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Economic Assessment of Hydrogen Energy Production in Norway

An Economic Analysis of Strategies for
Implementation of Hydrogen Fuel Produced
by Renewable Energies in Norway

Mahdis Moradi

Globalization
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Supervisor: John Eilif Hermansen, IØT
Co-supervisor: Haley Knudson, IØT

Norwegian University of Science and Technology
Department of Industrial Economics and Technology Management

Never give up on what you really want to do

"The person with big dreams is more powerful than the one with all the facts"

Albert Einstein

Problem statement

Hydrogen energy is an energy carrier that is supposed to play an important role in achieving sustainability and reducing GHG emissions in the near future. Sustainability has always been an very important issue in Norway. It was actually the Norwegian Prime Minister, Brundtland, who introduced the concept of sustainable development in 1987. She changed the way of thinking about future environment and generations. Norwegian government currently supports new ways and technologies to achieve sustainability. Climate change is an important challenge for the country and to fulfil SDG 13, a national follow-up of the Paris Agreement is available. Norway is committed to reduce emissions by at least 40 % by 2030, compared with the 1990 level. As a result, the country integrated renewable energies into its energy system. Hydropower is the main renewable energy source that is used to produce clean electricity in Norway, and the country is one of the first adopters of electric cars in the transportation section. Nevertheless, it is important to find new ways to reduce CO2 emissions significantly to achieve the desired goals and solve the climate puzzle. Previous studies indicate that hydrogen can act as a promising fuel especially in the transportation section. Currently, hydrogen energy is one of the interesting topics in Norway and there has been many discussions and researches about it. Hydrogen energy is a secondary energy carrier; therefore, the availability of primary sources of energy is necessary for its production. In addition, to establish an efficient hydrogen energy market it is important to examine the availability of required infrastructure and regulations. As a result, the research questions of this study are if it is beneficial to produce hydrogen energy in Norway and how Norway can create competitive advantage from hydrogen energy production. To answer these questions, the status of hydrogen energy production in Norway is evaluated from an economic perspective. This study:

- Assesses the important stakeholders in the hydrogen energy market in Norway.
- Conducts a Strengths-Weaknesses-Opportunities-Threats analysis for hydrogen energy market in Norway.
- Conducts a cost analysis for different methods of hydrogen energy production.

Preface

This thesis is the result of independent research and analysis conducted for the MSc in Globalization, Culture and Transnationalism at the Norwegian University of Science and Technology (NTNU) in Trondheim. It is written under the supervision of the Department of Industrial Economics and Technology Management (IØT) during the spring semester 2018.

Inspiration for this thesis stemmed from an internship during fall 2017 while I was working on “renewable energy and supply in Norway”. I consider hydrogen energy as a fuel of future and as a bridge to sustainability. The results of this thesis are presented at two international conferences:

- “An Economic Assessment of Hydrogen Energy Production in Norway and the Context of UN SDG”, presented at Establishing and Supporting Hydrogen Energy Supply Chains Conference, 14-15 May 2018 in Trondheim, Norway.
- “An Economic Assessment of Hydrogen Energy Production in Norway”, presented at 24th Annual Conference of International Sustainable Development Research Society, 13-15 June 2018 in Messina, Italy.

Furthermore, a manuscript is currently being prepared for submission to the International Journal of Hydrogen Energy.

I would like to thank my supervisor, John Eilif Hermansen, Associate Professor at NTNU, Department of IØT, for his knowledge, support and supervision through both my internship report and this master thesis. I would also like to thank Christofer Skaar for his useful advices at the initial stages of this research. Gratitude is extended to my advisor, Haley Knudson for her valuable comments.

I am grateful for my family’s continuous love and support who always show me the right way. To my *parents*, thank you for being my champions through the past years, teaching me how to combat challenges, and encouraging me to follow my dreams no matter where they take me. I would like to thank my love *Ashkan*, my incredibly supportive husband, who has opened a new chapter of life to me. It was impossible to do this research without his support. His unconditional love and support has meant the world to me, I hope that I have made him proud.

Abstract

Hydrogen energy is expected to become an important part of the energy system in Norway and play a significant role in transition to green fuels in the near future. The global attempt to protect the environment against economic growth, global warming and recent oil crisis, which increased the demand for more secure energy, is a great incentive to shift to clean energies. Currently, hydrogen market is not competitive and its production is only for satisfying internal demands of specific industries. It is necessary to take into account the challenges of hydrogen energy integration into the current energy system.

This study investigates strengths, weaknesses, opportunities and threats of hydrogen energy market in Norway. It addresses a research gap by determining and prioritizing the important factors influencing the success of hydrogen energy in the energy market. Furthermore, a cost analysis is conducted to compare the costs of different methods of hydrogen energy production. This cost analysis is useful to choose a more cost effective method to produce hydrogen energy. The results of this thesis could be useful for decision makers and stakeholders to implement efficient strategies. The results show that availability of different primary resources to produce hydrogen energy and strong research and development organizations help Norway create competitive advantage from hydrogen energy and its related technologies. However, to make hydrogen energy competitive it is important to develop the required infrastructure, increase the support from the government and make alliance with local politicians or business owners. Prioritization of the important factors of the success of hydrogen energy shows that feasibility, production costs and reliability, are the most important factors. Cost analysis demonstrates that the most cost effective way to produce clean hydrogen energy is to produce it on-site by electrolysis.

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Acronyms

AHP	Fuzzy Analytic Hierarchy Process
CCS	Carbon Capture and Storage
CO2	Carbon dioxide
EAC	Equivalent Annual Cost
Fuzzy AHP	Fuzzy Analytic Hierarchy Process
GHGs	Greenhouse Gases
GDP	Gross Domestic Product
MCDM	Multi Criteria Decision Making Method
MDGs	Millennium Development Goals
SDGs	Sustainable Development Goals
SWOT	Strengths-Weaknesses-Opportunities-Threats
UN	United Nations
PV-based	photovoltaic based electrolysis
R&D	Research and Development

1 Introduction

Globalization has provided many possibilities as well as many critical challenges. To address one of the most important issues, climate change, hydrogen energy production has been introduced and gained attention recently. Energy plays an important role in development and increasing productivity in both industrial and agricultural sectors. Increased utilization of fossil fuels as the main driver of economic growth created many critical environmental issues. To address these problems and save the planet, United Nations presented Sustainable Development Goals (SDGs) with 17 goals and 179 targets. One of the main targets of these goals is achieving sustainability that means meeting the needs of the present without compromising the future, and accentuating environmental and community stewardship (Porter and Kramer, 2006). SDGs focus on the necessity of better management and utilization of natural resources and preserving earth's life support system. One way to do that is to promote energy policies and new sources of energy that spur sustainable economic growth. This cannot be achieved without collaboration between governments, private and public sector organizations and civil society organizations. One of the most important countries which is committed to achieve sustainability is Norway, though it is rich in fossil fuels such as oil and gas. The country integrated renewable energies, mainly hydropower, into its energy system. In addition, with abundant natural resources, strong research and development and progressive technology capacity, Norway makes efforts to supply a low-priced and clean fuel. The affordable and clean energy is particularly significant for secure supply of energy, global stability and peace according to vital role of energy in industrial and technological developments around the world. Hydrogen energy proved to be one of the best available options and has gained interest recently. This study aims to shed light on hydrogen energy production in Norway and seeks to perform an economic assessment of energy production in Norway. Climate change combat and energy security are the incentives that motivated Norway to shift to green energy production approaches. In addition, Norway tries not to let the future economic growth destroy the environment, so the shift to more sustainable and green practices are of interest. Recent oil crisis also increased the demand for more secure energy supplies. One of the main purposes of the shift to renewable energies is to reduce greenhouse gas emissions. Norway is particularly well positioned with high availability of hydropower and wind power resources. Norway is the sixth largest producer of hydropower in the world, and the largest in Europe and it has several plants in wind power and solar technology. The country is politically stable and the economy is open and mixed with a combination of private and public ownership. Furthermore, the country has ambitious goals and targets for renewable energy development. The following introductory chapter outlines the background of study and its limitation, the purpose of the study followed by the scope and the structure of the thesis.

1.1 Background of the Study

Background of the topics of how hydrogen energy production can help combat the climate change is given to set the stage for the formulation of the research issue. In addition, it will be important to consider as the thesis moves on to encounter complex concepts and theoretical resources.

1.1.1 The contribution of hydrogen energy to sustainability

Climate change, global warming, increasing energy demand and unstable energy prices and markets stimulated countries to find new solutions that spur not only economic growth but also sustainable solutions. This has shed more lights on hydrogen energy as an energy carrier. It is accessible and its characteristics show that hydrogen energy can create a link between sustainable energy technologies and sustainable energy economy and play a significant role in transition to a low carbon future. In Figure 1.1, possible problems as a result of increased utilization of fossil fuels are presented. It shows why it is important to substitute fossil fuels with clean energies. Midilli et al. (2005) illustrated that the increase in the consumption of fossil fuels causes climate change, international tensions, economic recession and negative effects on the standard of living as it is shown in Figure 1.1. As a result, it is important to shift to renewable energies and consider hydrogen energy as a bridge and facilitator of more utilization of renewable energies.

The combination of hydrogen energy production from natural gas and carbon capture helps Norway utilize its gas reserves and reduce negative externalities of fossil fuels on the environment. By producing green hydrogen energy, Norway will have the opportunity to become the front-runner of hydrogen energy and related technologies. Many valuable researches about hydrogen energy are available. For instance, Midilli et al. (2005) examined hydrogen energy strategies, status and need. They explained the role of hydrogen as a clean energy carrier and illustrated hydrogen technologies and strategies from environmental, sustainability and other perspectives.

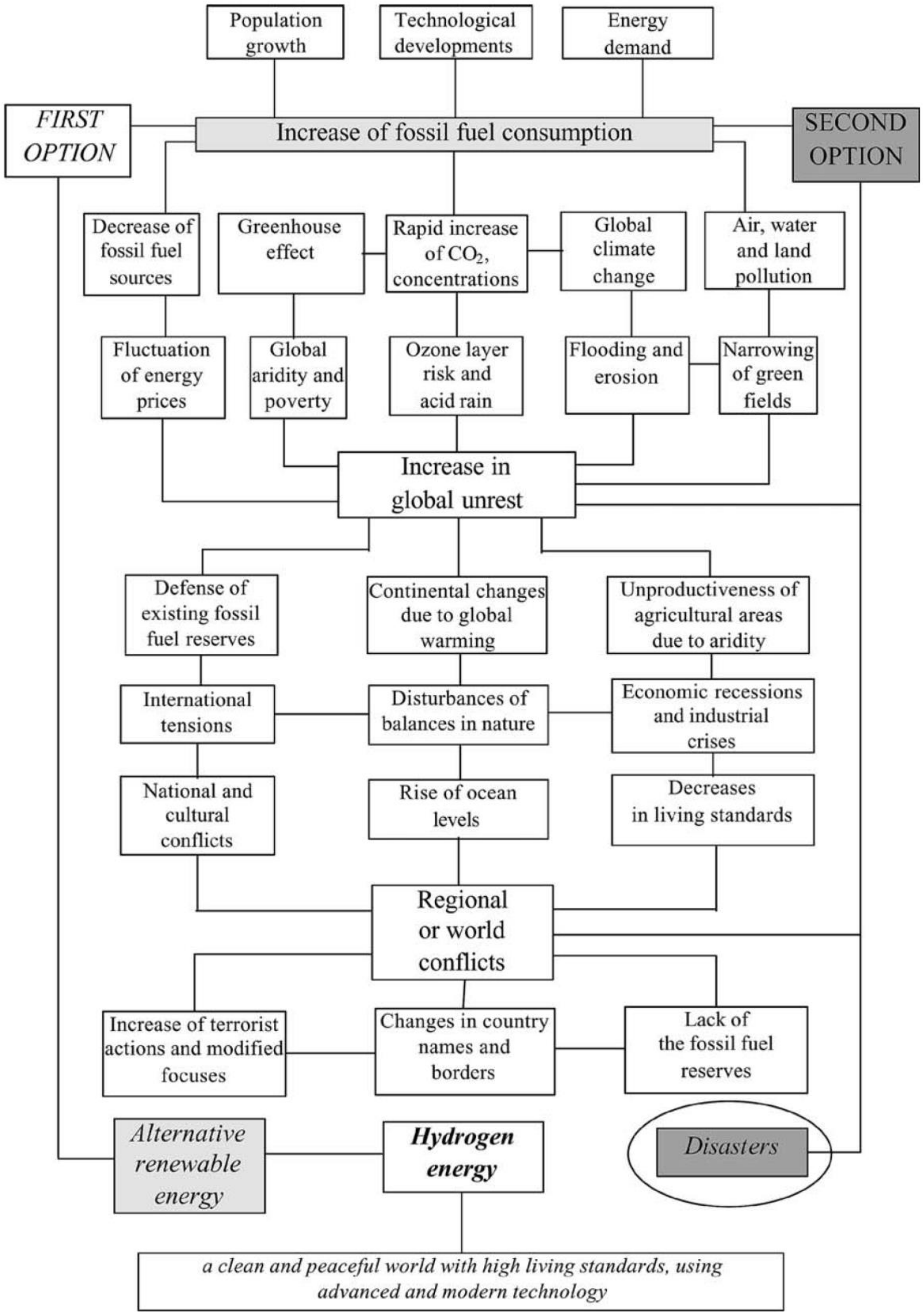

Figure 1.1 Possible global problems from increasing use of fossil fuels (Midilli et al., 2005)

In addition, they explored that the needs for hydrogen energy and systems allow future strategies incorporating hydrogen energy to be considered in a logical manner. They concluded that hydrogen energy could have a positive impact on conflict, stability and sustainability. Andrews and Shabani (2012) investigated whether or not hydrogen energy fits into a global sustainable energy strategy when there are challenges of irreversible climate change and uncertain oil supply. The question was addressed by sketching a sustainable energy strategy that is based predominantly on renewable energy inputs and energy efficiency, with hydrogen playing a crucial and substantial role in future energy combination. In this survey, the role of hydrogen in a sustainable energy strategy, broadly applicable at national and international levels, was evaluated with consideration of irreversible climate change, uncertain oil supply, increasing pollution and strong challenges to hydrogen. The findings show that hydrogen is currently produced, stored and consumed locally, rather than being produced at a few large-scale facilities and then transmitted via long-distance pipelines centralized to distant cities as given in the original hydrogen economy concept. Bulk hydrogen storage would provide the strategic energy reserve to guarantee national and global energy security in a world relying increasingly on renewable energies. The conclusion is that it is necessary to do more research on policy-making, development and commercialization of this kind of energy. Thengane et al. (2014) performed a cost-benefit analysis of different hydrogen energy technologies using AHP and Fuzzy AHP. The technologies examined are steam methane reforming, coal gasification, partial oxidation of hydrocarbons, biomass gasification, photovoltaic-based electrolysis, wind-based electrolysis, hydro-based electrolysis, and water splitting by chemical looping. For each of the hydrogen production technologies, five criteria are used for evaluation: greenhouse gas emissions, raw material and utilities consumption, energy efficiency, scalability, as well as waste disposal and atmospheric emissions. Results showed that the fossil fuel based processes appear to have less beneficial qualities, including greater environmental impacts, but are more cost-effective. On the other hand, the renewable based processes appear to have more benefits, while being more expensive for hydrogen production.

1.2 Scope and purpose of the study

The scope of this study is limited to economic evaluation of hydrogen energy in Norway. The purpose of this study is to examine how hydrogen energy production contributes to the achievement of UN SDGs and understand hydrogen energy relevant stakeholders. In addition, strengths-weaknesses- opportunities-threats of hydrogen energy market in Norway is evaluated and prioritized. To have a better understanding of the market, important factors are determined and prioritized using fuzzy AHP. Furthermore, cost analysis is conducted to determine which method of hydrogen production is economic in Norway.

1.3 Limitations

This research is restricted in Norwegian hydrogen energy market. However, it is attempted to include both transportation and stationary market. Due to lack of evidence and information about the stationary sector, the focus is on transportation sector and its relevant issues and challenges. Many of the required information and data are in Norwegian; as a result, there is a chance for missing data in this thesis. In addition, the expert team had 10 participants and it was difficult to persuade more people to participate. This research evaluates hydrogen energy status in Norway from an economic point of view; technical assessment is not included.

1.4 Thesis structure and outline

This thesis is composed of six chapters to evaluate different aspects of hydrogen energy in Norway. An introduction is given in chapter 1, including the research background and problem statement. Chapter 2 discusses the hydrogen energy concept, its production, storage and distribution methods and gives a summery of different parts of hydrogen energy market in Norway. Chapter 3 examines theoretical framework, discussing sustainable development and stakeholder theory. In chapter 4, methodological framework is presented. This chapter includes research methodology and data collection method to create a foundation for conducting the analysis. Chapter 5 is dedicated to the results of the analysis performed in this thesis, based on the theoretical and methodological framework presented in previous chapters. The main findings of this work are given in chapter 6. Some recommendations for further research and policy making are also presented. The structure of this thesis is summarized in Figure 1.2.

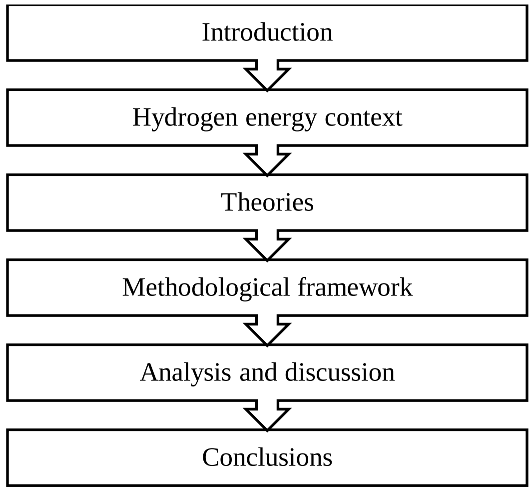

Figure 1.2 Structure of the thesis

2 Hydrogen Energy Context

Hydrogen energy is expected to be an influential fuel in the future economy and development. It is therefore important to increase the awareness about hydrogen energy. The aim of this chapter is to discuss hydrogen characteristics, its benefits, challenges and value chain. In addition, the hydrogen energy status quo in Norway is discussed.

2.1 Hydrogen energy: characteristics and advantages

To have a better view of hydrogen capabilities, it is reasonable to study its characteristics. The combustion of hydrogen provides a very clean reaction. The following formula shows that the product of this reaction is just pure water and energy:

$$2\ H_2 + O_2 \rightarrow 2\ H_2O + 572\ kJ \tag{2.1}$$

Hydrogen itself is one of the simplest and abundantly found elements on earth. An atom of hydrogen consists of only one proton and one electron. However, this element is always combined with other elements and it is hard to find it as a pure gas. Hydrogen characteristics show that this element has good energy density by weight, but poor energy density by volume compared to hydrocarbons. Different properties of hydrogen are presented in Table 2.1.

Table 2.1 Fundamental hydrogen properties (adopted from Hamacher, 2016)

Property	Value	Unit
Density (gaseous)	0.899	kg/Nm^3
Density (liquid)	70.79	kg/m^3
Melting temperature	14.1	K
Boiling temperature	21.15	K
Lower heating value	3.00	kWh/Nm^3 (volumetric)
	2.79 (liquefied)	kWh/l
	33.33	kWh/kg (gravimetric)
Gross calorific value	3.5	kWh/Nm^3

Edwards et al. (2008) made a comparison of the energy produced from different fuels, as presented in Table 2.2. It shows that hydrogen produces considerable amount of energy although it has very low density.

Table 2.2 Specific energy and energy density of fuels (Edwards et al., 2008)

Fuel	Specific energy(kwh/kg)	Energy density(kwh/dm^3)
Liquid hydrogen	33.3	2.37
Hydrogen (200 bar)	33.3	0.53
Liquid natural gas	13.9	5.6
Natural gas (200 bar)	13.9	2.3
Petrol	12.8	9.5
Diesel	12.6	10.6
Coal	8.2	7.6
Methanol	5.5	4.4
Wood	4.2	3.0
Electricity (Li-ion battery)	0.55	1.69

According to hydrogen characteristics, it can be concluded that it is a promising energy carrier. Furthermore, hydrogen value chain should be analyzed. The hydrogen value chain is presented in Figure 2.1. According to this figure, production, storage, safety codes and standards, transport and delivery and applications are components of hydrogen energy value chain. Figure 2.1 also shows that it is necessary to plan carefully and make connections between different sectors of the value chain to shift to a hydrogen economy from fossil fuels.

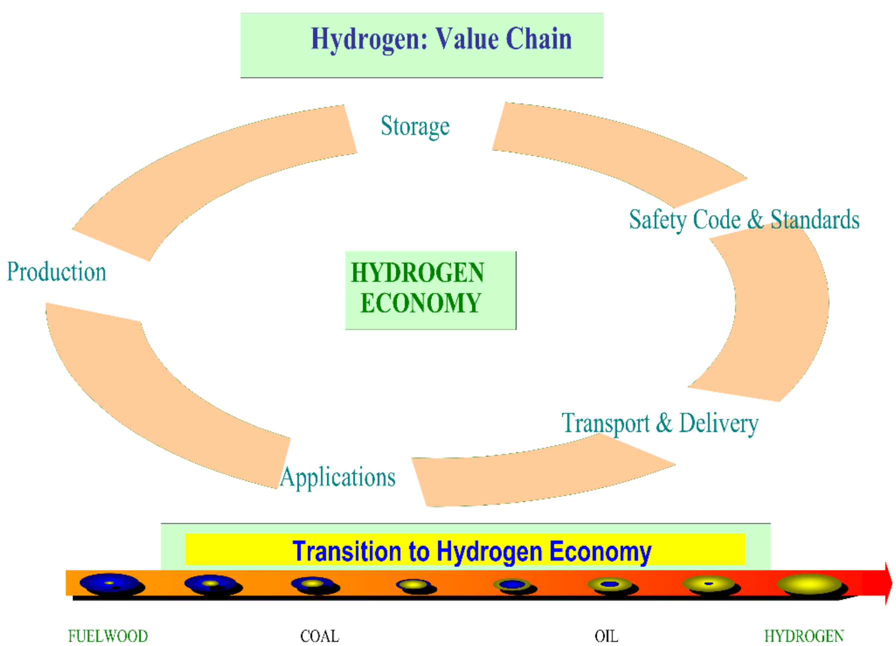

Figure 2.1 Hydrogen value chain (Jain et al., 2103)

Therefore, to establish an efficient hydrogen market it is necessary to examine each factor carefully.

2.1.1 Hydrogen energy production

In this section, different methods of hydrogen energy production are divided in two different categories, non-green and green, as presented in Figure 2.2 and Figure 2.3, respectively.

