Techno-economic assessment of key hydrogen production and distribution technologies in Western Norway

NAHID ZOUBIN

MASTER OF SCIENCE IN CLIMATE CHANGE MANAGEMENT

FACULTY OF ENGINEERING AND SCIENCE
DEPARTMENT OF ENVIRONMENTAL SCIENCE

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Supervisory Team

Main Supervisor: DEJENE ASSEFA HAGOS (PHD)
Co-Supervisor: NEGAR SAFARA NOSAR

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Sammendrag

Industri- og transportsektoren er hovedkildene til CO_2-utslipp i Norge. Disse sektorene er vanskelige å av karbonisere gjennom direkte elektrifisering, hovedsakelig på grunn av teknologiske begrensninger, og utgjør en stor utfordring mot energi- og klimamålene for 2050. I tråd med det klimamålet til den norske regjeringen om å redusere klimagassutslippene med 55% i 2030 og 95% i 2050 sammenlignet med 1990-nivået, er det en økende politisk interesse for dyp de karbonisering av industri og transport ved bruk av hydrogen. For å nå dette målet er det viktig å identifisere de billigste produksjons- og distribusjonsmetodene for hydrogen i Norge. For tiden produseres hydrogen i Norge hovedsakelig fra naturgass med dampreformeringsteknologi, men potensielt kan hydrogen produseres fra flere fornybare energikilder. Det er viktig å sammenligne ulike hydrogenproduksjons- og distribusjonsteknologier for å identifisere de billigste løsningene og nøkkel parameterne som påvirker kostnadsestimatet. I denne oppgaven utvikles og sammenlignes konvensjonelle reformatorer og elektrolysebaserte hydrogenproduksjons- og distribusjonsveier for Vestlandet. Produksjonsanleggene er klassifisert i sentrale og distribuerte anlegg basert på den daglige produksjonskapasiteten. De antatte sentrale hydrogenproduksjons- og distribusjonsteknologiene som er relevante i Vest-Norge-sammenheng er polymerelektrolyttmembran (PEM) elektrolyse, "Solid Oxide Electrolysis (SOEC)", "Steam Methane Reforming

(SMR)", og "Auto-thermal Reforming med CCS (ATR-CCS)" teknologier brukes i et sentralt og distribuert anlegg.

Veiene er avhengig av hydrogenproduksjonsteknologiene, anleggskonfigurasjonen og typen distribusjonsteknologi som brukes. Kostnadsestimatet er gjort ved hjelp av en excel-basert modell utviklet ved "National Renewable Energy Laboratory" (NREL). Resultatet viser at SMR-veien er den billigste hydrogenproduksjons- og distribusjonsveien med 25,63 Kr/kg. Sammenlignet med SMR koster ATR med CCS-vei mer enn det dobbelte med 56,63 Kr/kg. Dette skyldes først og fremst de ekstra investeringskostnadene til CCS og det høye forbruket av råstoff (naturgass) sammenlignet med SMR. De sentrale PEM-elektrolysebaserte banene viser generelt en høyere hydrogenkostnad sammenlignet med SMR, men mindre enn for ATR med CCS-vei. Hydrogenkostnaden avhenger av kilden til elektrisiteten, både når det gjelder kostnad og tilgjengelighet av elektrisitet. Sentralnettet PEM viser 50,93 Kr/kg, havvind, 59,13 Kr/kg, landvind 39,13 Kr/kg, og solenergi PV 75,33 Kr/kg. Sammenlignet med alle elektrolysebaserte veier gir nettet PEM lavere hydrogenkostnader. Dette skyldes først og fremst den høyere årlige tilgjengeligheten av elektrisitet og dermed bedre anleggskapasitetsutnyttelse av PEM-elektrolysatoren. De høyere hydrogenkostnadene til de fornybarbaserte elektrisitetsveiene skyldes dermed deres intermitterende natur og dermed lavere kapasitetsutnyttelse av PEM-anlegget i deres respektive traseer. Sammenligning av alle PEM-elektrolysørveiene, har landvind, nett-PEM, offshore-vind-PEM og solenergi-PEM de lavere kostnadene for hydrogenproduksjon i økende rekkefølge.

Sammenlignet med de respektive sentrale PEM-banene, viser de distribuerte banene en høyere produksjonskostnad for hydrogen på grunn av de dårlige stordriftsfordelene. Ikke desto mindre blir denne fordelen med sentrale PEM-

veier oppveid av transportkostnadene for hydrogen til industrier og bensinstasjoner. På grunn av denne effekten viser de distribuerte banene en lavere total hydrogenkostnad enn deres respektive sentrale PEM-veier. De sentrale SOEC-passerte banene viser generelt en høyere hydrogenkostnad sammenlignet med deres respektive sentrale PEM-baserte veier. Dette skyldes først og fremst de høyere investeringskostnadene og årlige utskiftingskostnadene til stabelen. Avhandlingen hadde også nytte av sensitivitetsanalyse for ulike teknoøkonomiske nøkkelparametere Elektrisitetsbruk, strømpris og anleggskapasitetsutnyttelsesfaktor er nøkkel faktorer som påvirker hydrogenproduksjonskostnadene for elektrolysebaserte teknologier mens naturgassbruk og pris er funnet å være sensitive faktorer for de reformatorbaserte banene. Det er viktig å nevne at resultatene er sensitive for de antatte teknoøkonomiske parameterne. De antatte Faktorene for hydrogenproduksjonsteknologiene reflekterer bare de beste estimatene for øyeblikket og tar ikke hensyn til den fremtidige utviklingen av kostnadene. Det bør derfor bemerkes at betydelig endring i disse kostnadene vil ha en betydelig innvirkning på resultatene.

Abstract

The industry and transportation sectors are the main sources of CO_2 emissions in Norway. These sectors are difficult to be decarbonized through direct electrification, mainly due to technological limitations, and pose major challenge towards the 2050 energy and climate targets. In line with the enhanced climate goal of the Norwegian government to reduce GHG emissions by 55% in 2030 and 95% in 2050 compared to 1990 level, there is a growing political interest for deep decarbonisation of industry and transportation using hydrogen. Towards achieving this goal, it is important to identify the least-cost hydrogen production and distribution methods in Norway.

Currently, hydrogen is being produced in Norway mainly from natural gas with steam reforming technology. But potentially hydrogen could be produced from several renewable energy sources. It is important to compare various hydrogen production and distribution hydrogen technologies to identify the least-cost solutions and the key parameters that affect the cost estimation. Thus in this thesis conventional reformer and electrolysis-based hydrogen production and distribution pathways are developed and compared for Western Norway. The production plants are classified into central and distributed plants based on the daily production capacity. The assumed key hydrogen production and distribution technologies that are relevant in the context of Western Norway are: the polymer electrolyte membrane (PEM) electrolysis, Solid Oxide Electrolysis (SOEC), Steam Methane Reforming (SMR), and Autothermal Reforming with CCS (ATR-CCS) technologies are used in a central and distributed plants. The pathways are dependent on the hydrogen production technologies, the plant configuration, and type of distribution technologies used. The cost estimation is done using an excel-based model developed at the National Renewable Energy Laboratory (NREL).

The result shows that the SMR pathway is the least-cost hydrogen production and distribution pathway with 25.63 kr/kg. Compared to SMR, the ATR with CCS pathway costs more than double with 56.63 kr/kg. This is primarly due to the added investment cost of CCS and the high feedstock (natural gas) consumption compared to the SMR.

The central PEM electrolysis-based pathways, in general, shows a higher hydrogen cost compered to SMR but less than that of ATR with CCS pathway. The hydrogen cost depends on the source of the electricity, both in terms of cost and availability of electricity. The central grid PEM shows 50.93 kr/kg, offshore wind, 59.13 kr/kg, onshore wind 39.13 kr/kg, and solar PV 75.33 kr/kg. Compared to all electrolysis based pathways the grid PEM results in lower hydrogen cost. This is primarly due to the higher annual availability of electricity and hence better plant capacity utilisation of the PEM electrolyser. The higher hydrogen costs of the renewable-based electricity pathways are thus due to their intermittent nature and hence lower capacity utilisation of the PEM plant in their respective pathways. Comparing all the PEM electrolyser pathways, onshore wind, grid PEM, offshore wind PEM, and solar PEM have the lower cost of hydrogen production in the increasing order.

Compared to the respective central PEM pathways, the distributed pathways shows a higher hydrogen production cost due to the poor economies of scale. Nevertheless, that advantage of central PEM pathways is offset by the transportation costs of hydrogen to industries and refuelling stations. Due to this effect the distributed pathways shows a lower total hydrogen cost than their respective central PEM pathways.

The central SOEC passed pathways in general shows a higher hydrogen cost compared to their respective central PEM based pathways. This is primarly due to the higher investment costs and annual replacement costs of the stack. The lower capacity utilisation in solar PV

The thesis also benefited from sensitivity analysis for various key techno-economic parameters The electricity use, electricity price, and plant capacity utilisation factor are the key parameters that influences the hydrogen production costs for electrolyser-based technologies while natural gas use and price are found to be sensitive parameters for the reformer-based pathways.

It is important to mention that the results are sensitive to the assumed techno-economic parameters. The assume parameters of the hydrogen production technologies reflect only the current best estimates and does not consider the future developments of the costs. Therefore, it should be noted that significant change in these costs will have a significant impact on the results.

Preface

This master's thesis is written at the Department of Environmental Science, HVL, Sogndal for the completion of the master of science degree in climate change management.

The main objective of this thesis is to evaluate the levelized cost of hydrogen production and distribution of the most relevant technologies and hydrogen sources in Western Norway. It includes steam reformer and electrolyser technologies, central and distributed hydrogen production plants, and hydrogen distribution to industries and refuelling stations. The thesis also includes the development of specific hydrogen supply pathways that are suitable for Western Norway.

The guidance and support I received from my supervisors, Dejene Assefa Hagos & Negar Safara, have been invaluable. Your support helped me to overcome all the challenges that I have faced and learn a lot, for which I am grateful. I also would like to thank my family for all their support. My appreciation also goes out to my reader as well. I hope you enjoy my writing.

I confirm that the work is self-prepared and that references/source references to all sources used in the work are provided, cf. Regulation relating to academic studies and examinations at the Western Norway University of Applied Sciences (HVL), § 12-1.

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Nomenclature

ATR	Autothermal Reformer
CO_2	Carbon dioxide
CCS	Carbon Capture and Storage
H2A-Lite	Hydrogen Analysis Lite Production Model
kWh	Kilowatt hour
LCOE	Levelised Cost of Energy
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
PEM	Proton Exchange Membrane
SOEC	Solid Oxide Electrolysis Cell
NFPA	The National Fire Protection Association

1 Introduction

1.1 Background

The industry and transportation sectors global CO_2 emissions has significantly increased in between 2000 and 2018; industry increased by 60% and transport by 32% [9]. These sectors are difficult to be decarbonized though direct electrification, mainly due to technological limitations, and pose major challenge towards the 2050 energy and climate targets. For the same period, the industry emissions in Norway however reduced by 22% and the transport emissions kept stable or slightly increased by 6% [2]. Owing to the hydro-dominated power sector in Norway, the industry and transportation are the main sources of emissions in Norway. In line with the enhanced climate goal of the Norwegian government to reduce GHG emissions by 55% in 2030 and 95% in 2050 compared to 1990 level [10], there is a growing political interest for deep decarbonisation of industry and transportation using hydrogen and biofuels.

To reach near zero carbon by 2050, all buildings and homes in the world will need low-carbon heating solutions. Five substantial choices have been suggested for decarbonizing heat at the world scale including demand reduction, green gas, electrification, heat networks, and onsite renewables [11]. Hydrogen and fuel cell technologies were not included in most energy systems and building stock models until recently. Space heating, water heating, and gas cooking can be performed with hydrogen instead of natural gas. There are safety standards in place for industrial processes that use hydrogen due to its physical and chemical properties. As a fuel for buildings, hydrogen presents a variety of risks, but there is very little knowledge about them [12]. Although electrification is not currently cost-competitive with heating oil, propane, or natural gas in many areas, for low-grade heat, it is unlikely that hydrogen will ever be more cost-effective than electrification in the long run.

Fig. 1.1 presents the global demand for pure hydrogen between 1975 and 2018. Globally hydrogen is currently being used in industry mainly for oil refining, ammonia production, & methanol production. The oil refinery uses hydrogen to reduce the sulphur content of the diesel fuel. Fossil fuels are the main sources of the hydrogen production and is responsible for more than 830 million tonnes of CO_2 emissions per year. The natural gas contributes for 75% of the global hydrogen production and accounts for nearly 6% of global natural gas production. The remaining hydrogen is supplied mostly from coal and accounts for 2% of global coal production.

In Europe almost 90% of the hydrogen is being produced from natural gas using the steam reformer technology. This technology is the most matured and least-cost hydrogen production method. Recently, however, hydrogen production using electrolysis has shown a big interest in Europe mainly for (1) decarbonising the industry and transportation, and (2) integrating excess electricity from variable renewable energy sources into the energy system such as wind and solar via hydrogen. It is also used to upgrade biogas (50-65% methane) into renewable natural gas or biomethane (98% methane), to produce synthetic fuels such as gasoline/diesel/kerosene/methanol. The fuels produced in electrolysis, methanation, and synthesis are usually called electro fuels or e-fuels.

