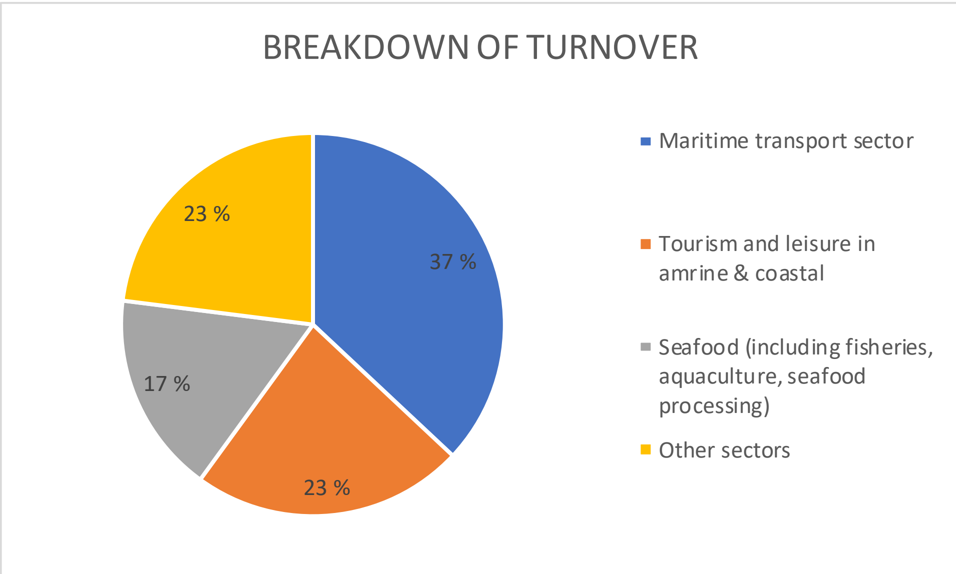

Figure 5 - Breakdown of turnover in the establised maritime sector of Ireland [57]

4.6.3 Projected Market Demand – Australia

The Australian market assessment in this report focuses on the potential of a hydrogen export industry alone, the domestic use for energy purposes has been neglected. Australia is already a significant energy exporter and is well positioned to become become a major supplier of hydrogen if a global market does emerge.

In a report prepared for the Australian Renewable Energy Agency, several potential future hydrogen scenarios were investigated. A summary of Australia's potential exports is provided in Table 8. It displayes potential exports in these various scenarios. Japan, Korea, Singapore and China were identified as the key import markets based on criterias such as likely size of import market, government policies and Australia's competitive position for providing hydrogen compared to competitors [28].

Table 8 - Australia's potential exports of hydrogen [28]

Scenario	Country	2025	2030	2040
		10^3 tonnes	*10^3 tonnes*	*10^3 tonnes*
Low hydrogen scenario	Japan	17.3	182.2	392.1
	Korea	8.0	40.1	107.4
	Singapore	0.3	3.9	12.5
	China	0.5	11.6	88.9
	Rest of the world	0.4	4.3	20.3
	Total	**26.5**	**242.1**	**621.3**
Medium hydrogen scenario	Japan	106.1	368.1	852.2
	Korea	23.9	78.1	233.6
	Singapore	2.1	7.4	22.6
	China	2.6	37.6	197.3
	Rest of the world	1.8	11.0	44.8
	Total	**136.5**	**502.1**	**1,350.4**
High hydrogen scenario	Japan	275.0	803.0	1,978.8
	Korea	53.0	167.4	569.5
	Singapore	4.2	15.1	62.5
	China	7.9	79.3	463.9
	Rest of the world	4.8	23.5	105.6
	Total	**344.8**	**1,088.4**	**3,180.4**

4.6.4 Summary

Today, hydrogen is mostly utilized in oil refining and fertiliser production. For hydrogen to play a significant role in the clean energy transition, it also needs to have a bigger presence in other sectors, such as transport, heating and power generation [33]. Hydrogen is already scaling up globally, as sizable investments are being made [42]. Different projections of potential hydrogen demand have been made by various outlets, and the projected rate of growth varies significantly. One difference lies in the time frame of their projection, whereas another difference arises from the fact that unalike volumes of hydrogen demand has been used as a starting point. However, there is a clear consensus that hydrogen has the potential to serve as an important low-carbon option across various sectors, and that the sector will grow [4, 5, 28, 32, 34, 42]. It is also clear that in order for hydrogen to be a competitive alternative to conventional fuels, there is a need for policy support, user demand, and an increase in investments [33]. The hydrogen industry is ready to to help enabling the energy transition to a net-zero world.

4.7 Introduction to the Case Studies

In order to get a more in-depth and detailed examination of hydrogen production at different locations, three case studies will be carried out. The goal of Case Study 1 is to develop an energy system for a Norwegian off-grid facility running entirely on renewable energy, with excess energy stored in the form of hydrogen. The hydrogen will power the energy system when output from renewable energy sources is scarce. The goal of Case Study 2 is to size a hydrogen plant powered by renewables, so that it will be able to supply University College Cork (UCC) with hydrogen throughout the year. The hydrogen will replace the current natural gas consumption of the Irish University. Case Study 3 aims to showcase the possibility of supplying the worlds first liquid hydrogen carrier with green hydrogen produced from FPV by sizing a hydrogen plant powered entirely by FPV. In reality, the vessel is set to transport grey hydrogen from Australia to Japan. Therefore, the hydrogen plant developed in the case study will be placed in Australia. The locations selected for the case studies exhibit hydrogen production powered by FPV at locations with various degrees of solar radiation.

5. Case Study 1 – Hydrogen Based Zero Emission Off-grid Facility

The project owner of the Hydrogen Based Zero Emission Off-grid Facility Project has defined parts of this section as confidential. This is because it includes sensitive information about the project.

The case study aims to develop an energy system for an off-grid facility running entirely on renewable energy, with excess energy stored in the form of hydrogen. The hydrogen will supply the energy system with energy at times when output from the renewable energy sources is scarce. All data regarding the operation of the facility was provided through private communication with Trond Strømgren [58].

5.1 Site Description

The project owner of the Hydrogen Based Zero Emission Off-grid Facility Project has defined parts of this section as confidential. This is because it includes sensitive information about the project.

The case study examines an off-grid facility located on the west coast of Norway.

5.2 Energy Consumption

The project owner of the Hydrogen Based Zero Emission Off-grid Facility Project has defined parts of this section as confidential. This is because it includes sensitive information about the project.

Most of the energy consumed during daily operations is provided by four main energy consumers. These consumers each have a capacity of 29 kW, and the operation time varies from just a few hours a day in the winter to around 11 hours a day during the summer months. The total energy consumption is 302 375 kWh/yr. The monthly consumption is shown in Table 9.

Table 9 - Consumption on a monthly basis from the main energy consumers

Month	Operating hours [h/d]	Basic Load [kWh/month]	Variable Load [kWh/month]	Total [kWh/month]	[kWh/day]
Jan	6	3650	15513	19163	630
Feb	6	3650	15513	19163	630
Mar	7	3650	18098	21748	715
Apr	8	3650	20683	24333	800
May	10	3650	25854	29504	970
Jun	11	3650	28440	32090	1055
Jul	11	3650	28440	32090	1055
Aug	10	3650	25854	29504	970
Sep	10	3650	25854	29504	970
Oct	8	3650	20683	24333	800
Nov	7	3650	18098	21748	715
Des	6	3650	15513	19163	630

The basic power of the system is set to 5 kW, whilst the main energy consumers will operate at a cumulative effect of 85 kW during operation hours, which will give a total effect of 90 kW. The monthly total energy consumption varies greatly throughout the year because of the considerable variation in operation hours. To estimate the total energy consumption for every day for an entire year, this report used the available data in Table 10 to make a daily operational profile for each month. It is assumed that the daily profile for January will be the same for each day during that month. The same goes for all the other months. The result can be seen in Table 10.

Table 10 - Daily Operational profile for each month (kW)

	Januar	Februar	Mars	April	Mai	Juni	July	August	September	Oktober	November	Desember
00:00	5	5	5	5	5	5	5	5	5	5	5	5
01:00	5	5	5	5	5	5	5	5	5	5	5	5
02:00	5	5	5	5	5	5	5	5	5	5	5	5
03:00	5	5	5	5	5	5	5	5	5	5	5	5
04:00	5	5	5	5	5	5	5	5	5	5	5	5
05:00	5	5	5	5	5	5	5	5	5	5	5	5
06:00	5	5	5	5	5	90	90	5	5	5	5	5
07:00	5	5	90	90	90	90	90	90	90	90	90	5
08:00	5	90	90	90	90	5	5	90	90	90	90	5
09:00	90	90	5	5	5	90	90	5	5	5	5	90
10:00	90	5	5	90	90	90	90	90	90	90	5	90
11:00	90	5	5	90	90	5	5	90	90	90	5	90
12:00	5	90	90	5	5	90	90	5	5	5	90	5
13:00	5	90	90	5	90	90	90	90	90	5	90	5
14:00	90	5	90	90	90	90	90	90	90	90	90	90
15:00	90	5	5	90	5	90	90	5	5	90	5	90
16:00	90	90	5	5	90	90	90	90	90	5	5	90
17:00	5	90	90	5	90	5	5	90	90	5	90	5
18:00	5	5	90	90	5	90	90	5	5	90	90	5
19:00	5	5	5	90	90	90	90	90	90	90	5	5
20:00	5	5	5	5	90	5	5	90	90	5	5	5
21:00	5	5	5	5	5	5	5	5	5	5	5	5
22:00	5	5	5	5	5	5	5	5	5	5	5	5
23:00	5	5	5	5	5	5	5	5	5	5	5	5
Total	630	630	715	800	970	1055	1055	970	970	800	715	630

As can be seen in Figure 6 and Figure 7, the daily operational profile during a winter month is very different from that of a summer month. There is a total of 10 hours operating time in May, whilst January only has 6 hours operating time. This is due to the increased power consumption in the summer months.

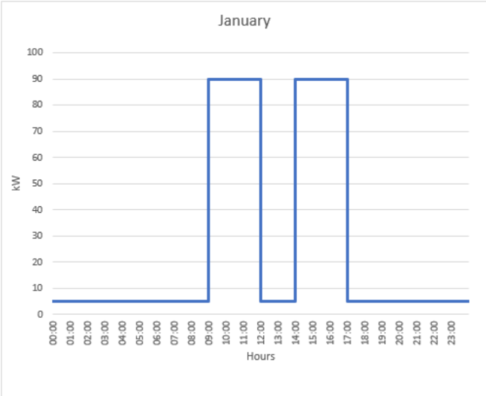

Figure 6 – Daily power demand (kW) profile in January

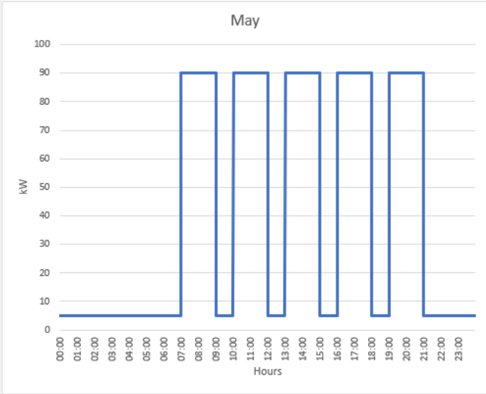

Figure 7 - Daily power demand (kW) profile in May

5.3 Renewable Energy Resource Assessment

5.3.1 PV Resource Assessment

The solar data was obtained from the the Ninja Automator, and the methodology was described in section 2.2 Quantitative Methods. In this case the latitude and longitude of facility was used. When deciding on what tilt the solar panels in the system should be set to, the power output from the tilts ranging from 30-43˚ was compared, as shown in Figure 8. The result showed that a tilt of 39˚ would provide the highest total output of energy. The tilt of 39˚ was used in all further calculations in this case study. The capacity of the array was at first set to 1 MW, but the results could simply be scaled up or down from there. The monthly solar power generated is displayed in Figure 9.