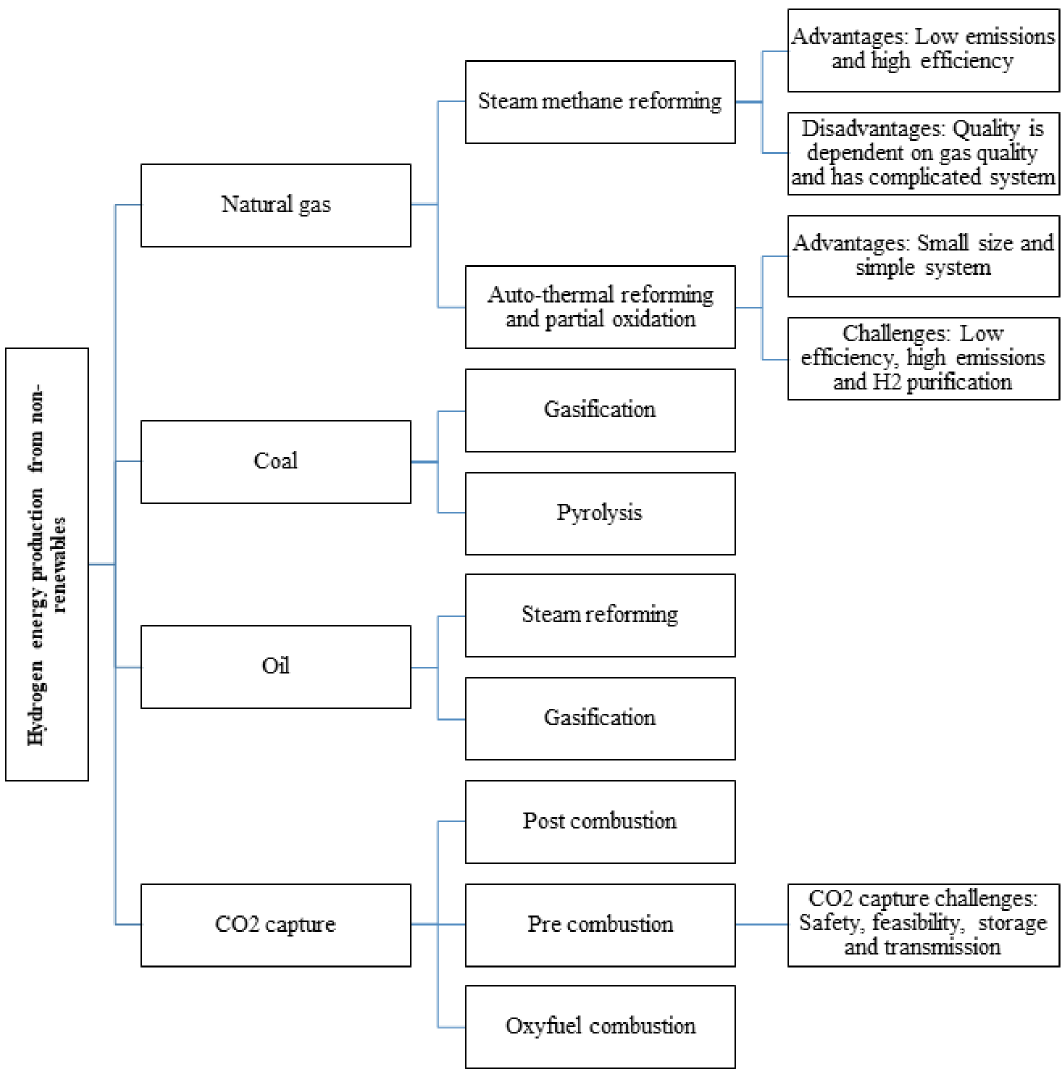

Figure 2.2 Hydrogen energy production from non-renewables (adopted from Jain et al., 2013, Dincer 2012 and Makridis, 2016)

The significant problem with these methods is CO_2 emission (except the last one). Since the main intention to substitute fossil fuels with other energy sources is to reduce GHG emissions, it seems more logical to use renewables.

Dincer (2012) presented different paths to produce hydrogen energy from green energy sources, as shown in Figure 2.3. The electrical and thermal energy can be produced from renewable energies (like solar, wind, geothermal, tidal, wave, ocean thermal, hydro, biomass), or from nuclear energy, or from recovered energy.

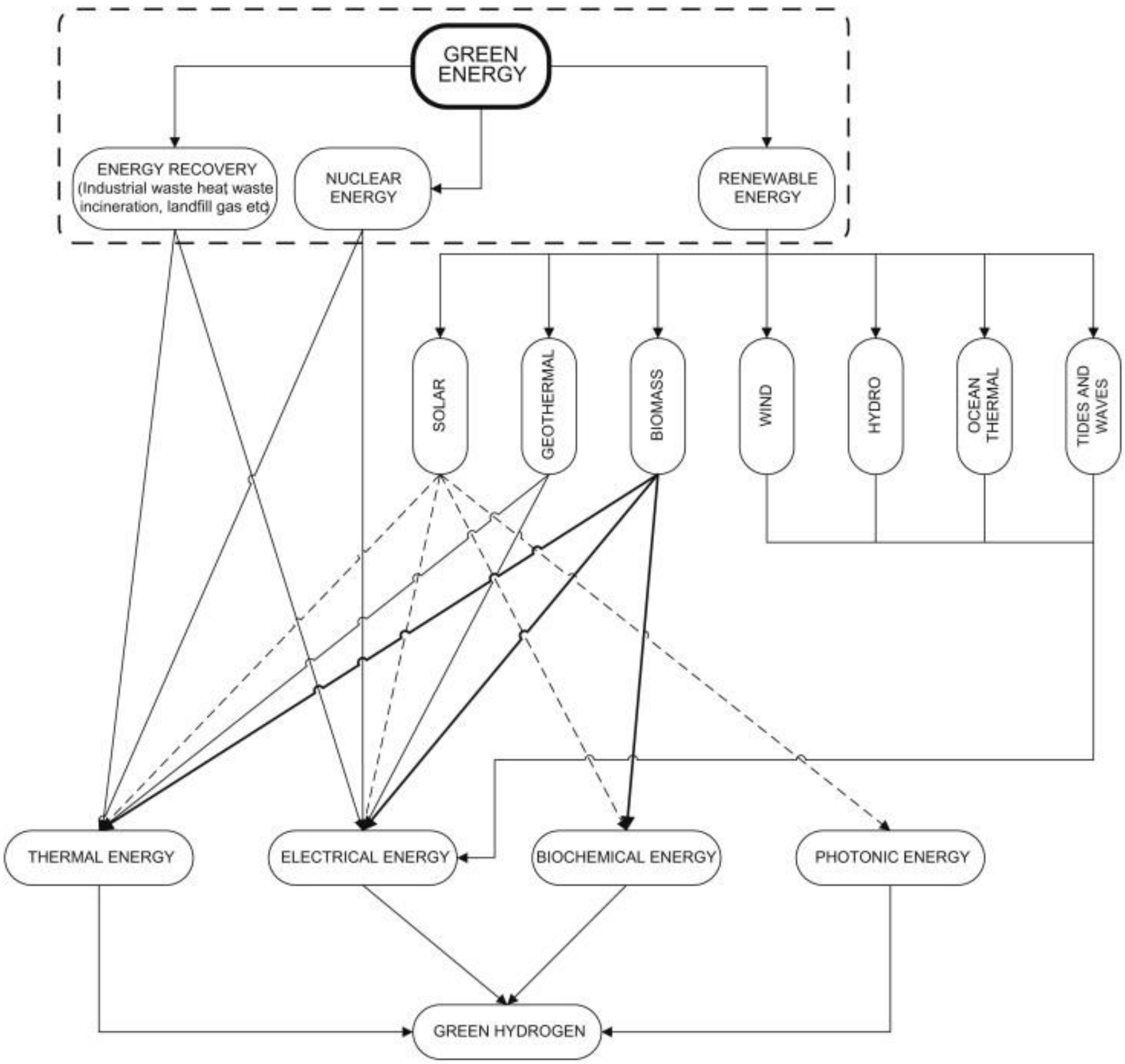

Figure 2.3 Different paths of green production of hydrogen energy (Dincer, 2012)

The photonic energy is produced from solar radiation only. The biochemical energy is the energy stored in organic matter (in form of carbohydrates, glucose and sugars). This type of energy can be manipulated by certain micro-organisms that can extract hydrogen from various substrates, or can be chemically converted to thermal energy. Biochemical energy can be assisted by solar radiation to generate energy, depending on the case (Dincer, 2012).

2.1.2 Hydrogen storage

It is possible to store hydrogen in different forms as mentioned below:

Gaseous hydrogen

To store hydrogen in gaseous form, steel tanks are one of the most common methods; another option that resists higher pressures is light weight composite tanks. Glass microspheres is the most recent method that makes it possible to store hydrogen gas at high pressures (Makridis, 2016).

Liquid hydrogen

Liquid hydrogen can be stored in cryogenic tanks at -252 C (21 K) at ambient pressure. Other options are NaBH4 (sodium borohydride) solutions and rechargeable organic liquids (Dutta, 2014). Makridis (2016) postulates that hydrogen liquefaction consumes huge amounts of energy to reach low temperatures and high pressures. The energy consumption, leakage along with safety issues are among the reasons this option is only used for special applications.

Solid hydrogen

It is possible to state that solid hydrogen storage is the safest and the most efficient way to store hydrogen. There are two common methods to store hydrogen as solid: absorption and adsorption. The first one relies on the formation of a chemical bond between the solid material and a hydrogen atom, chemisorption. This method involves breaking the hydrogen-hydrogen bond, and forming a new hydrogen to solid bond. Being one of the lightest elements, makes hydrogen diffusion exceptionally fast in many materials. This is a big challenge confronting hydrogen energy to be used as a medium for storage (Makridis, 2016).

Chemical and physical storage are other available options. In summary, according to Jain et al. (2013) it is possible to categorize different methods of hydrogen storage as presented in Figure 2.4.

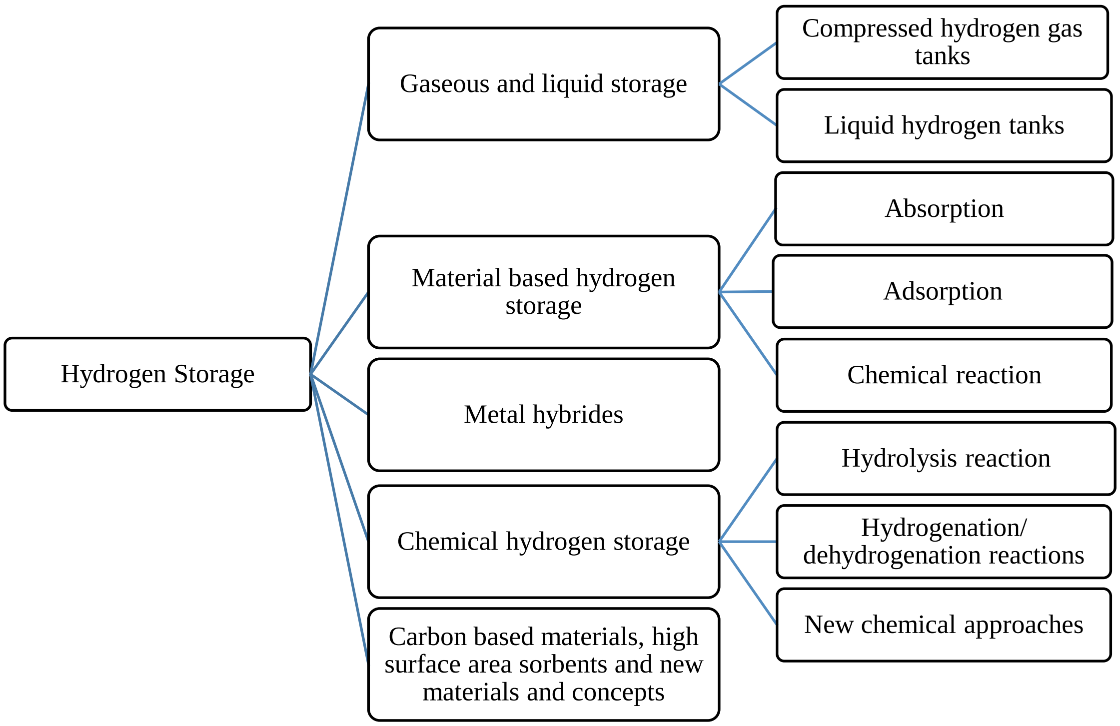

Figure 2.4 Different hydrogen storage methods (Jain et al., 2013)

2.1.3 Hydrogen distribution (transport and delivery)

The hydrogen distribution is highly dependent on the type of hydrogen (gaseous, liquid, etc.) and the available transmission infrastructure. The main available options to transport hydrogen are using high-pressure tube trailers (transporting compressed hydrogen gas) and liquefied hydrogen tankers by using trucks, ships etc. In addition, it is possible to utilize the existing water or gas pipelines.

2.1.4 Hydrogen safety

Safety is a significant issue both technologically and socially. Currently, there are concerns regarding hydrogen flammability. Safety problems can also be observed in high pressures and low temperatures of the currently available high-pressure and cryogenic hydrogen storage methods and fuel cells technology (Edwards et al., 2007). Therefore, it is important to monitor hydrogen refill stations, storage and transportation processes regularly to prevent probable leakages. It is also necessary to provide efficient hydrogen sensors to detect leakages. Since hydrogen is a colorless, odorless and tasteless gas, it is highly permeable and difficult to be detected. There are also concerns about the possible adverse environmental impacts of widespread use of hydrogen. There is no critical evidence to show that hydrogen energy can harm the environment. However, there are concerns that a large volume of hydrogen can change the equilibrium and concentration of constituent components of the stratosphere.

2.1.5 Hydrogen energy applications

It is possible to use hydrogen energy for both transportation and stationary purposes. Figure 2.5 presents various applications of hydrogen energy and put them in different categories as industrial applications, aeronautics, navigation, domestic applications, application for power generation and vehicle applications.

2.2 How to integrate hydrogen energy into the energy systems

One of the most important challenges hydrogen energy encounters, is integration into the energy systems. For example, if it is planned to provide a city with electricity supply from hydrogen energy, how is it possible to integrate and utilize it besides other types of energies? Although innovations play an important role to make the integration process more facilitated and possible, it is necessary to make effective plans and assign comprehensive policies. This makes the transition process easier. Dincer and Acar (2018) define integration as "*a process, which energy systems/subsystems are combined and/or hybridized to achieve better efficiency, cost effectiveness, resources use and environment*". They also mention that to have a truly sustainable hydrogen economy, it is necessary to have sustainable hydrogen production, infrastructure, markets and societal aspects that are integrated and developed interdependently.

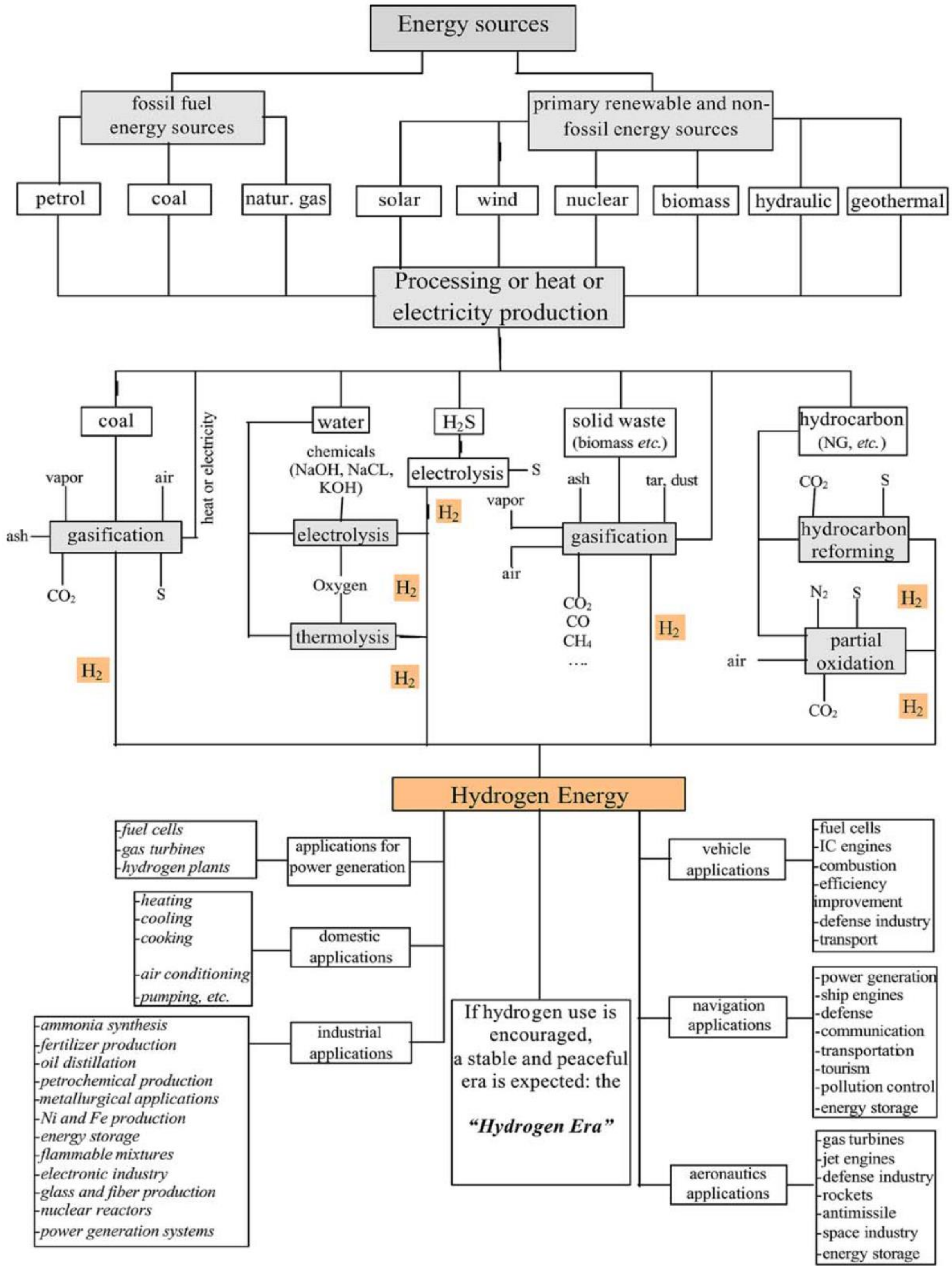

Figure 2.5 Hydrogen energy applications (Midili et al., 2005)

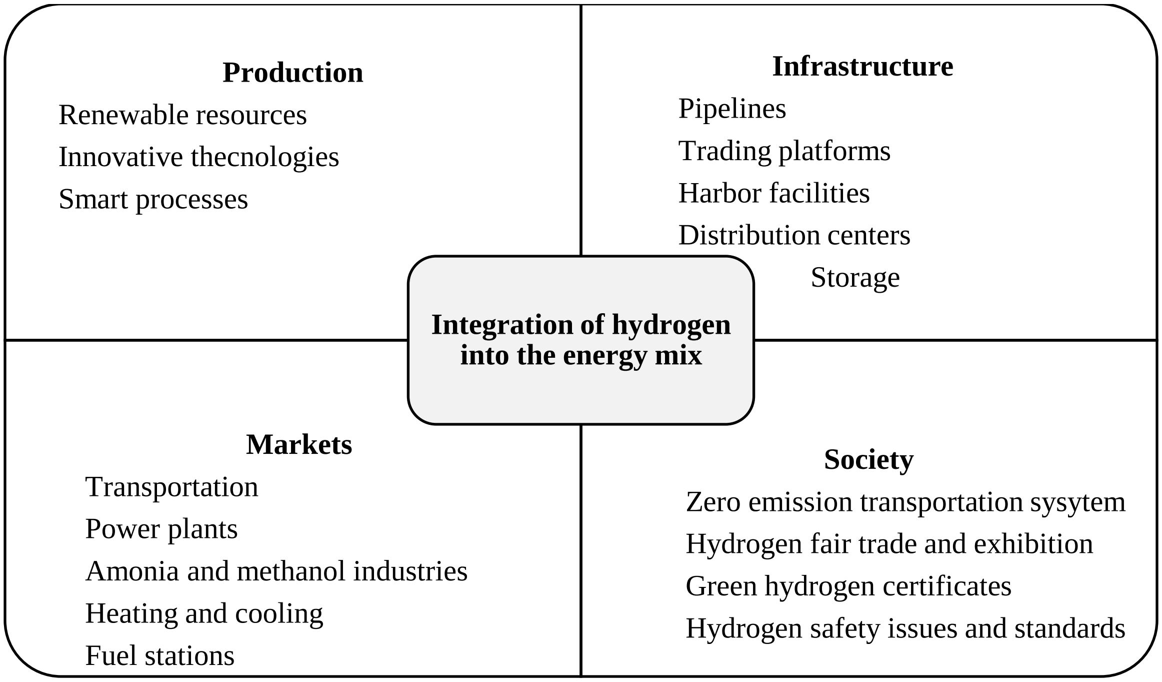

Figure 2.6 Integration framework of hydrogen energy solutions into the future energy systems (Dincer and Acar, 2018)

The model presented in Figure 2.6 displays the importance of prerequisites to popularize hydrogen energy and to make it competitive with fossil fuels. At first, it is important to see whether the country has primary energy sources and required infrastructure to produce clean and renewable hydrogen energy in large scales. Second, the country must develop markets and assign efficient policies, codes and standards to influence the public acceptance positively. In the next part, these different aspects are examined in Norway.

2.3 Domestic hydrogen market in Norway

In 2005, Statkraft, Norsk Hydro and Statoil [1] evaluated the feasibility of hydrogen as a transportation fuel in Norway. The result showed that achieving a zero-emission transportation system in Norway, and shifting to a new source of energy seems reasonable. They asserted that the available bioenergy is not sufficient and it is impossible to cut carbon emissions drastically with hybrid cars. Therefore, it seems hydrogen energy could act as a good solution. Based on their evaluation, by 2050 the hydrogen supply base in Norway would most likely be a mixture of on-site electrolysis, natural gas and by-product hydrogen, plus some gasified biomass (the share of

[1] The company has recently changed name to Equinor (this study was done before this name change).

each strongly depends on technological developments). The overall investment required was assessed (in 2005) at €1.5 billion until 2050 (Fuel cells and Hydrogen in Norway, 2013). In 2003, the Norwegian government appointed a committee to develop a national hydrogen program, with support from the Ministry of Petroleum and Energy and the Ministry of Transport and Communication. The committee set the following goals:

1. Production of hydrogen from natural gas with carbon capture, at a cost that is competitive with petrol or diesel, for use in Europe;

2. Early introduction of hydrogen vehicles in Norway;

3. Development of internationally leading competence in hydrogen storage, with competitive products and services;

4. Development of a ‘hydrogen technology industry’, comprising participation of Norwegian companies in international supply chains for hydrogen technology; the supply of hydrogen refueling stations using electrolysis; competence in the use of fuel cells in ships, and R&D of an international standard in the fields related to hydrogen (Fuel cells and Hydrogen in Norway, 2013).

Annual electricity consumption more or less averages annual production, but import and export through power lines to Sweden, Denmark, Finland, Russia and Holland are significant – directions changing depending on time of the day, season, climate and electricity markets. Norway’s electricity production is around 95% hydroelectric, and price stability and security of supply benefits strongly from interaction with other countries. For this reason, there are plans to construct power connections also to Germany (scheduled operational in 2018) and to England (2021) (Future energy demand in Norway, 2013). The hydrogen development in Norway still needs government financial and political support. It is good to mention that Norway is rich in resources and the country satisfies its citizens’ needs. Therefore, the hydrogen energy can increase their energy supply even more and give them the opportunity to export their surplus energy and get a good position in European energy market. This can be considered as a sustainable and environmental friendly hydrogen energy production motivation. Nevertheless, the focus of Norway’s energy sector is on oil, gas and hydroelectric power and this can reduce stimulations to engage in hydrogen production. Another factor that can affect hydrogen production in Norway is the industrial demand, for example maritime industry or automotive industry. As mentioned earlier, transition to a more sustainable transportation system especially in marine sector increases opportunities to new industries. Therefore, with the surplus energy production, Norway could become a large contributor to the security of the energy in Europe in a sustainable way (Norways, 2009). It is possible to conclude that the main incentive for Norway to invest in hydrogen energy and fuel cell technologies are:

2.3.1 Environmental commitment

Norway's goal is to become a zero emission country in the future. Furthermore, to achieve sustainability it is important to provide a safe and consistent supply of energy. Therefore, the country is searching for a clean and non-nuclear fuel to foster its sustainable growth.

2.3.2 Deregulation of energy markets

Deregulation of domestic energy markets happened in 1990s and changed energy sector completely. In addition, a unified Nordic market for trade in electricity was established. These changes created more competition to address energy demand and stimulated innovations and development to increase the supply of energy.