In Norway, currently 225 ktonnes of hydrogen is being produced and 80% is produced from natural gas and the rest 20% mainly as by product of petroleum production. And more than 80% is used for ammonia and methanol production in chemical industry, the rest used in oil refineries for desulfurization of the diesel fuel. The hydrogen demand in transportation in Norway is currently almost null, but it is forecasted to significantly increases by 2030 next to industry demand (ammonia and methanol) as shown in Fig. 1.2. Green hydrogen has several advantages in a fossil fuel dominated energy system. In the context of Norway, however, the role of hydrogen is seen to play a significant role both for deep decarbonisation and introducing flexibility into the energy system.

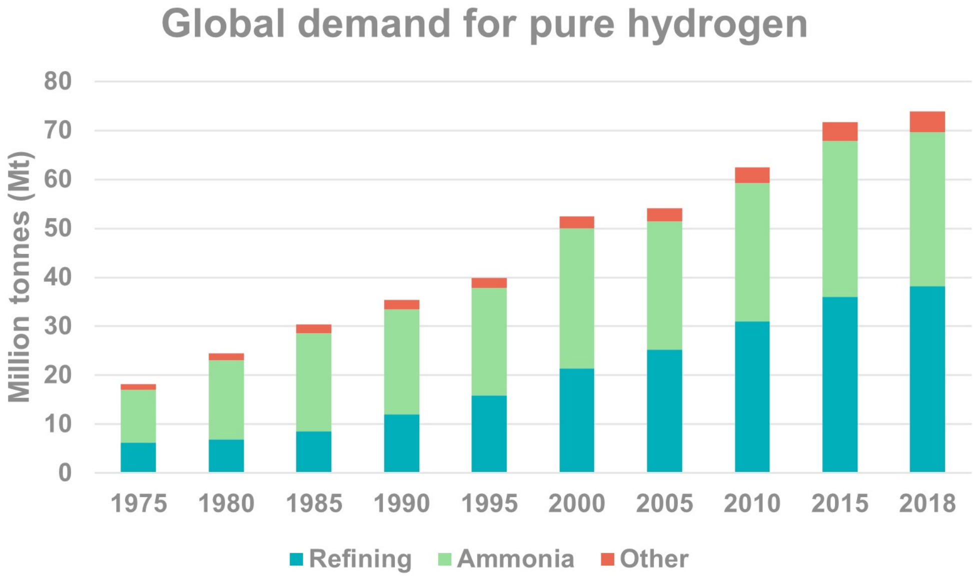

Figure 1.1: Global demand for pure hydrogen [1]

When it comes to the differentiating the source of hydrogen production, the industry uses colour coding. These are: (1) hydrogen produced from fossil fuels using gasification process is called black/brown hydrogen (example: coal in gasification), and it has a very high GHG emissions during hydrogen production, (2) hydrogen from fossil fuels using steam reformer is called grey hydrogen (example: natural gas in steam reformer), and it has a lower GHG emissions compared to black/brown hydrogen, (3) hydrogen from fossil fuels using steam reformer but with carbon capture and storage is called blue hydrogen (example: natural gas in steam reformer with CCS), and it has a lower GHG emissions compared to grey hydrogen, (4) hydrogen from renewable energy sources is called green hydrogen, and it has a lower GHG emissions compared to blue hydrogen.

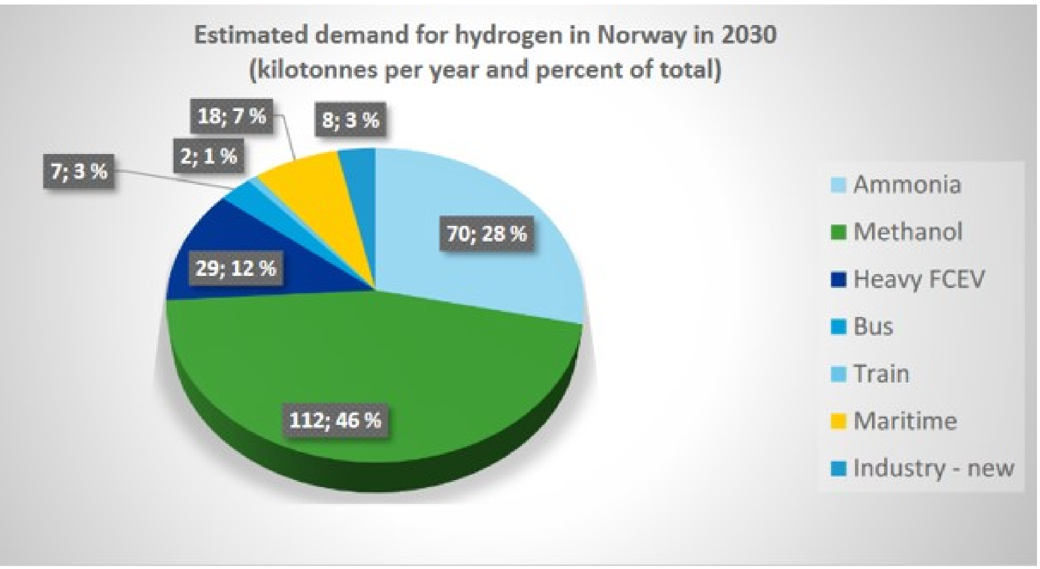

Figure 1.2: Hydrogen demand forecast in Norway by 2030. [1]

The industry uses hydrogen primarily for oil refining, ammonia production, methanol production, and steel production. Thus to move towards a net zero emission society, hydrogen can act more than a chemical feedstock for ammonia production or oil refining [13]. For instance, hydrogen could be burnt instead of oil or gas to produce heat, or hydrogen and ammonia can be alternatives for natural gas in upgraded gas turbines [13]. The role of hydrogen in this structural change can result in massive changes in economy and energy and power market perspective also..

1.2 The Norwegian Energy System

1.2.1 Current Status

The Norwegian energy system is dominated by hydropower originating electricity. Fig. 1.3 presents the total energy use in Norway. Electricity is the main energy commodity used both for heating and electricity-specific appliances. The use of fossil fuels for heating is very low or negligible in residential and commercial sectors. Fossil fuels for heating is mainly used in industry as shown in Fig. 1.4. District heating is at infant stage, but it is increasing recently. The low share of district heating is due to the low population density and wide use of direct electric heaters that hampers the penetration of waterborne heating systems. The renewable share in total energy consumption is 74.5% by 2019 [2], the remaining 25% is mainly due to fossil fuel use in industry and transportation. As shown in Fig. 1.3, the total energy consumption between 2010 and 2018 is relatively constant, this is mainly due to the improved energy efficiency of buildings and phasing out of fossil fuels that offsets the increase in demand due to population growth and construction of new buildings.

The electricity sector is dominated by hydropower with more than 93% share in total electricity production in Norway. There exist also thermal power plants used mainly as a backup or reserve capacity and onshore wind power

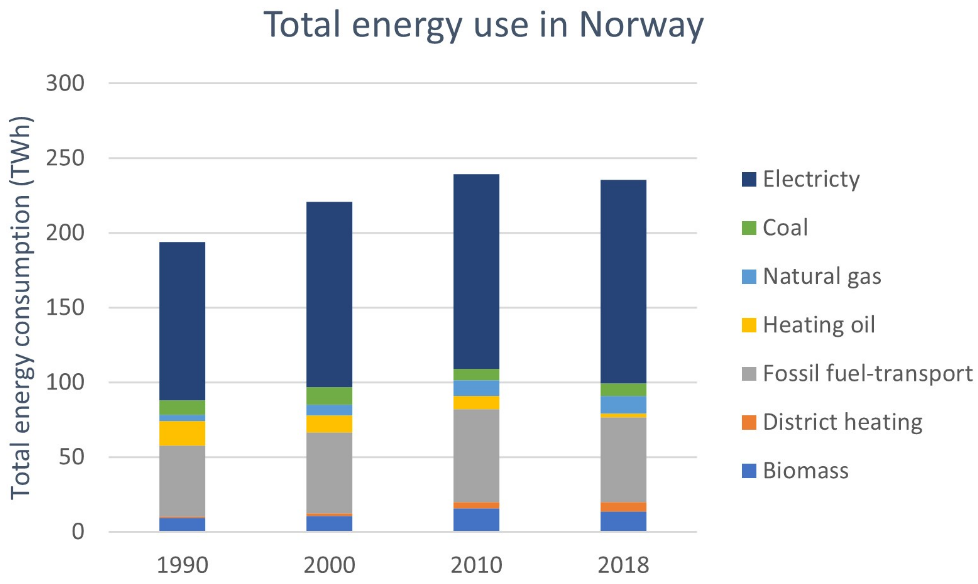

Figure 1.3: Total energy use in Norway between 1990 and 2018. [2]

is growing recently. There is a big interest in developing offshore wind power in Norway. Grid connected solar PV is growing rapidly in the last 5 years but the share in total electricity production is negligible. Norway also imports electricity via the Nordpool electricity market when the precipitation /rain fall is low specifically during winter period and exports a large amount when the precipitation /rain fall is high during summer. The maximum installed hydro capacity is 32.8 GW (1143 stations), wind turbine 2.9 GW (46 stations), and thermal power plant 1.1 GW (33 stations) in 2019. In 2021, wind turbine installed capacity has increased to 4.1 GW (56 stations and 1194 turbines). The total hydro reservoir capacity in Norway is about 87.2 TWh.

As shown in Fig. 1.5, in road transportation diesel is the main transport fuel. This is due to the promotion of diesel instead of petrol cars in the last decade, for efficiency reason. Electric vehicles in Norway are growing exponentially mainly due to the excessive incentives allocated for electric vehicles such as

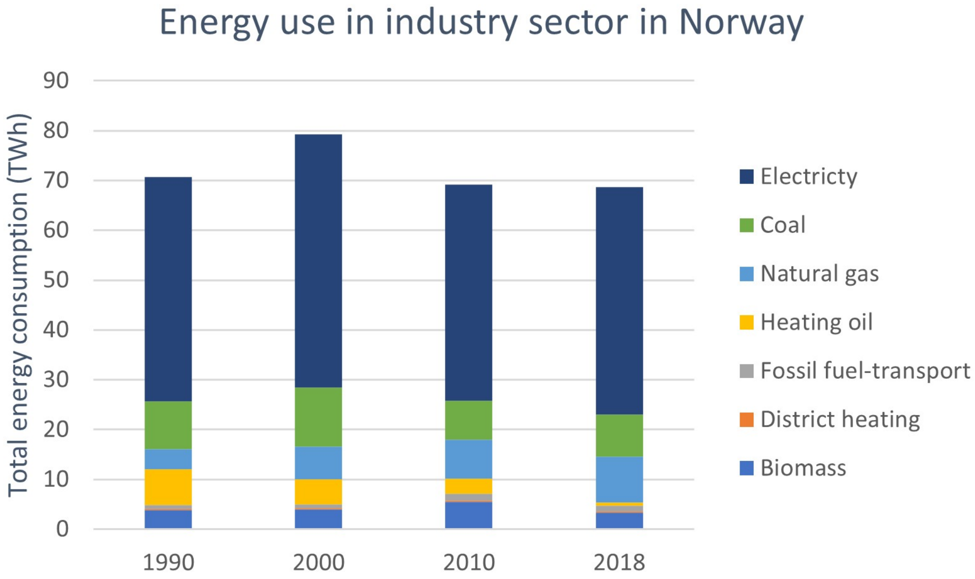

Figure 1.4: Energy use in industry in Norway between 1990 and 2018. [2]

VAT exemption, free bus lanes, free parking, and others. Following this the electricity use in road transportation has increased recently. Compared to other EU countries, the share of renewables in transportation is very high, approximately 30% by 2020. The growth has been remarkable since 2016. Also, the EU has set 14% renewable share targets in transportation by 2030. Most countries except few fails to meet the earlier 10% target by 2020.

1.2.2 Hydrogen Potentials

There is potential to cut emissions in transportation using hydrogen and hydrogen-based systems. If batteries are used for storing a large amount of energy, they might be too heavy. On the other hand, biofuel is not a reliable resource for long-distance transportation. Transport that involves longer distances or requires longer refuelling times might benefit from hydrogen. A potential segment in this perspective is heavy goods transportation

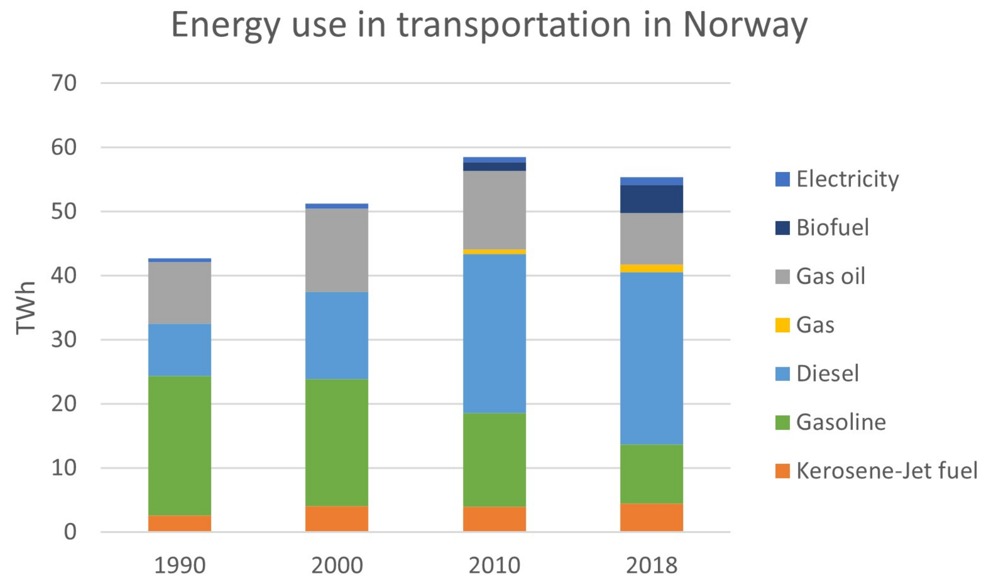

Figure 1.5: Energy use in transportation in Norway between 1990 and 2018. [2]

and maritime. Since hydrogen technologies are developing at a rapid pace, it is difficult to predict where hydrogen will gain a competitive advantage over the long term. Following that, hydrogen may play a role in reducing emissions in heavy goods transportation by road. As compared to batteries, its weight-to-range ratio is lower, and sustainable bio-based fuel may be limited. Additionally, hydrogen tanks can be refilled as quickly as diesel tanks, which is considerably faster than an equivalent battery vehicle charging. As well as hydrogen, other technologies are rapidly developing. So, the future competitive advantage of hydrogen is difficult to predict, particularly in the long run.