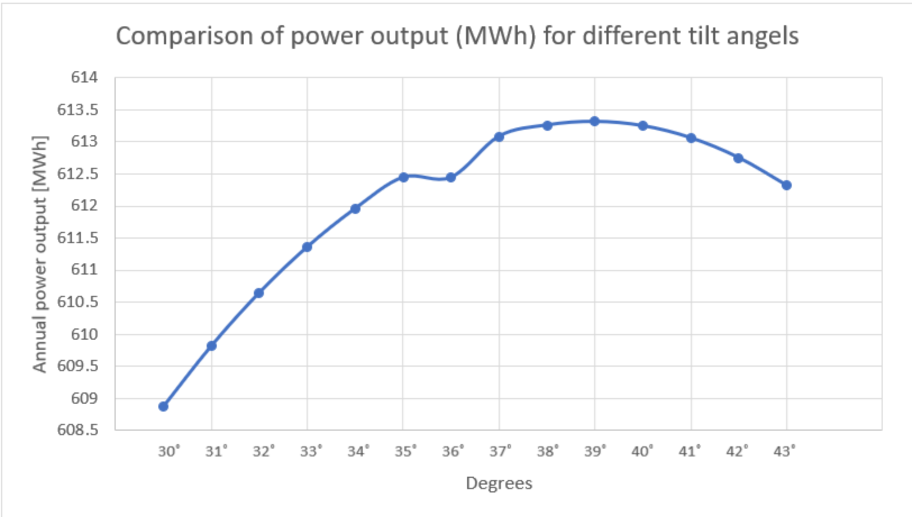

Figure 8 - Comparison of power output (MWh) for different tilt angels for the FPVs

5.3.2 Wind Resource Assessment

Hourly wind speed data was obtained from the Norwegian Climate Service Center [59]. The data was recorded at a local weather station with a height of 9 m. The methodology is outlined in section 2.2 Qualitative Methods. By using the loglaw, the wind speeds are extrapolated to the height of the WES100 wind turbine at 31 m. A data series from 2018 was chosen. It is not 100 % complete, as there is a period of roughly 3 weeks in April-May without any data recorded, however, there is missing data in most wind speed data sets. These 3 weeks were treated as a maintenance period for the wind turbine. The power curve used in the calculation and additional information around the WES 100 turbine was retrieved from Attachment 1. The monthly wind power generated is shown in Figure 9.

5.3.3 Hydrogen Components Assessment

NEL Hydrogens C30PEM electrolyser was chosen for the project, as the capacity of that electrolyser matches the surplus output from the renewable energy sources. The electrolyser has a capacity of 175 kW and can produce up to 65 kg/day of hydrogen at a pressure of 30 bar. Information used in the calculation can be seen in Attachment 2, 3 and 4. The system could easily be scaled up with more electrolysers if needed. It is assumed that the electrolyser will start producing hydrogen at 15 % of max capacity. This specific assumption was made after an interview with Bjørn Gregert Halvorsen in NEL [16]. The amount of hydrogen produced at each hour throughout the year was calculated by interpolarization between the values for max and min nominal production rate specified in attachment 2. It proved to be extremely hard to get information from fuel cell manufacturers. Therefore, a specific fuel cell was not chosen, but a fuel cell with a modest efficiency of 50 % was used in calculations [4].

5.3.4 Summary Resource Assessment

The focus of this thesis is to explore hydrogen production from FPV, but solar energy is a variable and intermittent source of energy. Therefore it is concluded that it would be wise to add a wind turbine, as it is a complementary energy source. The yearly output from a wind turbine and a solar array is displayed in Figure 9, and clearly shows that wind and solar are complementary sources of energy. When the output from the FPV array is low, the output from the wind turbine is usually higher. It is important to note that the capacity of the solar array is substantially larger than that of the wind turbine.

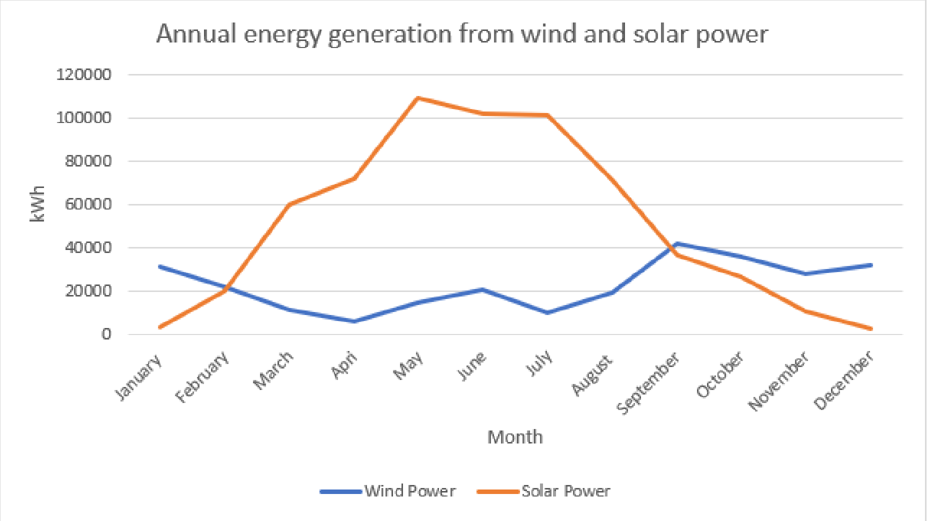

Figure 9 - Annual energy generation from wind and solar power (kWh)

5.4 Scenarios with Renewables as the Solution

The goal of the case study was to design an energy system for a off-grid facility running entirely on renewable energy, with excess energy stored in the form of hydrogen. At times with scarce output from the renewable energy sources, the system will run on hydrogen. The results will be presented in the form of three scenarios. The first one is very basic, whereas the succeeding scenarios each will have more variables and parameters added than the former. Consequently, the simulations will continuously become more realistic and feasible. The following bullet points give a quick overview of each of the scenarios.

- Scenario 1
    - Building a base for the rest of the scenarios on a basic level
    - Adding and sizing FPV array
    - Running the electrolyser non-stop during the year
    - Sizing the overall system under these conditions
- Scenario 2
    - Adding the power load for having the electrolyser on standby to the demand
    - Looking at operating the electrolyser from March to the end of October
    - Resizing the overall system after changes are implemented
- Scenario 3
    - Adding a wind turbine
    - Adding losses related to storing and filling hydrogen
    - Resizing the overall system after changes are implemented

Simulations was carried out using Microsoft Excel. It is important to note that one common parameter for all of the scenarios is that at the beginning of each simulation, the system will already have been supplied with the amount of hydrogen needed to end up at a net zero at the end of the simulation. The system will for the most part run on hydrogen during the winter months of the year. As the solar output increases in the summer, excess energy will be used to produce more hydrogen. This will be the case from early March until late September. From this point on, there is limited solar output and the system will again mostly run on hydrogen.

5.4.1 Scenario 1 – Basic System Sizing

In Scenario 1, several factors were not included in the Excel simulations. The facility only had to cover the demand from the main energy consumers. The demand needed to power the electrolysers was neglected. Another key assumption in this scenario was that the electrolysers could be turned on/off instantly, and as a result, produce hydrogen more easily.

The system in Scenario 1 comprises a floating solar array with a capacity of 900 kW, two C30PEM electrolysers, and a fuel cell. After running several simulations with different FPV capacities, it was concluded that in order to produce enough hydrogen to supply the system with energy during times of scarce solar output, a solar array of such a size would be adequate. It would cover an area of around 5040 m^2. The hydrogen storage profile for Scenario 1 throughout the year can be seen in Figure 10.

The storage profile shows that at one point, 5 tonnes of hydrogen needs to be stored. This is a large amount considering facilites storing more than 5 tonnes of hydrogen will be categorized as a “Major Accident Facilites” [60]. Therefore, adjustments need to be made so that the maximum amount of hydrogen stored is decreased. The basic power load of the electrolysers need to be considered as well, as this will make the simulations more realistic.

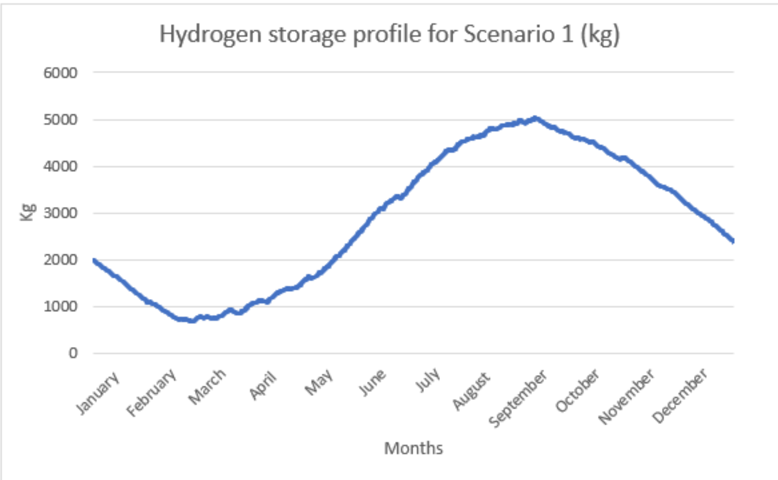

Figure 10 - Hydrogen storage profile for Scenario 1 (kg)

5.4.2 Scenario 2 – Increased FPV Capacity

In Scenario 2, the electrolysers basic power consumption load of 5 kW each was included in the total demand. Consequently, the need for a solar array with larger capacity became present. Another adjustment made was that the electrolysers would be continuously running from 1st of March to the 31st of October, whereas they would be turned off in the remaning months. This was done because hydrogen production throughout the winter was scarce in Scenario 1. Keeping the electrolysers on standby would therefore be a waste of energy.

In order to be able to power the updated demand of the facility, the installed FPV's capacity was increased to 1 MW. This would cover an area of 5600 m^2. However, the adjustments made did not have much of an impact on the hydrogen storage profile of the system, as shown in Figure 11. The storage profile is very similar to the one in Figure 10. Therefore, to optimise the system, more adjustments need to be made.

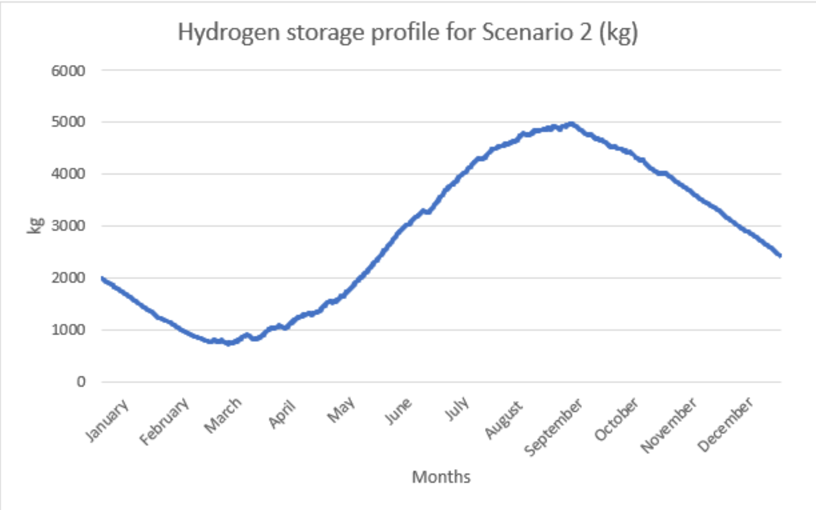

Figure 11 - Hydrogen storage profile for Scenario 2 (kg)

5.4.3 Scenario 3 – FPV + Wind Energy

In Scenario 3, a WES 100 wind turbine was added to the system. This was done to decrease the required hydrogen storage capacity. The WES 100 is a 31 m high, two-bladed model with a rotor diameter of 18 m. The grid voltage is 400 V ± 10 %, therefore it is within the regulations of the Norwegian energy law, which states that any construction that produces, converts, transfers or distributes electrical energy with a voltage higher than 1000 V, is not allowed to be built or operated without concession [61]. This model has a cut in wind speed at < 3 m/s and a cut-out wind speed at 25 m/s. This means that it will produce electrical energy during wind speeds only within this interval. The expected lifetime is 20 years and has been scheduled for maintenance twice a year as seen in Attachment 1.

Adding a 100 kW wind turbine to the system made it possible to decrease the installed capacity of the solar array from the 1 MW utilized in Scenario 2, down to 650 kW. Consequently, the total area covered by FPV would then amount to 3640 m^2. Another adjustment made in Scenario 3 was that roundtrip energy losses during the storage process were considered. Factors like chemical composition of the gas, filling speed, inlet temperature, compressors etc. all contributed to make the filling efficiency 75-95 % (see Attachment 5). In this scenario the efficiency was set to 85 %. The addition of these losses made the simulation even more accurate. The hydrogen storage profile presented in Figure 12 shows that the changes made had a substantial impact on the results of the simulation. The required storage capacity of hydrogen has decreased considerably from roughly 5 tonnes to 2.8 tonnes, compared to the previous scenario. This makes the system less reliant on hydrogen.