2.3.3 More consumption of natural gas resources in Norway

Norway is a country rich in natural gas resources and the third exporter of gas in the world. The country is deprived from natural gas resources for its domestic purposes. As a result, there are lots of debates about what is required to be done to develop the industry and create value from it. One of the most recommended ideas is to produce hydrogen energy from natural gas. This is the main reason that there are lots of researches on the hydrogen production from natural gas in Norway.

2.3.4 Hydrogen energy applications in Norway

There are many different applications for hydrogen energy in Norway. The most important applications are utilization of hydrogen energy in transportation sector, in industrial sector and for export.

Hydrogen energy in transportation sector in Norway

Transportation and fast and efficient mobility play an important role in economic growth and there is no doubt that with the increase of population and the importance of high-speed transportation, demand will increase. Unfortunately, transportation is one of the major sources of CO_2 emissions in the world. In Norway, approximately 36 % of the annual CO_2 emissions, close to 17.2 million tons of CO_2 equivalents, are from transportation sector (Norwegian environment agency, 2016). As a result, to achieve the country's environmental objectives it is very important to cut CO_2 emissions. The solution is the shift to a more environmental friendly and efficient transportation system. Norway believes that emissions from transport must be reduced through measures particularly in three areas: technology/fuels, the zero-growth objective for passenger car traffic in urban areas, and improved efficiency/modal shift in freight transport (National transport plan, 2017). Hydrogen vehicles are a reasonable solution for future. Hydrogen seems to be better than the batteries in the more energy intensive and long distance tasks. In this regard, hydrogen can contribute a lot to Norwegian transportation system to reduce CO_2 emissions in heavy transportation vehicles such as busses, trains, ferries, and airplanes.

Hydrogen energy in industrial sector in Norway

There is no doubt that a modern society depends on industrial products such as oil, metals, chemicals and cement. Norwegian industry production contributes 25 % of the nation's GDP and 8 % of its jobs, so it creates value to the society. According to statistics, industrial sector accounts for 50 % of total Norwegian GHG emissions, 23 % from onshore industries and 30 % from the offshore petroleum sector, as a result there is a need to decarbonize the system (Enova, 2017). It seems that the country tries to adopt cleaner technologies and fuels in energy intensive industries to reduce GHG emissions. However, it is necessary to assign more incentives and measures to facilitate the transition. Hydrogen can be used as feedstock in the fertilizer and to some extent in ferroalloy industries, and can replace natural gas in offshore oil and gas and refineries (Enova, 2017). It seems that hydrogen energy can contribute a lot to Norwegian industry and different scenarios for hydrogen energy should be studied.

Hydrogen energy for export

In addition to substantial export of oil and gas, Norway has the potential to become one of the main exporters of renewable and clean electricity, produced from wind and hydropower to European Union to make the supply of energy secure. Hydrogen energy enables Norway to produce more electricity and to integrate more renewable energies into their energy system with less harm to the environment. In addition, export of hydrogen from renewable electricity by hydrogen pipelines and ships appeared energetically and economically interesting against the direct export of electricity through high-voltage direct current lines (Norways, 2009). Furthermore, there is the possibility to export hydrogen technologies to other countries since Norway has a very strong position in hydrogen energy research and development.

2.3.5 Hydrogen energy infrastructures in Norway

One of the most important hydrogen energy infrastructures is pipeline to transport it to different stations. However, it should be mentioned that type of transportation and refueling stations depend on access to on-site hydrogen, the production method and storage method. Due to geographic characteristic of Norway, it is most preferable to produce hydrogen on-site. As a result, there is no need for long distance pipelines. The first prototype hydrogen stations in Norway opened in the period 2006-2012. After that, valuable competence from the operation and maintenance of the station network has been accumulated, and the stations continued to be operated and further developed by the world's first dedicated hydrogen station operation company, HYOP (Hydrogen guid, 2017). HYOP is establishing a robust hydrogen infrastructure to facilitate the introduction of hydrogen cars in eastern Norway. It operates four hydrogen stations in Oslo suburbs at Økern and Gaustad, 150 km to the south at Herøya in Porsgrunn, and 50 km to the north at Oslo Airport in Gardermoen. During 2015, HYOP moved some of its stations to allow site expansion and to be able to serve a larger fleet of hydrogen cars (Fuel cells bulletin, 2015). Installation of the first operating stations happened with the help and financial supports from regional municipalities and authorities. With the early adopter experience and the long-term know-how on hydrogen technology in Norway, the last years have led to a massive ramp-up of industrial and investor interest and engagement. One hydrogen station was built in autumn 2016 in Bærum Municipality in the western Oslo metropolitan area including an innovative integration of surplus solar energy converted to hydrogen, and an additional eight other stations were planned installed in the major cities within 2017. The next cities on the list are Bergen and Trondheim (Hydrogen guide, 2017). Another hydrogen station opened in Bærum in December 2017. The station is at Høvik, and is operated by HYOP (Norwegian hydrogen forum, 2018). In Figure 2.7, six of available hydrogen refueling stations are presented with their hydrogen resource.

Location	Operated by	In operation	H_2 source
Oslo HyNor, Økern	HYOP	May 2009	Trucked-in hydrogen from electrolysis
H2 moves Oslo Gaustad	HYOP	November 2011	Electrolysis on-site
Oslo Bus station CHIC	Air Liquide	April 2013	Electrolysis on-site
Drammen, Kjellstad	HYOP	May 2009	Trucked-in hydrogen from electrolysis
Lillestrøm, Kjeller	HYOP	June 2012	Electrolysis, steam reforming - on-site via solar PV; reforming of land fill gas
Porsgrunn, Herøya	HYOP	June 2007	By-product from chlorine production delivered via pipeline
HyNor Stavanger	Statoil	October 2006 – December 2011	CGH2 delivery by AGA from Sweden, based on electrolysis

Figure 2.7 Overview of a number of available refueling stations in Norway (Skordato and Klitkou, 2014)

3 Methodological Framework

The methodological framework for the conducted research is presented in this chapter. The purpose of this chapter is to show the research process and explain how the data is collected. Literature survey is performed and research strategy is chosen in this research.

3.1 Mixed methods research

In this research, to do an efficient economic assessment of hydrogen energy in Norway and answer the research questions presented in chapter 1, a mixed method approach is used. This method is chosen after literature review and comprehensive evaluation of the research issue. Mixed methods research enables the researcher to answer research questions by adopting a research strategy that employs more than one type of research method. The methods may be a mix of qualitative and quantitative methods, a mix of quantitative methods or a mix of qualitative methods. Quantitative research involves the collection and analysis of numerical data. However, qualitative research considers narrative data. In this research, qualitative and quantitative methods are used to study the topic comprehensively. Bryman (2008) refers to a mixed method as "*multi strategy research*" since in this type of research, researcher works with different types of data, investigators and even sometimes different research paradigms. It should be noted that there are differences between a mixed method and a multi-method research. As Halcomb and hickman (2015) postulated, in contrast to multi-method research, which has only the advantage of collecting data using multiple methods, mixed methods research has the potential to combine qualitative and quantitative characteristics across the research process, from the philosophical underpinnings to the data collection, analysis and interpretation phases. To do a comprehensive evaluation of hydrogen economy, it is important to consider different aspects of hydrogen energy and how the shift to a new fuel can affect the society. Therefore, the research should be based on both pragmatism and social constructionism. In addition, Easterby-Smith et al. (2012) illustrated that a mixed method approach can increase the confidence and credibility of the results and consequently enhance validity of the findings. This is the main reason that in this master thesis, a mix methodology is chosen. The qualitative approach is used for in-depth understanding of the research topic, determining relevant SDGs, studying the hydrogen market, discovering important factors in the market, clarifying the important stakeholders and their positions in the market and analyzing the strengths, weaknesses, opportunities and threats of this new market in Norway. The quantitative approach is used to perform a cost analysis for different hydrogen production methods. The aim is to link these two methods and give recommendations for relevant stakeholders and policy makers. The research strategy is designed based on the mixed approach presented in Figure 3. 1.

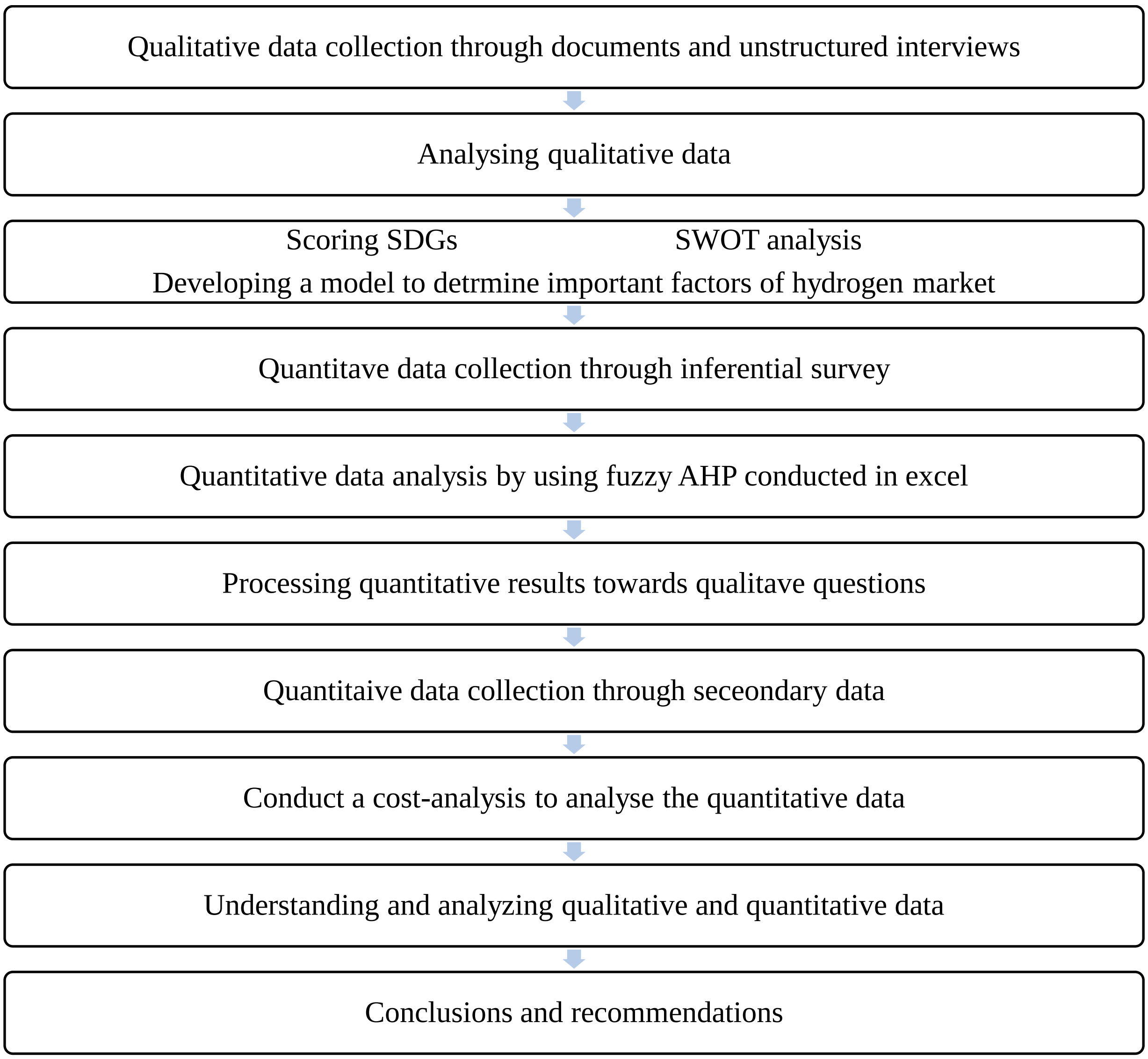

Figure 3.1 Research strategy

3.2 Research model

To address the research questions and issue in this thesis, it is better to combine theoretical and empirical framework of the research, as illustrated in Figure 3. 2. Abduction method can be considered as a continuous problem solving process. Several previous studies about hydrogen energy used this methodology as well. As a result, this thesis moves from theoretical framework that is based on sustainable development, stakeholder and market theory to the hypothesis that hydrogen energy is beneficial for Norway. The findings of the research result in the emergence of new questions that need to be addressed as this process continues to create strong perspectives on the subject and give conclusions. This process is conducted by the model presented in Figure 3. 3 This model was inspired by Davis (1998) in "*business research for decision making*". The figure presents different research pieces that constitute this thesis. According to Davis (1998), this model has five pieces: "*observation, context, concept, construct and conclusion*". There are also three types of arrows to show different kinds of connection, direct, indirect and hypothetical relationships between the processes. Based on these connections and relationships between different pieces of the research, new research questions emerge that may result in the change or adaptation of theories and themes as the research progresses. (possibility of change is illustrated in Figure 3.3, as well)

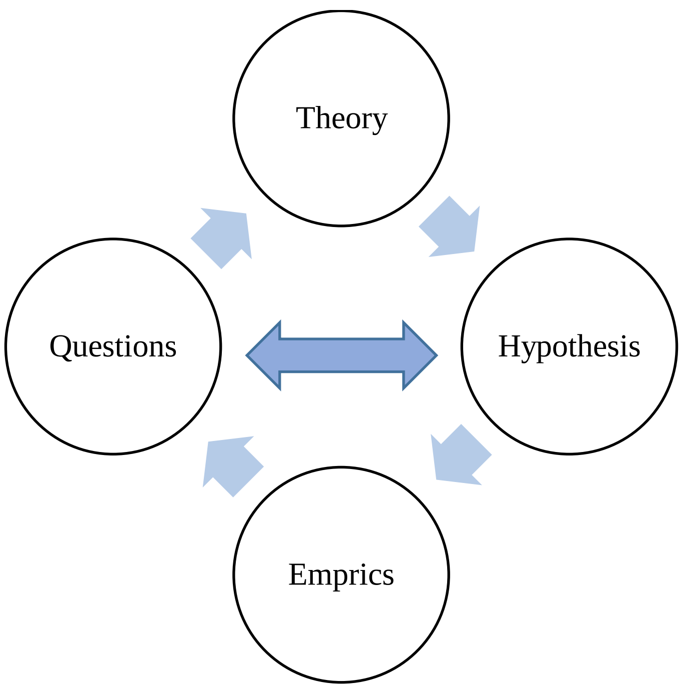

Figure 3.2 The abduction process (adopted from Jensen, 2008)

Different chapters of this thesis are formed based on this model and the relationships[2] between different pieces of the research and the process from observations to conclusions is obvious.

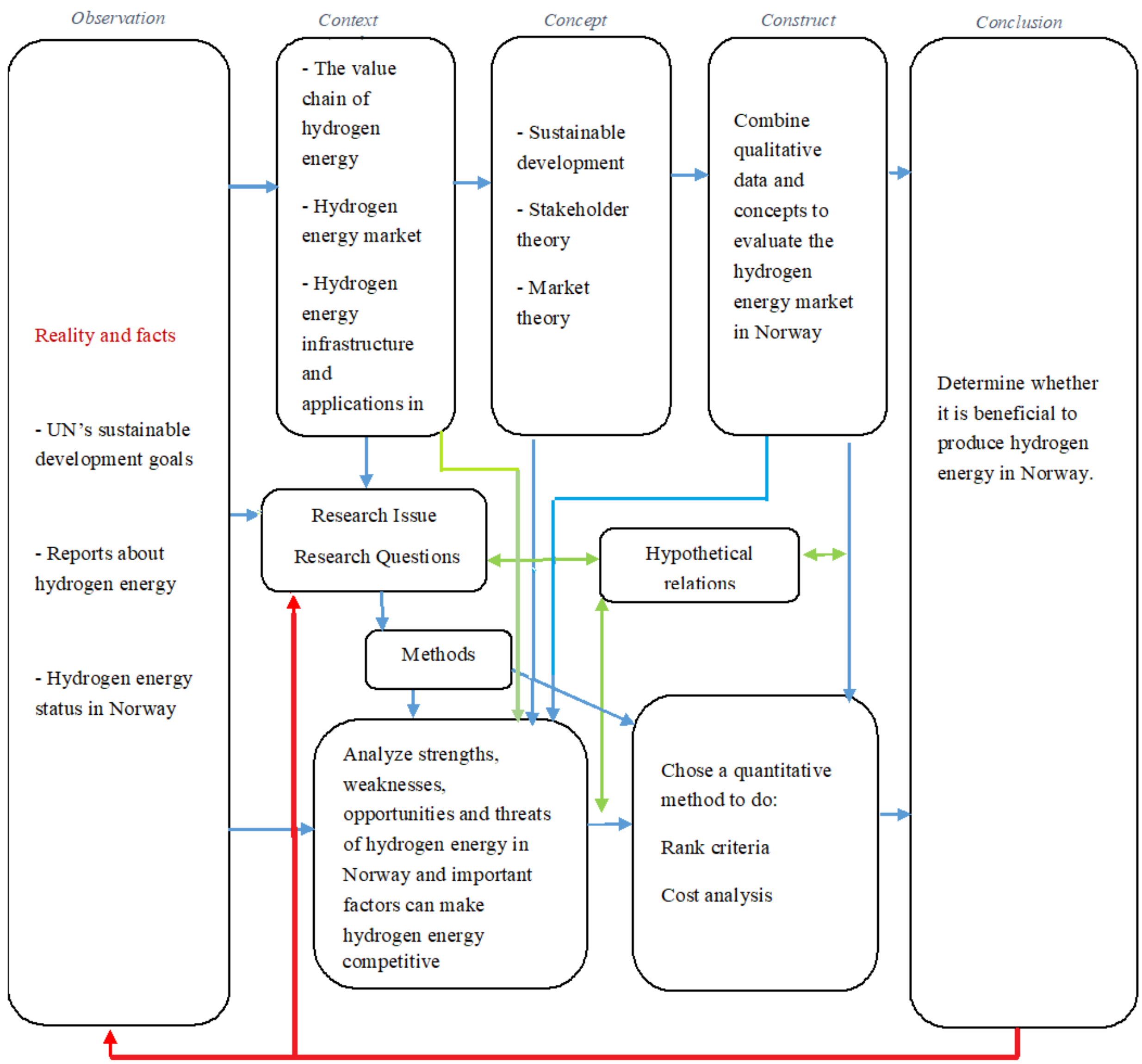

Figure 3.3 Research model (adopted from Davis, 1998)

[2] Blue: direct relations, red: indirect relations and green: hypothetical relations

3.3 Data collection method

In this thesis, both qualitative and quantitative approaches are used as explained bellow:

3.3.1 Qualitative data collection

The qualitative data collection methods applied are secondary literature and unstructured interviews with relevant stakeholders.

Secondary literature

This study relies on secondary literatures, journal articles and online scientific databases and webpages including Scopus, Science Direct, Google Scholar and Research gate. In addition, a large number of published reports and documents from Norwegian government, United Nations, International Energy Agency and many important research and development institutes that are relevant to hydrogen energy including SINTEF, Norwegian Research Council, Norwegian University of Science and Technology and Norwegian Hydrogen Forum are used in this research. All of these institutions are well distinguished; therefore, their publications and reports are considered as trustworthy sources of information, and it is possible to use them in a scientific research. The searches for this study were based on the keywords such as SDG implementation, sustainable development, renewable energies, hydrogen energy, hydrogen market, hydrogen energy production, advantages and disadvantages of hydrogen energy, Norway's energy policies and prioritized SDGs, shifting to hydrogen energy and hydrogen energy stakeholders. All of these literatures helped strengthen the empirical data collection and are considered important and beneficial to combine several sources of data to obtain better understanding and knowledge about the research topic to answer the research questions. For example, reviewing the work done by Sachs (2015), Griggs et al. (2013), and Porter and Kramer (2006) contributed to better understanding of sustainable development. Furthermore, documents such as Norwegian Hydrogen Guide (2017) and Fuel Cells and Hydrogen in Norway (2013) give the researcher critical information about Norway's hydrogen energy market, infrastructure and status. By using this type of data, the theoretical basis of the thesis is formed, the hydrogen market is evaluated and its strengths, weaknesses, opportunities and threats are identified. In addition, this data was useful to identify important factors of the model presented in chapter 4, to make questionnaires and to verify the data from interviews.

Unstructured interviews

To answer the new questions emerged during the research and to develop knowledge about the research topic, unstructured interviews are applied. According to Bryman and Bell (2007), in an unstructured interview the researcher has an interview guide with pre-prepared topics for research, but the structure can vary from interview to interview. These interviews are usually conducted as an informal questioning between the interviewer and the interviewee. Unstructured interviews were employed in this thesis to obtain personal viewpoints as well as scientific information about hydrogen energy, challenges, opportunities and stakeholders. All of the interviewees were experts on the research topic. Interviews were done in person and most of them were performed during an international hydrogen and fuel cell conference, H2 conference in Trondheim, Norway, May 14-15, 2018.

A combination of these qualitative data collection were very useful to understand how United Nations SDGs can be useful in shifting to renewable energies, the current status of hydrogen market in Norway, its strengths and weaknesses, the potential market stakeholders and the necessity of efficient policies and government supports in commercialization of hydrogen energy in Norway.

3.3.2 Quantitative data collection

Quantitative data collection was necessary in this thesis to prioritize the results from the SWOT analysis, to prioritize different factors of the presented model that influence the hydrogen market and to conduct a cost-analysis.

Data collection for prioritization

The chosen method for prioritization in this thesis is based on one of multi criteria decision-making (MCDM) techniques that is called fuzzy AHP. The common process to collect data in this method is creating questionnaires. Bailey (1987) illustrates that to create a questionnaire it is important to pay attention to: "*the relevance of the objectives of the study to practice; the relevance of the questions to the objectives of the study; and the relevance of the questions to the individual respondent"*. It has been tried to consider these important factors to create a questionnaire for this research. As a result, after choosing the right variables through literature review and interviews, the required hierarchy is built. Then, based on the hierarchy and Saaty (1980) scale, questionnaires are developed. Afterwards, ten experts (related to hydrogen market) were chosen and were asked to fill the questionnaires. They filled out the questionnaires according to the instructions given to them to make comparison between different factors of the model. The questionnaire sample is presented in Appendix C.

Data collection for cost-analysis

To do a cost analysis in this research, at first it was necessary to determine the required variables. This is done through a literature review and it is mainly based on Ramsden et al. (2009), Peters and Timmerhaus (2006), Norways (2009), Thengane et al. (2014). The important variables to conduct the cost analysis are plant capacity, capital cost, variable and fixed operating cost, plant chemical index and consumer price index. These data are collected from the literature: Ramsden et al. (2009), and statistics Norway.

Sample

Interviewees and respondents were chosen during the H_2 conference in Trondheim, based on their knowledge and relation to the research topic.

3.4 Qualitative data analysis

3.4.1 Scoring SDGs methodology

After collecting the required data from literature reviews to examine the contribution of hydrogen energy to the achievement of United Nations' sustainable development goals, the interactions between SDGs are examined. The trade-off between SDGs is evaluated based on the methodology proposed by ICSU (2017). According to this methodology, interactions between SDGs should be examined and scored based on the criteria presented in Table 3.1.

According to ICSU (2017), "*the framework identifies categories of causal and functional relations underlying progress or achievement of goals and targets. The scale ranges from -3 to +3, from instances where progress on one target acts to cancel progress on another to where progress on one goal is inextricably linked to progress on another*". In this method, entry goals (the goals that are important to be achieved for the study) are selected and based on different dimensions, their trade-offs with other goals are evaluated.

Table 3.1 Seven scale goal scoring guidance (adopted from ICSU, 2017)

Interaction	Name	Explanation
+3	Indivisible	Inextricably linked to the achievement of another goal.
+2	Reinforcing	Directly aids the achievement of another goal.
+1	Enabling	The pursuit of one objective helps the achievement of the other objective.
0	Consistent	No significant positive or negative interactions.
-1	Constraining	Limits options on another goal.
-2	Counteracting	Clashes with another goal.
-3	Cancelling	Makes it impossible to reach another goal.