Maritime transport, hydrogen, and ammonia can be beneficial for several vessel types based on the energy needs and operating profiles of each vessel. It has been estimated that in Norway, almost two-thirds of the ferry sector's energy needs will be met by electricity [14]. For the remaining routes, hydrogen-based hybrid systems can be used. Since high-speed ferries demand more energy and should be lighter, hydrogen could be more practical for a higher percentage of these routes. Sustainable jet biofuel, synthetic fuel (e-fuels) and electrification appear to be the currently available alternatives to fossil fuels in aviation. There are generally very high safety requirements for aviation, including those for the use and storage of hydrogen. It is obvious that hydrogen is an effective energy carrier on long flights because of its energy content per unit weight. However, we cannot say for sure yet.

Using hydrogen in railways faced by challenges associated with safety. Tunnels are a particularly good example of this because gases can collect there. Pilot projects involving hydrogen operations should not proceed for the moment, according to the Norwegian Railway Directorate. Nevertheless, they should actively stay informed about relevant investigations and development, as well as the progress with hydrogen-powered trains.

In Norway, hydrogen can be produced more cheaply because the power supply is renewable, flexible, reliable, and has an affordable price. While hydrogen has a high value in the European energy system, it is lower in Norway due to the lower costs and higher reliability of Norway's hydropower. The hydrogen system can be competitive for some specific applications without grid access [15].

Because of the availability of a hydro-dominated grid and offshore wind power potential, hydrogen is a potential and promising energy commodity for deep decarbonization of the industry and transportation sectors in Norway. In this regard, there is a great interest and ongoing activities in developing hydrogen technology, particularly in West Norway. Nevertheless, there exists limited knowledge regarding hydrogen production and distribution technologies methods in Western Norway. This master's project thus aims to investigate and compare the various possible ways or methods of hydrogen production and distribution in Western Norway.

1.2.3 Hydrogen in Western Norway

The availability of hydro-dominated grid and offshore wind power potential, hydrogen is considered as a potential and promising energy commodity for deep decarbonisation of the industry and transportation sectors in Norway. In this regard there is a big interest and ongoing activities in developing hydrogen technology specially in West Norway. Nevertheless, there exist limited knowledge regarding hydrogen production and distribution technologies methods in Western Norway. This master's project thus aims to investigate and compare the various possible ways or methods of hydrogen production and distribution in Western Norway.

The Western Norway region has a population of 36115 people. The energy industry is the largest industry in Western Norway, and the Bergen region is particularly strong in the supply chain within petroleum and hydropower production as shown in Fig. 1.6. The total electricity production in Western Norway make up 23 % of the total electricity production in Norway. On the other hand, the energy consumption is shown in the table below since 2015.

The Western Norway is suitable for hydrogen development in Norway due to its: (1) strong offshore wind power potential, (2) the ports have the largest potential for hydrogen bunker in Norway, and (3) it is a potential hub for hydrogen export, (4) availability of energy-intensive industries for hydrogen uptaking, and (5) availability of interested stakeholders engaged in research and development on hydrogen.

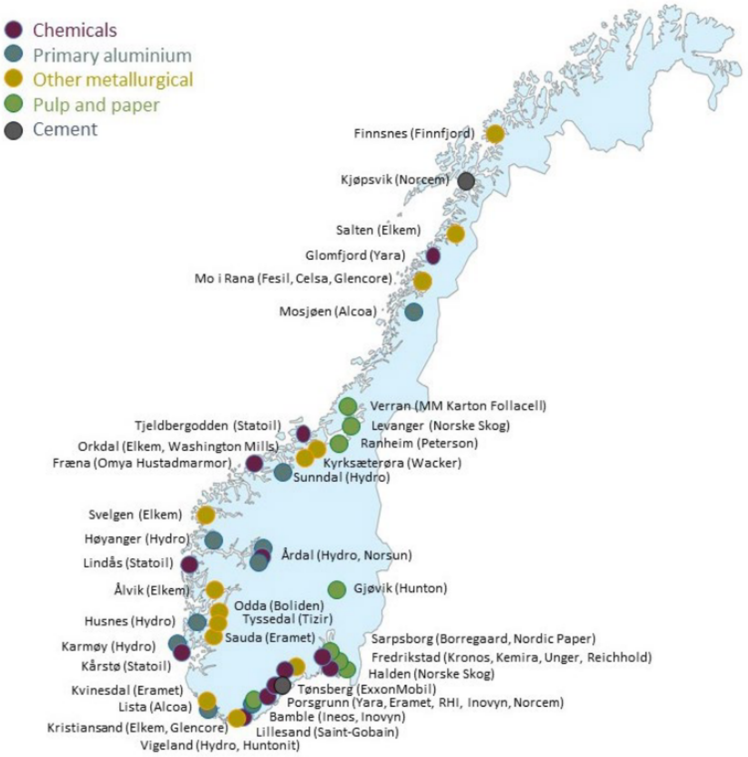

Figure 1.6: Geographical distribution of process industries in Norway [3].

1.3 Objective

Currently, hydrogen is being produced in Norway mainly from natural gas with steam reforming technology. It is matured and least-cost solution. But potentially hydrogen could be produced from several renewable energy sources such as wind, solar, hydro, biomethane, methanol, and ethanol. Thereafter it could either be compressed at high pressure or liquefied at low temperature before it is distributed to customers' site. In an electricity intensive energy system, however, it is important to compare electricity-based hydrogen production technologies with the widely used steam reforming technology.

Hydrogen is one of the key alternative fuels for industry and transportation. The whole supply chain of hydrogen production and distribution involves many steps and needs to be evaluated to compare the cost of hydrogen production and distribution with other alternative fuels. In this thesis the focus is thus on the cost of hydrogen production and distribution to industries and transportation (refuelling stations).

It is of interest in this thesis also to compare central and distributed (such as at the end-user's facility or at the refuelling station) hydrogen production plants for cost. This is because distributed production of hydrogen from natural gas requires small scale plants and is popularly benefited from low or zero distribution costs as it is located at the consumer site. This seems cost effective solution when demand for hydrogen is small. Nevertheless, as demand increases, large central plants could also be benefited from economies of scale but with added distribution costs. In central production plants, high pressure tube and liquid hydrogen trucks are the most widely used distribution systems for hydrogen delivery. Also, knowledge of its advantage and disadvantage compared with distributed steam reforming and on-site electrolysis is crucial.

The main research questions are:

I What is the levelised cost of hydrogen production and distribution in Norway?

II Which hydrogen technologies are the least-cost solutions in Norway?

III What are the key parameters that affect the cost estimation?

1.4 Structure of report

Chapter 2 presents the applied theory that the thesis is built on such as the physics of hydrogen, the role of hydrogen in the energy system, and the hydrogen infrastructures. Chapter 3 presents the methodology used to answer the research questions such as the general approach followed, the levelised cost of hydrogen production, the hydrogen production model, the developed pathways, and data sources and assumptions. Chapter 4 presents the results and discussions, followed by conclusions in Chapter 5.

2 Theory

2.1 The physics of hydrogen

Hydrogen is the simplest element on earth, it consists of only one proton and one electron. It is an energy carrier, not an energy source. Hydrogen can store and deliver usable energy, but it doesn't typically exist by itself in nature and must be produced from compounds that contain it. Hydrogen is currently used in industry mainly for oil refining, ammonia production, & methanol production. Refineries use hydrogen to lower the sulphur content of diesel fuel. Hydrogen could be used in power, building, and transportation sectors. But it has a very low density and needs to be transported either in compressed (350 bar/700 bar) or liquefied form (cooling it to below -253°C) as shown in Table 2.1.

The density of hydrogen at room temperature is 0.083 g/L. In liquid phase, however, the density of hydrogen at atmospheric pressure is 71.1 g/L, about 856 times denser than its gaseous form at atmospheric pressure. The flammability ranges in between 4 to 75% and the ionization energy is 13.5989 eV [16].

According to chemistry and biochemistry, hydrogen is the world's simplest closed-shell molecule and has considered an energy carrier [17]. Energy car-

Table 2.1: Volumetric and gravimetric energy densities of common fuels [7].

Fuel	**Gravimetric energy density (MJ/kg)**	**Volumetric energy density (MJ/L)**
Hydrogen (liquid)	143	10.1
Hydrogen (compressed at 700 bar)	143	5.6
Hydrogen (ambient pressure)	143	0.0107
Natural gas (ambient pressure)	53.6	22.2
Natural gas (liquid)	53.6	9
Gasoline	46.4	34.2
Diesel	42.2	33

riers operate at an intermediate stage of the energy supply chain between primary sources and end-users. It is possible to store and transport or use hydrogen as fuel. Hydrogen can be obtained from water and oxidized back to the water, which can be considered safe energy for the environment [18]. Due to its properties and characteristics, hydrogen is both a chemical fuel with advantages and disadvantages:

Producible: Hydrogen can be produced from both hydrocarbon (steam-methane reforming and coal gasification) and non-hydrocarbon (water electrolysis and thermo-chemical water decomposition) and integrated (steam-methane reforming linked to the non-hydrocarbon-based processes) energy sources [19].

Utilizable: Hydrogen is utilized in various sectors such as transportation, buildings, and industry. Figure 1 illustrates the supply options and main demands for hydrogen [20].

Storable: Hydrogen storage in large quantities is possible, including compressed hydrogen, liquid hydrogen, and storage materials. It depends on the purpose to determine which forms are the best to store [21].

Transportable: A wide variety of transportation methods are available for hydrogen (e.g., rail, road, ship). *Producible:* Environmentally benign: hydrogen can be used through oxidation, and water is a direct product. *Producible:* Recyclable: As an energy carrier, hydrogen can be recycled since it oxidizes to water, which can be separated to produce hydrogen. *Producible:* Synergistic: Many synergies are involved in hydrogen energy systems. As a result, other demands of the system can also be met by hydrogen as an energy carrier [18].

There are also some unpleasant characteristics of hydrogen, including:(1) at present, hydrogen is produced from low-carbon energy at a high cost [22], (2) widespread adoption of hydrogen is hampered by the slow development of hydrogen infrastructure, and to deal with this issue, it is likely that industry, government, and investors will need to work together to plan and coordinate a solution, (3) on both a mass and volume basis, hydrogen storage has lower energy storage densities than gasoline storage. This is particularly troublesome when hydrogen is used as a fuel in automotive applications. Moreover, as a result of its low density and small molecule size, it can leak from containment vessels [18].

Hydrogen safety issues are related to ignition and combustion characteristics consisting of a wide flammability range and low ignition energy. Hydrogen has high flame velocity and can diffuse rapidly. Leakage and explosion can be the main hazard in the storage, transmission, and usage [23].

2.2 Hydrogen in the energy system

At present, hydrogen is getting a lot of attention both politically and business wise, with a significant number of policies and pilot-scale projects all over the world. To make hydrogen a competitive alternative fuel, the green hydrogen production technology must be scaled up and make use of its economies of scale to lower hydrogen costs. Hydrogen is an alternative fuel to achieve emissions reduction and it can influence the whole energy system.

The use of green hydrogen can reduce air pollution in addition to GHG emissions reduction. All GHG emission sources are also the sources of air pollutant emissions implying that replacing fossil fuels will contribute for both GHG emissions and air pollutant emissions reduction such as, for example, from power generation, industry, and transportation.