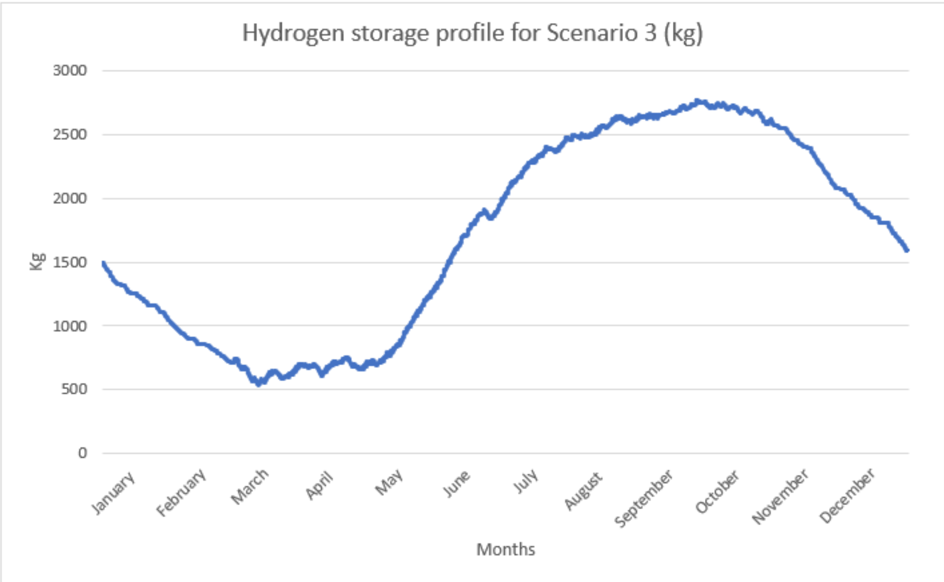

Figure 12 - Hydrogen storage profile for Scenario 3 (kg)

As displayed in Figure 12 there is around 500 kg of hydrogen stored at the lowest point during the year. This could be usefull in case of longtime maintenance of electrolysers or the renewable power generators. Then the energy demand could be covered by the extra hydrogen stored as contingency.

5.5 Further Development of System based on Scenario 3

The results of the simulation in Scenario 3 made the project way more feasible due to the added versatility wind power contributes to the system. Further development of the system based on the concept in Scenario 3 will now be presented.

5.5.1 Placement of the Facility

The project owner of the Hydrogen Based Zero Emission Off-grid Facility Project has defined parts of this section as confidential. This is because it includes sensitive information about the project.

[redacted]

Figure 13 - Location of the facility

5.5.2 Overview of the Energy System

A total of 885.3 MWh was generated from the renewable energy sources throughout the year. Solar and wind contributes as follows: 613.3 MWh from solar, and 271.9 MWh from wind. 273.9 MWh was covered directly by the renewable resources, 458.8 MWh was used to produce hydrogen, and the total waste power accumulated to 152.6 MWh. This is displayed in Figure 14.

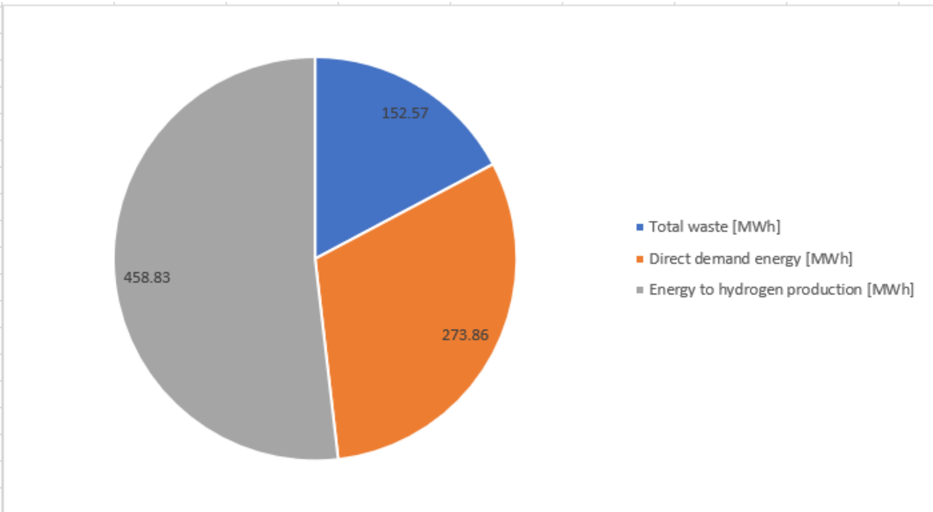

Figure 14 - Generated electricity usage (MWh)

The demand was for the most part covered by the renewable energy sources. If at any time there was insufficient output from the renewables, hydrogen was used in combination with the fuel cell to cover the rest of the demand. In Figure 15, a visualisation of the power coming directly from the renewables and the power from the fuel cell is displayed. The figure shows that roughly three-quarters of the demand was covered directly by the renewable energy sources, while the rest was covered by hydrogen.

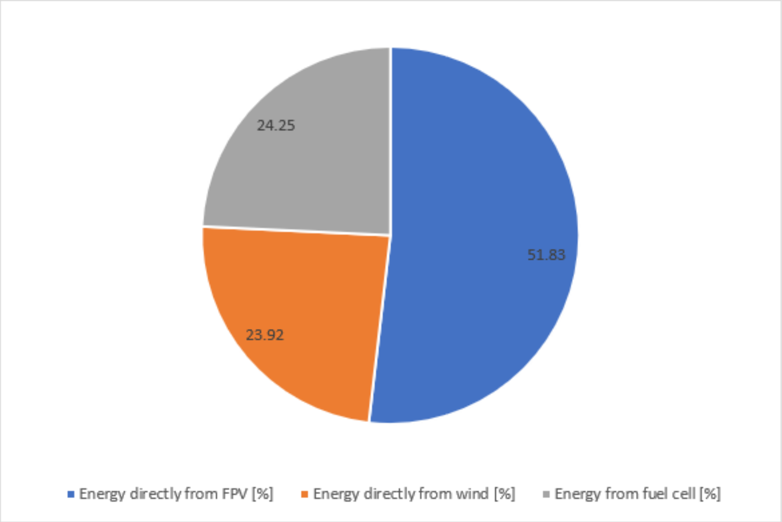

Figure 15 - The various types of energy covering the demand (%)

There is a big difference between the amount of energy needed for production of hydrogen, and the energy output from the fuel cell. As seen in Figure 14, more than half of the total energy produced from wind and solar is used to produce hydrogen. And as seen in Figure 15, just 24.25 % of the demand is covered by hydrogen. This is due to losses in the hydrogen system.

The overall efficiency of the electrolyser was 46 % when looking at the energy input of renewable energy and output in the form of hydrogen. Usually PEM electrolysers operate at an efficiency ranging from 65-78 %. That makes the efficiency of this electrolyser quite low in comparison. This result will be discussed further in the discussion section of the report. When adding a 15 % loss in the storage and fuelling process, a fuel cell efficiency of 50 %, the roundtrip hydrogen system efficiency totals at 20 %. That explains why just one-quarter of the demand was covered by hydrogen when over half of the energy produced went to hydrogen production. A summary of some of the findings in Scenario 3 is given in Table 12.

Table 11 - Findings in Scenario 3

Findings	
Total load demand	361.51 MWh
Total of solar power generated	613.31 MWh
Total of wind power generated	271.94 MWh
Total of renewable power generated	885.25 MWh
Total of wast power	152.57 MWh
Total production of hydrogen	6294.46 kg
Efficiency electrolyser	45.72 %
Efficiency storing and fuelling	85 %
Efficiency fuel cell	50 %
Total hydrogen system efficiency	20 %

5.5.3 P&ID

In order to give a more detailed overview of what the hydrogen system could look like, pipeline and instrument diagrams (P&ID) of the system was created. These drawings give a more detailed insight on how a system could be built, and shows how the different components of the system could be set up in order for it to run in an optimal way. The legend in Figure 16, describes the symbols used in the P&ID.

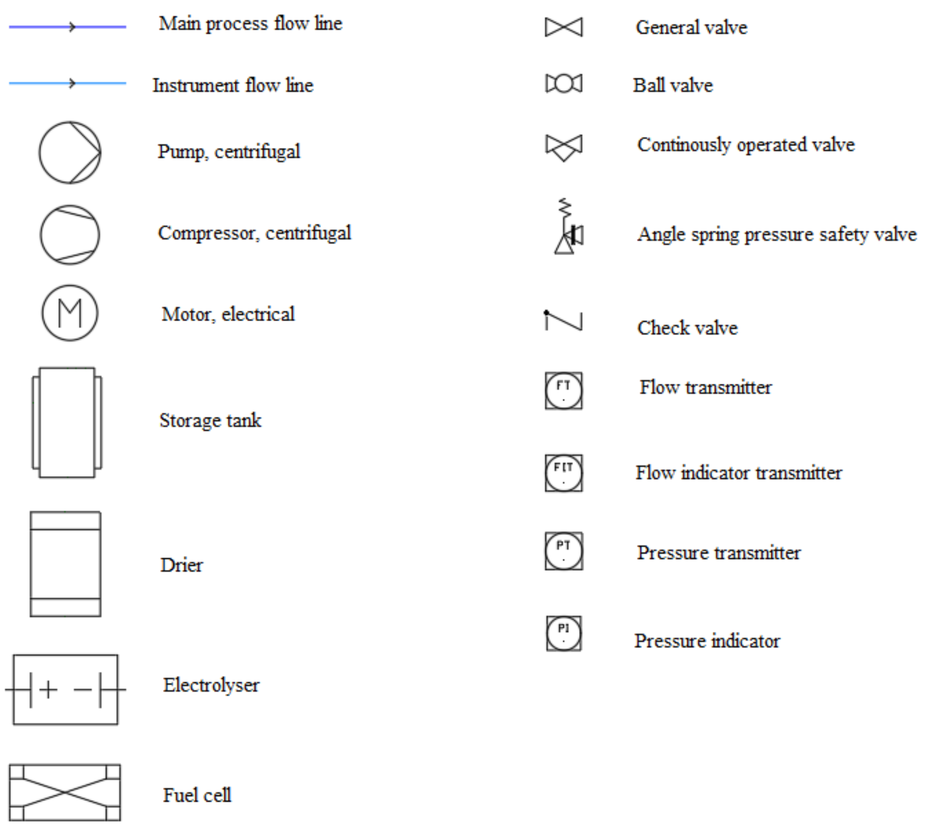

Figure 16 - Legend for the P&ID

Runthrough of the desalination process

In order to produce the required amount of hydrogen, 32,000 litres of water is needed. This water has to be at least water quality type II, but type I is prefered. This is a standard made by the American Society for Testing and Materials (ASTM) where type I is the purest of four types [62]. This means that the water going through the electrolysers needs to have a purity of minimum 1µS/cm (see Attachment 3). This leaves two options, either desalinate sea water and clean it near the facility, or buy clean water from an external source.

The first option includes installing a water desalination system near the facility and desalinate sea water directly from the ocean. The Norwegian manufacturer Norwater were contacted with regards to their reverse osmosis system. According to them, the energy required to produce the amount of water the electrolysers need is around 5-6 kWh/m^3 for drinking water quality. Furthermore, the power demand would increase slightly if the water should have technical quality, see Attachment 6. Therefore, it was assumed that a power demand of 8 kWh/m^3 would be sufficient to desalinate the seawater. With this assumption it would require between 250-300 kWh to desalinate enough seawater to provide the system for a year. The cost of building a desalination system might not be profitable in the long run, due to the fact that buying the technical water might be a cheaper solution, both short term and long term.

The P&ID of the desalination process is presented in Figure 17. The pump (P-003) pumps seawater through a pipeline into the desalinator (K-002). Between the pump and the desalinator there is a pipeline that can be used for potential system drains. There are also two transmittors, one is transmitting flow (FIT) and the other is transmitting pressure (PT). After the water has gone through the desalinator it is ready to be used in the electrolysis process. Downstream of the desalinator there is another pipeline that gives a possibility for a system drain. Draining the system would be beneficial when performing maintenance on the various pieces of equipment. The other option is to order technical water directly from an external supplier. This will remove the cost of installing and operating a desalination system.