3.4.2 SWOT analysis methodology

SWOT analytical method is mostly used to formulate strategy by constituting an important fundament for learning the situation of the studied object and for designing future strategies to solve the existing problems (Ren et al., 2015). SWOT analysis gives a general overview of characteristics of a business and its environment. Analyzing the external (not controllable by the business) opportunities and threats as well as the internal (controllable by the business) strengths and weaknesses of the business plays a significant role in strategy formulation and development of that business, especially in a high market competition. Riston (2008) presented the process of SWOT analysis. The process demonstrated in Figure 3.4 is useful to identify strengths, weaknesses, opportunities and threats of a market to be put in the SWOT analysis matrix presented by SWOT manual (2013), as illustrated in Figure 3.5.

Barney (1991) indicated that SWOT analysis enables a company to enhance its performance only when their current strategies utilize new opportunities or neutralize potential threats. Therefore, these analyses could be useful to make better decisions and help decision-makers and stakeholders have better overview of the market to improve the current situation. As a result, SWOT analysis can be considered as an appropriate tool in this research to identify significant factors in the hydrogen market, status of the market and the possible changes and improvements.

The focus of this thesis is on hydrogen market and as mentioned earlier the purpose of hydrogen economy is to produce hydrogen from carbon-dioxide-free sources and use it as an alternative fuel for transport and stationary applications. The aim of the analysis in this thesis is to summarize the empirical findings and to help decision makers and stakeholders in the hydrogen economy better understand the situation of the market in Norway.

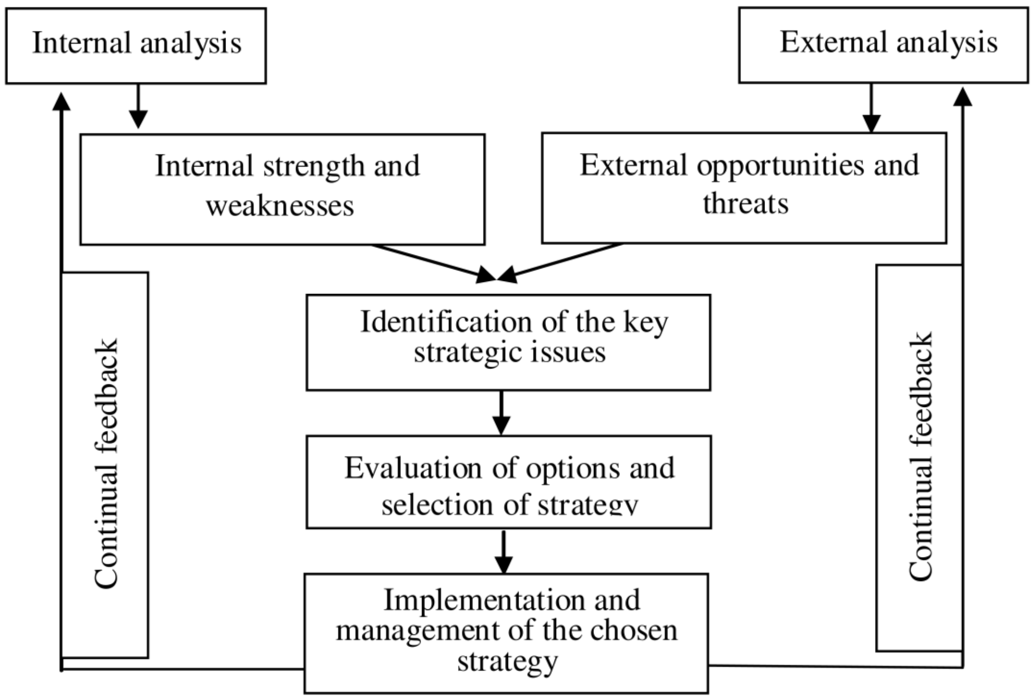

Figure 3.4 The SWOT process (Riston, 2008)

	Strengths what the unit does very well *internally*	**Weaknesses** where functions are performed *internally* less than preferred
Opportunities potentially favorable *external* conditions for the unit	S&O: Pursue opportunities that are a good fit with the program's strengths.	W-O: Overcome weaknesses to pursue opportunities
Threats potentially unfavorable *external* conditions for the unit	S-T: Identify ways the program can use its strengths to reduce its vulnerability to external threats.	W-T: Establish a defensive plan to prevent the program's weaknesses from making it highly susceptible to external threats.

Figure 3.5 SWOT analysis matrix (SWOT manual, 2013)

To conduct a SWOT analysis in this survey, the following steps are employed:

Step 1: Material and data collection: To have a better understanding of hydrogen energy and market status in Norway, books, articles, legislations and reports about hydrogen energy in Norway are collected and reviewed.

Step 2: Interviews with a number of experts and PhD students concerning the research topic.

Step 3: Based on the obtained results from previous steps, all the significant factors about strengths, weaknesses, opportunities and threats are discussed, categorized and formed the SWOT matrix.

Step 4: In this step, SWOT matrix is utilized to identify strengths–opportunities (SO) strategies, weaknesses–opportunities (WO) strategies, strengths–threats (ST) strategies and weaknesses–threats (WT) strategies, as illustrated in Figure 14.

To create *SO strategies*, internal strengths are matched with external opportunities, and strengths are used to take advantages of opportunities. *WO strategies* are obtained by matching internal weaknesses with external opportunities, and overcoming the weaknesses by taking advantages of opportunities. In order to identify *ST strategies*, internal strengths are matched with external threats, and strengths are utilized to avoid threats. At the end, to achieve *WT strategies*, internal weaknesses are matched with external threats, and weaknesses are minimized to avoid threats. (Whalley, 2010 and Ren et al., 2015)

3.5 Quantitative data analysis

3.5.1 MCDM techniques

After literature review and unstructured interviews, the qualitative data is analyzed by SWOT method. Strengths, weaknesses, opportunities and threats are determined. To have a better judgment, it is better to rank them. In addition, to prioritize important factors that can make hydrogen energy market successful in Norway, a method is required. The multi-criteria decision making (MCDM) is one of the useful tools for analyzing complex problems with the potential to critically analyze the alternatives for different criteria to select the best/suitable alternative(s). MCDM is a combination of qualitative and quantitative method. any relevant studies are investigated and it has been clear that they used this methodology as well. For example, Thengane et al. (2014) used this method to conduct a cost-benefit analysis for different methods of hydrogen production. For this study, the Analytic Hierarchy Process (AHP) proposed by Saaty (198S0) is chosen. This method is a very popular approach to MCDM that can take care of both quantitative and qualitative criteria. In a general AHP model, the objective is in the first level, the criteria and sub-criteria are in the second and third levels, respectively. This model has been improved by fuzzy logic approach to include vagueness for personal judgement (Ahyan, 2013). Fuzzy AHP represents the elaboration of a standard AHP method into fuzzy domain using fuzzy numbers for calculating instead of real numbers (Ahyan, 2013 and Petkovik, 2012). In Fuzzy AHP, linguistic variables are used to make the pair-wise comparisons of criteria, which are represented by triangular numbers. Saaty (1980) fuzzy triangular numbers that are used in this work to form questionnaires and determine the experts' preferences are presented in Figure 3.6. To make the method more practical, Chang (1996) introduced a new method related with the usage of triangular numbers in pair-wise comparisons.

Saaty scale	Definition	Fuzzy Triangular Scale
1	Equally important (Eq. Imp.)	(1, 1, 1)
3	Weakly important (W. Imp.)	(2, 3, 4)
5	Fairly important (F. Imp.)	(4, 5, 6)
7	Strongly important (S. Imp.)	(6, 7, 8)
9	Absolutely important (A. Imp.)	(9, 9, 9)
2	The intermittent values between two adjacent scales	(1, 2, 3)
4		(3, 4, 5)
6		(5, 6, 7)
8		(7, 8, 9)

Figure 3.6 Linguistic terms and corresponding fuzzy numbers (Ahyan, 2013)

To conduct the fuzzy AHP method these steps are used:

- Different criteria based on literature review and experts' opinions are identified.
- The hierarchy of criteria is designed.
- Questionnaires of fuzzy AHP are designed.
- Convert the raw data of questionnaires to fuzzy triangular numbers

- According to averaged preferences, pair-wise contribution matrices are formed
- The geometric mean of fuzzy comparison values of each criterion is calculated
- The fuzzy weights of each criterion is found.
- The numbers are de-fuzzified by center of area method proposed by Chou and Chang (2008)
- De-fuzzified numbers are normalized
- Weight of each criteria is calculated and criteria are ranked based on their weights

These steps help determining the best criteria that gained the highest rank. The results are useful for decision makers to choose the best strategies to achieve their desired goals. The extended mathematical calculations for each step are given in the Appendix B. Figure 3.7 presents the hierarchy created for the model of the study.

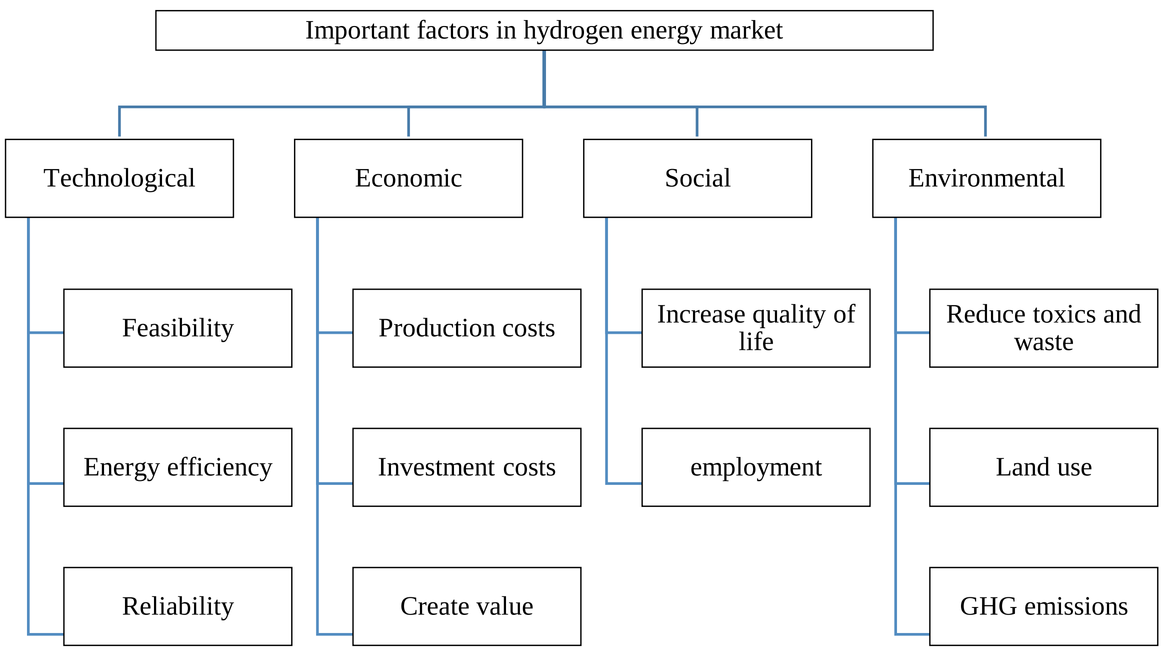

Figure 3.7 The hierarchy of the model for the study that is presented in chapter 5

3.5.2 Cost analysis

The author chose the methodology for cost analysis according to the availability of the data and the research objectives. This methodology is used in many researches to perform an efficient cost analysis of various projects. The aim of this cost analysis is to evaluate different production costs of hydrogen energy under different scenarios. It should be mentioned that environmental, social, transportation and storage costs are not considered in this survey due to lack of reliable data. In addition, the author assumed that the most important factor in commercialization of hydrogen energy is its production costs (infrastructure, investment cost, etc.). As a result, different production scenarios and their costs are evaluated based on the availability of data. However, the focus of the thesis is on green hydrogen production; both renewable and non-renewable production methods are examined to create stronger perspectives and conclusions. The most important costs in the production of hydrogen energy are capital cost, the fixed operating cost and variable operating cost (Ramsden and et al., 2009).

The data collected for this analysis are secondary and from different literature reviews and consequently from different years. To make the data comparable, it is very important to create all the data in a specific year, that is 2017 in this research. To calculate the capital cost in present[3], it is important to use chemical engineering index: (Peters and Timmerhaus, 2006 and Thengane et al., 2014)

$$Cp = Ci\ (Ip/Ii) \quad (3.1)$$

In this formula, **Cp** is the present capital cost, **Ci** is the initial capital cost (i.e., cost for the year the data were collected), and **I** is the chemical engineering plant cost index. The sum of cost of labor, property taxes, insurance, and administrative expenses in the hydrogen production process form fixed capital cost, and variable costs include the cost of feedstock, utilities, electricity, waste treatment, and some other miscellaneous costs (Ramsden and et al., 2009 and Thengane et al., 2014). To estimate the operating costs in the present year, price index is used as it is shown in Equation (3.2).

$$Op = Oi\ (Pp/Pi) \quad (3.2)$$

[3] 2017 is considered as the present year based on the availability of required indices for calculations.

In Equation 3.2, **Op** is the present operating cost, and **Oi** is the initial operating cost (i.e., cost for the year the data were collected), and **P** is the consumer price index. It is important to mention that these data are from different plants with different capacities; therefore, to have a better comparison it is better to covert the data for the same plant capacity. To do this, Peters and Timmerhaus (2006) recommend using six-tenths factor rule as presented in Equation 3.3 to calculate the costs of plant with new capacity:

$$\text{Cost of plant with new capacity} = (\text{Cost of plant with initial capacity}) \times R^{f} \qquad (3.3)$$

In this equation, **R** is the ratio of new plant capacity to the known capacity and value of the factor **f** is 0.6.

The next step is to annualize all costs to categorize them with constant units. As a result, the equivalent annual cost (EAC), the cost per year of owning and operating an asset over its entire lifespan should be calculated: (Thengane et al., 2014)

$$EAC=NPV \times CRF(r,t) \qquad (3.4)$$

Where **NPV** is the net present value of a project, and **CRF** is the capital recovery factor for an economic lifetime **t** and discount rate **r** defined by Equation (3.5):

$$CRF(r,t)= r(r+1)^{t}/(r+1)^{t} - 1 \qquad (3.5)$$

The fixed and variable operating costs are reported on annual basis whereas the capital cost is not significantly dependent on the plant life. Hence, in this study, the plant economic life is assumed to be 20 years with a discount rate of 5 % for all the technologies. Assuming the fixed operating costs are on a real value basis, thus constant over the plant life, the equivalent annual cost is calculated as:

$$EAC= (\text{Capital Cost} \times CRF(r,t)) + \text{Fixed operating cost} + \text{Variable operating cost} \qquad (3.6)$$

The aim of this cost analysis is to evaluate the cost of large-scale (both central and on-site) hydrogen energy production with different scenarios. Based on the plant capacity reviews, the plant capacity of 500 tons of hydrogen per day is chosen. The interest rate is assumed to be 10 % in this study. Because there are uncertainties about hydrogen energy and it is risky to enter this market and produce hydrogen, this interest rate seems reasonable.

3.6 Research ethics

Bryman and Bell (2007) presented four main areas within ethical values of research. These areas are: harm to participants, deficiency of informed consent, invasion of privacy and involved deception. To prevent any of these to happen, the researcher followed all the required instructions to do a scientific research and interview. At first, to avoid any harm to the participants, they are fully aware about their participation in this study and they had the opportunity to withdraw if they wished to. Furthermore, before the interview started, the researcher and participant agreed on how they wished to be referred to in this survey. In addition, the researcher respected the dignity of participants and tried to do interviews in a comfortable but engaging and motivating atmosphere. To ensure a complete consent of the participants, they were given whatever information they needed about the research method to fill out the questionnaires. Another important issue is confidentiality and anonymity when conducting a secondary analysis of qualitative data to prevent any damage to the privacy of the participants. Transcripts and field notes should only be presented in a way that will prevent individuals or places from being identified (Bryman and Bell, 2007). In this thesis, the researcher respected this rule completely and there was a focus on anonymity, the only person with access to the conducted data was the researcher. The last factor involved is deception. Bryman and Bell (2007) illustrate that deception can occur in various degrees within a research, mostly because researchers want to limit the participant's understanding and knowledge of the research. To prevent this to happen as mentioned earlier, the researcher tried to give all the information to the participants and the aim is to make better understanding and clarification of hydrogen energy and its market. Furthermore, all the collected data from secondary sources used in this study, are referred to or are mentioned in the reference list at the end of the thesis. No other sensitive issues were considered to be related to this study.

3.7 Reliability and validity

Reliability and validity of the research are very important since they strengthen the quality of the research and its conclusions and findings. Reliability of a research makes it possible to replicate the results, when the same methods are utilized. Bryman and Bell (2007) mention three important factors in the reliability of a measure: stability, internal reliability and inter-observer consistency. To increase the reliability of this research, the researcher attempts to explain every part of the research precisely and in depth to show the study design and objectives and how methods are used to answer research questions. In addition, several methods are used for data collection such as interviews, questionnaires, literature reviews and statistic websites. To increase the internal reliability of the research, the author tried to choose the best method that is consistent with the research objectives and conclusions. For interviews and questionnaires, the researcher selected a group of participants with excellent knowledge about hydrogen energy, its challenges and opportunities. It should be noted that research questions and objectives are developed under the supervision of the academic supervisor of this master thesis. Different parts of the research are designed through deep discussions to prevent the pre-developed perceptions influence the thesis.

The validity refers to the integrity of how the findings have been derived, how credible the conclusions are, how the analysis has been conducted and how the researcher has chosen to interpret the data. Therefore, researcher and research participants play an important role in building validity in the different phases of the research from data collection to data analysis and interpretation. There are different instruments for collecting the data and conducting the analysis. Since the quality of these tools influence the results and validity of the research, it is very important to choose the best instruments. To increase the content validity, the researcher reviewed the research questions and data with the help of academic supervisor to prevent anything vague or not answered in the survey. In addition, since research participants are considered experts in this topic, the researcher used their viewpoints to enhance the quality of the research. In addition, as mentioned earlier several data collection methods are used that increase the validity of this research. In the end, it should be noted that all the important issues regarding reliability and validity are carefully considered in this master thesis and the participants were given the opportunity to review the results if they requested.

4 Theoretical Framework

The most relevant theoretical resources and framework for the analysis of the research issue are presented in this chapter. The theoretical concepts discussed are sustainable development, stakeholder theory and market theory.

4.1 Sustainable development

Brundtland Commission report in 1987 emphasized on the importance of the sustainable development concept and defined it as "*seeking to meet the needs and aspirations of the present without compromising the ability to meet those of the future*" (Griggs et al., 2013). Sustainability and sustainable development are two different concepts that are sometimes used interchangeably. Sustainability is "*a process and mechanism to achieve the intended sustainable development*", but sustainable development is "*a process of intentional change and improvement*" (Senge et al., 2007). They presented three different world views about sustainability. These views are: "*rationalism*" that recognizes the need for efficient utilization of resources througth *meeting the needs of the present without compromising the ability of future generations to meet their own needs;* "*naturalism"* that emphasizes on the importance of *bringing industrial systems into harmony with nature by not depleting resources beyond their rates of regeneration*, and "*humanism"*, that believes *sustainability depends on an intrinsic human desire to be part of healthy communities that preserve life for ourselves, other species and future generations*."

Griggs et al. (2013) define sustainable development in the Anthropocene as "*development that meets the needs of the present while safeguarding Earth's life support system, on which the welfare of current and future generations depends*". Sustainable development is multidimensional and its three important pillars are economic, environmental and social. Environmental sustainability is about restricting human activity within the carrying capacity of the ecosystem (such as materials, energy, land, water, etc.). It makes efforts to improve the quality of life for people equally. The economic sustainability considers the efficient use of resources to enhance operational profit and maximize market value. The social sustainability focuses on the social well-being of the population, balancing the need of an individual with the need for the group (equity), public awareness and cohesion, and participation and utilization of local labors and firms. Ehrenfeld (2005) postulates that sustainable development and economic development are not the same and explain how economic development itself is undermining the very roots of sustainability. Instead of being an appropriate market mechanism for creating human satisfaction, consumption has become a central cause of unsustainability in both environmental and human terms. Efforts to foster development put more pressure on earth and increase risks of widespread, abrupt and possibly irreversible changes to basic earth-system processes such as water shortages, extreme weather, deteriorating conditions for food production, ecosystem loss, ocean acidification and sea-level. These negative consequences not only threaten development, but also create humanitarian crises across the globe. To prevent this, it is very important for businesses to follow SDGs and persue a multi-stakeholder approach, collaborate and try to achieve development by using sustainable approaches. As a result, it can be stated that sustainable development is both a problem and a solution. Ehrenfeld (2005) believes to achieve sustainable development, managers and business owners must evaluate critically the core values and mission of their business in terms of both the unsustainability and the sustainability they create. They should know that reducing sustainability and creating sustainability are two different concepts.

Griggs et al. (2013) showed that to achieve sustainable development, it is important to create goals by considering people and planet. They use the equation “Planet + People = SDGs”, that is shown in Figure 4.1 and make efforts to show the complexities in this system.