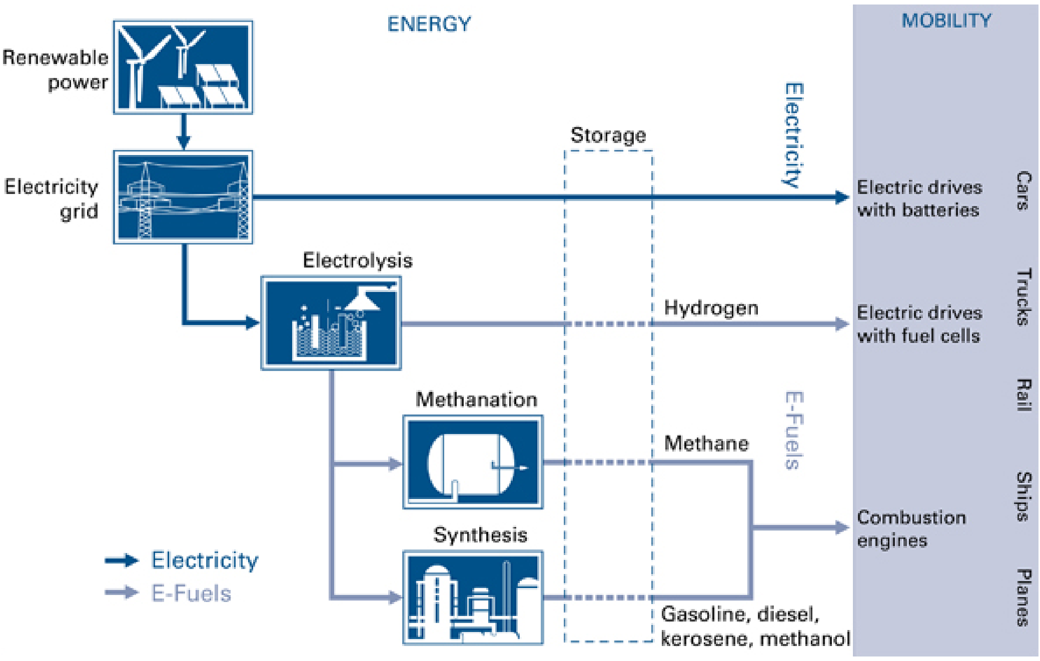

Figure 2.1: Hydrogen sources and end-users in the energy system [4].

Hydrogen can be used to create synthetic fuels or the so-called electro fuels that have versatile application in the energy system as shown in Fig. 2.1. It is very difficult to fully decarbonise the energy system using direct electrification alone and hence the use of hydrogen for synthetic fuel production is very important to create a flexible energy system and integrate more wind and solar into the power grid.

2.3 Hydrogen infrastructure

2.3.1 Hydrogen production technologies

Hydrogen can be produced using steam reformer, autothermal reformer, and electrolysers. The steam reformer is the most widely used technology used to produce hydrogen from natural gas through the steam reforming process. A blue label is applied to hydrogen if the carbon produced by steam reforming is captured and stored underground using carbon capture and storage (CSS). Green hydrogen is produced using electrolysis of renewable-based electricity.

Steam Methane Reforming (SMR)

The SMR is the most matured and least-cost hydrogen production technology [24]. The feedstock is normally natural gas. The methane gas reacts with steam under 3–25 bar pressure and presence of a catalyst to produce H_2 and CO. The schematic process is shown in Fig. 2.2

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Then after using the water-gas shift reaction, the carbon monoxide and steam are reacted using a catalyst to produce CO_2 and additional H_2.

$$CO + H_2O \rightarrow CO_2 + H_2$$

Finally in a pressure-swing adsorption process, the CO_2 and other impurities are removed to produce a pure H_2. The process is an endothermic process that requires heat addition and hance some of the natural gas is used as a heat source.

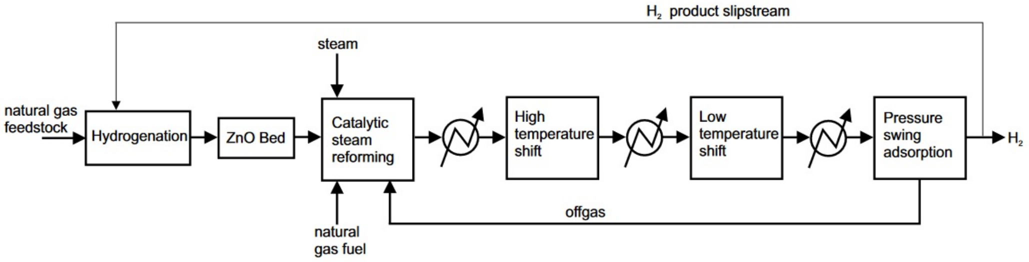

Figure 2.2: SMR basic process design [5].

Autothermal reforming (ATR)

The ATR is a combination of the SMR process and partial oxidation reaction (POX) process. The key difference is the ATR process has a flexibility when it comes to making the process endothermic, thermal neutral, or exothermic by controlling the POX process [25]. In the POX reaction the methane and other hydrocarbons in the natural gas react in a lean-oxygen environment and produces mainly hydrogen and carbon monoxide, and nitrogen if the source of the oxygen is the ambient air.

$$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$$

In the subsequent water-gas shift reaction, the carbon monoxide reacts with water to form carbon dioxide and more hydrogen.

$$CO + H_2O \rightarrow CO_2 + H_2$$

Also, compared to SMR, the process is typically much faster and requires a smaller reactor vessel. Because of this the investment cost is usually a bit lower than the SMR technology. As seen in the chemical equation, the ATR process produces less hydrogen per unit of the input fuel than is obtained by steam reforming of the same fuel.

Polymer Electrolyte Membrane Electrolyser

The proton exchange membrane (PEM) is one of electrolysis-based hydrogen production technologies. It uses a fixed membrane that separates the cathode and the anode electrodes and allow only proton exchange between the two electrodes as shown in Fig. 2.3. The electrons flow through an external circuit. The PEM water electrolysis electrochemically splits water into hydrogen and oxygen at their respective electrodes, hydrogen at the cathode and oxygen at the anode [6]. A number of PEM cells connected in parallel called stack. The schematic diagram of the whole system is shown in Fig. 2.4.

The PEM is suitable for the integration of variable renewable energy sources such as wind and solar. It is compact in design, it has a higher current density, and can operate under relatively low temperatures, in between $70°C$ - $90°C$..

Solid Oxide Electrolyser Cell

The other electrolysis-based emerging hydrogen production technology is the solid oxide electrolyser (SOEC). As opposed to PEM, SOEC uses a less valuable material as electrolyte. It uses solid ceramic materials as electrolyte that selectively allows only oxygen ions at higher operating temperature. The steam enters at the cathode electrode and combine with the electron to produce hydrogen has and oxygen ions. The oxygen ions passes through the

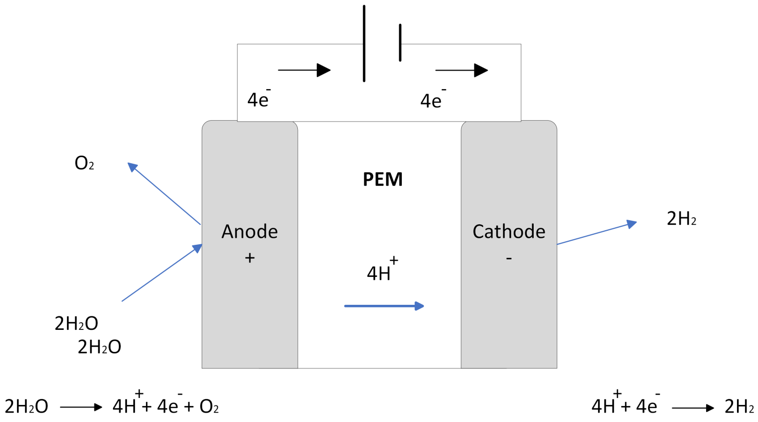

Figure 2.3: Chemical reaction of PEM at anode and cathode electrodes.

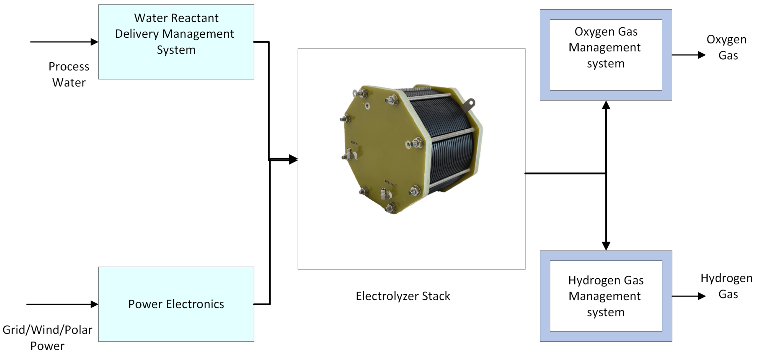

Figure 2.4: PEM electrolysis basic process design [6].

electrolyte and form oxygen at the anode electrode.

The main advantage of SOEC is its high efficiency and the use of less valuable electrolyte material. Nevertheless, it needs to operate at higher temperature for the electrolyte to function properly in the range of $700°C$ - $800°C$. This is higher than the PEM operating temperature, which is in between $70°C$ - $90°C$. The schematic diagram of the whole system is shown in Fig. 2.5.

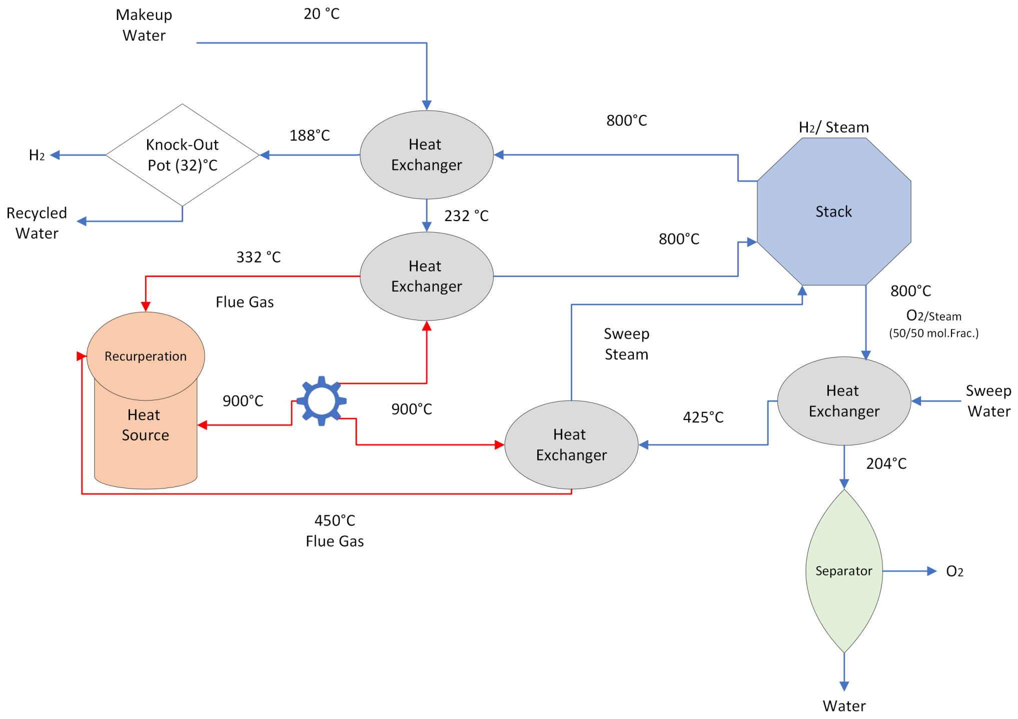

Figure 2.5: SOEC basic process design.

2.3.2 Hydrogen storage and distribution technologies

Hydrogen storage technologies play a critical role in enabling the use of hydrogen as a fuel source for various applications, including transportation, power generation, and industrial processes. The storage of hydrogen is challenging because of its low density and flammability. To overcome these challenges, several hydrogen storage technologies have been developed, including compressed gas storage, liquid storage, and solid-state storage [26]. Compressed gas storage involves storing hydrogen gas in high-pressure tanks, while liquid storage involves storing liquid hydrogen in cryogenic tanks.

Hydrogen storage is key for storing hydrogen at the point of demand and for transportation and distribution to industries and refuelling stations. In central hydrogen production the storage serves both purposes while in distribution plants the storage serves the former. The storage is usually made from composite material for weight and strength reasons. For example the manufacturer in [27] supplies composite storage tanks with a storage capacity of 345 kg of hydrogen at 250 bar. Solid-state storage, on the other hand, involves storing hydrogen in materials that can absorb and release hydrogen, such as metal hydrides and chemical hydrides.

One promising approach for hydrogen storage is the use of metal-organic frameworks (MOFs). MOFs are porous materials made up of metal ions or clusters connected by organic molecules. They have high surface areas and can adsorb large amounts of hydrogen, making them an attractive candidate for hydrogen storage [28]. MOFs can also be tailored to optimize their hydrogen storage capacity, selectivity, and stability [29]. However, there are still challenges that need to be addressed, such as the need for high-pressure conditions and low-temperature operation for effective hydrogen adsorption and desorption.

2.3.3 Hydrogen policy drivers

Hydrogen is one of the desirable options capable of replacing hydrocarbons and abate climate change [30]. Its development is expected to proceed more rapidly than many thoughts. However, some challenges act as a brake to slow down the movement. The potential brakes in hydrogen technology can be in production, infrastructure investments, storage, transport and distribution, safety consideration, and matching supply-demand uncertainties [31]. Research is ongoing to improve and find solutions to hydrogen technology barriers.

3 Method

3.1 General approach

In this thesis, technology specific hydrogen production pathways are developed for key hydrogen production and distribution technologies that are relevant in the context of Western Norway. The region is known for its good offshore wind power potential and the availability of energy intensive industries that facilitate the rapid uptaking of hydrogen. Thus, in this thesis, the polymer electrolyte membrane (PEM) electrolysis, Solid Oxide Electrolysis (SOEC), Steam Methane Reforming (SMR), and Autothermal Reforming with CCS (ATR-CCS) technologies are used in a central and distributed plants. The pathways are dependent on the aforementioned hydrogen production technologies, the plant configuration (central or distributed), and type of distribution technologies used.