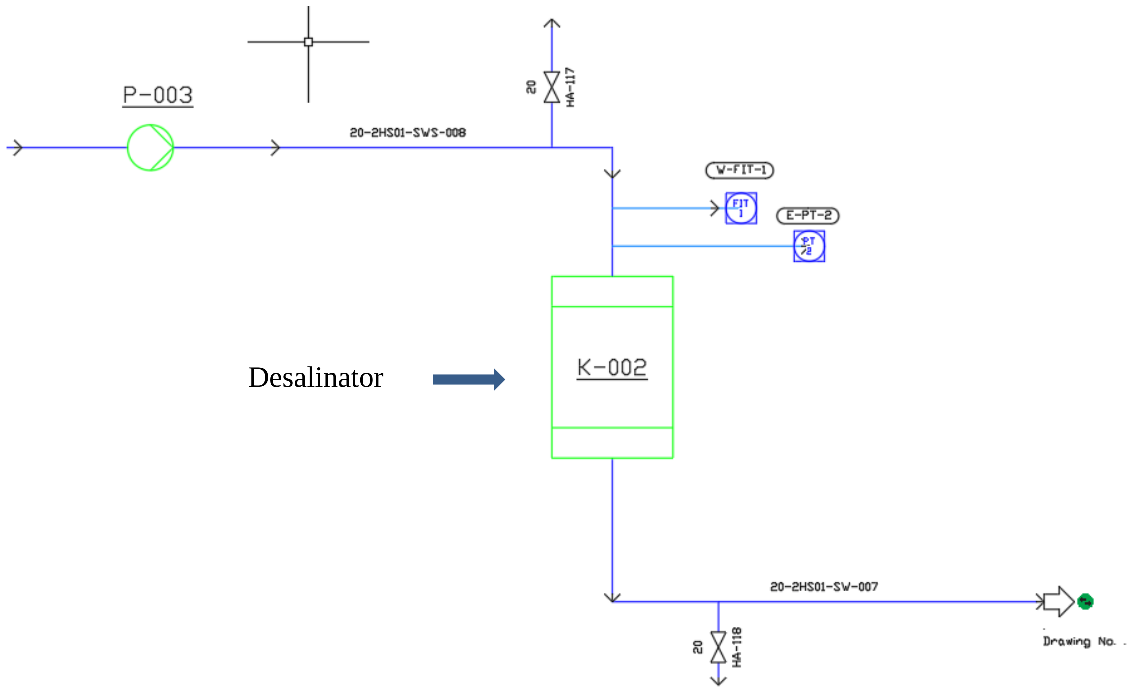

Figure 17 - P&ID of the desalination process

Runthrough of the process from electrolysers to storage

The next stage of the process can be seen in Figure 18. After the water has been desalinated, it is pumped through one of the two pumps (P-001 or P-002). The plant is planned to have two pumps, one active and one standby. This provides the ability to maintain production even though one is out of order, or under maintenance. Downstream of the pumps there are check valves (HA-127/HA-128) to prevent the pressured water from the active pump to run in a cycle through the standby pump. The valves HA-001, HA-002, HA-131 and HA-132 are placed on each side of the pumps so that they can be taken out for maintenance. On the pipeline downstream of the pumps there is a pressure transmitter (PT) and a flow indicator transmitter (FIT). Monitoring these either in a control room or in the field gives an indicator if the flow is too low or high, or if the pressure is within the preferred range. In order to be able to regulate this, continuously operated valves are installed.

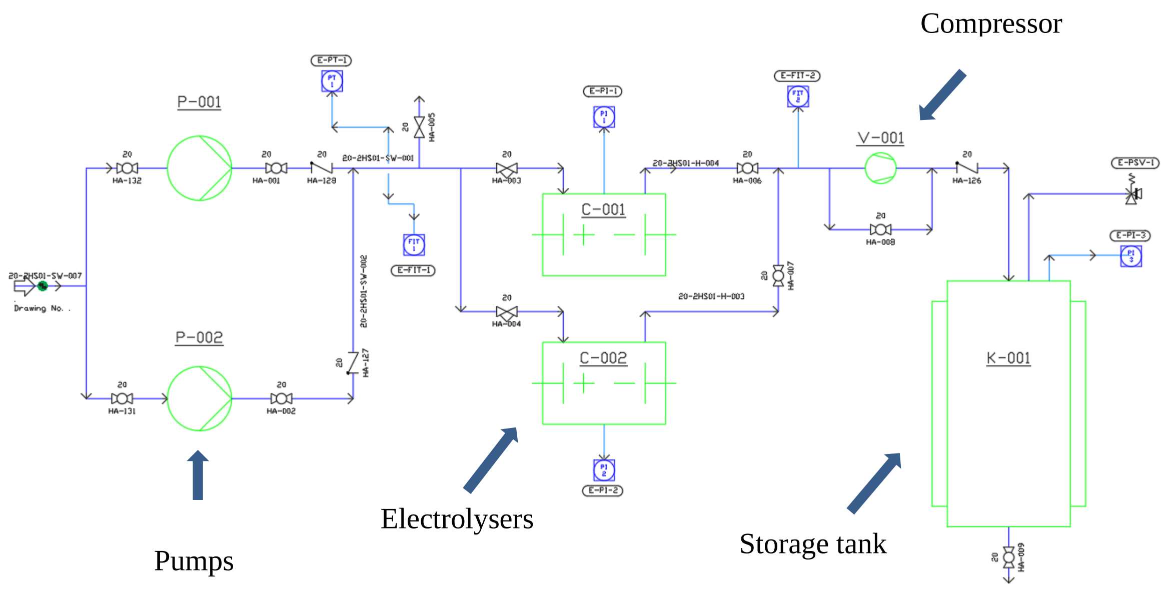

Figure 18 - Overview of the process from electrolysers to storage

The water then goes through the electrolysers (C-001/C-002) where the process explained in Section 4.1.2 happens. The processed hydrogen gas then passes through a valve (H-006/H-007). This valve prevents the gas from going backwards into the other electrolyser if only one is running. The gas then goes through a compressor (V-001) before entering the storage tank. The gas also goes through a check valve to prevent the pressured gas to go backwards through the compressor and into the elctrolyseres if the pressure upstream the tank falls below the tank pressure. There is a by-pass loop around the compressor in case there is no need to compress the hydrogen gas. On top of the storage tank there is a pressure safety valve (PSV). This safety valve has a spring inside it set to a certain pressure. If the pressure in the tank exceeds the set pressure of the spring, the valve will open and let out excess gas until the pressure is below the set pressure. This is to ensure the safety of the system when working with pressurised gasses.

Runthrough of Storage tank to Fuel cell

When the system requires energy from the stored hydrogen, the valve downstream of the tank opens up to allow the gas to go into the fuel cell, as seen in Figure 19. The fuel cell (C-003) process is explained further in Section 4.3. Both upstream and downstream of the fuel cell there are flow indicators (FI) and pressure indicators (PI). The waste product goes out to the sea, while the electricity from the fuel cell powers the system.

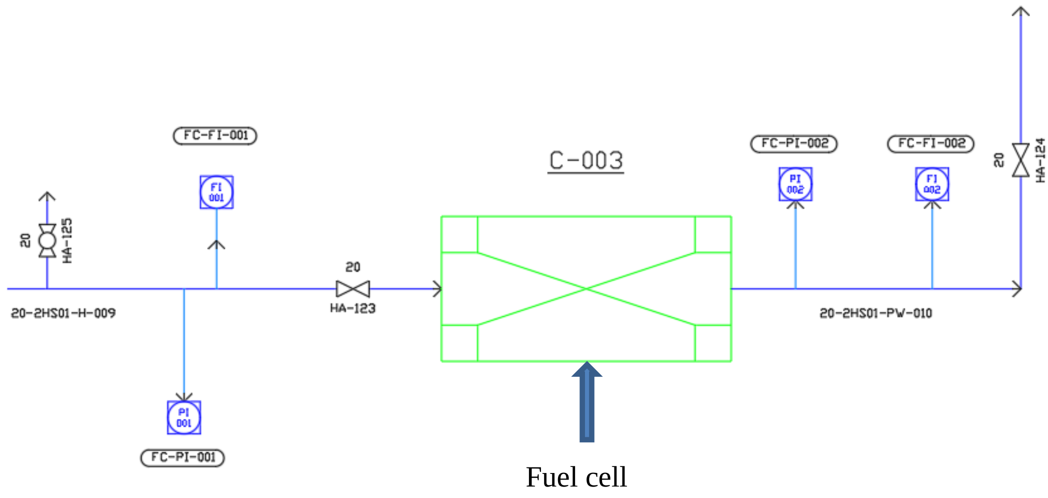

Figure 19 - Storage tank through fuel cell

5.5.4 Storage

This system required a storage capacity of 2770 kg hydrogen at 300 bars. Hexagon's X-Store 45 ft. storage module was selected. One module can hold 950 kg of hydrogen at the pressure of 300 bars and the dimensions are 13.176 m x 2.438 m x 2.743 m. Module information is displayed in Attachment 5. In this case, three modules was needed in order for the plant to be able to store the required amount of hydrogen. Since there was no continous usage of hydrogen, the possibility of storing the hydrogen in liquid form was not considered. In addition there is significant energy losses related to process liquifying hydrogen [43].

5.5.5 Waste Power

During the process there was a considerable amount of energy wasted. As previously mentioned, the electricity was used to cover the demand of the facility and produce as much hydrogen as possible. In the months of January, February, November and December, when the electrolysers was shut down, all surplus energy produced was waste energy. The results showed that a total of 100.6 MWh went to waste during these months. During the rest of the year when the electrolysers are operating, there were intervals when the excess energy could not be used to produce hydrogen. This is displayed in Figure 20. The figure shows the power available for hydrogen production for a random day, July 1st 2018. The blue line shows power available for hydrogen production, whilst the orange and grey lines represent the electrolysers production range. When the blue line is within this range, hydrogen was produced. This means that when the blue line was above 0 kW and below the orange line, the energy was not utilized. This is due to the fact that this amount of energy will not be sufficient to start the hydrogen production, neither will it be needed to cover demand. Also, when the blue line is above the grey line, all the energy above the line will go to waste because there is no way to store or utilize the energy without adding a battery or another electrolyser. This adds a total of 52.6 MWh of waste power.

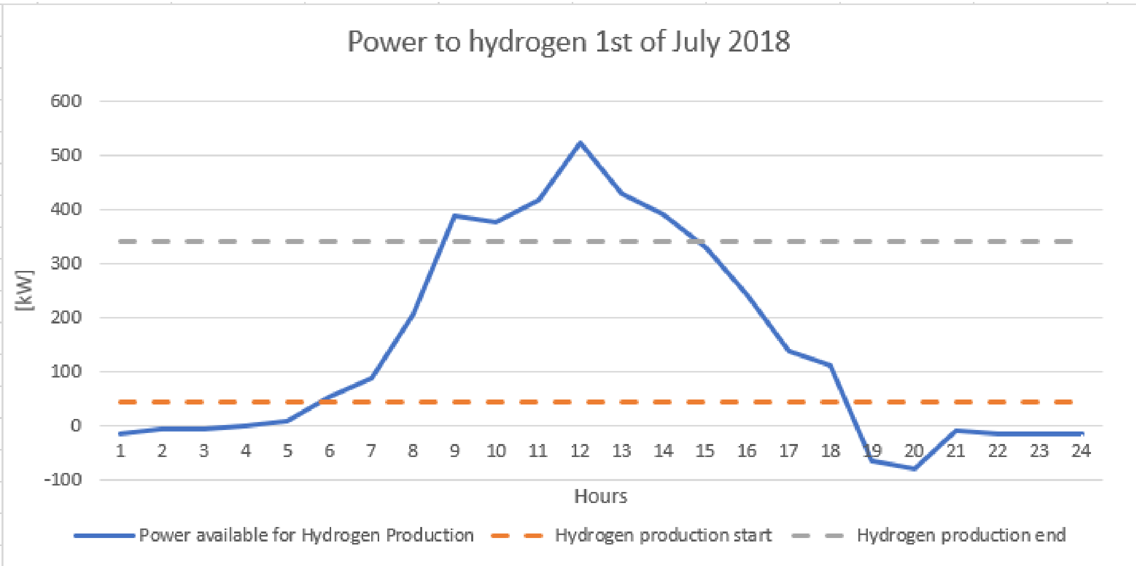

Figure 20 - Showcasing when the surplus energy could be used to produce hydrogen (kW)

During the entire year there was a total of 152.6 MWh waste power. This accumulates to 17.2 % of the total energy generated. The waste energy could have been used to charge a battery package or to power other parts of the facility.

5.5.6 Health, Safety and the Environment

When it comes to safety regulations and standards associated with working with hydrogen, every project is being handled individually. As of now the laws and legislations surrounding hydrogen production and storage is inadequate. By Norwegian law, up to five tonnes of hydrogen can be stored without being categorized as a "Major Accident Facility" [60]. At maximum, 2800 kg of hydrogen was stored. This means that the facility can operate without having to report to the Norwagian Directorate for Civil Protection (DSB).

Guidelines from the manufacturers was considered when assessing the layout of the hydrogen facility. Both the fuel cell and the electrolysers are placed inside a building to be able operate under the most ideal conditions. These machines are not built to withstand rough weather and variating temperatures. It is important to have good ventilation inside to prevent an accident if a leak occurs. With a high ceiling the natural properties of the hydrogen gas could be taken advantage of since it has a high buoyancy and diffusivity, and therefore the hydrogen would quickly rise and minimize the chance of ignition. The storage tanks are placed outside the building in safe distance from the other critical equipment. This is done because the storage tanks are where the highest quantity of hydrogen are at any time and therefore leaks and other accidents around the storage tanks could have fatal concequences.

6. Case Study 2 – Replacing Natural Gas with Hydrogen at UCC, Ireland

Natural gas plays a major role in the Irish energy mix, almost 50 % of the fuels used to generate electricity comes from natural gas. A total of 27 % of the primary Irish energy requirement comes from natural gas [63]. By burning this natural gas, substantial amounts of CO_2 will be emitted. By implementing sustainable energy solutions, the emissions will decrease.