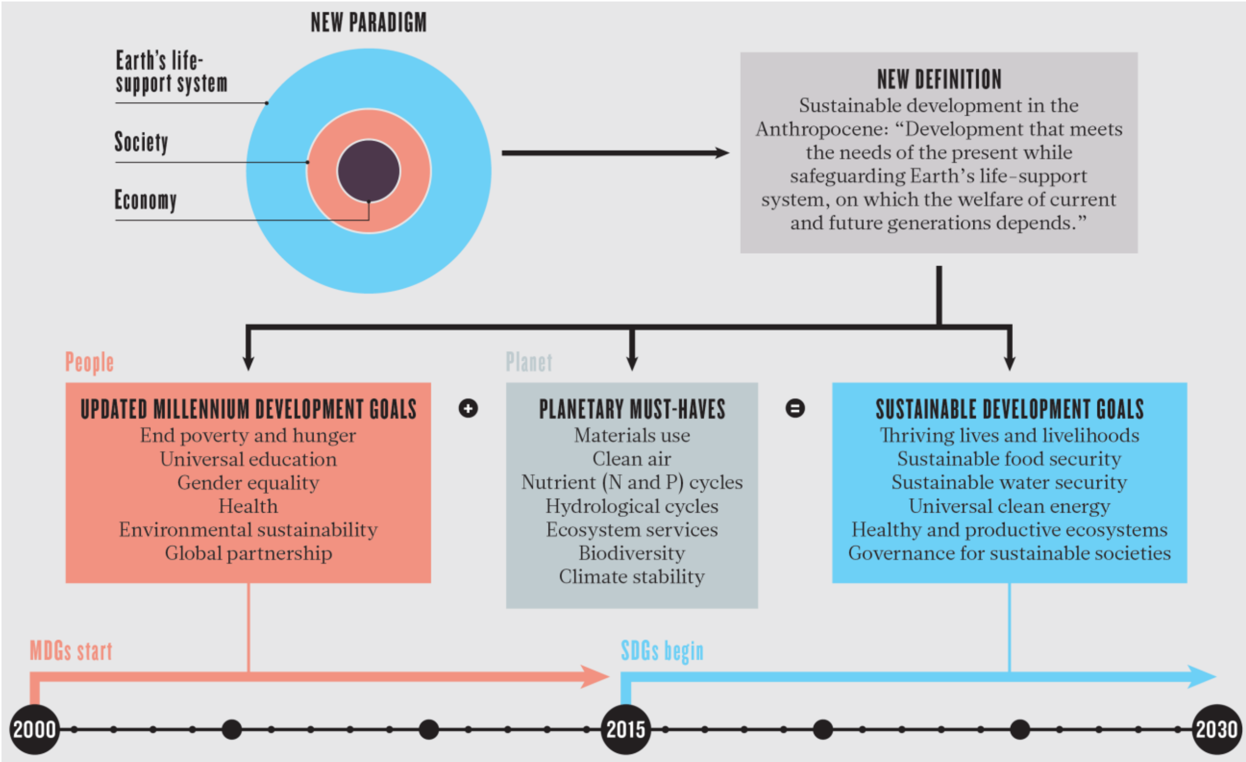

Figure 4.1 A Unified framework (Griggs et al., 2013)

A set of proposed SDGs follow from combining the MDGs with conditions necessary to assure the stability of Earth's systems

According to the unified framework in Figure 4.2, Griggs et al. (2013) explain the interactions between different SDGs and show how achieving one target can influence the achievement of others. For example, they discussed how energy provision and climate change prevention conflict with each other. Yohe et al. (2007) also mention that there is a bilateral relationship between sustainable development and climate change, as shown in Figure 4.2. Countries that are looking for long-term growth, but want to take a climate change measure as well, especially reducing the greenhouse emissions, should modify the structure of growth, and not restrict their growth to decrease vulnerabilities. As a result, it is important for them to make revolutions in their infrastructures and take more sustainable approaches. In order to guide sustainable development, United Nations published a list of 17 sustainable development goals and created a transformative global roadmap to achieve them. *Sustainable Development Goals: "The 17 Sustainable Development Goals form a cohesive and integrated package of global aspirations the world commits to achieve by 2030. Building on the accomplishments of their predecessors, the MDGs, the SDGs address the most pressing global challenges of our time, calling upon collaborative* *partnerships across and between countries to balance the three dimensions of sustainable development - economic growth, environmental sustainability, and social inclusion*." (UNDP, 2015) (For more information, refer to the Appendix A)

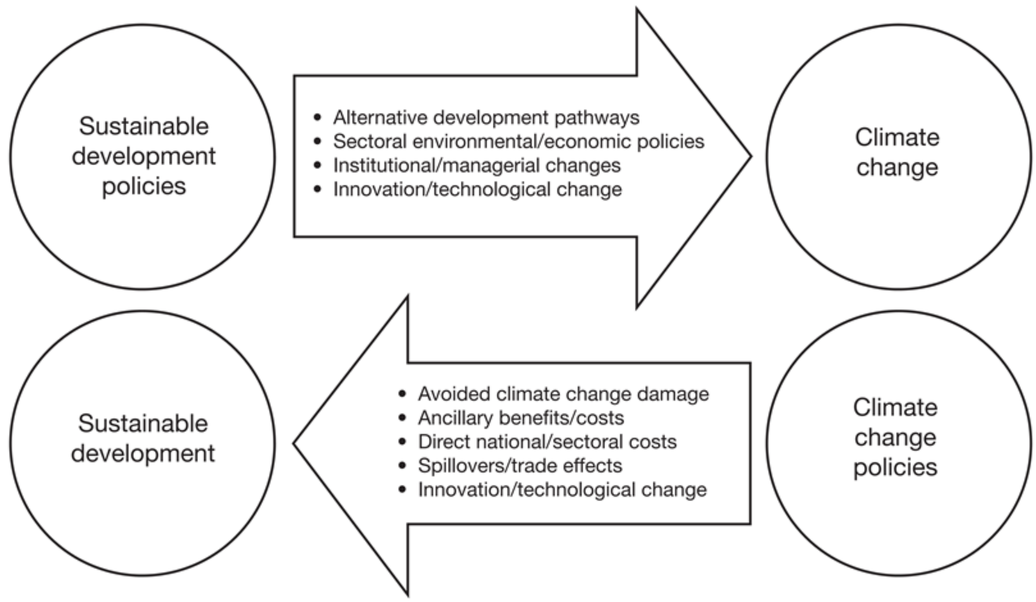

Figure 4.2 Two-way linkages between climate and sustainable development. (Yohe et al., 2007)

Although the SDGs are identified at the global level, their implementation happens at the scale of countries, regions and communities. Global SDGs need to be converted into national policies and programs as it is happen in many different contexts around the world. Therefore, it is really important for policy makers to consider a link between climate change and their policies; so, they should combine climate policies with non-climate national sustainable development strategy in order to enhance the effectiveness of mitigation efforts. Encouraging innovations in green growth, increasing knowledge and awareness about climate change, besides using integrated assessment models (IAMs), which are useful in analyzing global level problems, are also useful. In addition, a range of sustainable development indicators helps measuring the progress and makes choices at different levels of aggregation. Karstad (2009) explained how hard it can be to make decisions to save the environment. This dilemma is shown in the triangle in Figure 4.3. He illustrates that there is a trade-off between economic growth, environmental concerns and energy security. As a result, the decisions that a country makes are highly dependent on its priorities. It seems difficult to create a balance between these three factors at the moment.

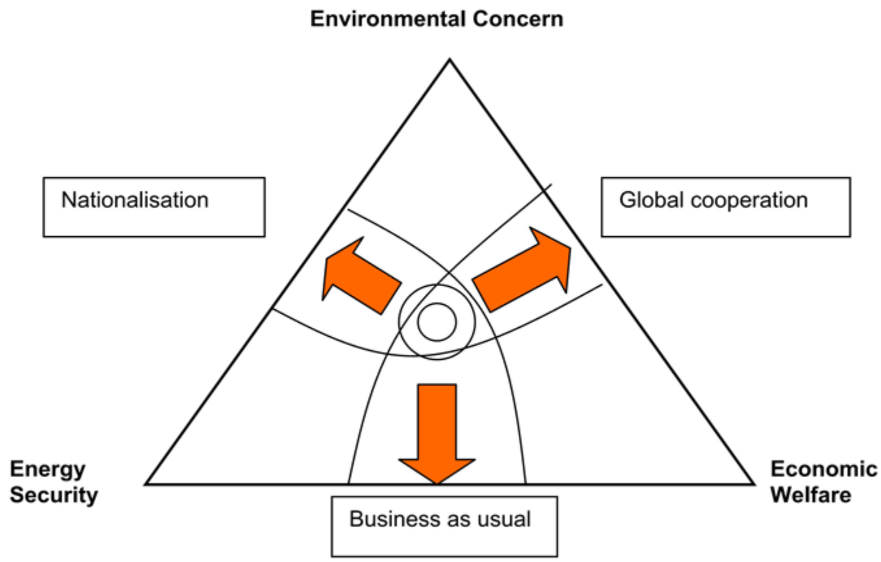

Figure 4.3 Preference triangle (Karstad, 2009)

Therefore, it seems the level of (public and government) knowledge and awareness about different subjects related to energy sector, such as environmental issues, threats and the danger of fossil fuels or other source of energies, is important to solve the dilemma as it helps not to choose fossil fuels since they are cheaper. If people know the danger to the earth, they substitute fossil fuels with a less dangerous source of energy. Then, government policy-making and public awareness matter a lot. In addition, it is important to change national policies such as carbon pricing, place a value on natural capital and a cost on unsustainable actions and strengthen the international governance of the global commons. Borel-Saladin and Turok (2013) mentioned the green economy and illustrated its core assumption, "*that environmental progress cannot be separated from economic growth and development*". Stakeholders play an important role in moving towards the green economy.

4.2 Stakeholder theory

Since hydrogen energy market is new, it is necessary to determine important stakeholders and their role in the development of hydrogen energy and market in Norway. In this part, stakeholder theory is presented. The aim is to understand who the relevant stakeholders are, what their interests are and how they can influence the business.

The rise of globalization, the dominance of information technology, the liberalization of states, especially the demise of centralized state planning and ownership of industry, and increased societal awareness of the impact of business on communities and nations have all been suggested as reasons to revise the understanding of business. As a result, to understand business and the relationship between different related stakeholders, Freeman (1983) introduced stakeholder theory that was concerned with trade and value creation. Baumgartner and Ebner (2010) believe that "*stakeholder theory helps business owners to be responsive to external environmental and unexpected changes*".

Stakeholders proved to play an important role in the achievement of objectives of an organization. Porter and Kramer (2006) believe that in a world with more knowledge and information about climate change and global warming, external stakeholders like governments, civil society organizations and the media are seeking to hold companies accountable for their social and environmental impacts and expectations of business behavior is changing. As a result, stakeholders are very important in the development of new technologies that positively affect the environment and human life. They can foster the development of new markets, change the public attitudes and create supply and demand.

"Stakeholder theory" is fundamentally a theory about how business works at its best, and how it could work. It is descriptive, prescriptive, and instrumental at the same time, and, as Donaldson and Preston (1995) have argued, it is managerial.

Stakeholder theory is about value creation, trade and how to manage a business effectively. "*Effective*" can be seen as "*create as much value as possible*". The traditional definition of a stakeholder is "*any group or individual who can affect or is affected by the achievement of the organization's objectives*". (Freeman, 1984)

Stakeholders can be seen from different perspectives. De witt and Meyer (2010) draw an emphasis on the differences between stakeholders and shareholders, which is presented in Figure 4.4. They defined shareholders as those who own a share or stock in a company and stakeholders as those who have some stake or interest in the company and its operation, for example civil societies, local communities, government and media. Effective stakeholders must have comprehensive knowledge about the issue to take advantage of them in the policy making process. Engaging different stakeholders leads to interactive decision making, that is increasing the influence of citizens and interest groups on public policy making and enhancing the quality of decision making. Stakeholders have both different contributions to make and different involvement needs at different phases of a decision-making process.

	Shareholder value perspective	*Stakeholder values perspective*
Emphasis on	Profitability over responsibility	Responsibility over profitability
Organizations seen as	Instruments	Joint ventures
Organizational purpose	To serve owner	To serve all parties involved
Measure of success	Share price and dividends (shareholder value)	Satisfaction among stakeholders
Major difficulty	Getting agent to pursue principal's interests	Balancing interests of various stakeholders
Corporate governance through	Independent outside directors with shares	Stakeholder representation
Stakeholder management	Means	End and means
Social responsibility	Individual, not organizational matter	Both individual and organizational
Society best served by	Pursuing self-interest (economic efficiency)	Pursuing joint-interests (economic symbiosis)

Figure 4.4 Differences between shareholder and stakeholder perspective (De Witt and Meyer, 2010)

Stakeholders belong to two different groups: primary or secondary, owners and non-owners of the company, owners of capital or less tangible aspects, actors or those acted upon, those in a voluntary or involuntary relationship with the company, moral claimants or contractors, resource providers to or dependents of the firm, risk-takers or influencers (Mitchell et al. 1997). Primary stakeholders have formal, official, or contractual relationships, and have a direct and important economic influence on the company. Secondary stakeholders however can influence or be affected by a company's activities, and are indirectly involved in the economic activities of the company. Different types of stakeholders are illustrated in Figure 4.5.

Stakeholders depend on the situation and the issues (Savage et al., 1991). Stakeholders can also restrict the process as regulators. Freeman (2001) postulated that organizations not only should respect the law, but also should try to meet claims by all stakeholders equally. It is good to mention that sometimes stakeholders' needs and claims conflict with each other and it is managers' responsibility to balance them.

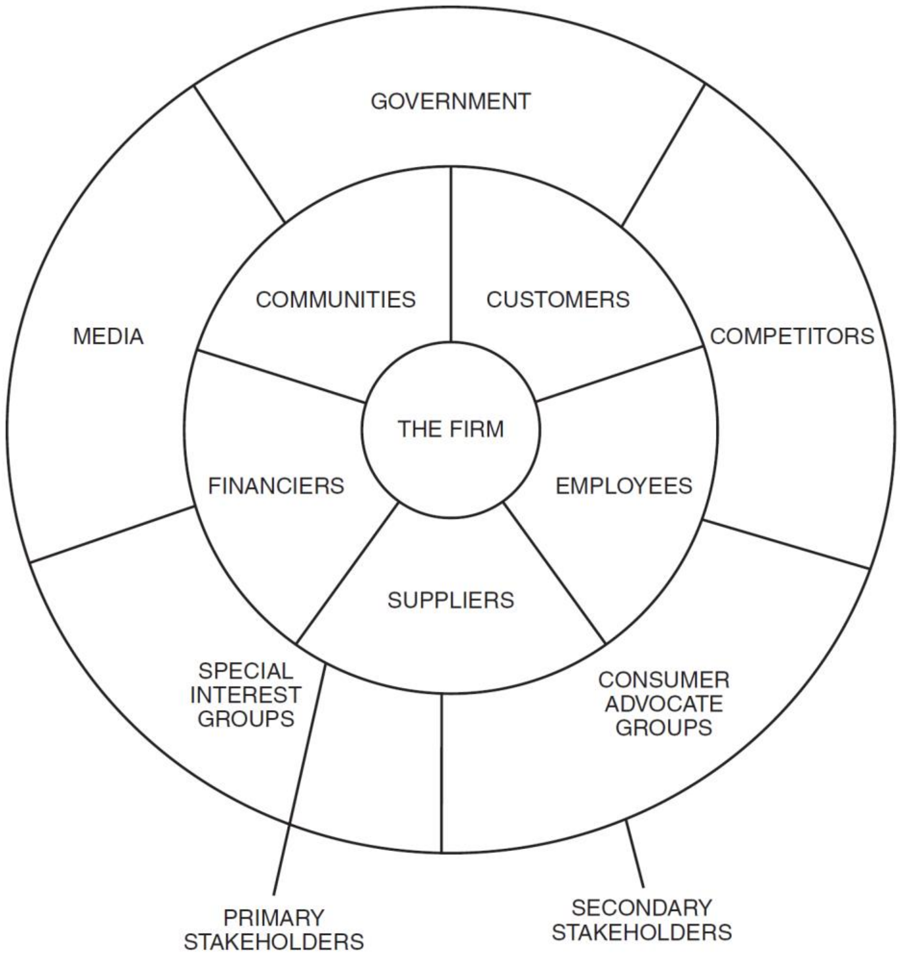

Figure 4.5 Different types of stakeholders (Freeman et al., 2010)

To achieve a successful business, the existence of a sustainable and good relationship between different stakeholders are necessary, and this puts more emphasis on stakeholder management. As a result, stakeholders must be actively involved in the business and they should work together to make plans and foster the development. Bal et al. (2013) illustrated how stakeholder engagement can result in sustainability. They presented the five stages model, shown in Figure 4.6.

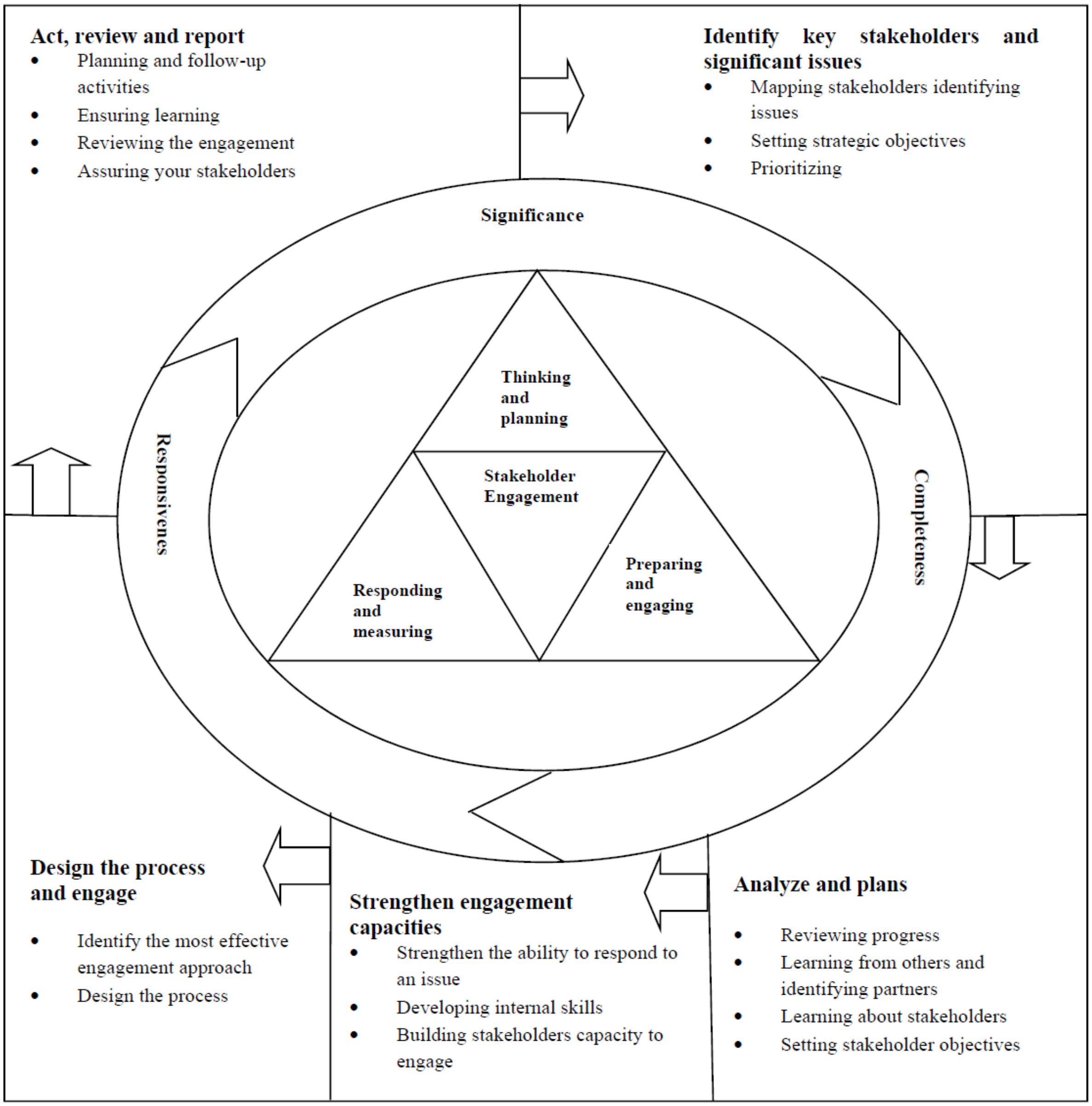

Figure 4.6 Stakeholder engagement model (Bal et al., 2013)

Bal et al. (2013) illustrated five stages of stakeholder engagement model as: Identify key stakeholders and significant issues; Analyze and plans; Strengthen engagement capacities; Design the process and engage; Act, review and report. They stated that engaging stakeholder creates a durable relationship based on respect between different stakeholders and business owner that leads to better understanding of market condition, more flow of knowledge and information, understanding priorities and the needs of stakeholders, mitigating threats and uncertainties and prompting reputation. As a result, stakeholder engagement promotes sustainable approaches that is helpful to achieve sustainability.

4.3 Market theory

Market is a place where supply transaction between the producer and the consumer takes place; in real life, the two parties are, respectively, sellers and buyers or customers. However, there is a more important difference. In real life, the seller is rarely a producer. He/she is both a buyer and a seller, that is, a merchant. Markets bring together buyers (demanders) and sellers (suppliers) and exist in many forms.

To gain advantages of a market economy, a society must first put in place the organizations and institutions that generate the innovative capabilities that underpin economic development and make the emergence of well-functioning markets possible in capital, labor and products. With these capabilities and markets in place, a society can then turn to the ongoing tasks of promoting the innovation process and controlling the operation of markets to achieve stable economic growth. According to Figure 4.7, the market equilibrium is where supply and demand curves intersect. Therefore, to reach equilibrium, price must be adjusted until there is neither an excess supply nor an excess demand. This adjustment is called the market mechanism, and it is characterized in the following way: in the case of excess supply, price will fall; in the case of excess demand, price will rise; and in the case of neither excess supply nor excess demand, price will not change (Salvatore, 2011).

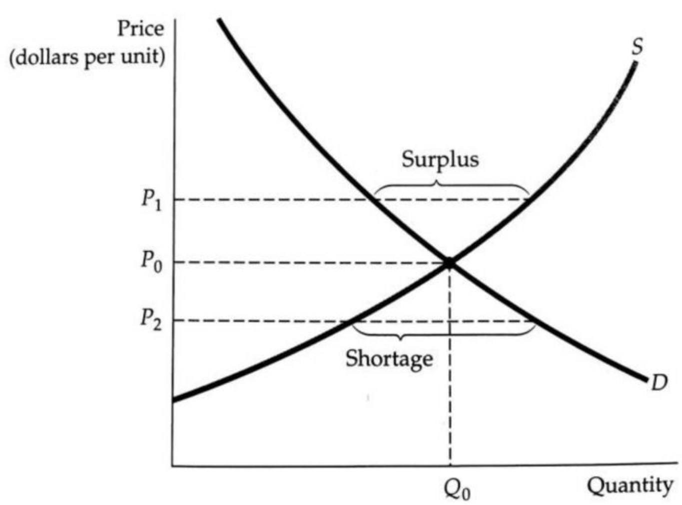

Figure 4.7 Market equilibrium (Pindyck and Rubinfeld, 2013)

Many factors affect the supply and demand and cause a shift of supply or demand curve or movement along them. As a result, market responses to new conditions, new supply and demand and the market equilibrium will change. This helps us to evaluate the most important factors that can influence the supply and demand in hydrogen energy market in Norway to have a better overview of the market.

5 Analysis and Discussion

Sustainability is one of the ways that helps a country or a business create competitive advantages. As mentioned earlier in theory chapter, the achievement of sustainable development goals will smooth the path towards sustainability. Sustainable natural resource management and climate change mitigation and adaptation are priority areas for Norway. Integrating climate and environmental concerns into the country SDG follow-up efforts is the key to achieve lasting sustainable development results (regjeringen.no, 2016). Achieving sustainability by practicing sustainable approaches, innovations and utilization of green hydrogen energy helps Norway create green value and gain competitive advantage in green technologies. According to theories presented in chapter 4, there are interactions between SDGs and it is important to identify these trade-offs to make better decisions and set more efficient policies. As a result, to see how hydrogen energy contributes to the achievement of sustainability and creating competitive advantage, the interactions between SDGs are examined. According to the country's priorities and relevance to the study, goals 7 and 13 are chosen as entry goals. The detailed investigations of these two SDGs with other SDGs are presented in Appendix A.

Goal 7 – Ensure access to affordable, reliable, sustainable and modern energy for all

Goal 13 – Take urgent action to combat climate change and its impacts (Undp, 2015)

The study shows that there are more enabling, reinforcing and indivisible than neutralizing or restricting interactions. The score most often allocated is +1. As a result, green hydrogen energy makes the achievement of other SDGs possible.

5.1 Stakeholders of hydrogen energy market in Norway

In this section, stakeholder analysis for hydrogen energy production in Norway is performed based on the stakeholder theory presented in chapter 3. The aim of this stakeholder analysis is to identify relevant stakeholders, their interests and objectives. Based on stakeholder theories, stakeholders can affect or could be affected by production of new products and services. As a result, it is important to determine important stakeholders and their role in the in hydrogen market in Norway.

5.1.1 Norwegian government

Continuous increase in Norway population, its boosting economic growth, and reduction of negative environmental externalities emphasize the need for new energy resources. These reasons stimulate hydrogen energy production and possible export of sustainably produced hydrogen as well as its related technologies. Since Norway is an exporter of manufactured goods, this can lead to economic growth. In addition, Norway has significant natural gas reserves, that if combined with carbon capture and storage (CCS) could be used to produce clean hydrogen energy and green value creation for the country. Therefore, Norwegian government found hydrogen energy profitable for the country and stated in the Report. No. 9 (2002-2003) "on domestic use of natural gas, etc. (Gas Announcement)" that has agreed to increase the focus on hydrogen and facilitate a larger national hydrogen program, which will contribute to the development of expertise for further development of hydrogen technologies in Norway. They launched a new strategy in which all hydrogen related activities will be administered and financed on basis of a common platform in August 2005 (KanEnergy As, 2005). Such activities include research and development (R&D), demonstration projects, development of safety standards, regulatory framework, etc. The new strategy focuses on all aspects of the hydrogen value chain and the use of hydrogen serving stationary purposes as well as within the transport sector. The involvement of a government in launching new industries and technologies is very important since it holds powerful tools and instruments to develop a new market. This engagement also increases the industry-government cooperation.