The cost of hydrogen production depends on the type of the hydrogen sources, the size of the plant, the capacity factor or utilisation of the plant, the technology development status. On the other hand, the cost of hydrogen distribution depends on the volume of hydrogen, the transport distance, the transport means, and the state of the hydrogen being transported. The aforementioned factors are thus considered in this thesis. It is important to mention that the cost of the electrolysers represents the current estimates based on a short-term projection of commercially available plants.

The Hydrogen Analysis Lite Production (H2A-Lite) model is used to calculate the LCOE of hydrogen production for all pathways. The LCOE of onshore/offshore wind production and ground mounted solar PV is estimated using excel-based model developed for this specific thesis.

3.2 Levelized Cost of Energy (LCOE)

The levelised cost of energy (LCOE) is a key parameter often used in the energy industry to compare the techno-economic performances of energy technologies such as wind and solar PV. The annual cash flows, annual energy production, discount rate, and project period are key parameters used to calculate the LCOE. The method is based on the net present value of all the cash flows as shown in the equation below:

$$LCOE = \frac{\sum_{n=0}^{n} C_n \ (1+d)^{-n}}{\sum_{n=0}^{n} E_n \ (1+d)^{-n}}$$

Where C_n is the annual cash flows (Investment, Fixed and Variable operational costs, fuel costs etc), E_n is the annual hydrogen production or distribution (kg), d is the discount rate (%), and n is the year.

3.3 Hydrogen Analysis Lite Production Model

Hydrogen Analysis Lite Production (H2A-Lite) is a user-friendly Excel-based model that provides a techno-economic view of various levels of hydrogen production technologies. It is developed and maintained at the National

Renewable Energy Laboratory (NREL), USA [6]. The calculation is based on the LCOE method explained in section 3.2.

It has few separate sheets that guide the user through the model. The description sheet provide the general overview of the model, purpose, and quick start guide. The information can serve to provide a general overview of the model function and help users familiarize themselves with the parameters and default values.

The H2ALite sheet is the main model-sheet that the user populate the techno-economic data of the chosen hydrogen production pathway. The hydrogen production cost by component is the main result output of the model. The model also has functionality to perform sensitivity analysis on all key parameters. The sensitivity analysis results are displayed in a tornado chart and allows the user to see which parameters are highly sensitive or less sensitive to the cost of hydrogen production.

3.4 Hydrogen Pathway Development

In this thesis, technology specific hydrogen production pathways are developed for key hydrogen production and distribution technologies that are relevant in the context of Western Norway. The region is known for its good offshore wind power potential and the availability of energy intensive industries that facilitate the rapid uptaking of hydrogen. Thus, in this thesis, the polymer electrolyte membrane (PEM) electrolysis, Solid Oxide Electrolysis (SOEC), Steam Methane Reforming (SMR), and Autothermal Reforming with CCS (ATR-CCS) technologies are used in a central and distributed plants. The pathways are dependent on the aforementioned hydrogen production technologies, the plant configuration (central or distributed), and type of distribution technologies used.

3.4.1 Central Reforming Pathways

The central reformer pathways are based on the SMR and ATR with CCS hydrogen production technologies. In both reformers natural gas is the main feedstock to produce hydrogen. Fig. 3.1 shows the pathways from feedstock to end users.

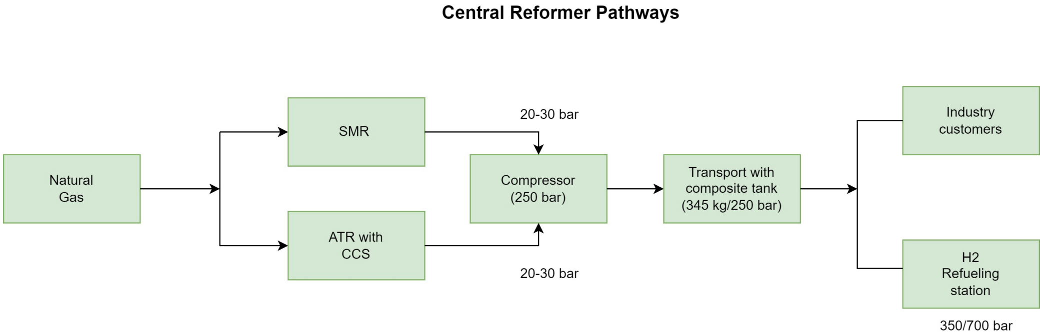

Figure 3.1: SMR and ATR with CCS based central reforming pathways.

Steam methane reforming (SMR) plants process natural gas with 20 to 30 bar. The natural gas is mixed with steam at $395°C$ with steam-to-carbon of 2.45. The reaction in the reactor is an endothermic reaction and needs external heating source. The heat source is the exhaust gases from the pressure swing adsorber (PSA) and natural gas.

The ATR reactor includes a partial exothermic oxidation process and a subsequent endothermic steam reforming process. the steam to carbon ratio is 1.5 and the oxygen to carbon ratio is 0.65. In the CCS 94.5% of product CO_2 will be captured, dried, and compressed for transportation and sequestration.

The central plants produce hydrogen between 20 to 30 bar and needs to be compressed to a higher pressure for transportation and distribution. The assumed compressor increases the pressure to 250 bar at the central plant and the storage tanks are transported to the industry and refuelling stations using storage tanks. The assumed storage tanks comprises of composite tanks with 345 kg of hydrogen storage capacity at 250 bar [27].

3.4.2 Central Electrolysis Pathways

The central electrolysis pathways are based on the PEM and SOEC electrolysis-based hydrogen production technologies. In both electrolysers the sources of the input electricity is either the grid, onshore wind, offshore wind, or ground mounted solar PV. On the basis of this the capacity utilisation of the electrolysers will be different. This is because the availability of wind and solar are highly variable while the grid has the highest availability. Electricity is the main feedstock to produce hydrogen. Fig. 3.2 shows the pathways from feedstock to end users.

Similar to the reformer plants, the central electrolysers produce hydrogen in between 20 to 30 bar and needs to be compressed to a higher pressure for transportation and distribution. The assumed compressor increases the pressure to 250 bar at the central plant and the storage tanks are transported to the industry and refuelling stations using storage tanks. The assumed storage tanks comprises of composite tanks with 345 kg of hydrogen storage capacity at 250 bar [27].

3.4.3 Distributed Electrolysis Pathways

Fig. 3.3 shows the distributed electrolysis pathways from electricity sources to end users. The distributed pathways are normally similar to the central pathways, but it does not need transportation and distribution. Nevertheless,

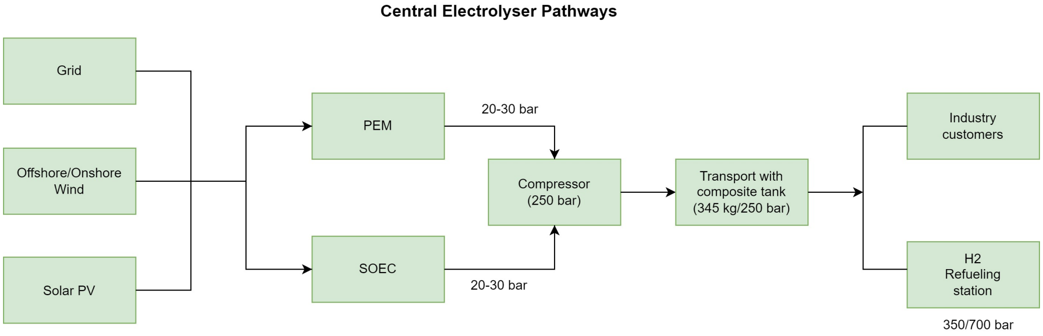

Figure 3.2: PEM and SOEC based central electrolysis pathways.

it is assumed that the gas will be compressed to 250 bar similar to the central pathways.

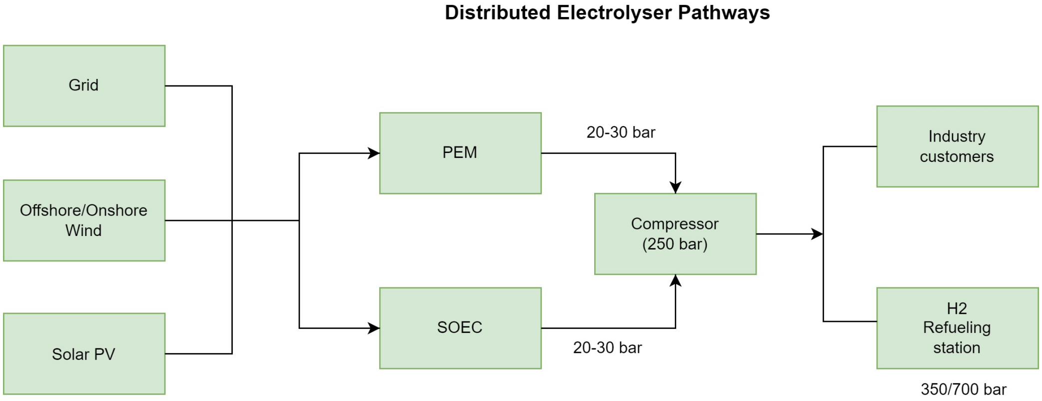

Figure 3.3: PEM and SOEC based distributed electrolysis pathways.

3.5 Data sources and assumptions

Table 3.1 and Table 3.3 presents the assumed techno-economic data. In this thesis, the investment and operation costs of the electrolysers represents the current best estimates based on a short-term projection of commercial and pilot-scale plants.

The electrolyser stack lifetime and hence the replacement is assumed to be 7 years for PEM and 4 years for SOEC. The project lifetime is assumed to be 40 years.

The average electricity price for energy-intensive industry in 2020 is assumed to be 0.67 kr/kWh. This is lower price compared to household price. The year 2020 is chose as the reference year for prices and costs due to the current electricity price crisis in Europe caused by the Russia and Ukraine war.

Table 3.1: Techno-economic parameters of wind and solar plants [8].

Parameter	**Offshore Wind**	**Onshore Wind**	**Ground Mounted Solar PV**
Inv. Cost (kr/kW)	29737	10071	6000
Fix. Operation cost (kr/kW/yr)	923	0	90
Var. Operation cost (kr/kWh)	0	0.1	0
Capacity factor (%)	54%	46%	12.5%
Lifetime (yr)	25	25	30
Annual degradation (%)	0.1%	0.1%	0.2%

The LCOE formula is applied to estimate the LCOE of offshore and onshore wind and solar PV production costs. The capacity factor of offshore wind is assumed to be 54%, onshore wind power is 45%, and solar PV is 13% [8].

The assumed hydrogen production capacity of the plants is 2500 kg/day for distributed plants and 50000 kg/day for central plants.

Enova, a public organisation that promote green technologies in Norway, is responsible for promoting energy production and use that is environmentally friendly. Enova supports development of new technology for producing hydrogen through the program “Technology for sustainable energy carriers”. The support for industrial research the support is 50% of the pilot project, for experimental research the support is 45% for small companies, 35% for medium sized companies, and 25% for large companies, of the costs of the pilot project. This information were obtained through direct communication with Enova's contact person. In this stud, the 25% support is assumed for financial incentives. The assumed discount rate is 6%, equity is assumed to be 40% with 2% interest rate.

Table 3.2: Techno-economic parameters of the reformer technologies [6].

Parameter	**SMR**	**ATR with CCS**
Plant Capacity (kg/day)	50000	50000
Total Capital Cost (kr/kg/day)	1090	1090
Total Gas Usage (kWh/kg)	45	46
Net System Efficiency (%)	78	72
Average gas Price (kr/kWh)	0.1	0.1
Hydrogen Outlet Pressure (bar)	25	25
Replacement Cost (% inv)	10	25

Table 3.3: Techno-economic parameters of the electrolyser technologies [6].

Parameter	**PEM Distributed**	**SOEC Distributed**	**PEM Central**	**SOEC Central**
Plant Capacity (kg/day)	2500	2500	50000	50000
Total Capital Cost (kr/kW)	7130	10561	5880	8710
Total Electrical Usage (kWh/kg)	55.5	53.3	55	53.3
Net System Electrical Efficiency (%)	60.2	62.7	60.2	62.7
Electrolyzer Power Consumption (MW)	5.7	5.5	115.6	111
Average Electricity Price (kr/kWh)	0.6	0.6	0.6	0.6
Hydrogen Outlet Pressure (bar)	25	25	25	25
Installation Cost (% of inv.cost)	12	12	12	12
Replacement Interval (years)	7	4	7	4
Replacement Cost (% of inv.cost)	15	15	15	15

4 Results and Discussions

In this section, the levelised cost of hydrogen results are presented and discussed for the developed pathways and in the light of the applied assumptions. The sensitivity case results for key parameters of each pathway are also presented.