Almost 50 % of the energy consumption at University College Cork (UCC) comes from natural gas. This gas is being burned and supplies UCC with electricity and heating. It is estimated that UCC will consume 14,744,000 kWh of natural gas from October 2019 to September 2020 [64]. This case study examines how this energy could be replaced with hydrogen. It is important to note that this case was based on simple energy calculations and assumptions like constant hydrogen production at 65 % efficiency and no losses in hydrogen transportation. The facility will be grid connected, but most of the energy will come from solar and wind power.

6.1 Energy Consumption

If the natural gas was to be replaced by hydrogen, there is a need for a massive hydrogen production facility. With a fuel cell efficiency of 50 % and a hydrogen mass density of 33.33 kWh/kg, 888.7 tonnes of hydrogen is required to produce 14,744,000 kWh. This is shown in Equation 2.

$$Mass = \frac{14{,}477{,}000\ kWh}{\frac{33.33\ kWh}{kg} \times \frac{1000\ kg}{tonnes}} \times 0.5 = 888.72\ tonnes$$

Equation 2 - Total mass of Hydrogen

As the energy profile was not available, it was simply assumed that UCC required the same amount of energy every hour during the whole year, which meant that a total of nearly 101 kg of H_2 was required each hour. This assumption was made to showcase the possibility of changing the fuel from natural gas to hydrogen.

6.2 Site Description

Roches Point was chosen as the location of the FPV array and the wind turbine. The main reason this location was found suitable, was due to the nearby wind station where data could be extracted. Roches Point is located 20 km south-east of UCC, and the FPV array will cover an area of 224 000 m^2. The wind turbine would be placed nearby. The location of the solar array is given in Figure 21.

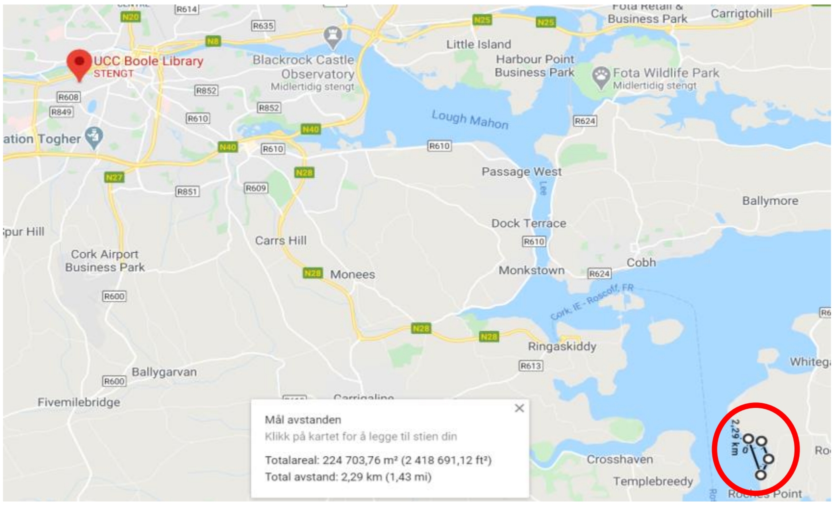

Figure 21 - Showcasing the FPV placement and the distance to UCC

6.3 Renewable Energy Resource Assessment

6.3.1 PV Resourse Assessment

The solar data used in this case study was obtained from The Ninja Automator and the latidude and longitude of the weather station at Roches Point was used. Data from 2016 was chosen since the wind data used was from the same year. When deciding on the tilt of the solar panels, the output from the tilts ranging from 30-38˚ was compared. The results showed that a tilt of 36˚ would provide the highest total output of energy, see Figure 22. The capacity of the array was set to 40 MW and a tilt of 36˚ was used.

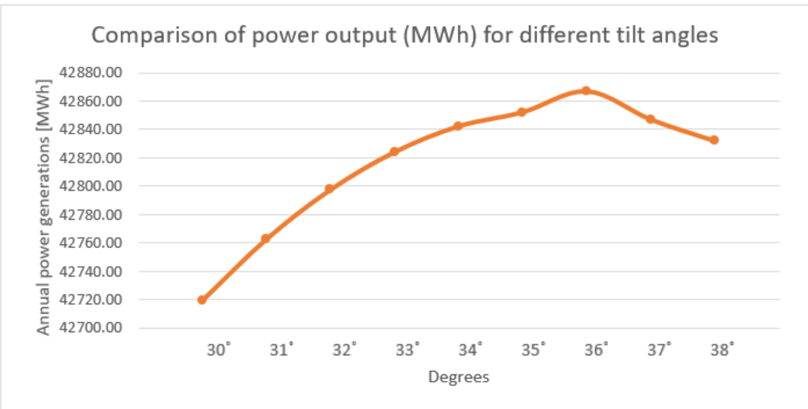

Figure 22 – Comparison of power output (MWh) for different tilt angels for the FPV

6.3.2 Wind Data

Hourly wind speed data was obtained from the Irish Meterological Service [65]. The data was recorded at a weather station at Roches Point at the height of 40 m. Data series from 2016 was chosen, as it was the most recent complete dataset. By using the log law, the wind speeds were extrapolated to the height of a Vestas V90 2 MW wind turbine at 105 m. The output from the wind turbine was calculated using the wind turbine's power curve [66].

6.4 The Solution

In order to produce enough hydrogen to cover the energy demand that UCC required, the possibility of building a hydrogen production facility at Roches Point, 20 km south-east of UCC was looked at. The facility was powered by a 40 MW floating solar array and a 2 MW wind turbine. This would provide a total of 49 GWh to the facility during the year, 43 GWh from solar power and 6 GWh from wind power. The demand from UCC, which was almost 101 kg H_2/h was produced by an electrolyser with an efficiency of 65 %. The electrolyser required 5164.6 kWh to produce the required amount of hydrogen. To fulfil the demand, additional power from the grid was required. This was more relevant in the winter months, when the output from the renewables was especially scarce. On the other hand, in the summer months there was surplus power after the hydrogen production, which was sold back to the grid. The amount of power bought and sold for each month are displayed in Figure 23. Throughout the year, a total of 24.5 GWh was bought from the grid and 28.2 GWh was sold back to the grid. The blue columns represent the amount of power bought from the grid, while the orange columns represent the amount of power sold to the grid.

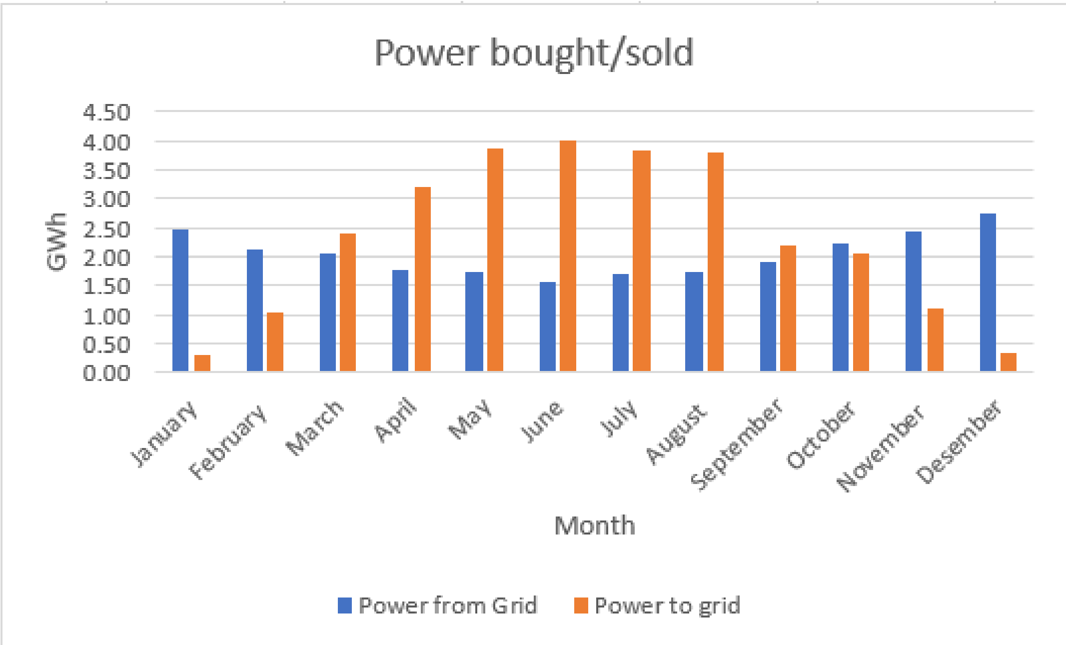

Figure 23 - Power bought/sold each month

It was assumed that a straight pipeline connected the facility and UCC, and that it would be used for hydrogen transportation. All of the transportation losses in the case study was neglected. At UCC, the fuel cell had an efficiency of 50 % and supplied the campus with 1678.5 kWh of electricity every hour. This was enough to cover the annual demand of 14.744 GWh.

Table 12 - Calculation regarding the power output from the fuel cell

H_2 transferred to UCC/h	**H_2 gravimetric density**	**Efficiency Fuel Cell**	**Power from fuel cell**
100.72 kg	33.33 kWh/kg	50 %	1678.5 kWh

7. Case Study 3 – Supplying the Kawasaki LH_2 Carrier with Green Hydrogen

Kawasaki has launched a pilot procjet called Hydrogen Energy Supply Chain (HESC). This project will see hydrogen produced by brown coal in Australia being shipped to Kobe, Japan by a ship specially designed to transport liquid hydrogen (LH_2) [67]. This case study will showcase the possibility of supplying the LH_2 carrier with green hydrogen all year long. This would eliminate the pollution that comes with burning coal. The system will exclusively rely on power from FPV. It will be sized according to the vessels maximum storage capacity of 1250 m^3 LH_2, and a rough estimate of travel time from Hastings, Australia to Kobe, Japan.

In this case study, several assumptions have been made. All challenges associated with permissions, laws and legislations within the boundries of reason has been assumed to be granted and/or not a problem. Missing/required infrastructure in order for this to be possible has been neglected, concitations to wildlife has been neglected.

7.1 Site Description

When choosing an appropriate location for the case, proximity to Hastings bay, as well as a sufficient body of water for the FPV was the key factors. Devilbend Reservoir, located west of Hastings bay is approxematly 10 km away in air distance, as shown in Figure 24. This location looked suitable in regards to the distance to the bay and water body size. When looking at the location through Google maps and pictures online, it did not look like shading from surrounding elements would be a factor. The size would also allow the possibility for future expansion due to the sizing of the array in comparison to the watersurface available. The array will have a size of around 201,600 m^2 to be able to supply the electrolysers with enough power. This leaves plenty of space for future expansions. It is important to clarify that the area marked in Figure 24, is for reference only, and that the floating solar array can easily be split up to several smaller modules.

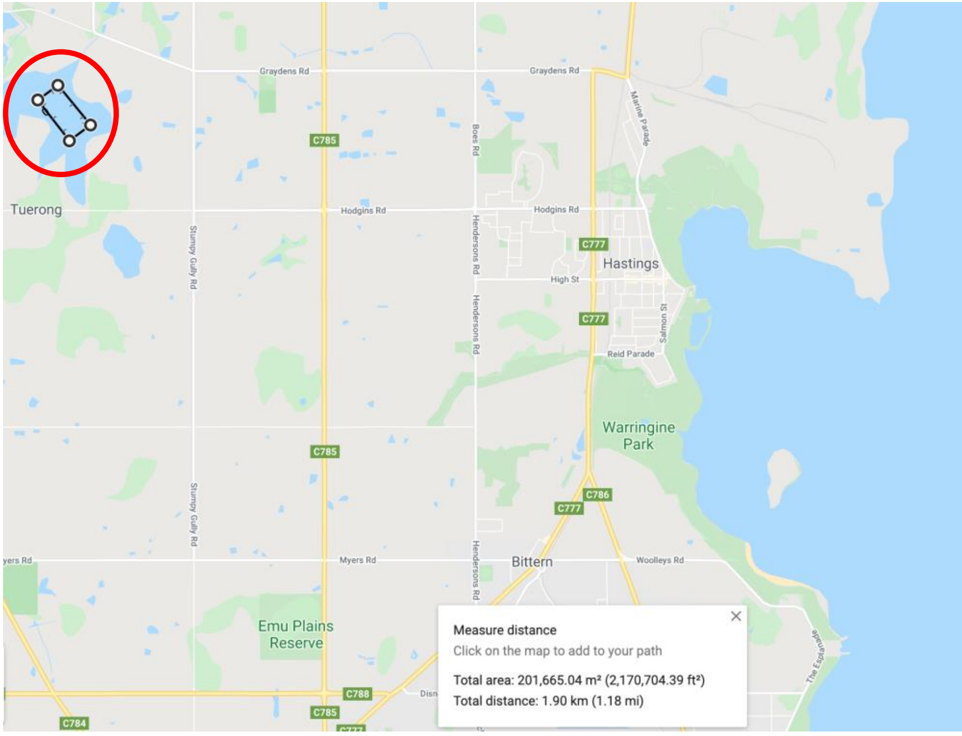

Figure 24 – Location of the plant + distance to Hastings bay

7.2 Renewable Energy Resource Assessment

The solar data used in this case study was obtained from The Ninja Automator and the latidude and longitude of Devilbend Reservoir was used. Data from 2015 was chosen as the year in the dataset, as it the data series were complete. When deciding on what tilt the solar panels in the system should be set to, the output from the tilts ranging from 23°- 30˚ was compared. The comparison showed in Figure 25 displayed that a tilt of 27° gave the highest annual output, and was therefore chosen.