Government plays a key role in the early stages of hydrogen energy production by supporting technology research and development, encouraging market development and early adoption of fuel cell and hydrogen energy technologies through proper policies. The government should assign supportive laws, regulations, and subsidization to lower the costs of hydrogen production at the first stages. *"The government can also utilize preferential long-term loans, equity-loan hybrids, or refining schemes for first movers, which are tailored to the utilization rates during the ramp-up period."* (Enova, 2017). In addition, Norwegian government has a great experience in utilization of a set of practical incentives to stimulate the use of electric cars. Offering such consumer incentives will be helpful to commercialize hydrogen vehicles as well. Even though the government has the power to protect its domestic market through subsides and tariffs, monetary and fiscal policies, it is important to support the research institutes to contribute more to market development. As a result, Norwegian government allocated a specific amount of the annual budget to support research and development, development and adaptation of new technologies to reduce GHG emissions. It is done via collaboration among ministry of climate and environment, ministry of transportation, hydrogen research council and universities and research institutes nationally and internationally.

Currently, the Norwegian hydrogen technology is immature and it is not profitable for individual private businesses; therefore, it is important to give them financial incentives and supports. Enova (2017) presents a statement "*The technology is there. If we were forced to, we could achieve zero emissions. But this would be costly, and our competitors would need to face the same requirements*". This statement shows how government interventions could be useful. In addition, Nel ASA (2017) in its prospectus presents the following statements "*Governmental subsidies have had a material effect on the Company's operations and are expected to continue to do so in the foreseeable future*". Furthemore, "*Policy measures to support emission free technology such as fuel cell vehicles, for example through political means such as reduction of taxes and duties on specific technologies, may have positive effect on the Company either directly or indirectly through increase in demand for the Company's products*". These examples underpin Norwegian government plays an important role as a stakeholder in the development of hydrogen market. It seems that most of the active companies in hydrogen market except the ones that are connected to maritime industry, are not powerful and need the government financial supports (Pütz et al., 2012).

5.1.2 Innovators

Norway has a very extensive R&D program within the field of renewable energies. Since hydrogen energy and fuel cell technologies are considered as a part of government's plan to shift to renewable energy, there are excellent competent research and development centers that are working on this subject. The government and Norwegian Research Council support most of these research centers. The innovator stakeholders include both companies and public research organizations. A number of important innovator stakeholders are mentioned in the following. Innovation Norway is the Norwegian Government's most important instrument for innovation and development of Norwegian enterprises and industry. Innovation Norway supports companies to enhance innovation and to develop their competitive advantage. The Norwegian Fuel Cell and

Hydrogen Centre is a joint initiative taken by three major Norwegian R&D stakeholders (SINTEF, IFE and NTNU), engaged in Fuel Cells and Hydrogen (FCH) technologies and has a clear nation-wide character and impact. There are other important stakeholders in R&D sector such as Norsk Hydro, Statoil, University of Oslo and University of Bergen.

5.1.3 Political groups

One of the main factors supporting the hydrogen market is the deep collaboration between regional authorities and business owners. Norway took a step forward due to a positive gratitude of several municipalities towards introducing hydrogen in their area. As a result, currently there are many collaborations between these groups to facilitate the development of hydrogen market especially in transportation sectors. A number of active municipalities in hydrogen market in Norway are mentioned bellow.

The County of Akershus: is leading an interesting process of developing a hydrogen strategy for the Oslo region. They proposed a three-phase strategy to develop the hydrogen market and their aim is to make sure that Oslo region will be noted as "*an international leader of Hydrogen Refueling Stations (HRS) infrastructure development, and hydrogen related technology and having favorable incentive schemes for import and sales of zero emission vehicles"* (Hydrogen strategy, 2017).

Hordaland County Council (HCC): aims to reduce GHG emissions by 40 % from 1991 to 2030 based on the region's rich natural and human resources. Therefore, they promote clean hydrogen production, distribution and usage. The municipality also invested in both hydrogen and biogas energies. Their focus is on road transportation and marine industry. The municipality promotes research and development in hydrogen energy and financially supports many projects. Recently, they installed two hydrogen stations and made a good cooperation between local authorities and private companies. (The Norwegian Hydrogen guide, 2017)

Stranda municipality: is another municipality that has established a hydrogen production plant in the town of Hellesylt to protect the world heritage, Geirangerfjord and Nærøyfjord. Stranda as a municipality has special leadership positions in order to take action against harmful emissions. Therefore, their main intention is to shift to renewable fuels. The availability of an efficient zero emission fuel, which can alternate fossil fuels, especially in long distance trips[4] seems necessary. Using hydrogen energy for this purpose helps moving towards a more sustainable planet. It also fosters the regional development and prevents international companies to build hydrogen production plants there. (Internship project, 2017)

5.1.4 Producers

There are many companies, which are engaged in hydrogen production in Norway. Yara is a fertilizer company, which produces hydrogen as a by-product by the use of electrolyzers, and steam methane reforming. The Norsk Hydro is another company that produces hydrogen as a by-product in the production of chlorine related products. Statoil is also involved in hydrogen production as a part of their methanol production and at refinery operations. Other companies, involved in hydrogen related market are: *"Raufoss Fuel Systems and Hystorsys that are active within hydrogen storage; Nordic Power systems is developing fuel cells; ZEG Power, GasPlas, NEL Hydrogen and RotoBoost that are active within technologies to improve hydrogen production".* In addition, *"a number of very central maritime companies are positioning themselves within battery electric and fuel cell electric propulsion for ships"* (Pütz et al., 2012). The aim of all these companies is to make Norwegian hydrogen market more competitive and to contribute to national value creation from hydrogen production and environmental targets.

5.1.5 Customers

There are many potential customers for the Norwegian hydrogen market such as:

Road and marine transportation system: Although hydrogen and fuel cell vehicles have great capacity to reduce emissions in all types of transportations, it seems that these new technologies can play a more important role in marine transportation, heavy-duty trucks and railroad transportation.

Industrial sector: Norway is a manufacture producing country and has many active industries including food, chemicals, fertilizer, paint, metal processing, petrochemical, etc., which emit a large amount of CO2 annually. To cut these emissions, they can utilize hydrogen in their production cycle.

[4] It is possible to use batteries in short distances.

Government and private companies: They can use hydrogen and fuel cell technology to generate power for their stationary and heavy transportations purposes. In addition, Norway can use hydrogen in reserve power systems for emergency centers such as hospitals to prevent possible accidents due to power outages (in the harsh Norwegian winters power outages resulted from cable destructions is probable).

Private customers: Commercialization of personal hydrogen cars and vehicles will definitely attract private customers to the market and create new demands.

Renewable energy producers: Hydrogen can be considered as a large-scale energy storage medium for renewable energies and provide solutions for situations of electricity surplus or deficit. Producers of renewable energies in Norway can utilize hydrogen to address renewable energies intermittency, handle grid fluctuations and secure their energy supply.

Telecommunication: hydrogen can be used to generate power for telecommunication, which requires a constant and highly reliable electricity supply. This can be very helpful in remote and sparsely populated areas and islands in Norway that are hard to access. In addition, with rapid extension of telecommunications, more back-up power sources are necessary and hydrogen energy and fuel cell technology can provide a reliable source of energy.

International costumers: Norway has a great potential to become an exporter of hydrogen manufacture goods and technology. In addition, due to the country's potent research and development, they can get involved in international contracts and help other countries establish their own hydrogen industry.

5.1.6 Competitors

Hydrogen energy market in Norway has many competitors both domestically and internationally:

International hydrogen producer companies: there are a number of countries, besides Norway, like Germany, Japan, USA, England, China and Canada, which play an important role in international hydrogen market. These countries set ambitious targets for the penetration of hydrogen fuel cells. All of them can positively affect the global hydrogen market and contribute to its growth in the near future. They collaborate with each other in many projects, but they are considered competitors since each country tries to obtain a comparative advantage and gain a larger share of the market. By comparing these countries, it is possible to say that Norway has more types of primary energies to produce hydrogen energy. As a result, rich resources and strong research and development enable Norway to gain high market shares. A number of active international companies in hydrogen market are mentioned here. The companies represented in the hydrogen electrolyzer market are "*Hydrogenics, PERIC, Proton OnSite, McPhy Energy, ITM Power, Siemens, Teledyne Energy Systems, Suzhou Jingli Hydrogen and Hitachi Zosen*". The companies currently represented in the hydrogen fueling market are "*Linde, Air Products, Air Liquide and Powertech*". (Pütz et al., 2012)

National energy companies: There are a number of active energy companies in the Norwegian energy market. Unfortunately, fossil fuel companies dominate Norwegian energy market. However, many of them like Statoil (now Equinor) changed their strategies recently and prefer to be known as an energy company active in both fossil fuel and renewable energies. It seems that still fossil fuel is their priority though. In addition to fossil fuel companies, there are renewable energy producers as well that could be considered as competitors for hydrogen producing companies. Companies in hydropower and wind energy, which have a long history of production, obtained a noticeable share of Norwegian energy market. By considering challenges and barriers confronting hydrogen energy, it is still difficult to compete with these companies.

5.1.7 Activist groups

The most important environmental activist group in Norway is *Bellona*, an international environmental NGO based in Norway. The Bellona Foundation is an independent non-profit organization that aims to fight climate challenges through identifying and implementing sustainable environmental solutions (Vedled, 2018). This organization tries to be a bridge builder between industry and policy makers. Bellona works closely with different industries to help them respond to environmental challenges in their fields. It also proposes policy measures that promote new technologies with the least impact on the environment (The Norwegian hydrogen guide, 2017). According to their reports, it seems that they are highly concerned about the negative externalities of marine transportation on the pure Norwegian environment especially the "*World Heritage fjords*". Therefore, they accentuate on the necessity of changes in the shipping industry and they support shifting to a zero emission marine transportation system in Norway. Furthermore, they illustrated how hydrogen energy can positively contribute to marine ecosystem and make a revolution in marine industry. Bellona is engaged in both policy development and campaigning for hydrogen as an energy carrier (The Norwegian hydrogen guide, 2017). In addition, literature reviews show that there are no activist group against hydrogen energy in Norway. Another active non-profit organization is *The Norwegian Hydrogen Forum (NHF)*, a group of scientists and engineers that promote the role of hydrogen as a beneficial energy carrier.

5.1.8 Media

Media has always been considered as a very important stakeholder, which plays a significant role in informing people and increasing their awareness. Media has a wide reach and audience and therefore, it has the power to influence people in different areas. Media should present the information neutrally and give voice to different stakeholders to distribute important information and increase transparency and knowledge. It has been mentioned that one of the main barriers and challenges that hydrogen market encounters is lack of social acceptance; therefore, it seems that media can play an important role in propagating useful information about the benefits of hydrogen energy and various hydrogen projects in Norway. Although it is possible to find many useful information about hydrogen energy in Norway, its contribution to Norway's economy and its challenges in newspapers, on TV talk shows, opinion blogs and etc. is not enough. Therefore, there is a need for more collaboration and interaction between media and other involved stakeholders in hydrogen energy in Norway to make it easier for hydrogen energy to be accepted as an efficient clean source of energy. The history shows that Norwegians are fast implementers of new technologies. As a result, more focus on the distribution of information through media can be very helpful to create a multilateral public-private collaboration to facilitate the hydrogen market. Stakeholders' interactions play an important role to develop a market for a new technology. Therefore, interactions between various hydrogen energy stakeholders in Norway lead to overcome the challenges confronting the hydrogen market and create a mature and developed market.

5.2 Strengths–Weaknesses–Opportunities–Threats (SWOT) analysis and strategies prioritization of hydrogen economy in Norway

In this part, SWOT analytical method is used to analyze strengths, weaknesses, opportunities and threats of the hydrogen market in Norway. This method can identify the strengths (elements to leverage and build on), weaknesses (areas to seek assistance and support), opportunities (areas to leverage for the advantages) and threats (elements to hinder the development of the object) of the studied objects (Mainali et al., 2011). The purpose of the SWOT analysis is to help stakeholders and decision makers have a better view of the status of hydrogen market in Norway and make better decisions to improve the market efficiency. It is also helpful to show how Norway can gain competitive advantage from hydrogen energy. These types of analysis are practical to create a roadmap for hydrogen energy production in a country like Norway. In addition, conducting this analysis makes it possible to propose better and more efficient methods to integrate hydrogen energy in a country's energy system, because this analysis reflects real life conditions by considering not only technological but also country-specific institutional, geographic and socio/economic barriers and opportunities.

Table 5.1 Comparison of strengths, weaknesses, opportunities and threats of hydrogen market

<table>
<tr><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td>
More diversity in resource utilization

Multiple sources and various production methods
Extract value from waste since it is possible to produce it from waste and as a by-product
Reduce dependence to fossil fuels and increase energy diversity
Enables communities to manage their own energy supply
Has potential to integrate intermittent renewable energies in the energy system
Can be used as a feedstock in other industries

Environment conservation

Environmental friendly and reduce the amount of GHG emissions
Less noise pollution compared to other energy production methods

A key to sustainable development

Great development potential
The possibility of production in rural and remote areas
Stimulate research and development
Increase employment

</td><td>
Lack of support from the government

Insufficient cooperation between political authorities and enterprises

Unavailability of an efficient hydrogen infrastructure

Incomplete hydrogen infrastructure
Limited access and availability (unavailability of enough hydrogen refill stations)
Lack of an efficient distribution and storage system to overcome hydrogen explosiveness
Lack of recycling plans

Introduction risks

Public acceptance since it is a new product
Lack of effective tools for the first introduction of hydrogen energy for transportation
The development of support services such as insurance is still very immature
The integration of hydrogen into the energy system is not tested on an industrial scale
System complexity

High costs

High production costs especially in small scales
High initial installation costs

</td></tr>
</table>

• Consistent energy supply and energy security (It could be considered as a never ending source of energy) • Sustainable transportable energy source • Have numerous applications in stationary and transportation market **Technical strengths** • High potential for energy storage • Integration with smart grid • Can handle power fluctuations • High efficiency of fuel cell vehicles • Relatively low sensitivity to the impurities in the fuel (Sun and Stimming, 2007) • The possibility of utilizing current fuel transportation infrastructure • Reduce the dependence on long distance pipelines	• Procurement costs • High adaptation costs • High energy price • Lack of focused development works from major companies to develop the equipment and reduce costs • The need to change current distribution system in residential buildings **System integration** • Lack of comprehensive policies, regulations and codes and standards • Lack of awareness of capabilities and potential benefits of hydrogen • Resistance from other energy actors in the country • Weak supply network • Safety issues • Unavailability of clear marketing policies and strategies • Unclear plans about combing electricity and hydrogen energy

Opportunities	Threats
New business opportunity • Emergence of hydrogen market • Export hydrogen and create value from that • Emergence and engagement of more companies in energy sector • Job creations **Increase cooperation** • Deepened cooperation with local authorities and make alliance with local politicians or business owners • Collaboration opportunities among line ministries, departments and other system actors **Development potential** • Sustainable development • Innovations and technological development • Effective utilization of hydrogen via fuel cell technology • Stimulate R&D • Hydrogen and fuel cells technology enables investment in sustainable energy infrastructure **Improve energy security** • Energy diversification **Environmental benefits** • Emission free mobility • Reduction of negative environmental externalities	**Technical** • Limited practical experience in both producers and consumers • Insufficient storage required/more cost-efficient alternatives are available **Economic** • Lack of potential suppliers and demanders • Lack of potential investors • Inadequate commercialization plans • Competitions with other renewables such as hydropower • Strong position of fossil fuel producers, the difficulty to compete with the current fossil fuel market **Social** • Public acceptance is unclear • Weak support to shift to hydrogen energy • Incomplete legislation

5.2.1 Strengths

More diversity in resource utilization: Hydrogen energy increases and secures the energy supply if it is produced from any locally available primary energy resources. Furthermore, by considering hydrogen energy as a storage medium, it is more practical to utilize intermittent renewable energies, integrate them in the energy system and decrease the dependence to fossil fuels. In addition, by combining carbon capture and storage and hydrogen energy, the country can create green value from fossil fuels. It is also possible to produce hydrogen as a by-product of chemical industry and from waste. This results in utilization of resources more efficiently.

Environment conservation: Characteristics of hydrogen energy is mentioned thoroughly in chapter 2 and it is noted how hydrogen energy can reduce negative environmental externalities. To do this, it is very important that policy makers prioritize hydrogen energy and set policies to promote green hydrogen energy production. Hydrogen energy makes less noise pollution since the required equipment to produce hydrogen makes less noise compared to fossil fuels.

A key to sustainable development: Hydrogen energy is a key to sustainable development and has great potential to provide clean energy for Norway's economic and social growth. It has the capacity to satisfy three important societal needs of Norway, which is presented by Innovation Norway (2016); reliable energy supply, help to fulfil Norway's climate obligations and maximize economic growth and employment based on clean energy.

Technical strength: Hydrogen energy has a great storage capacity, which enables handling power fluctuations and renewable energies intermittency. Furthermore, it enhances energy efficiency since it has the ability to convey a lot of energy for every pound of fuel. It is also possible to utilize part of the current transmission infrastructure such as old gas pipelines to distribute hydrogen energy.

5.2.2 Weaknesses

Insufficiency of support from the government: The Norwegian government supports hydrogen energy projects. Even though the government set a committee to develop a national hydrogen program in 2003 and a national hydrogen strategy was formulated to profit from an emerging global hydrogen economy (Fuel cells and Hydrogen in Norway, 2013), more support is needed. Norwegian government is one of the biggest shareholders of the major Norwegian petroleum company Statoil. As a result, it seems that still fossil fuel market is very important for the country and this is the reason why hydrogen energy is not prioritized in the government policies. Introduction risks are amongst the most important challenges hydrogen energy encounters. To level out the introduction risks, more support and interventions from the government to subsidize and measure efficient policies is necessary. The government has also an influential role of creating potential demand in hydrogen market by different instruments it has, such as policy-making or regulations in favor of hydrogen energy or public procurement of hydrogen vehicles. It is expected that Norwegian government puts more efforts in this regard.

Unavailability of an efficient hydrogen infrastructure: The hydrogen market still suffers from the unavailability of enough and efficient required infrastructures to use this energy at large scale. For example, if it is supposed to use it in transportation system, it is necessary to build more infrastructure and refueling stations. Current stations do not cover all the roads in Norway. This leads to less utilization of hydrogen vehicles. In addition, there are technical challenges in the distribution of hydrogen energy.

Introduction risks: Public acceptance is an important part of the risks a new technology encounters at its early stages of production. Public acceptance can be considered as the willingness to adopt or use the new technology, or to support its development. Media, knowledge, beliefs, values, emotions, experience and perception of risk significantly influence public judgments. As a result, it is vital to give the public more information and awareness about the capabilities and accomplishments of hydrogen energy to solve one of the most important social barriers in front of the hydrogen energy utilization. Both consumers and producers prefer to utilize new technologies after they prove to satisfy their needs. The analysis shows that Norwegians are positive to environmental friendly transportation, concluded from the large number of electric cars in the country. However, they are a bit afraid of hydrogen personal cars. They have fears about how complex the system will be and how difficult it will be to use hydrogen passenger cars. There are also concerns about their performance in the Norway's harsh climate. Since the system is not tested in the large-scale, it is difficult to satisfy them. These concerns show that the system suffers from lack of effective tools to introduce hydrogen energy and the commercialization phase has barely started and has a long way to proceed. Therefore, to introduce hydrogen energy, the availability of a good market strategy seems necessary and many incentives should be set to motivate people to use hydrogen energy vehicles. It seems that it is better to launch hydrogen energy in the public transportation system, then after making sure that this new energy source is accepted by the public, start to build distribution and consumption infrastructures. By starting from small-scale, the producers have the chance to recognize system deficiencies and try to solve those problems by innovations. Therefore, this process not only boosts research and development, but also helps society burden less risks and costs. To reduce risks, it is significant to determine potential customers that have technical skills to give efficient feedbacks about the performance. For example, maybe it is better to start with commercial trucks, buses or cruises. Forming clusters is also useful to reduce the introduction risks and costs.

High costs: To promote sustainable massive production of hydrogen, it is important to reduce costs. The production cost is highly dependent on the feedstock prices; that is the main reason that makes hydrogen energy production from renewables more expensive. To make it more cost effective, it is necessary to assign supportive policies in Norway. It is also possible, because of Norway's demographic and geographic characteristics, to exploit resources locally, to produce and deliver hydrogen in the region. This is a good solution in less populated areas. Unfortunately, due to high costs of hydrogen value chain, currently it is not a popular fuel. Continuous technology innovations and performance improvements are also very helpful. Farrell et al. (2003) indicated the important role of "*least adopters*[5]", "*learning by doing*" and "*learning by searching*". In addition, the economy of scales are helpful to reduce costs in the future, the more production supplied to the market, the lower production costs could be.

System integration: There is no effective plan to integrate hydrogen energy into energy system in Norway. To solve this, it is important to increase government support, public awareness and formulate clear marketing policies and strategies. It is also significant to establish practical and clear plans about combining electricity and hydrogen energy in the energy system to increase energy efficiency.

[5] who are willing to pay for the new technology

5.2.3 Opportunities

The infant and newly introduced hydrogen market results in many opportunities that are listed below:

New business opportunities: New technology for producing environmental friendly hydrogen is being developed in Norway, including new electrolyzer technology and novel processes for producing hydrogen from methane with integrated carbon capture (Fuel cells and Hydrogen in Norway, 2013). These technologies strengthen the role of Norway as a pioneer in this market and have a great potential to create value from hydrogen energy. Hydrogen energy seems to have the potential to expand to other markets as well. Therefore, more customers will be attracted. The increase in demand results in attracting more companies to become engaged in hydrogen industry.

Furthermore, Norway has great capacity in tourism industry and lots of tourists visit Norway annually to experience the pure nature. However, this profitable industry jeopardizes the beautiful nature of the country. Hydrogen energy helps developing the zero-emission tourism industry. Maritime industry has always been perceived as a potential market for hydrogen energy as well. By the way, as mentioned earlier, introducing hydrogen energy to Norwegian market stimulates research and development. Increasing research and development besides growing hydrogen market and industry leads to more job opportunities.

Development potential: The country's appetite to adapt new technology leads to more engagement in hydrogen energy and stimulates research and development, which is a key for further development. It is difficult to evaluate the exact effect of launching hydrogen energy on Norway's gross domestic product, but it has a great development potential and positively affects the economic growth. Revenues from sale of hydrogen as a green fuel and its related technologies could be used as an investment for developing new infrastructures and innovations. Norway has a great potential to become one the major producers of hydrogen ferries, which increases employment and creates a market to export these goods to other countries. In addition, launching hydrogen energy enables Norway to engage sparsely populated or remote communities in hydrogen energy's supply chain and increase the employment. As a result of this employment and consequent income effect, reduction in environmental externalities and improvements in energy efficiency and Gross Domestic Product (GDP) could be affected positively. Therefore, it could be concluded that hydrogen energy has a potential to create innovation led growth and employment, to attract inward investment and to create export opportunities both for hydrogen and for related technologies. As a result, it is possible to create more value domestically, directly, indirectly and via implied effects, to foster further development.

Increase cooperation: To make great progress in hydrogen industry in Norway, it is important to deepen the cooperation with local authorities and make alliance with local politicians or business owners, and increase collaboration among line ministries, departments and other system actors. Bringing together all the major actors and stakeholders in this market is the best way to address barriers and challenges to stabilize hydrogen market in Norway, to provide required investment and build the infrastructure in a joint work. These collaborations are necessary to have a better perspective of the current and future market and to make better policies and evaluations to foster further market developments. Ball and Weeda (2015) concluded, "*A wide cooperation between municipalities, local companies and public sector, and ingenious business model to share the initial investment is critical*". To make further progress in hydrogen energy, Norway is involved in many national and international cooperation. A number of examples of national cooperation are brought in stakeholder analysis. "*The Scandinavian Hydrogen Highway partnership*" is one of its international collaborations.