4.1 Levelised Cost of Hydrogen

Table 4.1 presents the total levelised cost of hydrogen for Central PEM electrolysis-based pathways. The result shows that the SMR pathway is the least-cost hydrogen production and distribution pathway with 25.63 kr/kg. Compared to SMR, the ATR with CCS pathway costs more than double with 56.63 kr/kg. This is primarly due to the added investment cost of CCS and the high feedstock (natural gas) consumption compared to the SMR. The central PEM electrolysis-based pathways, in general, shows a higher hydrogen cost compered to SMR but less than that of ATR with CCS pathway. The hydrogen cost depends on the source of the electricity, both in terms of cost and availability of electricity. The central grid PEM shows 50.93 kr/kg, offshore wind, 59.13 kr/kg, onshore wind 39.13 kr/kg, and solar PV 75.33 kr/kg. Compared to all electrolysis based pathways the grid PEM results in lower hydrogen cost. This is primarly due to the higher annual availability of electricity and hence better plant capacity utilisation of the PEM electrolyser. The grid has 86% capacity utilisation while the offshore wind has 54%, onshore wind 46%, and solar PV 12.5%. The higher hydrogen costs of the renewable-based electricity pathways are thus due to their intermittent nature and hence lower capacity utilisation of the PEM plant in their respective pathways. Comparing all the PEM electrolyser pathways, onshore wind, grid PEM, offshore wind PEM, and solar PEM have the lower cost of hydrogen production in the increasing order.

Table 4.1: Central SMR and ATR with CCS Cost Results Summary

Cost Component	**SMR**	**ATR with CCS**
Capital (kr/kg)	2	4.1
Fixed O&M (kr/kg)	2.7	4.7
Feedstock (kr/kg)	6.5	22.2
Other raw material (kr/kg)	0.7	0.7
Other variable (kr/kg)	2.3	13.5
Compression & distribution (kr/kg)	11.43	11.43
Total hydrogen cost (kr/kg)	25.63	56.63

Onshore wind PEM has the lowest cost. This is because of the lower electricity production cost of onshore wind power. The capital cost contribution is relatively high in onshore wind than grid and offshore wind because of the lower capacity utilisation of the plant.

Solar PEM has the highest total levelised cost of hydrogen mainly due to the low-capacity utilisation of the solar PV and hence the electrolyser.

Table 4.2 presents the total levelised cost of hydrogen for distributed PEM electrolysis-based pathways. Comparing the respective central and distributed

Table 4.2: Central PEM Electrolysis Cost Results Summary

Cost Component	**Grid PEM**	**OffWind PEM**	**OnWind PEM**	**Solar PEM**
Capital (kr/kg)	1.9	3	3.6	12.5
Fixed O&M (kr/kg)	2.1	3.4	4	13.9
Feedstock (kr/kg)	33.3	38.3	16.7	27.2
Other raw material (kr/kg)	0.6	0.6	0.6	0.6
Other variable (kr/kg)	1.6	2.4	2.8	9.7
Compression & distribution (kr/kg)	11.43	11.43	11.43	11.43
Total hydrogen cost (kr/kg)	50.93	59.13	39.13	75.33

PEM pathways, the distributed PEM pathways shower a higher hydrogen cost. This is mainly due to the higher economies of scale in central PEM pathways. This can be noted at the capital cost contribution in total hydrogen cost.

The assumed specific investment cost of the compressor cost is 100,000 kr/kg/hr [32], the capacity utilisation is 95%, the electricity consumption is 1.05 kWh/kg, the lifetime is 10 years. The cost of hydrogen compression at the central and distributed plants is thus estimated to be 2.93 kr/kg. The hydrogen transportation cost in Western Norway within 500 km radius has been estimated in [33] to be 8.5 kr/kg and it is added to the central plant pathways.

The distributed electrolysis-based pathways are normally similar to the central electrolysis pathways except the lower daily capacity (2500 kg/day) of the plant and the need for hydrogen transportation to industries and refuelling station. In terms of the hydrogen production costs, for similar reason as the central PEM pathways, the grid-based PEM shows the lower hydro-

Table 4.3: Distributed PEM Electrolysis Cost Results Summary

Cost Component	**Grid PEM**	**OffWind PEM**	**OnWind PEM**	**Solar PEM**
Capital (kr/kg)	2.3	3.7	4.4	15.2
Fixed O&M (kr/kg)	2.6	4.1	4.9	16.9
Feedstock (kr/kg)	33.3	38.3	16.7	27.2
Other raw material (kr/kg)	0.6	0.6	0.6	0.6
Other variable (kr/kg)	1.8	2.9	3.3	11.6
Compression (kr/kg)	2.93	2.93	2.93	2.93
Total hydrogen cost (kr/kg)	43.53	52.53	32.83	74.43

gen cost than onshore wind, offshore wind, and solar PV based distributed PEM pathways. Compared to the respective central PEM pathways, the distributed pathways shows a higher hydrogen production cost due to the poor economies of scale. Nevertheless, that advantage of central PEM pathways is offset by the transportation costs of hydrogen to industries and refuelling stations. Due to this effect the distributed pathways shows a lower total hydrogen cost than their respective central PEM pathways.

The central SOEC passed pathways in general shows a higher hydrogen cost compared to their respective central PEM based pathways. This is primarily due to the higher investment costs and annual replacement costs of the stack. The lower capacity utilisation in solar PV SOEC further increases the total hydrogen cost and makes it the most expensive hydrogen production and distribution pathway of all the assumed pathways.

In the current global hydrogen production system, less than 0.1% is derived from water electrolysis. The cost of renewable electricity is decreasing, and electrolytic hydrogen is gaining traction. Solar PV and wind power costs

Table 4.4: Central SOEC Electrolysis Cost Results Summary

Cost Component	**Grid SOEC**	**Offshore Wind SOEC**	**Onshore Wind SOEC**	**Solar SOEC**
Capital (kr/kg)	1.5	2.5	2.8	10.2
Fixed O&M (kr/kg)	7.9	12.2	14	50.5
Feedstock (kr/kg)	24.7	38	12.1	27
Other raw material (kr/kg)	0.2	0.2	0.2	0.2
Other variable (kr/kg)	5.4	7	7.5	18.4
Compression & distribution (kr/kg)	11.43	11.43	11.43	11.43
Total hydrogen cost (kr/kg)	51.13	71.33	48.03	117.73

are declining, so hydrogen could be supplied at low cost by building electrolysers in areas with excellent renewable resource conditions [34]. In [34] it is shown that offgrid solar driven PEM pathway is more expensive than the SMR pathway due to the higher LCOE of solar PV. Its comparison with grid connected system shows that the solar driven system profitability largely depends on the solar resource, access to grid, and the electricity price. The results are in line with [35] where SOEC pathway is costlier than PEM pathway and the electricity sources or costs are the key parameters that affect the hydrogen cost. Also, the study showed that SOEC pathway could be cheaper than PEM if the heat source is waste heat from adjacent power plant instead of electricity, which is assumed to be electricity in this thesis. In [36] the techno-economic benefits biomass-gasification based hydrogen production were compared with SMR and ATR pathways. The result showed that with the assumed 26.5 kr/GJ natural gas price and grid electricity price 1.08 kr/kWh electricity price, the minimum biomass price should be 600 kr/tonne or less for the biomass-gasification based hydrogen to be profitable over SMR with CCS and 400 kr/tonne over ATR with CCS. Although biomass-gasification based pathways are not included in this thesis, the results emphasis that it is worth including biomass gasification pathways in future studies.

4.2 Sensitivity Analysis

Fig. 4.1 to Fig. 4.4 show the sensitivity of various key techno-economic parameters on the hydrogen production cost in the central PEM based pathways. The sensitivity cases assume a 10% increase and decrease over the assumed base case assumptions. The results show that the electricity use, electricity price, and plant capacity utilisation factor are the key parameters that impacts the hydrogen production costs at the central plants.

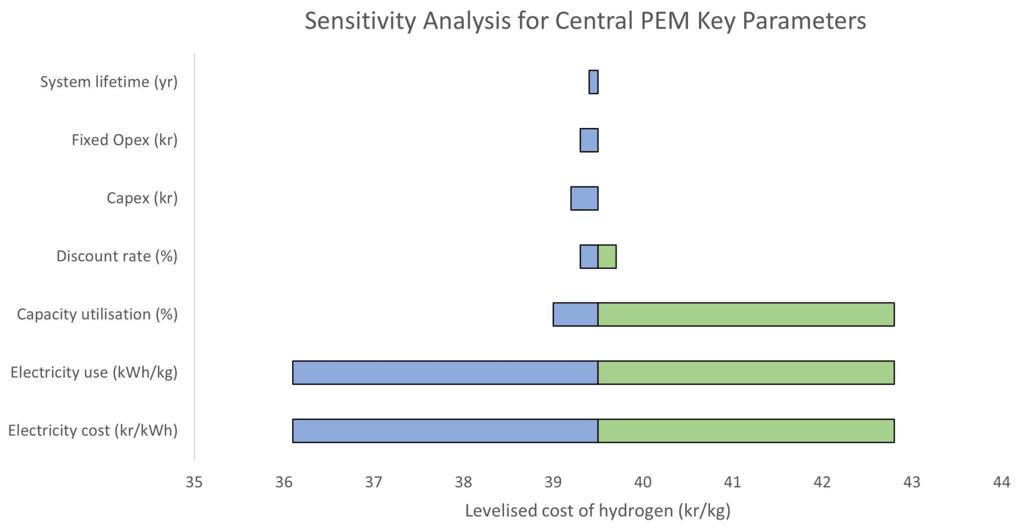

Figure 4.1: Sensitivity analysis for key parameters for central grid PEM

The sensitivity results also shows that the impact of the investment costs have little influence on the hydrogen production costs.

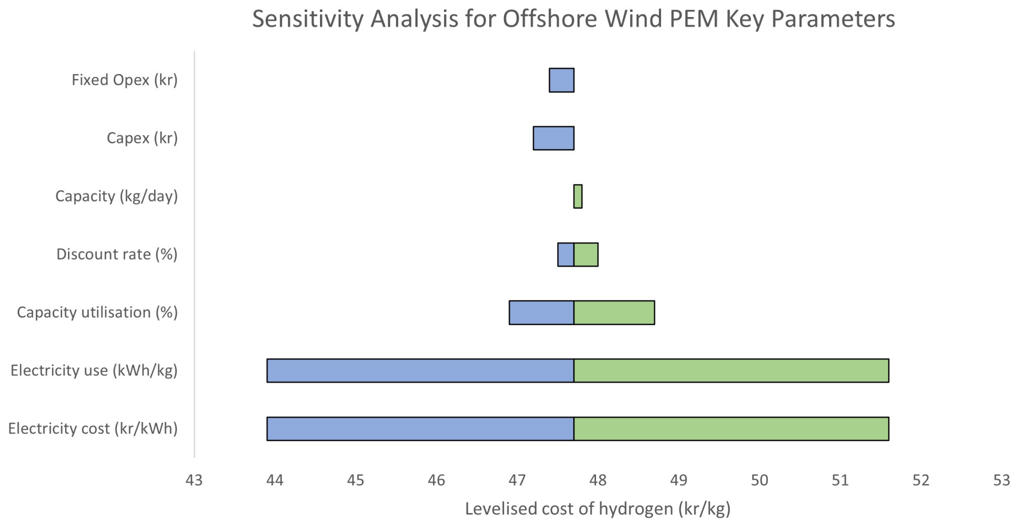

Figure 4.2: Sensitivity analysis for key parameters for central offshore wind PEM

The results indicated that the levelised cost of hydrogen is dependant on the size of the plant and the capacity factor or utilisation of the plant. The grid-based electrolyser has a higher capacity utilisation as compared to offshore- and onshore wind and solar PV. The solar-PV based electrolysis demonstrated the lowest capcity utilisation due to the lower solar radiation level in Norway. This is in line with the results reported in [32].

It is worth mentioning that the advantage of economies of scale could be offset by the lower capacity utilisation and vice versa. Therefore, it is important to utilise the installed capacity of large-scale installations to the maximum possible. The modular grid-based electrolysers have a unique advantage in this regard. It is possible to increase the capacity of the station as demand for hydrogen increases in such a way that the capacity utilisation of the plant would be maintained.