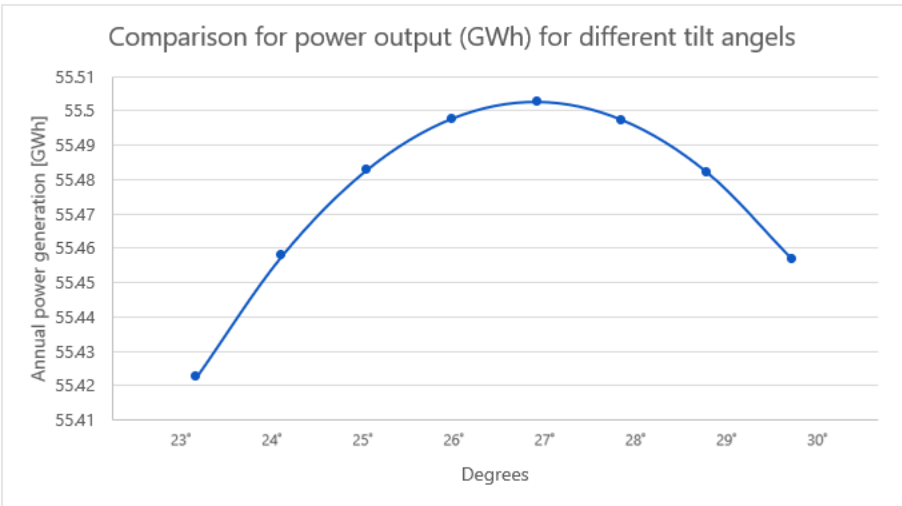

Figure 25 – Comparison for power output (GWh) for different tilt angels for the FPV

7.3 The Solution

The estimated travel time from Hastings to Kobe is approximately 1 month, or 30 days, which means a roundtrip would take about 2 months. This was used in the calculations when sizing the plant. The Kawasaki LH_2 carrier has a maximum load of 1250 m^3 LH_2, and this was what the case used as the load. The carrier was set to travel back and forth between Australia and Japan every second month. The carrier would fill up in Australia, transport it to Japan, then return to Australia empty. When sizing the plant, a 36 MW capacity was found to be the size that best fit the target. This would give an output of approximately 55.5 GWh per year.

When calculating the amount of hydrogen produced, a system efficiency of 65 % was used for the electrolysers, based on calculations from the previous case studies. It was assumed the process of liquifying the hydrogen gas would have an efficiency of 70 %, and a 0.1% monthly storage loss due to boil-off [68]. A 20 % loss due to filling the boat was also included as shown from the efficiency range during the filling process in Attachment 5. It is important to note that the data in the attachment is for compressed hydrogen, and therefore this information could be misleading. All losses after loading the boat is neglected, as this is not in the range of the case study.

For the plant to be able to sustain itself it needs to have hydrogen stored before the first pick up, therefore, the plant will begin to produce hydrogen in December the year prior to the first pick up. The first pickup will be on February 1st and after that it will be a pickup the 1st of every second month throughout the whole year.

The graph in Figure 26 shows how the storage volume would change according to the amount produced and the regular pickup on the 1st of every second month. In the calculations there is a 30-day period in December where the hydrogen produced would be excess compared to how much we need for the next pickup. This 30-day period would function as a buffer period in case of unforeseen events that impact the production, or if the production has been as expected throughout the year, it would be possible to sell the power to the grid. This has to be done in order to keep the storage volume at a stable level throughout multiple years.

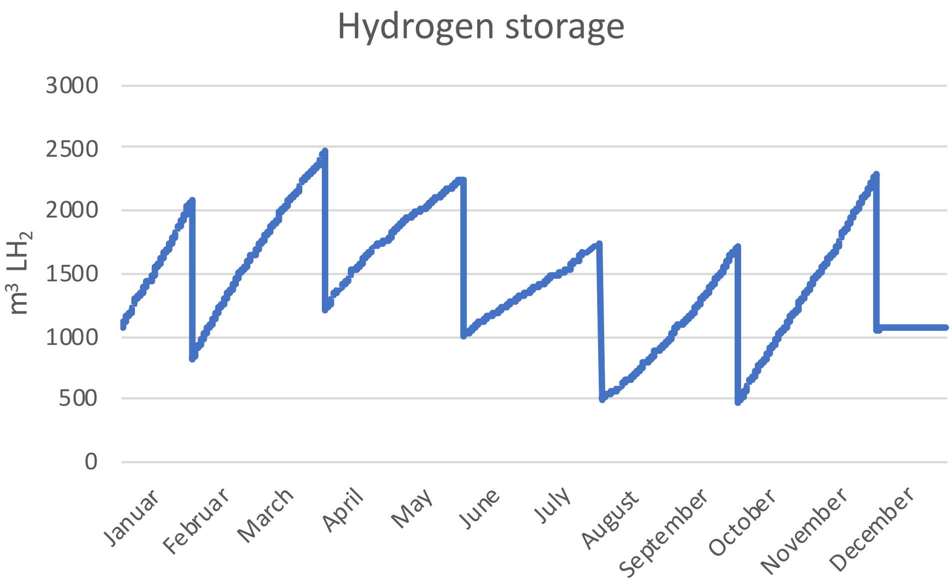

Figure 26 - Hydrogen Storage profile (kg)

8. Discussion

In order to assess the feasibility of FPV powered hydrogen plants at various locations around the globe exhibiting differing degrees of solar radiation, three case studies were carried out. The case studies ran simulations in order to determine the required sizing of each respective hydrogen plant. The goal was to assess engineering aspects, such as energy calculations, technical solutions etc. Cost analysis was neglected.

The goal of Case Study 1 – Hydrogen Based Zero Emission Off-grid Facility was to develop an energy system for a Norwegian off-grid facility running entirely on renewable energy. A 650 kW FPV array supported by a 100 kW wind turbine was able to produce enough hydrogen to power the plant at times when wind and solar resources was insufficient. The total demand of the facility was 361.2 MWh/yr. The goal of Case Study 2 – Replacing Natural Gas with Hydrogen at UCC, Ireland was to size a hydrogen plant powered by renewables, so that it would be able to supply UCC with enough hydrogen to replace their current natural gas consumption. Case Study 3 – Supplying the Kawasaki LH_2 Carrier with Green Hydrogen, was carried out in order to investigate the possibility of supplying the worlds first liquid hydrogen carrier with green hydrogen produced from FPV. It was found that a hydrogen plant powered by a 36 MW FPV array would be adequate.

The possibility of adding batteries has not been included in this thesis, as the main focus of the report was the use of hydrogen as an energy carrier. If batteries were included, some of the waste power discussed in Section 5.5.5 could have been stored and used to cover the peaks during the hydrogen production.

During the calculations made in all the case studies, the advantages in regards to efficiency that FPV provide was not included. As stated in Section 3.1, FPV has a higher power generation than standard PV installations, due to the reduced thermal loss. The fact that this has not been taken into concideration in the calculations has probably affected the results to a small degree. This is especially relevant in Case Study 3, as it was set to Australia, where the temperatures of the air can get very high.

The project owner of the Hydrogen Based Zero Emission Off-grid Facility Project has defined parts of this section as confidential. This is because it includes sensitive information about the project.

As previously mentioned, the case studies did not include a cost analysis. However, some of the economical issues regarding Case Study 1 will be discussed here. As of today there are no public incentives in place that make it financially viable to build an off-grid facility run on renewables. The alternative of having it run on conventional fuels is still cheaper. However, from a sustainability standpoint, there is clear value in installing such a system.

The electrolyser efficiency of 46 % found in Case Study 1 was surprisingly low, as it is more than 20 % lower than that of a typical PEM electrolyser. The reason for this might be the fact that the hydrogen production rate was not constant during the simulations, as it was depended on the output from the renewable energy sources. If the electrolyser was operated at steady capacity at all times, that might improve the efficiency of the production process.

The project owner of the Hydrogen Based Zero Emission Off-grid Facility Project has defined parts of this section as confidential. This is because it includes sensitive information about the project.

The efficiency of the electrolyser in regards to the overall efficiency of the system could increase if the oxygen produced during the electrolysis was utilized. Also, the overall efficiency of the fuel cell could increase if the waste heat produced by the fuel cell was utilized.

The wind data that was used in the first case study were inconclusive, and contained a period of three weeks where no data had been recorded. It was decided not to fill in the gaps of data, instead the three week interval of missing data was treated as a maintainance period for the wind turbine. The use of the log law was also completed with a few assumptions. When calculating the wind speed at the turbine height it was assumed that the turbine was built with its base at sea level. The wind turbine would realistically be located a few meters above sea level, but the calculated wind speeds would increase by approximatly 0.1 m/s if the correct heights were used. It is not likely that this would have made a big impact on the total energy generated throughout the year.

The efficiency of the fuel cell utilized in Case Study 1 and 2 was set to 50 %. This was done in order to simplify the calculations, but also due to the fact that obtaining detailed operational data from manufacturers proved to be difficult. Furthermore, the fuel cell was not running at a constant load, which again impacts its efficiency [4]. The fuel cell used in in Case Study 2 was operated at a constant load, and therefore the efficiency of the fuel cell would be more accurate in reality.

The facility in Case Study 2 had to connect to the grid, and buy a significant amount of electricity. This could be looked at as problematic, as most of the Irish electricity mix is responsible for large amounts of emissions [63]. However, the facility ended up with a net positive electricity trade balance of approximately 3.7 GWh.

In Case Study 3, the azimuth angle of the FPV array was at first set to 0°. The ensuing calculations showed that the optimal tilt angle of the FPV would be 1°, which did not seem right, based on previous calculations, experiences and knowledge. After further investigating the issue, it was found that the correct azimuth angle would be 180°. At first, the definition of azimuth angle had been misinterpreted. It turned out that an azimuth angle of 180° always points towards the equator, whereas at first it was treated as if that was not the case. After figuring out how to properly set the correct azimuth angle, the results of the calculations became more logical.

In Case Study 3, a key assumption regarding the boil-off loss in the storage sphere was made. The more accurate daily boil-off was substituted with a monthly boil-off in the calculations. This probably had a significant impact on the results, as there is a big difference between a 0.1 % loss each day, and a 0.1 % loss every month. The decision to add this assumption was made because the main goal of the case study was to investigate how large the solar array would have to be in order to produce enough hydrogen, rather than focusing on the technical aspects related to storage.

The results of the case studies suggests that the feasibility of a FPV powered hydrogen plant is dependent its application, as well as the location of the system. At locations with great solar resources, it is more feasible. Whereas plants located at locations with limited solar output might need to install other types of renewables, such as wind energy. The results of Case Study 2 and 3 clearly showcase this, as the installed FPV capacity in Case Study 2 is larger that that of Case Study 3, but the output from the latter is significantly larger. In addition, the system in Case Study 2 had to install a wind turbine, as well as connecting to the grid.

9. Conclusion

A literature review assessing the maturity of FPV and hydrogen technology was undertaken. It is concluded that hydrogen and FPV can play an important role in the green energy transition. The technologies are currently mature enough to contribute to reducing harmful emmisions, but improvements are expected to be made continuously throughout the coming decades.

A literature review of projected hydrogen market uptake was carried out. Several reports on the future demand of hydrogen, strategies for uptake, and scenarios under which hydrogen is likely to see growth was reviewed. Hydrogen can support decarbonisation of industry, transport, power generation, and heating of buildings. The hydrogen sector is expected to grow, but the projected growth rate varies from source to source, and it is dependent on suitable financial, infrastructural and policy support.

Three case studies were carried out in order to get a more in-depth and detailed examination of the feasibility of FPV powered hydrogen plants at several locations around the globe exhibiting various degrees of solar radiation.

Case Study 1 showed that a 650 kW FPV array and a 100 kW wind turbine need to be installed in order to cover an off-grid facility’s demand of 361.2 MWh/yr. In addition to this, a total of almost 6300 kg of hydrogen would be produced and utilized during the year. Case Study 2 showed that a grid connected hydrogen plant powered 40 MW FPV array and a 2 MW wind turbine was able to sufficiently replace UCCs natural gas consumption of 14.7 GWh/yr. Case Study 3 showed that a 36 MW FPV array is necessary in order to produce enough hydrogen to supply Kawasakis LH_2 carrier with 1250 m^3 of LH_2 every other month.