Improve energy security: It is an economic advantage for Norway to diversify domestic energy sources to secure its economic growth and reduce its dependency on limited fuels. Norway is a country with many less populated remote areas and islands, which makes it difficult and expensive to provide them with energy, because many of these small communities suffer from bad connections to the mainland electricity grid, or no connection at all. Launching hydrogen energy and possibility of exploiting local resources and produce energy to meet energy demands in those areas increase the supply of energy and consequently energy security. There are practical limits, both technological and ethical, in producing electricity from other resources such as biofuels and hydropower. As a result, the utilization of hydrogen energy in Norway stabilizes and secures the Norwegian electricity grid. In addition, hydrogen energy as a storage medium, enables handling power fluctuations and creating a consistent supply.

Environmental benefits: It was explained in previous parts how green hydrogen energy reduces negative environmental externalities from the utilization of fossil fuels, facilitates the path towards zero-emission transportation system and enhances the quality of the life in the country.

5.2.4 Threats

Technical: Unfortunately, hydrogen has been used in small-scales since there is limited practical experience, considering both producers and consumers. It is good to make a comparison between hydrogen and other available energy carriers in the country. Electricity has a longer history of production, more mature technology and more power in the energy system. It is possible to produce electricity from hydropower, wind and biomass domestically. If the hydrogen energy could not deliver the presumed characteristics due to technical issues or hydrogen market disfunctions, it could easily loose the market to electricity or other alternatives. Due to a fierce competition in the fuel market, technical issues are considered as a critical threat for the popularization of hydrogen energy. As a result, it is important to solve technical issues to provide a cost effective, efficient and high-storage capacity hydrogen energy to provide an attractive unsurpassable fuel.

Economic: Consumers regard hydrogen as a preferable fuel if it holds it comparable features and capabilities towards other available alternatives. Therefore, it is necessary to strengthen the required infrastructure for both hydrogen production plants and fuel stations to attract more consumers and even producers to boost hydrogen economy. Currently in Norway, there are a few private companies engaged in hydrogen economy. Therefore, the market is still risky and non-profitable and needs more support and subsidization to grow. The market suffers from lack of potential customers, producers and investors, which are necessary for development and popularization of hydrogen market and creation of more revenue and jobs. Therefore, it is highly important to attract investors to boost the market and be prepared to answer the increasing demand (it is considered that the hydrogen demand increases in the near future because of Norway's environmental commitment). Another important threat of the hydrogen market is the strong position of fossil fuel producers in the current energy market. They are powerful and capable to influence policy makers and rule the energy market based on their economic interests.

Social: As mentioned before, public acceptance is one of the most important social threats. Part of the uncertainties in hydrogen market results from lack of awareness, required standard (there are many international standards) and regulations and proper incentives. A set of proper incentives such as free parking fee, less tax, carbon tax, using bus lines and etc. seems reasonable to promote more utilization of hydrogen vehicles.

In this part, based on the SWOT analysis of hydrogen energy in Norway, a portfolio of strategies is formulated by matching the internal indicators including strengths and weaknesses with the external indicators including opportunities and Threats. Strategies are illustrated in Table 5.2.

Table 5.2 Recommended strategies

	Strengths **S_1** *More diversity in resource utilization* **S_2** *Environment conservation* **S_3** *A key to sustainable development* **S_4** *Technical strengths*	**Weaknesses** **W_1** *Unavailability of an efficient hydrogen infrastructure* **W_2** *Introduction risks* **W_3** *High costs* **W_4** *System integration*
Opportunities **O_1** *New business opportunity* **O_2** *Increase cooperation* **O_3** *Development potential* **O_4** *Improve energy security* **O_5** *Environmental benefits*	**SO_1** Combine hydrogen energy production and CCS. **SO_2** Develop hydrogen economy and market with comprehensive regulations and standards. **SO_3** Promote the utilization of hydrogen based vehicles in different sectors to make it more popular.	**WO_1** Financially support the suppliers and stimulate more development in hydrogen infrastructure. **WO_2** stimulate innovations and technical developments.
Threats **T_1** *Technical* **T_2** *Economic* **T_3** *Social*	**ST_1** integrate production strategies between hydrogen energy and other renewables to decrease the competition between them. **ST_2** Encouraging more cooperation between major energy companies, research centers and politicians.	**WT_1** Develop hydrogen infrastructures and technologies and promote regulated hydrogen economy. **WT_2** Absorb private and foreign investments to financially support ongoing projects and implement specific legislation to enhance safety and convenience in use.

All these strategies are considered useful to promote hydrogen energy market in Norway; however, there is no clear clue to identify how effective these strategies are. After this analysis, it is a good idea to prioritize strengths, weaknesses, opportunities and threats. It is helpful to see which criteria has more weight and if it is beneficial to produce hydrogen energy in Norway. To do that, according to the methodology presented in chapter 3, fuzzy AHP is used. The prioritization is based on the 10 experts' viewpoints. The result shows that weights of strengths and opportunities are more than the weights of weaknesses and threats as it is shown in Figure 5.1. Therefore, the production of hydrogen energy and investment in this market seems reasonable.

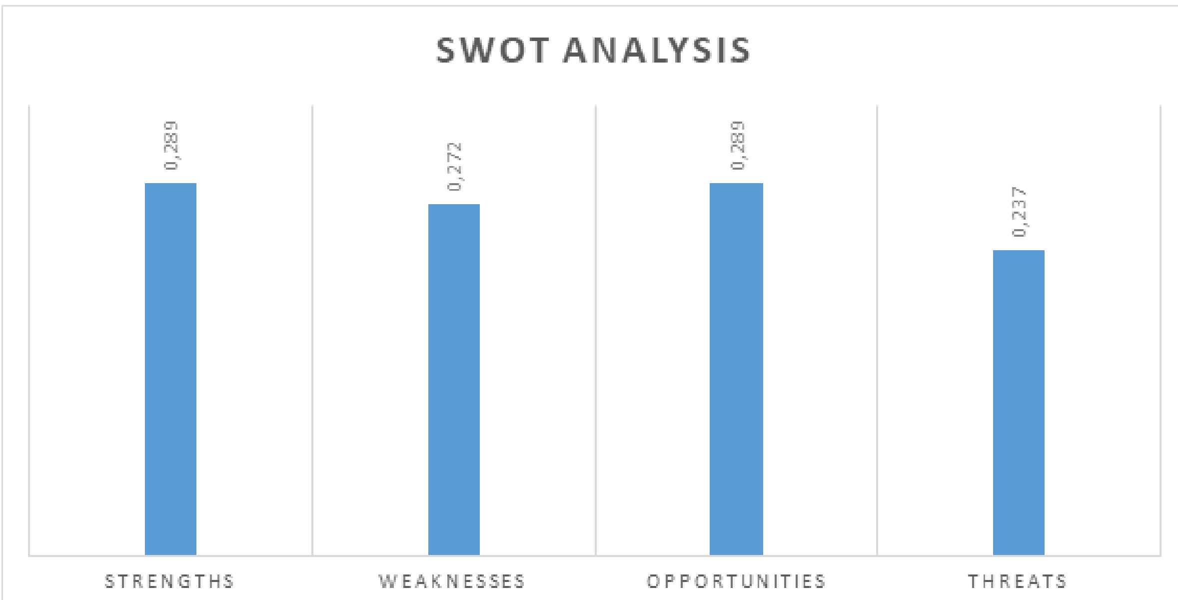

Figure 5.1 Ranking of strengths, weaknesses, opportunities and threats

5.3 Supply and demand in the hydrogen market

Based on the market theory presented in the previous chapter and SWOT analysis, it is possible to determine many of the important factors that influence supply and demand in the hydrogen market. The result is shown in Figure 5.2. Evaluating these factors helps better understanding of the market.

5.3.1 Factors affecting the supply side

Electricity price: Electricity price shows the variable fuel cost for electrolyze; therefore, it affects the hydrogen production and consequently its supply. Higher electricity prices mean more expensive hydrogen energy production and accordingly less supply.

Relative resource availability: This is an important factor in hydrogen energy production. With abundant resources, both renewable and non-renewable, it is possible to produce cheaper hydrogen energy. This factor affects the supply positively.

Hydrogen energy price: There is direct relationship between hydrogen price and its supply. As a result, there is more supply when the price is higher.

The penetration and integration of renewables in the energy system: With the availability of the required infrastructures to produce hydrogen from renewables in the country, it is more facilitated and beneficial to produce hydrogen energy, and consequently the supply of hydrogen will increase.

Potential demand: This factor will positively affect the hydrogen supply. Availability of the potential demand promotes supplier to produce more.

The availability of laws and regulations that support hydrogen energy producers: When there are efficient and supportive regulations and actions to support the producers, they tend to produce more hydrogen and this will increase the supply.

5.3.2 Factors changing the hydrogen energy demand

Market prices: The most important factor directly affecting the hydrogen energy demand is the hydrogen energy price in the market. The demand is less with the higher price and the other way around.

The fossil fuel prices: The demand for hydrogen energy can be influenced by changes in the prices of substitutes including fossil fuels or other renewables. Cheaper fossil fuel decreases the demand for hydrogen energy.

The availability and the power of green competitors: The competition in the energy market increases when there are more alternatives. This will negatively affect the demand for hydrogen energy. In this case, the hydrogen energy demand is more if it is cheaper than other alternatives and can satisfy customers' needs in a better way.

Safety and social acceptance: This has a direct relationship with hydrogen demand. If hydrogen is socially accepted and proved to be safe, the demand will increase.

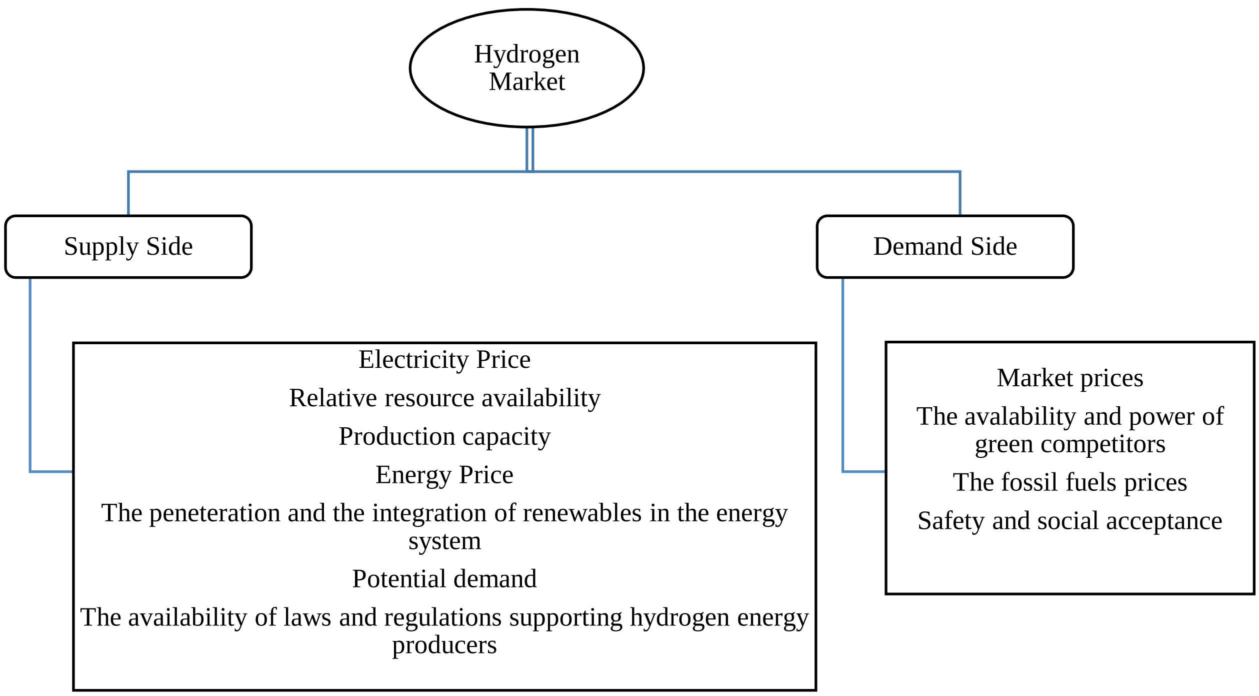

Figure 5.2 Factors influencing supply and demand of the hydrogen energy

5.4 A model to analyze the most important factors in hydrogen energy production in Norway

It is very important to see which factors can help hydrogen energy become successful in Norway. Based on literature reviews, SWOT analysis and interviews a set of important factors affecting the success of hydrogen energy are determined. Therefore, a model is created to show the important factors as it is illustrated in Table 5.3. It has been clear that to make hydrogen energy competitive in Norway and create competitive advantage, it is important to pay attention to these factors and prioritize them. These final criteria are chosen after discussion with the experts and comprehensive study of the market. These factors proved to be able to satisfy the needs of different stakeholders in the market and are useful for decision makers to set better strategies to make hydrogen energy successful and competitive in the energy market.

Table 5.3 Main criteria and related sub-factors of the Model

Symbol	Criteria	Sub-factors	Symbol
C_1	Technological	Feasibility	C_{11}
		Energy efficiency	C_{12}
		Reliability	C_{13}
C_2	Economic	Production costs	C_{21}
		Investment costs	C_{22}
		Create value	C_{23}
C_3	Environmental	Reduce toxics and wastes	C_{31}
		Land use	C_{32}
		GHG emissions	C_{33}
C_4	Social	Employment	C_{41}
		Enhance the quality of life	C_{42}

Technological criteria: The mature technology is a key of success in the energy market. The identified sub-criteria for this criteria are feasibility, energy efficiency and reliability.

Economic criteria: Economic criteria in this survey are potential to create value, potential to build energy security and production costs.

Social criteria: Social criteria demonstrate the social aspects of hydrogen energy and how it can affect the society. Its effect on the employment and the potential to enhance the quality of life of humans proved to be the most important sub-criteria for the social criteria.

Environmental factor: Environmental criteria consist of the amount of GHG emissions, potential to reduce toxic emissions and land use. The amount of GHG and toxic emissions reductions by using hydrogen energy system and the percentage of change in the concentration of GHG and toxics in the air are important factors in the environmental criteria. The installations of many of new energy systems require large areas or lead to change arable lands, which negatively affect the environment.

Based on the fuzzy AHP method presented in chapter 3, different factors and sub-factors of the model are analyzed and compared with each other to see which factor has more priority and is more important in the decision making process. In this analysis, there are four different criteria and eleven sub-criteria. Number of comparisons (N) is calculated based on Equation 5.1, where n is the number of criteria.

$$N = \frac{n(n-1)}{2} \tag{5.1}$$

For a four criteria analysis, the number of comparisons is therefore six.

The comparison in this part is done based on the methodology presented in chapter 3 and in the Appendix C. The extended calculations are presented in the Appendix C. The final results of the comparison of the main criteria of the model, are presented in Figure 5.3. According to the findings, technological criteria has a higher score, 0.410, compared to economic, social and environmental criteria. The scores of other criteria are, respectively, 0.33, 0.135 and 0.128.

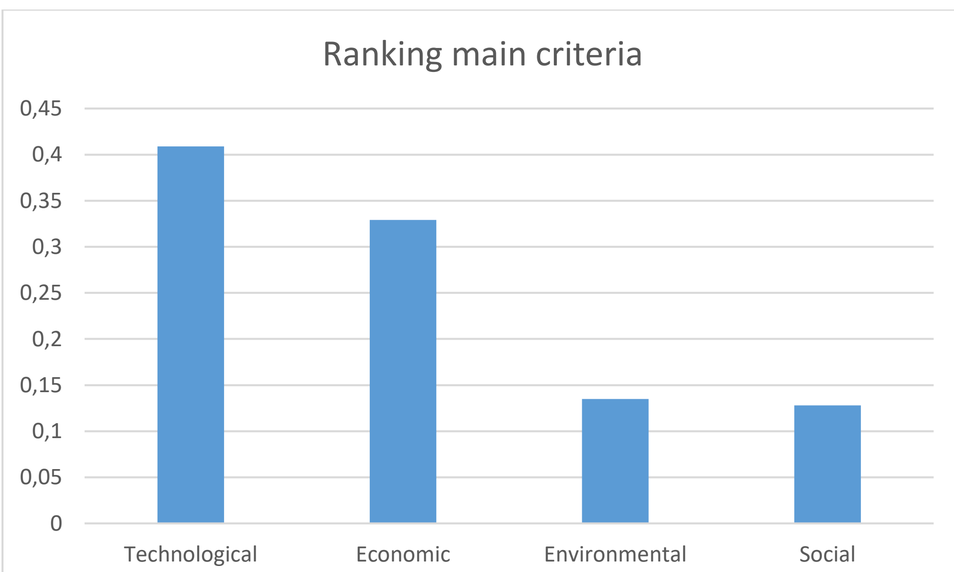

Figure 5.3 Prioritization of the main criteria of the model

As a result, to make hydrogen energy more competitive, it is very important to address its technological challenges.

5.4.1 Prioritization of technological sub-factors

As shown in Figure 5.4, the scores of three sub-criteria of technological criteria, that is, feasibility, energy efficiency and reliability are, respectively, 0.452, 0.252 and 0.295. As a result, the feasibility of the production and the availability of required infrastructure to produce energy has the highest score.

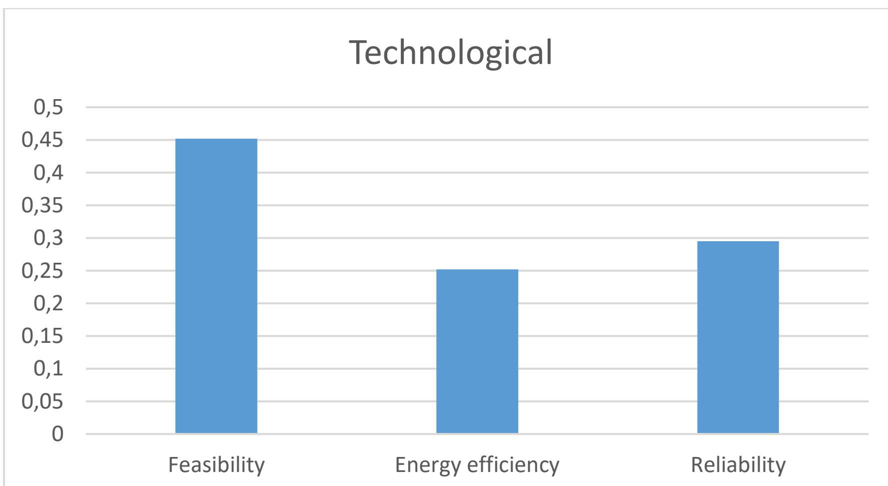

Figure 5.4 Ranking of technological criteria

The calculated inconsistency rate is 0.033 (which is less than 0.1). As a result, it is possible to validate the computations.

5.4.2 Prioritization of economic sub-factors

The result of comparison of production cost, investment cost and create value, that are three sub-criteria of the economic criteria, is illustrated in Figure 5.5.

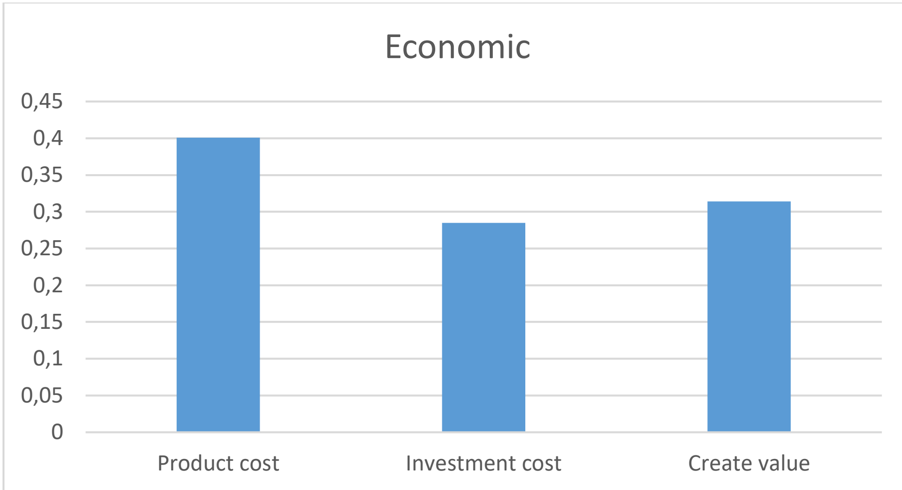

Figure 5.5 Ranking of economic criteria

The calculated inconsistency rate is 0.004 (which is less than 0.1). As a result, it is possible to validate the computations.

According to the findings, production costs has the highest score, 0.4. Investment costs and create value scores are, respectively, 0.285 and 0.314. It seems that decision makers have more tendency to choose a fuel with less production costs.

5.4.3 Prioritization of environmental sub-criteria

According to the results shown in Figure 5.6, GHG emissions has the highest rank, 0.454.

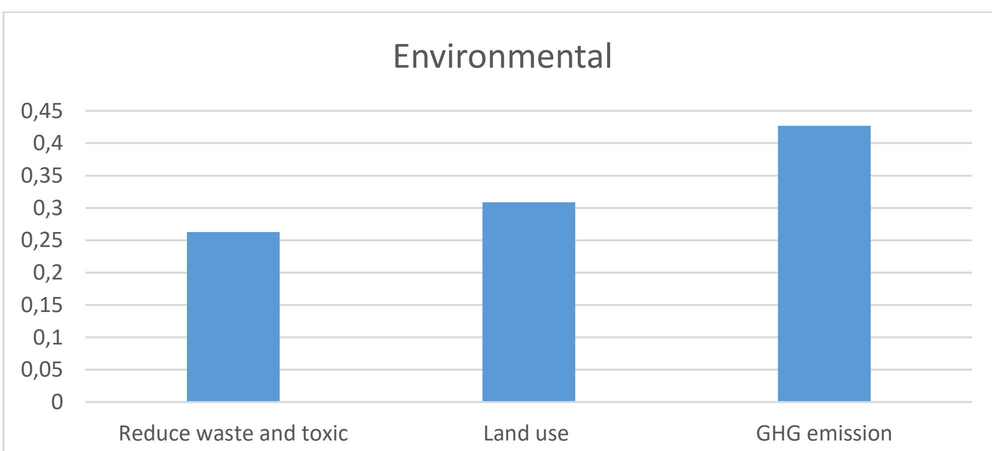

Figure 5.6 Ranking of environmental criteria

5.4.4 Prioritization of social sub-criteria

In this part, the comparison is done between two sub-criteria of social criteria, that are employment and increase of the quality of life. Since just one comparison is conducted, the inconsistency rate is zero.

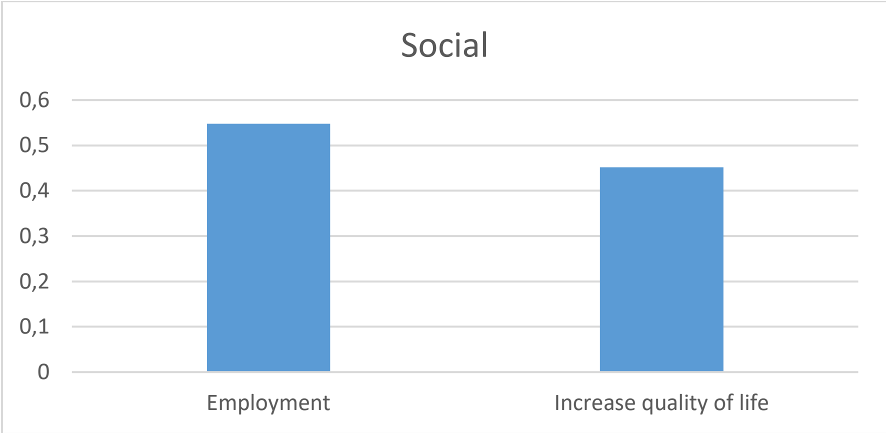

Figure 5.7 Ranking of social criteria

According to the results of the comparison shown in Figure 5.7, it is clear that employment criteria with the score of 0.548 is the most important criteria.