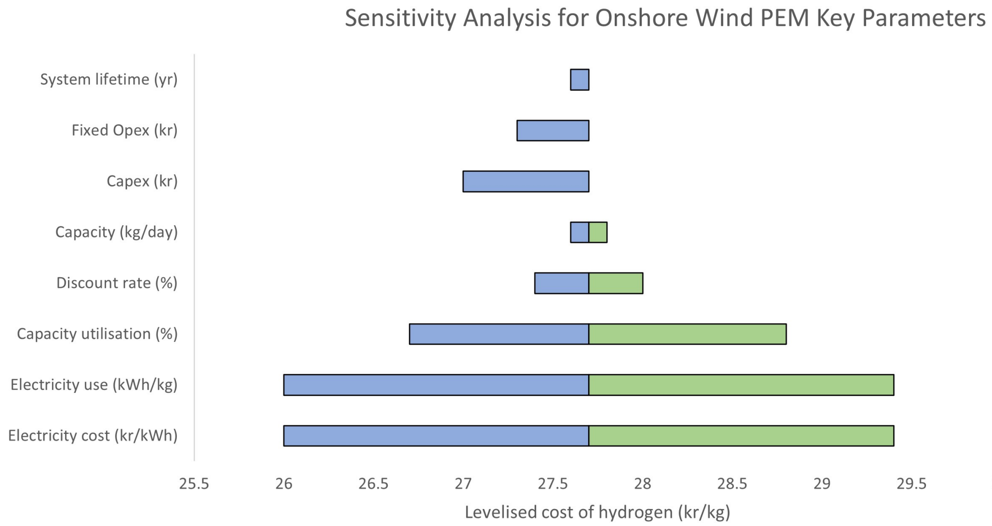

Figure 4.3: Sensitivity analysis for key parameters for central onshore wind PEM

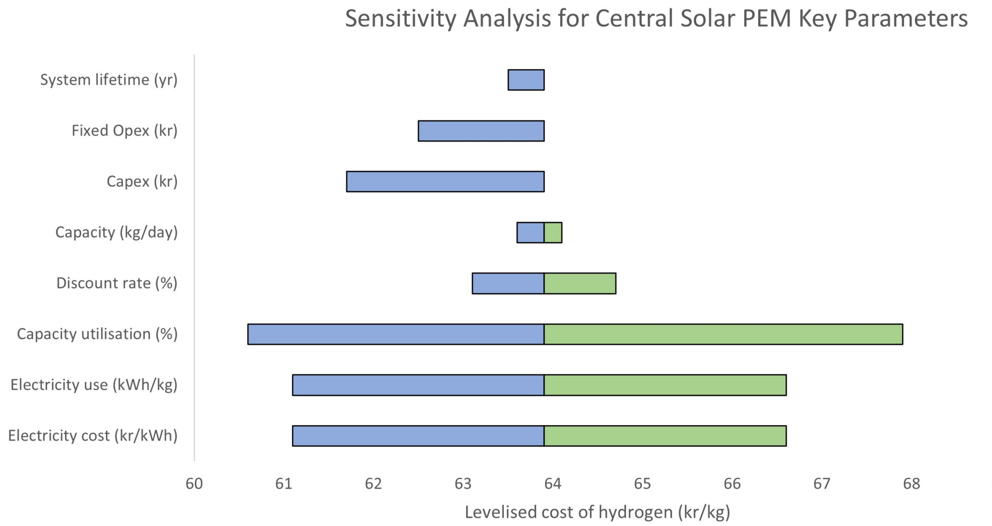

Figure 4.4: Sensitivity analysis for key parameters for central solar PV PEM

5 Conclusion

The decarbonisation of transportation and industry sectors in Norway requires the deployment of high energy density alternative fuels such as hydrogen. Nevertheless, the hydrogen production and distribution costs are both technology and path dependent and needs to be evaluated to identify the least-cost pathways. In this thesis, the natural gas reformer-based and electrolysis-based pathways are developed and evaluated for levelised cost of hydrogen supply to industry and refuelling stations.

The research questions and the results are highlighted point by point:

I What is the levelised cost of hydrogen production and distribution in Norway?

Based on the results, the SMR pathway is the least-cost hydrogen production and distribution pathway with 25.63 kr/kg. The ATR with CCS pathway costs 56.63 kr/kg. This is primarily due to the added investment cost of CCS and the high feedstock (natural gas) consumption compared to the SMR. The central PEM electrolysis-based pathways, in general, shows a higher hydrogen cost compered to SMR but less than that of ATR with CCS pathway. The hydrogen cost depends on the source of the electricity, both in terms of cost and availability of electricity. The central grid PEM shows 50.93 kr/kg, offshore wind, 59.13 kr/kg, onshore wind 39.13 kr/kg, and solar PV 75.33 kr/kg. Compared to all electrolysis based pathways the grid PEM results in lower hydrogen cost. This is primarly due to the higher annual availability of electricity and hence better plant capacity utilisation of the PEM electrolyser. The central SOEC passed pathways in general shows a higher hydrogen cost compared to their respective central PEM based pathways.

II Which hydrogen technologies are the least-cost solutions in Norway?

The result shows that the SMR pathway is the least-cost hydrogen production and distribution pathway with 25.63 kr/kg. But comparing electrolysis-based pathways, the central PEM pathways shower a lower hydrogen cost than the SOEC pathways. This is mainly due to the higher economies of scale in central PEM pathways. Comparing all the PEM electrolyser pathways, onshore wind, grid PEM, offshore wind PEM, and solar PEM have the lower cost of hydrogen production in the increasing order.

III What are the key parameters that affect the cost estimation?

The key parameters that affect the total levelised cost of hydrogen depends on the processes and activities along the supply chain of the specific pathway. The electricity use, electricity price, and plant capacity utilisation factor are the key parameters that influences the hydrogen production costs for electrolyser-based technologies while natural gas use and price are found to be sensitive parameters for the reformer-based pathways.

In this study the major assumptions regarding techno-economic parameters of the hydrogen production technologies reflect only the current best estimates and does not consider the future developments of the costs.

6 Limitation and future work

The investment and operation costs are current best estimate costs that reflect only the early stage of the technology development. To make use of future developments and a more realistic comparison with other alternative fuels, it is important to consider future estimates based on technology learning and economies of scale due to large-scale installations.

Also, in this thesis, few selected pathways are considered. For a holistic comparison of hydrogen with other alternative fuels, it is important to consider more alternative pathways and include the whole upstream and downstream supply chain of hydrogen production and distribution chain.

It is worth mentioning that this study did not include the refuelling stations cost. It is important to include thereof with 350 bar and 700 bar refuelling options in future studies so as to compare it with other alternative transport fuels.

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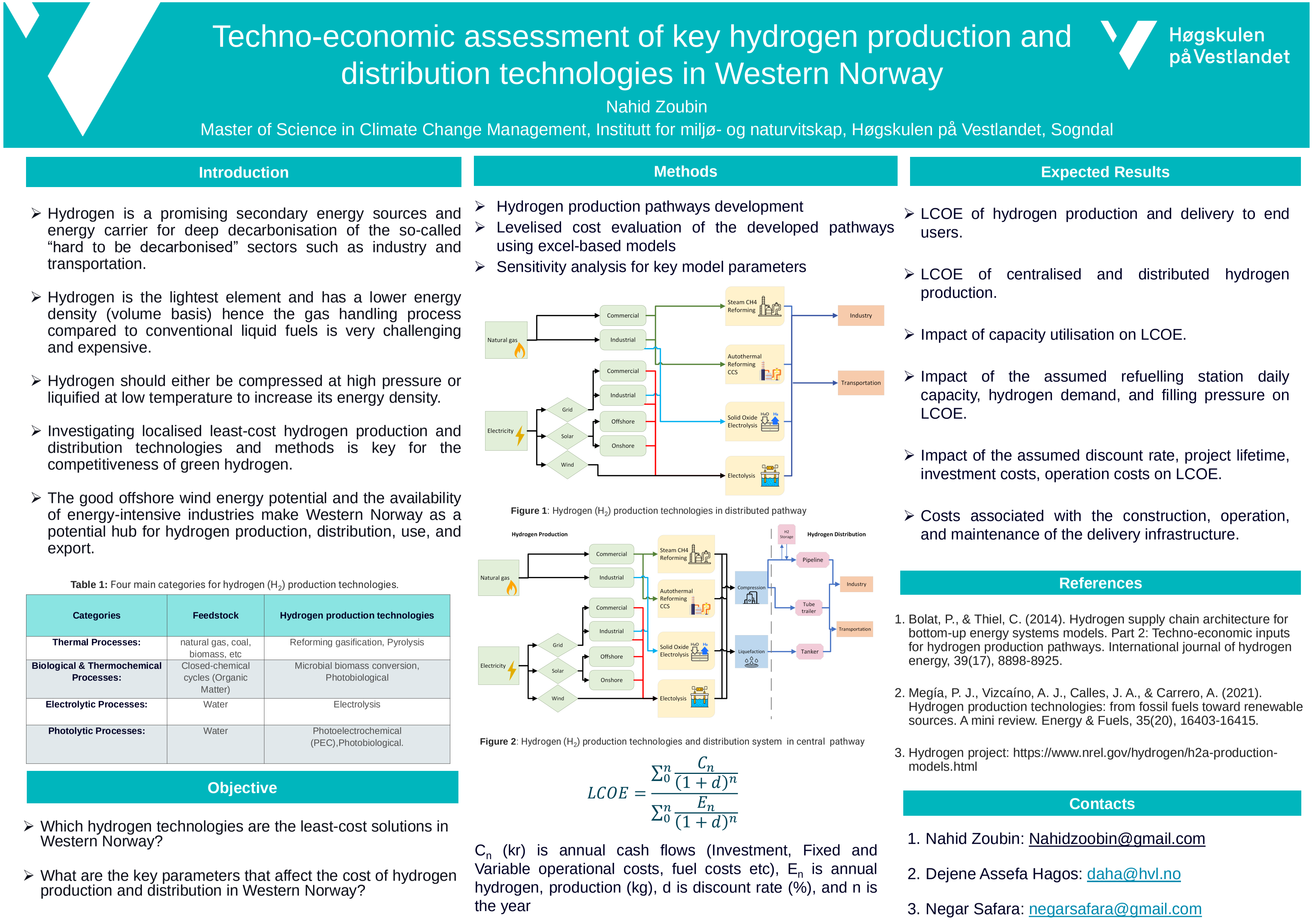
Appendices

A Poster Presentation



Techno-economic assessment of key hydrogen production and distribution technologies in Western Norway

Nahid Zoubin
Master of Science in Climate Change Management, Institutt for miljø- og naturvitskap, Høgskulen på Vestlandet, Sogndal

Introduction

- Hydrogen is a promising secondary energy sources and energy carrier for deep decarbonisation of the so-called “hard to be decarbonised” sectors such as industry and transportation.
- Hydrogen is the lightest element and has a lower energy density (volume basis) hence the gas handling process compared to conventional liquid fuels is very challenging and expensive.
- Hydrogen should either be compressed at high pressure or liquified at low temperature to increase its energy density.
- Investigating localised least-cost hydrogen production and distribution technologies and methods is key for the competitiveness of green hydrogen.
- The good offshore wind energy potential and the availability of energy-intensive industries make Western Norway as a potential hub for hydrogen production, distribution, use, and export.

Table 1: Four main categories for hydrogen (H_2) production technologies.

Categories	Feedstock	Hydrogen production technologies
Thermal Processes:	natural gas, coal, biomass, etc	Reforming gasification, Pyrolysis
Biological & Thermochemical Processes:	Closed-chemical cycles (Organic Matter)	Microbial biomass conversion, Photobiological
Electrolytic Processes:	Water	Electrolysis
Photolytic Processes:	Water	Photoelectrochemical (PEC),Photobiological.

Objective

- Which hydrogen technologies are the least-cost solutions in Western Norway?
- What are the key parameters that affect the cost of hydrogen production and distribution in Western Norway?

Methods

- Hydrogen production pathways development
- Levelised cost evaluation of the developed pathways using excel-based models
- Sensitivity analysis for key model parameters

Figure 1: Hydrogen (H_2) production technologies in distributed pathway

Figure 2: Hydrogen (H_2) production technologies and distribution system in central pathway

$$LCOE = \frac{\sum_0^n \frac{C_n}{(1+d)^n}}{\sum_0^n \frac{E_n}{(1+d)^n}}$$

C_n (kr) is annual cash flows (Investment, Fixed and Variable operational costs, fuel costs etc), E_n is annual hydrogen, production (kg), d is discount rate (%), and n is the year

Expected Results

- LCOE of hydrogen production and delivery to end users.
- LCOE of centralised and distributed hydrogen production.
- Impact of capacity utilisation on LCOE.
- Impact of the assumed refuelling station daily capacity, hydrogen demand, and filling pressure on LCOE.
- Impact of the assumed discount rate, project lifetime, investment costs, operation costs on LCOE.
- Costs associated with the construction, operation, and maintenance of the delivery infrastructure.