Lastly, it was concluded that the feasibility of a FPV powered hydrogen plant is dependent on its application, as well as the location of the plant. At locations with great solar resources, it is more feasible. Whereas plants located at locations with limited solar output would need to connect to the grid or install other types of renewables, such as wind energy.

Further studies should investigate the cost aspect of a FPV powered hydrogen plant, investigate safety regulations at a more detailed level, and assess the impact of adding batteries to such a system.

10. References

[1] United Nations Climate Change, “What is the Paris Agreement?,” [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement. [Accessed 24 Januar 2020].

[2] IRENA, “Climate Change,” [Online]. Available: https://www.irena.org/climatechange. [Accessed 25 Januar 2020].

[3] R. Islam, N. K. Roy and S. Rahman, Renewable Energy and the Environment, Singapore: Springer Nature, 2018.

[4] Shell, “Shell hydrogen study: Energy of the future? Sustainable mobility through fuel cells and H2,” Shell Deutschland Oil GmbH, Hamburg, 2017.

[5] DNV GL, “Hydrogen as an energy carrier: An evaluation of emerging hydrogen value chains,” 2018.

[6] IRENA, “ Transforming the energy system – and holding the line on the rise of global temperatures,” International Renewable Energy Agency, Abu Dhabi, 2019.

[7] D. Friel, M. Karimirad, T. Whittaker, J. Doran and E. Howlin, “A review of floating photovoltaic design concepts and installed,” 4th International Conference on Offshore Renewable Energy, Glasgow, 2019.

[8] World Bank Group, ESMAP and SERIS, “Where Sun Meets Water: Floating Solar Marked Report,” World Bank, Washington, DC, 2019.

[9] E. Ture, “Hydrogen Production from Solar Energy,” *Assessment of Hydrogen Energy for Sustainable Development. NATO Science for Peace and Security Series C: Environmental Security,* pp. 135-146, 2007.

[10] F. Barbir, “PEM electrolysis for production of hydrogen from renewable energy sources,” *Solar Energy,* pp. 661-669, May 2005.

[11] S. E. Hosseini and M. A. Wahid, “Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development,” *Renewable and Sustainable Energy Reviews Vol.57,* pp. 850-866, May 2016.

[12] S. Dahbi, A. Aziz, A. Messaoudi, I. Mazozi, K. Kassmi and N. Benazzi, “Management of excess energy in a photovoltaic/grid system by production of clean hydrogen,” *International Journal of Hydrogen Energy, Vol. 43(10),* pp. 5283-5299, 8 March 2018.

[13] M. Fereidooni, A. Mostafaeipour, V. Kalantar and H. Goudarzi, “A comprehensive evaluation of hydrogen production from photovoltaic power station,” *Renewable and Sustainable Energy Reviews, Volume 82, Part 1,* pp. 415-423, 2018.

[14] Z. M. Omer, A. A. Fardoun and A. M. Alameri, “Economic Feasibility Study of Two Renewable Energy Systems for Remote Areas in UAE,” *Energy Procedia, Vol. 75,* pp. 3027-3035, 2015.

[15] M. Temiz and N. Javani, “Design and analysis of a combined floating photovoltaic system for electricity and hydrogen production,” *International Journal of Hydrogen Energy, Vol. 45, Issue 5,* pp. 3457-3469, 2019.

[16] B. G. Halvorsen, Interviewee, *PEM vs Alkaline Electrolysis.* [Interview]. 21 Mars 2020.

[17] Renewables.ninja. [Online]. Available: https://www.renewables.ninja/.

[18] National Aeronautics and Space Administration , "MERRA-2 Project," National Aeronautics and Space Administration , 2 January 2019. [Online]. Available: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/. [Accessed 23 May 2020].

[19] Katabatic Power, "Wind speed extrapolation," Katabatic Power, [Online]. Available: https://websites.pmc.ucsc.edu/~jnoble/wind/extrap/?fbclid=IwAR3Sc5t_tt4y-9N1FnltfZUWmkHAFWRjqRZp_GigLLtg18ifhTy-MjA2ptk. [Accessed 23 May 2020].

[20] S. Djohra, S. Hadji and M. Koussa, "ResearchGate," April 2014. [Online]. Available: https://www.researchgate.net/figure/Typical-surface-roughness-lengths_tbl1_316971044. [Accessed 19 May 2020].

[21] United Nations, "Global Issues Overview," [Online]. Available: https://www.un.org/en/sections/issues-depth/global-issues-overview/. [Accessed 5 May 2020].

[22] United Nations, "Ocean Fact Sheet Package," 2017. [Online]. Available: https://www.un.org/sustainabledevelopment/wp-content/uploads/2017/05/Ocean-fact-sheet-package.pdf. [Accessed 05 May 2020].

[23] Y.-K. Choi, N.-H. Lee and K.-J. Kim, "Empirical Research on the efficiency of Floating PV systems compared with Overland PV Systems," Proceedings, The 3rd International Conference on Circuits, Control, Communication, Electricity, Electronics, Energy, System, Signal and Simulation. Vol. 25, 2013.

[24] M. Rosa-Clot, G. M. Tina and S. Nizetic, "Floating photovoltaic plants and wastewater basins: an Australian project," Energy Procedia 134, 2017.

[25] H. Ritchie and M. Roser, "Land Use," ourworldindata.org, September 2019. [Online]. Available: https://ourworldindata.org/land-use. [Accessed 28 January 2020].

[26] T. Wang, "Net consumption of electricity wordwide from 1980 to 2017," Statista, 2020 March 2020. [Online]. Available: https://www.statista.com/statistics/280704/world-power-consumption/. [Accessed 23 May 2020].

[27] F. Vogler and G. Sattler, "Hydrogen-fueled marine transportation," in *Compendium of Hydrogen Energy*, Elsevier, 2016, pp. 35-65.

[28] ACIL Allen Consulting, "Opportunities for Australia from Hydrogen Exports," ARENA, 2018.

[29] Hydrogen Europe , "Hydrogen Basics," Hydrogen Europe, 2017. [Online]. Available: https://hydrogeneurope.eu/hydrogen-basics-0. [Accessed 16 April 2020].

[30] Energymag, "Round Trip Efficiency," Energymag, [Online]. Available: https://energymag.net/round-trip-efficiency/. [Accessed 23 May 2020].

[31] S. Damman, E. Sandberg, E. Rosengren, P. Pisciella and U. Johansen, "Largescale hydrogen production in Norway - possible transition pathways towards 2050," SINTEF, Trondheim, 2020.

[32] IRENA, "Hydrogen: A renewable energy perspective," International Renewable Energy Agency, Abu Dhabi, 2019.

[33] IEA, "The Future of Hydrogen," IEA, Paris, 2019.

[34] DNV GL, "Produksjon og bruk av hydrogen i Norge," Klima- og miljødepartementet og Olje- og energidepartementet, Oslo, 2019.

[35] S. Hocevar and W. Summers, Hydrogen Technology: Mobile and Portable Applications, Berlin: Springer Berlin Heidelberg , 2008.

[36] A. J. Godula and D. Stolten, "PEM Water Electrolysis," in *Hydrogen Production: By Electrolysis*, John Wiley & Sons, Incorporated , 2015, pp. 63-76.

[37] A. J. Godula and D. Solten, "Alkaline Water Electrolysis," in *Hydrogen Production: By Electrolysis*, John Wiley & Sons, Incorporated, 2015, pp. 117-128.

[38] H. Dagdougui, R. Sacile , C. Bersani and A. Oummi, "Chapter 7- Hydrogen Logistics: Safety and Risk Issues," in *Hydrogen Infrastructure for Energy Applications*, Academic Press, 2018, pp. 127-148.

[39] J. Z. Zhang, J. Li, Y. Li and Y. Zhao, "Established Methodes Based on Compression and Cryogenics," in *Hydrogen Generation, Storage and Utilzation*, John Wiley & Sons, Incorporated, 2014, pp. 75-84.

[40] Hydrogen Europe, "Hydrogen Storage," Hydrogen Europe, [Online]. Available: https://www.hydrogeneurope.eu/hydrogen-storage. [Accessed 16 April 2020].

[41] Norsk Hydrogen Forum, "Brenselcella - utslipp: ren vanndamp," Norsk Hydrogen Forum, [Online]. Available: https://www.hydrogen.no/fordeler/brenselcella-utslippet-ren-damp. [Accessed 16 April 2020].

[42] Hydrogen Council, "Path to hydrogen competitiveness: A cost perspective," 2020.

[43] N. M. CleanTech, "Norwegian future value chains for liquid hydrogen," Stord, 2019.

[44] NEL ASA, "Nel ASA: Establishes joint venture to supply green hydrogen to Hyundai trucks in Norway," 20 December 2019. [Online]. Available: https://news.cision.com/nel-asa/r/nel-asa--establishes-joint-venture-to-supply-green-hydrogen-to-hyundai-trucks-in-norway,c2996152. [Accessed 28 March 2020].

[45] BKK, "PILOT-E midler for å utvikle en forsyningskjede for flytende hydrogen til skip," 13 December 2019. [Online]. Available: https://gamle.bkk.no/vannkraft/utvikler-forsyningskjede-for-flytende-hydrogen. [Accessed 28 March 2020].

[46] NCE Maritime CleanTech, "Major project to convert offshore vessel to run on ammonia-powered fuel cell," 23 January 2020. [Online]. Available: https://maritimecleantech.no/2020/01/23/major-project-to-convert-offshore-vessel-to-run-on-ammonia-powered-fuel-cell/. [Accessed 28 March 2020].

[47] plugboats.com, "Revolutionary fuel cell powered cruise ship for Norway fjords," 4 February 2020. [Online]. Available: https://plugboats.com/revolutionary-fuel-cell-powered-cruise-ship-norway/. [Accessed 29 March 2020].

[48] SEAI, "Energy in Ireland," 2019.

[49] SEAI, "Renewable Energy in Ireland," [Online]. Available: https://www.seai.ie/data-and-insights/seai-statistics/key-publications/renewable-energy-in-ireland/. [Accessed 15 May 2020].

[50] Hydrogen Ireland, "Hydrogen in Ireland," [Online]. Available: http://hydrogenireland.org/hydrogen-in-ireland/. [Accessed 31 March 2020].

[51] Hydrogen Mobility Ireland, "A Hydrogen Roadmap for Irish Transport, 2020-2030," Hydrogen Mobility Ireland, 2019.

[52] COAG Energy Council, “Australia's National Hydrogen Strategy,” Commonwealth of Australia, 2019.

[53] BOC Limited, “Queensland-first renewable hydrogen project commences at BOC production facility in Bulwer Island.,” 23 August 2019. [Online]. Available: https://www.boc-limited.com.au/en/news_and_media/press_releases/news_20190819.html. [Accessed 16 April 2020].

[54] I. Staffell, D. Scamman, A. V. Abad, P. Balcome, P. E. Dodds, P. Ekins, N. Shah and K. R. Ward, “The role of hydrogen and fuel cells in the global energy system,” Energy Environ. Sci., 12, 463, 2019.

[55] Gas Networks Ireland, “Vision 2050 - A Net Zero Carbon Gas Network for Ireland,” Ervia, 2019.

[56] T. A. Gunawan, A. Singlitico, P. Blount, J. Burchill, J. Carton and R. Monaghan, “At What Cost Can Renewable Hydrogen Offset Fossil Fuel Use in Ireland’s Gas Network?,” Energies 13(7): 1798, 2020.

[57] A. Vega and S. Hynes, “Ireland’s ocean economy,” 2017.

[58] T. Strømgren, Interviewee, *Hydrogen Based Zero Emission Project.* [Interview]. 5 February 2020.

[59] Norsk Klimaservicesener, “Observations,” Norsk Klimaservicesenter, 10 Mars 2020. [Online]. Available: https://klimaservicesenter.no/observations/. [Accessed 10 Mars 2020].

[60] Justis- og beredskapsdepartementet, “Storulykkeforskriften,” Justis- og beredskapsdepartementet, 2016. [Online]. Available: https://lovdata.no/dokument/SF/forskrift/2016-06-03-569#KAPITTEL_2. [Accessed 5 May 2020].

[61] Norges vass- og energidirektorat , “NVE.no,” Norges vass- og energidirektorat , [Online]. Available: https://lovdata.no/dokument/NL/lov/1990-06-29-50#KAPITTEL_1. [Accessed 30 Mars 2020].

[62] J. Burdg, “Articles,” Labconco, 8 December 2015. [Online]. Available: https://www.labconco.com/articles/water-type-difference. [Accessed 20 April 2020].

[63] Gas Networks Ireland , “Overview of Irish gas Market,” Gas Networks Ireland, [Online]. Available: https://www.gasnetworks.ie/corporate/company/our-network/irish-gas-market-overview/. [Accessed 16 May 2020].

[64] University College Cork, 2019. [Online]. Available: https://greencampus.ucc.ie/wp-content/uploads/2020/03/UCC-Energy-review-2018_19-1.pdf. [Accessed 3 May 2020].

[65] Met Éireann, “Historical data,” Irish Meterological Service , [Online]. Available: https://www.met.ie/climate/available-data/historical-data. [Accessed 28 April 2020].

[66] L. Bauer and S. Matysik, “Turbines,” Wind-turbine-models.com, 14 July 2017. [Online]. Available: https://en.wind-turbine-models.com/turbines/16-vestas-v90#datasheet. [Accessed 3 May 2020].

[67] Kawasaki Heavy Industries, Ltd., *Hydrogen Energy Supply Chain from Australia to Japan,* Kawasaki, 2019.

[68] Linde, *Liquid Hydrogen Distribution Technology,* Brussels: https://www.sintef.no/globalassets/project/hyper/presentations-day-2/day2_1105_decker_liquid-hydrogen-distribution-

technology_linde.pdf?fbclid=IwAR183B9XUorQyxTKysqnMYwkIQtxf1DRsiGS8HT9-wX1IeJ0qN1G7pFSSWs, 2019.

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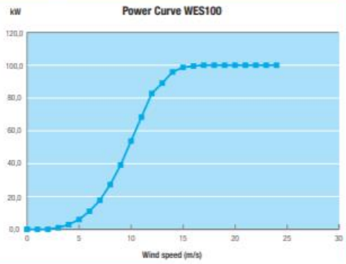
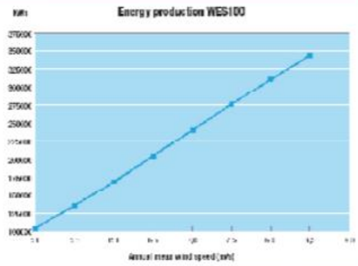
Attachment 1

TECHNICAL SPECIFICATIONS

Wind speed (m/s)	Power kW
0	0,0
1	0,0
2	0,0
3	1,0
4	2,9
5	6,0
6	11,0
7	17,7
8	27,3
9	39,2
10	53,8
11	68,4
12	82,8
13	89,1
14	95,9
15	98,7
16	99,5
17	100,0
18	100,0
19	100,0
20	100,0
21	100,0
22	100,0
23	100,0
24	100,0



Annual mean wind speed (m/s)	Energy annual kWh
5,0	104000
5,5	135500
6,0	169000
6,5	204500
7,0	240500
7,5	276000
8,0	310500
8,5	343500



GENERAL

Life expectancy:	Minimum 20 years
Rated power:	100 kW
Cut in Wind speed:	< 3 m/s (6.7mph)
Cut out Wind speed:	25 m/s (56mph)
Rated wind speed:	13 m/s (28mph)
Survival wind speed:	60 m/s (134mph)
Wind class:	II
Yawing:	Active
Passive power regulation:	Blade-angle adjustment
Active power regulation:	Fully variable back-to-back IGBT system
Towers heights:	18 m, 24 m, 30 m (31 m lattice)
Number of blades:	2
Rotor diameter:	18 m
Noise emission at 8 m/s:	45 dB(a) at 100 m
Operating temperatures:	from -20°C up to + 40°C

ELECTRICAL

Power:	100 kW
Voltage:	400V/50Hz 3 phase + neutral or 400V/60Hz 3 phase + neutral
Connection:	grid connected / Hybrid
Converter:	back-to-back inverter (IGBT)

MATERIAL SPECIFICATIONS

Blades:	carbon and glass fibre reinforced epoxy
Nacelle:	steel
Cover:	polyester
Tower:	steel (hot dip galvanized)
Foundation:	concrete block with anchor

Attachment 2

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PROTON® PEM

C Series

Hydrogen Generation Systems

MODEL	C10	C20	C30
Description	On-site hydrogen generator in two integrated, automated, site-ready enclosures Dual-mode Operation (Selectable): • Load Following mode automatically adjusts output 0-100% to match demand • Tank Filling mode operates with power-conservation mode during standby Full differential pressure, H_2 over O_2		
Electrolyte	Proton Exchange Membrane (PEM) – Caustic-Free		
HYDROGEN PRODUCTION			
Nominal Production Rate Nm^3/h @ 0°C, 1 bar SCF/h @ 70°F, 1 atm SLPM @ 70°F, 1 atm kg/24 h	10 Nm^3/h 380 SCF/h 179 SLPM 21.6 kg/24 h	20 Nm^3/h 760 SCF/h 359 SLPM 43.3 kg/24 h	30 Nm^3/h 1,140 SCF/h 538 SLPM 65.0 kg/24 h
Delivery Pressure – Nominal	30 barg (435 psig)		
Power Consumption by System per Volume of H_2 Gas Produced[1]	6.2 kWh/Nm^3 (16.3 $kWh/100\ ft^3$)	6.0 kWh/Nm^3 (15.8 $kWh/100\ ft^3$)	5.8 kWh/Nm^3 (15.2 $kWh/100\ ft^3$)
Power Consumed per Mass of H_2 Gas Produced[1]	68.9 kWh/kg	66.7 kWh/kg	64.5 kWh/kg
Purity (Concentration of Impurities)	ISO 14687-1 Type 1 grade C ISO 14687-2 Type 1 grade D 99.9998% [H_2O < 2 ppm, -72°C (-98°F) Dew Point, N_2 < 2 ppm, O_2 < 1 ppm, all others undetectable]		
Turndown Range	0-100% net product delivery (automatic)		
Upgradeability	Field upgradeable to a maximum of 30 Nm^3/h (1,140 SCF/h)		N/A

Attachment 3

DI WATER REQUIREMENT			
Consumption Rate at Maximum Production	9 L/h (2.4 gal/h)	17.9 L/h (4.7 gal/h)	26.9 L/h (7.1 gal/h)
Temperature	5-40°C (41-104°F)		
Pressure	1.0-4.1 barg (10-60 psig)		
Input Water Quality	Required: ASTM Type II Deionized Water, < 1 µS/cm (> 1 MΩ-cm) Preferred: ASTM Type I Deionized Water, < 0.1 µS/cm (> 10 MΩ-cm)		
HEAT LOAD AND COOLANT REQUIREMENT			
Coolant[2]	Liquid cooled; non-freezing, non-fouling; 5-35°C (41-95°F)		
Maximum Heat Load (Cooling Requirement)	32 kW (109,189- BTU/h) (9.1 tons refrigeration)	64 kW (218,377 BTU/h) (18.2 tons refrigeration)	96 kW (327,566 BTU/h) (27.3 tons refrigeration)
Coolant Flowrate	Up to 92 L/min (24.3 gal/min)	Up to 144 L/min (38 gal/min)	Up to 200 L/min (52.8 gal/min)
Pressure Drop (at Full Flow)	Up to ~1.1 barg (~14.5 psig)	Up to ~1.1 barg (~14.5 psig)	Up to ~1.1 barg (~14.5 psig)
ELECTRICAL SPECIFICATIONS			
Maxium Power Required within Expected System Life	85 kVA	160 kVA	236 kVA
Electrical Requirements	380,400,415 VAC, three phase, 50 Hz (+/- 10% from nominal voltage) 480 VAC, three phase, 60 Hz (+/- 10% from nominal voltage)		

Attachment 4

PHYSICAL CHARACTERISTICS				
Dimensions W x D x H	Product Est. Shipping	Electrolyzer Enclosure: 252 cm x 116 cm x 201 cm (99" x 46" x 79") Power Supply Enclosure: 169 cm x 103 cm x 201 cm (67" x 41" x 79") Electrolyzer Enclosure: 269 cm x 122 cm x 225 cm (106" x 48" x 89") Power Supply Enclosure: 269 cm x 122 cm x 225 cm (106" x 48" x 89")		
Weight	Product Est. Shipping	2,734 kg (6,026 lbs) 2,876 kg (6,340 lbs)	2,924 kg (6,446 lbs) 3,089 kg (6,810 lbs)	3,076 kg (6,781 lbs) 3,241 kg (7,145 lbs)
IP Rating		Overall unit rating of IP56		
ENVIRONMENTAL CONSIDERATIONS – DO NOT FREEZE				
Standard Siting Location		Indoor/sheltered; level ±1°, 0-100% RH non-condensing, non-hazardous/non-classified environment		
Storage/Transport Temperature		5-60°C (41-140°F)		
Ambient Temperature Range		5-40°C (41-104°F)		
Altitude Range – Sea Level		2,000 m (6,562 ft)		
Ventilation		Proper ventilation must be provided from a non-hazardous area, at a rate in accordance with IEC60079-10, Zone 2 NE		
SAFETY AND REGULATORY CONFORMITY				
Maximum On-board H_2 Inventory at Full Production		0.13 Nm^3 4.9 SCF 0.011 kg	0.17 Nm^3 6.4 SCF 0.015 kg	0.18 Nm^3 7 SCF 0.016 kg
Cabinet Ventilation with Environment		Vent fan draws fresh air up to 8.5 Nm^3/min (300 ft^3/min)		
Noise dB(A) at 1 Meter		< 75		
Conformity		cTUVus (UL and CSA equivalent), CE (PED, Mach. Dir., EMC), ISO22734-1		
OPTIONS				
• Factory matched RO/DI water system • Factory matched cooler/chiller		• Low ambient temperature package (-10°C to 40°C)	• High ambient temperature package (5°C to 50°C)	• Dew point monitoring • Equipment orientation

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Specifications are subject to change. Please contact Nel Hydrogen for solutions to best fit your needs.

1. Dependent on configuration and operating conditions.
2. Consult Nel Hydrogen Applications Engineering Department for specific requirements and cooling water temperatures other than 35°C.

www.nelhydrogen.com | +1.203.949.8697 | info@nelhydrogen.com MADE IN USA

ISO 22734-1 · ANAB Certified to ISO 9001:2015 · TÜV Rheinland · CE

 PD-0600-0068 Rev G

Attachment 5

X-STORE® GAS CONTAINER MODULES, VERSION ADR V2

FULL CARBON DESIGN, 300 BAR, H_2

HEXAGON

		X-STORE 10 ft	X-STORE 20 ft	X-STORE 30 ft	X-STORE 40 ft	X-STORE 45 ft
Approval	Cylinders	According to ISO 11119-3 / EN 12245				
	System	ADR approved and leak tested according to DIN EN 1779				
	Container	According to ISO 668 including CSC approval				According to CSC
	Corner castings	According to ISO 668				
Hydraulic capacity, approx.	l	8,400	18,900	29,400	39,900	45,150
Nominal transport capacity H_2 (15 °C) [1]	m^3	2,100	4,720	7,345	9,965	11,280
Container (length x width x height)	mm	3,048 x 2,438 x 2,743	6,058 x 2,438 x 2,743	9,087 x 2,438 x 2,743	12,192 x 2,438 x 2,743	13,176 x 2,438 x 2,743
Net weight container, approx. [2]	kg	4,695	9,700	14,610	19,365	21,800
Gas weight H_2 (D=0.084 kg/m^3) [1]	kg	175	395	615	835	950
Total container weight + H_2 [1] [2]	kg	4,870	10,095	15,225	20,200	22,750
Quantity cylinders, 350 l	pcs	24	54	84	114	129
Minimum residual pressure (15 °C)	MPa (bar)	1 (10)				
Operating pressure (15 °C)	MPa (bar)	30 (300)				
Burst pressure, min.	MPa (bar)	90 (900)				
Cylinder operating temperature min./max.	°C	-40 / +65				
Cylinder type		Type 4				
Cylinder marking		TC_500_5				
Cylinder design		Full carbon				
Cylinder liner material		High density polyethylene (HDPE)				
Service lifetime		Unlimited				
Inspection standard		ISO 11623				

1) The filling process underlies the complex physical laws of fluid mechanics. The actual filling volume depends on several factors: chemical composition of gas, ambient temperature, filling speed and inlet temperature which in turn, depend on the equipment of the compressor station (compressors, chillers, piping, valves and fittings). Therefore an exact statement about the real filling volume cannot be given. Typically filling efficiencies of 75-95% are reached.

2) +1 % tolerance due to manufacturing reasons

Metric unit system

CONTACT US:

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Otto-Hahn-Straße 5
34123 Kassel, Germany
Phone +49 561 58549 0
contact.purus@hexagongroup.com
www.hexagongroup.com

Attachment 6

KV

Kenneth Våge <kenneth@norwater.no>
må. 16.03.2020 11:28
Til: Sindre Sandøy <571995@stud.hvl.no>

Hei Sindre
Typisk kraftbehov for å produsere drikkevannskvalitet fra sjøvann i en slik «minityrskala» (0,2m³/dag)
vil være i størrelsesorden 5-6 kWh/m³
Dersom vannet skal behandles ytterligere til teknisk vann av en renere kvalitet enn drikkevann vil
det kunne være behov for ytterligere helt marginale kraftbehov.

Best regards / Med vennlig hilsen
NORWATER AS

KennethVåge
Technical Manager

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Mob +47 40 40 35 23
Email: kenneth@norwater.no
Web: norwater.no

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