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Contacts

1. Nahid Zoubin: Nahidzoobin@gmail.com
2. Dejene Assefa Hagos: daha@hvl.no
3. Negar Safara: negarsafara@gmail.com

Figure A.1: Poster presentasjon på klimaomstillingskonferansen på Quality Hotel Sogndal, May 3-5, 2023

B Sensitivity Analysis Results

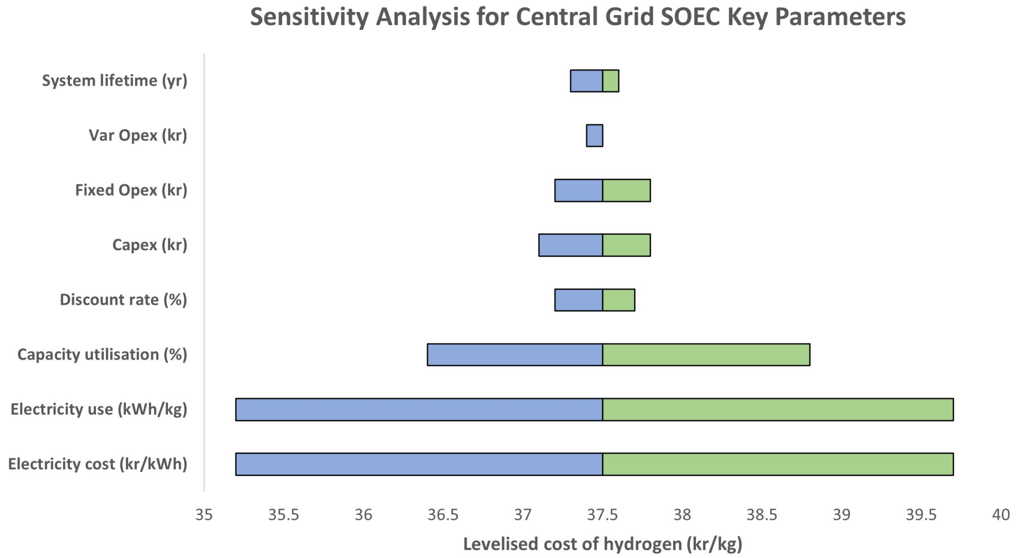

Figure B.2: Sensitivity analysis results for central grid SOEC key parameters

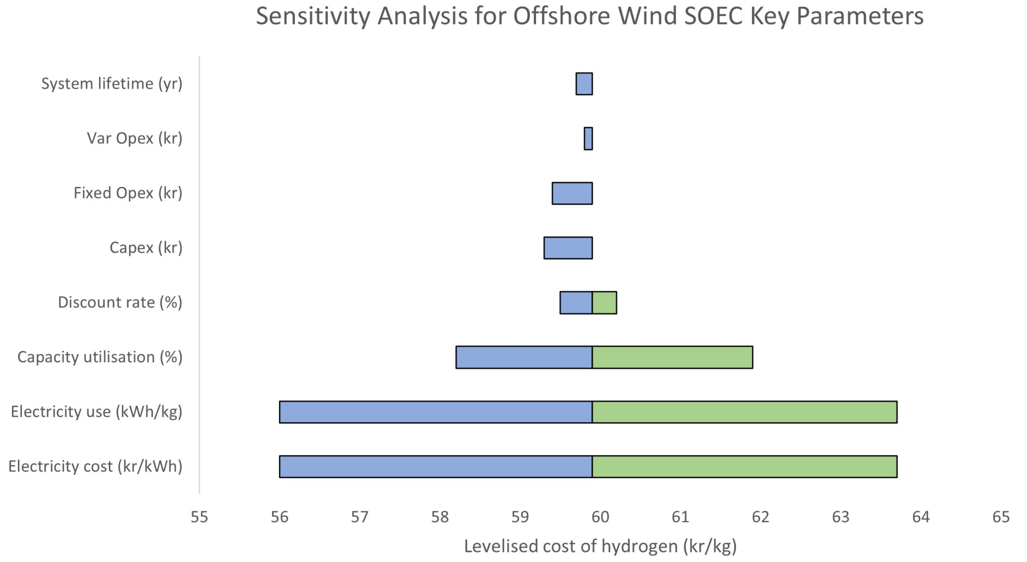

Figure B.3: Sensitivity analysis results for central offshore wind SOEC key parameters

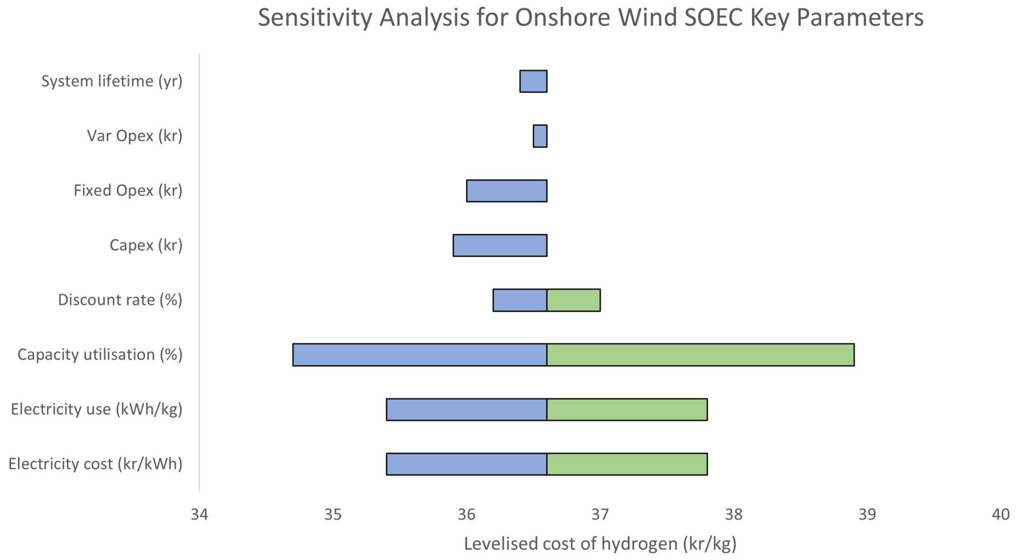

Figure B.4: Sensitivity analysis results for central onshore wind SOEC key parameters

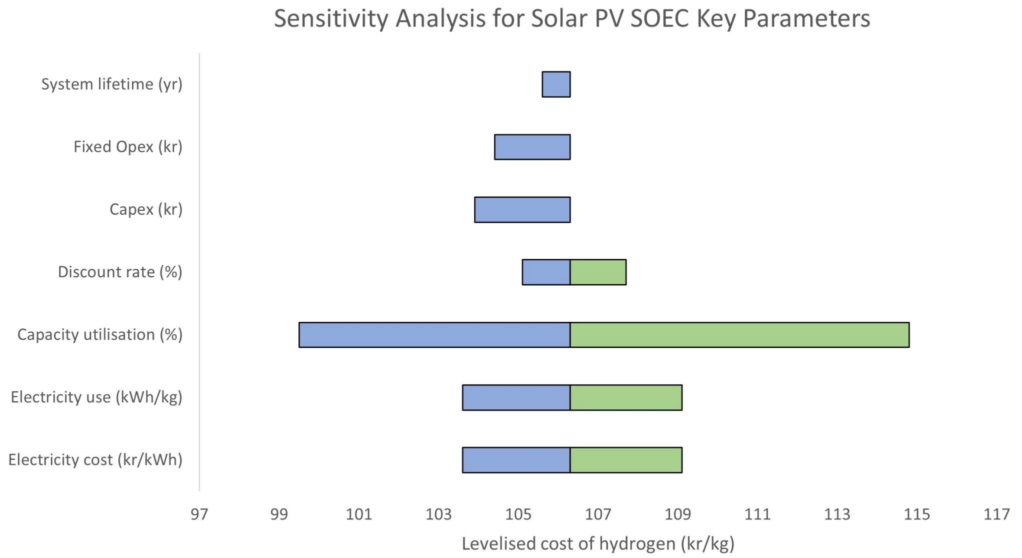

Figure B.5: Sensitivity analysis results for central solar PV SOEC key parameters

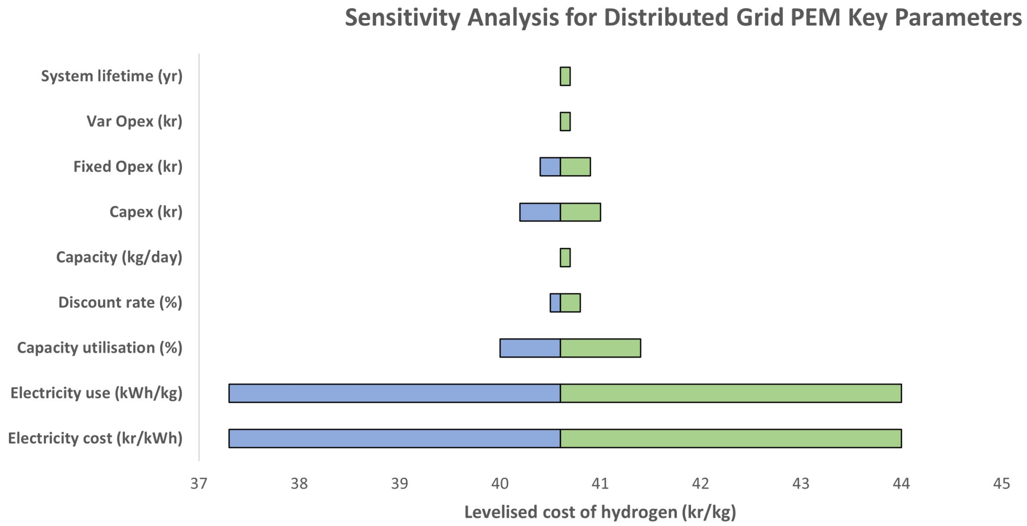

Figure B.6: Sensitivity analysis for distributed grid PEM key parameters

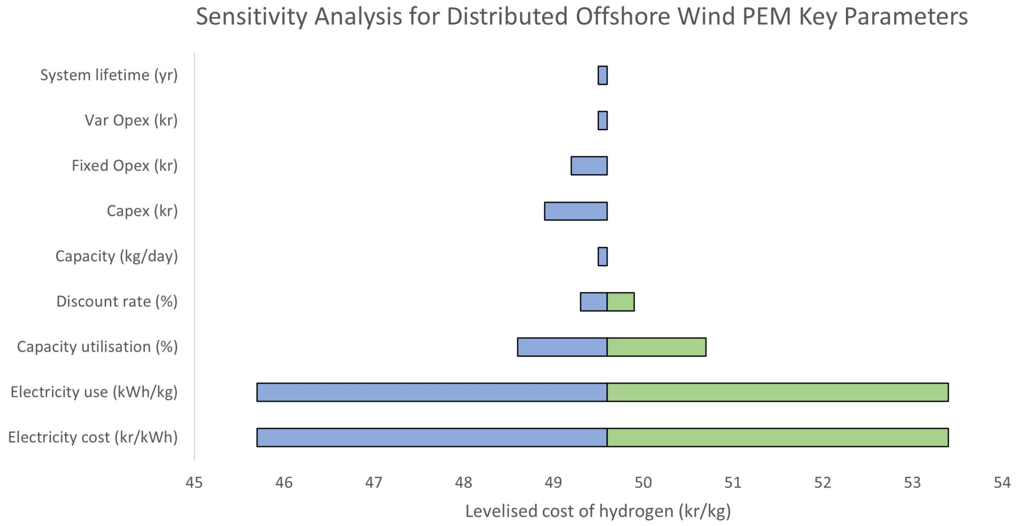

Figure B.7: Sensitivity analysis for key parameters for distributed offshore wind SOEC

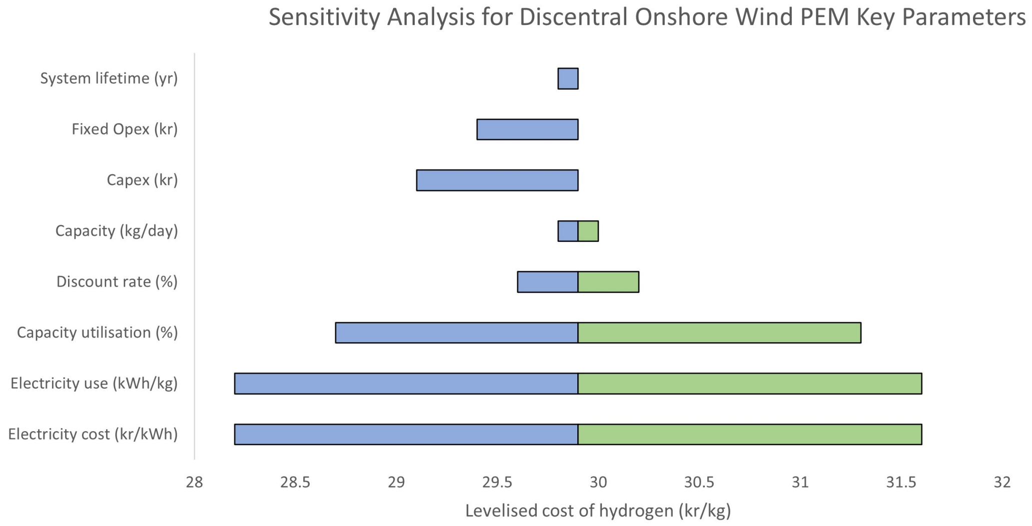

Figure B.8: Sensitivity analysis for key parameters for distributed onshore wind SOEC

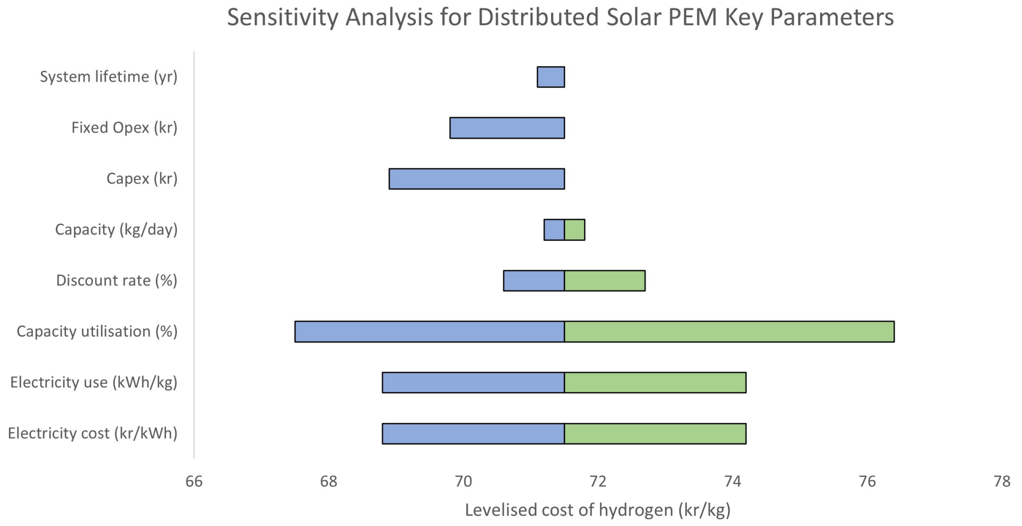

Figure B.9: Sensitivity analysis for key parameters for distributed solar PV PEM