5.4.5 Final rank of sub-factors

After calculating the weights of all criteria and sub-factors, it is important to calculate the final rank of each sub-factor to have a better perspective. To do this, the weight of each sub-factor should be multiplied by the weight of its main factor. Result is shown in Figure 5.8.

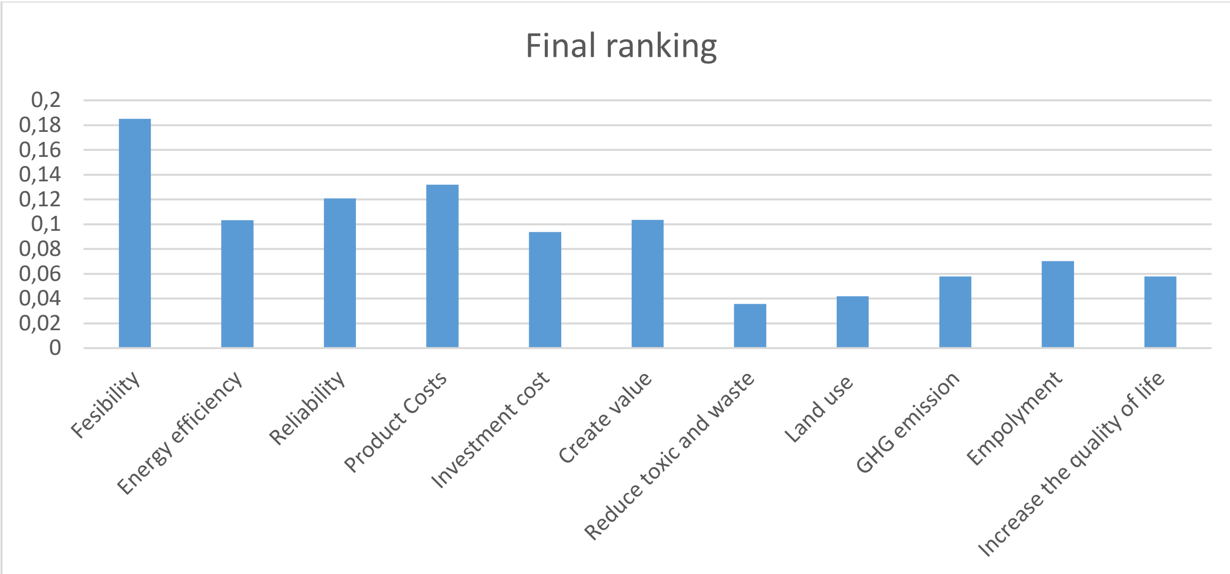

Figure 5.8 Final ranking of all criteria

It is important to rank all the sub-factors from the highest to the lowest. In Table 5.4, the weights of the main factors, primary weights of sub-factors and the final weights of sub-factors are presented.

Table 5.4 Final Ranking of all criteria

Criteria	weight	Sub-factors	Primary weight	Final weight	Rank
Technological	0.409	Feasibility	0.452	0.185	1
		Energy efficiency	0.252	0.103	4
		Reliability	0.295	0.120	3
Economic	0.327	Production costs	0.401	0.131	2
		Investment costs	0.284	0.093	5
		Create value	0.314	0.103	4
Environmental	0.135	Reduce toxics and wastes	0.263	0.035	9
		Land use	0.309	0.041	8
		GHG emissions	0.427	0.0577	7
Social	0.128	Employment	0.548	0.07	6
		Increase quality of life	0.451	0.0578	7

According to the results, feasibility, production costs and reliability are the most important factors that affect the success of hydrogen energy in Norway. As a result, to make hydrogen energy more competitive it is important to set strategies to improve these factors.

5.5 Cost analysis for different methods of hydrogen energy production

As mentioned in chapters 1 and 2, there are several methods of hydrogen energy production. According to the results of the previous section, production costs are the third most important factor in the success of hydrogen energy. As a result, it seems reasonable to choose a method with less production costs to produce hydrogen energy. The cost analysis in this section is done based on the methodology presented in chapter 3. The production costs of eleven different methods are calculated and presented in Table 5.5 and Figure 5.9. The environmental and social costs are not included in this analysis.

Table 5.5 Cost analysis of different methods of hydrogen energy production

Hydrogen energy production method	Capital cost	Variable operating cost	Fixed operating cost	Feedstock cost	EAC	Normalized EAC
Steam methane reforming	257.905	218.260	10.429	194.608	257.059	0.593
Central coal gasification without CCS	765.369	60.386	41.515	50.458	186.093	0.429
Biomass gasification	392.142	111.654	26.879	66.945	181.670	0.419
PV-based	581.075	346.463	23.097	374.475	433.479	1
Wind-based	581.075	162.538	23.097	171.217	249.554	0.575
Hydro-based electrolysis	581.075	128.319	23.097	133.76	215.335	0.496
Onsite electrolysis	34.911	7.266	1.990	6.728	13.097	0.030
Central grid electrolysis	581.075	278.228	26.877	258.307	369.024	0.851
Central natural gas without CCS	257.905	218.260	10.429	194.608	257.059	0.593
Central natural gas with CCS	477.232	234.585	16.324	194.179	303.404	0.699
On-site natural gas without CCS	6.001	0.95	0.423	0.900	2.0355	0.004

The results show that on-site production of hydrogen energy is cheaper than production in a central plant. The comparison between on-site hydrogen production from natural gas and electrolysis shows that production from natural gas is cheaper. The aim is to produce green hydrogen energy. Therefore, it is important to add the costs of carbon capture and storage to make better judgments.

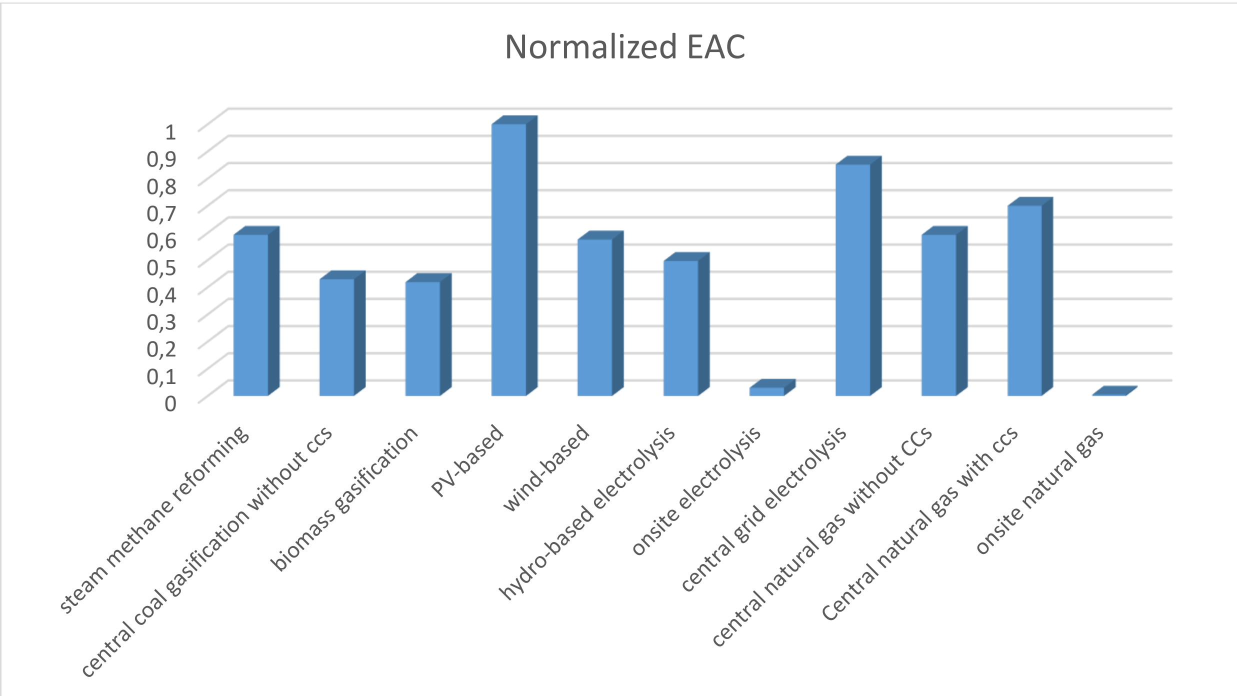

Figure 5.9 Comparison between different normalized EAC

The comparison of central methods of hydrogen energy production shows that biomass gasification and coal gasification are the most cost effective methods. The PV-based electrolysis proved to be the most expensive method of hydrogen energy production.

5.6 Validity of the research

As discussed in chapter 3, this study is considered to be valid as several criteria and methods are used to analyze hydrogen market in Norway. In addition, for the ranking of the model inconsistency rate proved the validity of the research.

6 Conclusions

The purpose of this study has been to develop a better understanding of the hydrogen energy in Norway. Therefore, this study has sought answers to determine whether it is beneficial to produce hydrogen energy and how it is possible to create competitive advantage from it. To address these questions:

- Interaction between SDGs were examined
- Important stakeholders in the hydrogen energy market in Norway were identified
- Strengths, weaknesses, opportunities and threats of hydrogen energy market in Norway were determined
- A model was created to identify the important factors influencing the success of hydrogen energy in the market
- A cost analysis for different methods of hydrogen energy production was conducted to determine the most cost-effective production method.

Based on the research conducted in this thesis, several findings and conclusions can be drawn, in addition to some recommendations.

6.1 Findings

This study indicates that hydrogen energy positively affects the achievement of SDG 7 and SDG 13. The Interactions between these two SDGs and other SDGs indicate that hydrogen energy could be considered as a bridge to sustainability. The stakeholder analysis illustrates that the government is the most important stakeholder in the hydrogen market, and that more support from government is necessary to grow the hydrogen market. This has been also confirmed by the SWOT analysis done in the study. Government has different potential tools such as policies, incentives, standards and regulations that could be helpful to make hydrogen energy competitive. It is necessary to utilize the most effective tools to reduce the dominance of the energy market by oil and gas industry and hydropower in favor of hydrogen energy. The deep cooperation between municipalities and business owners is another important factor that resulted in development of hydrogen energy in Norway. Comparison of strengths, weaknesses, opportunities and threats of hydrogen energy, together with the interactions between SDGs show that Norway will benefit from hydrogen energy. De-carbonization of transportation system, sustainable and regional development, improved energy security and resilience and more utilization of resources are amongst the most important benefits. Rankings of the four criteria of SWOT analysis indicate that weights of strengths and opportunities of hydrogen energy are more than its weaknesses and threats in Norway. As a result, it is concluded that Norway has the capacity to produce hydrogen energy, and investment in the hydrogen energy market will pay off. However, it is important to pay attention to weaknesses and threats of the market to combat challenges. To make the market more successful and to create green value from hydrogen energy, a number of strategies could be helpful. These strategies include encouraging more collaboration between business owners and authorities, assigning proper regulation and safety standards, combining hydrogen energy with carbon capture and storage and developing a clear plan to integrate hydrogen energy in the energy system. Ranking of the important factors of the success of hydrogen energy shows that feasibility, production costs and reliability, are the most important factors. The least important factors are toxic and waste reduction and land use. According to the higher ranks of technological and economic criteria than environmental criteria, it is concluded that just being an environmental friendly fuel is not enough for success. Since there are environmental friendly fuels in the market currently. The cost analysis indicates that the cheapest way to produce hydrogen energy is on-site hydrogen production from natural gas and the most expensive method is PV-based.

6.2 Recommendations

Some of the areas that need further in-depth investigations are addressed here for future work:

- Ranking the sub criteria of the SWOT analysis presented in the research.
- Calculating the price of hydrogen as a fuel in the market.
- Determining the best method of hydrogen energy production by using the model presented in the research, and compare it with the results from the cost analysis.

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Appendix

Appendix A

The detailed investigation of interactions between SDGs are presented in this part.

Figure A. 1 The list of 17 sustainable development goals (UN knowledge platform, 2015)

SDG 7 + SDG 1

Targets	Key interactions	Score
7.1 → 1.1	Energy is one of the most important needs of humans. Innovations and extended use of hydrogen energy lead to the supply of abundant and affordable energy all around the world. This can increase the disposable income of people since they spend less part of their income on energy. In addition, hydrogen energy production can create jobs, which is also helpful to increase the income level. There is also the possibility to take hydrogen infrastructure to deprived areas that have great potential in renewable energies production.	+2
7.1 → 1.4	As mentioned earlier, hydrogen energy is a secondary energy carrier, produced from different sources of energies. Therefore, it can provide more energy security, which definitely reinforces accessibility of poor to energy as one of their basic needs and achievement of this target.	+2
7.2, 7.3 → 1.4	Hydrogen energy is a clean source of energy that has the potential to enhance the deployment of renewable and energy efficiency to decarbonize energy systems. In the absence of innovations and supportive policies, hydrogen energy production might lead to increase in electricity prices. However, regarding oil price fluctuations and health expenditures caused by fossil fuel consumptions, hydrogen energy enables the provision of vast amounts of energy irrespective of fossil fuel reserves. In addition, it can play a vital role in helping developing countries accelerate their economic development and alleviate rural poverty.	+1
7.2, 7.3 → 1.5	Green hydrogen energy production is useful to build resilience and capacity to adapt to climate change, which is very important in the successful implementation of most of the SDGs. It makes it possible to decrease the burden of negative externalities of climate change on the poor.	0/+1

SDG 7 + SDG 2

Targets	**Key interactions**	**Score**
7.1 → 2.1	The availability and access to modern and affordable energy decrease the opportunity cost of the time spent on collecting fuel. Therefore, low-income households have more time to participate in agricultural activities and provide better food and income. Using hydrogen fuel in food delivery trucks reduces the transportation costs and it is possible to provide the poor with cheaper food. However, it could have an adverse effect if fuel prices increase due to hydrogen consumption in transportation section.	-1/+1
7.2 → 2.1	Various methods of production of hydrogen energy create less dependency on agriculture lands to grow energy crops. In addition, producing hydrogen energy from food waste could be helpful for food production.	0/+1
7.2 → 2.3	The use of hydrogen energy reinforces this target by creating jobs in deprived and rural areas as a result of building on-site hydrogen energy production plants or enhancing agriculture in the area by growing bioenergy crops. Furthermore, it is possible to take the infrastructure to rural areas and help them produce the energy and create income. It can reduce the cost of nitrogen fertilizers and make more lands suitable for agriculture.	+2
7.3 → 2.4	Increase in energy efficiency can reinforce resilient agricultural practices and make sustainable agriculture profitable. It is also a way to mitigate GHG emissions and increase resilience.	+2
7.2, 7.3 → 2.3, 2.4	Zero emission tractors can reduce GHG emissions. Energy efficiency enhances agriculture productivity by decreasing the amount of energy input. Hydrogen energy makes it possible to use different sources of renewable energies in rural areas to implement more sustainable agricultural practices. Producing energy from food waste also helps deforestations. In addition, the achievement of these targets enhances the quality of life for farmers.	+1

SDG 7 + SDG 3

Targets	Key interactions	Score
7.1 → 3.1	Hydrogen energy increases the availability of clean sources of energy; therefore, it will help those mothers in deprived areas who suffer from negative externalities of using biomass and coals. For example, the provision of clean fuel and clean stoves for cooking during pregnancy reduces negative risks of fossil fuel on their health. In addition, by better transportation system, as a result of abundant clean energy, they can reach the doctor and necessary medications faster and more facilitated. This also enables medical facilities to have a reliable energy supply for their operations.	+1
7.1 → 3.8	Universal clean energy access facilitates communications with deprived livelihoods to provide them with their basic needs, vaccines and medicines. Unfortunately, many healthcare facilities in these areas lack access to energy for basic services such as lighting, heating, effective storage for medicines and the powering of medical equipment.	+2
7.1, 7.2. 7.3 → 3.9	Clean hydrogen energy reinforces this target as a result of reduction in GHGs and boosting air quality.	+2
7.2, 7.3 → 3.6	This may increase the use of private cars that use clean energy. As a result, traffic and consequently death and injuries from road traffic accidents increase.	-1
7.2, 7.3 → 3.4	If the innovations in clean hydrogen energy lead to cheap energy and the availability of clean transportation vehicles, it may encourage more people to use their personal cars instead of walking or using bicycles. Therefore, rates of diabetes or heart disease could increase and this can have a negative health effect.	0/-1

SDG 7 + SDG 4

Targets	Key interactions	Score
7.1 → 4.1, 4.2, 4.3, 4.7	Provision of affordable energy leads to better transportation systems which encourage more students to go to schools or pursue their education (unfortunately, in deprived areas there are no schools and students should go to adjacent cities). In addition, this makes it possible to provide schools in rural areas with cheap and clean energy for lightening and other purposes.	+2
7.2, 7.3 → 4.4	Innovations in hydrogen energy and the extension of its production from various renewables encourage entrepreneurs and make it possible to build the infrastructure in the rural areas. This can also create jobs.	+1

SDG 7 + SDG5

Targets	Key interactions	Score
7.1, 7.2, 7.3 ⟶ 5	At first sight, it seems that SDG 7 is not related to targets of SDG 5, but the availability of an affordable clean source of energy and energy innovations can indirectly and directly influence the lives of too many women all around the world. This can enhance their health due to less exposure to fossil fuels like coal, they can allocate the time they use for fuel searching to leisure activities. Since renewable energy results in job creation and better transportation system, women have more possibility to work and continue their educations, which are key factors in women empowerment.	+2

SDG 7 + SDG 6

Targets	Key interactions	Score
7.1 ⟶ 6.1, 6.2, 6.3, 6.6	Provision of affordable and abundant energy results in increase in the supply of drinking water. Since it is more convenient for health authorities to go to rural and deprived areas, women have better access to health services and it is possible to get more information about their health and the ways they can improve their health and life.	+1
7.2, 7.3 ⟷ 6.1, 6.4	It is hard to determine the effects of green hydrogen energy and innovations on the supply of drinking water. On one hand, high quality water per year will be produced as by-product of hydrogen usage. On the other hand, the increase in water demand stimulates innovations in hydrogen energy storage to integrate different intermittent renewables like solar and wind into energy system. If hydrogen is produced from water through electrolysis, the water demand increases and this has a negative effect on supply of drinking water.	0/+1
7.2, 7.3 ⟶ 6.3, 6.6	Spread of hydrogen energy and increase in energy efficiency reinforce these targets since they decrease the waste water and amount of chemical in the water, and through circular economy and waste management they can help save water resources.	+2
7.2, 7.3 ⟶ 6.1, 6.4, 6.5	Hydrogen energy production from renewables and energy efficiency reinforce water access by using water more efficiently and producing water as a by-product. In addition, unlike hydropower, in this method, there is no need to build dams, which negatively affects the supply of drinking water.	+2

SDG 7 + SDG 8

Targets	Key interactions	Score
7.2, 7.3 → 8.3, 8.5, 8.6	Hydrogen energy and energy efficiency could result in many job losses in fossil fuel related industries, but they can create new jobs as well. Especially in deprived areas, these innovations make it possible for people to be involved in renewable energy production. In addition, they can empower women and give them more chances to be active in the society.	+1
7.2, 7.3 → 8.8	Green hydrogen energy and energy efficiency reinforce safe work conditions and environment, since workers are less exposed to fossil fuels and the negative effects on their health.	+2
7.2, 7.3 ← 8.9, 8.10	Promoting sustainable tourism and strengthening domestic financial institutions reinforce investments and financial supports in renewable energies, innovations in productions and storage methods and boosting energy efficiency.	+2
7.2, 7.3 → 8.4	Green hydrogen energy and energy efficiency increase global resource efficiency, and through practicing more sustainable approaches and circular economy, environmental degradation decreases. This can positively affect economic growth.	+1
7.1,7.2,7.3 → 8.9	The availability of abundant clean and affordable energy reduces pollution and promote economic development in different parts of the world. It also makes it possible to provide environmental friendly tourist facilities. As a result, achievement of these targets enables sustainable tourism to grow.	+1

SDG 7 + SDG 9

Targets	Key interactions	Score
7.1, 7.2, 7.3 ⟵ 9.1	Developing sustainable and resilient infrastructure reinforces boosting energy efficiency, innovations in new energy resources and more investment in green energies such as hydrogen energy. This promotes sustainable economic development and human well-being.	+2
7.2, 7.3 ⟷ 9.2	These targets have bilateral reinforcing effects on each other. Therefore, assigning policies promoting one supports the achievement of the other one, and the other way around.	+2
7.2, 7.3 ⟷ 9.4	There is a bilateral relationship between these targets. Prevalence of green hydrogen energy and energy efficiency reinforce upgrading industries and make them more sustainable. In addition, development of more sustainable infrastructures and industries increases the need for renewable energies and energy efficiency.	+2
7. 2, 7.3 ⟷ 9.5	Shifting to hydrogen energy and boosting energy efficiency require comprehensive scientific researches to find out new approaches and solutions to solve related problems. In addition, more scientific research and strong R&D sectors lead to innovations, which reinforce these targets.	+1
7.2, 7.3 ⟵ 9.3	Access of small-scale enterprises to financial resources enables them to shift to renewable energies and practice new approaches to enhance energy efficiency.	0/+1

SDG 7 + SDG 10

Targets	Key interactions	Score
7.2, 7.3 ⟶ 10.1	On one hand, extensive utilization of hydrogen energy creates jobs and especially in sparsely populated areas can positively affect the income level. On the other hand, it is very important to supply affordable and cheap energy, because high energy prices will result in more inequality.	0/+1
7.1 ⟶ 10.7	Abundant and affordable energy will make migration more facilitated by providing better and more facilitated transportation systems.	+1
7.1, 7.2, 7.3 ⟶ 10.6	Abundant and affordable clean energy may result in reducing inequality, but it is not promising to make the role of developing countries more important in decision-making processes.	-1/0

SDG 7 + SDG 11

Targets	Key interactions	Score
7.2, 7.3 ← 11.6	To reduce the negative environmental impacts of cities, it is necessary to shift to renewable energies and increase energy efficiency. Therefore, this target has a positive effect on shifting to hydrogen energy.	+2
7.2, 7.3 ↔ 11.3	Enhanced sustainable urbanization increases the demand for renewable energies and these targets will be achieved. In addition, hydrogen energy and energy efficiency help sustainable urbanization.	+2
7.2, 7.3 → 11.5	Transition to using clean energy sources and energy efficiency decrease negative consequences of global warming such as severe hurricanes and storms. However, this transition is helpful to build resilience. It is difficult to address all the indicators related to this target.	+1

SDG 7 + SDG 12

Targets	Key interactions	Score
7.2 → 12.3, 12.4	It is possible to produce hydrogen energy from waste. Therefore, bio hydrogen energy and circular economy reinforce the achievement of this target and reduce the amount of food waste.	+2
7.2, 7.3 ← 12.1, 12.6, 12.7	Implementing policies promoting sustainable consumption and production increases the demand for green sources of energy and energy efficiency enhancement.	+1
7.2, 7.3 → 12.1, 12.6	Hydrogen energy and improvements in energy efficiency act as a key factor to stimulate practicing more sustainable approaches in consumption and production.	+2
7.1 → 12.5	Hydrogen energy is green and environmental friendly and its abundant availability and consumption do not hurt the environment. This might stimulate people to ignore sustainable practices and waste energy.	-1/0

SDG 7 + SDG 13

Targets	Key interactions	Score
7.1 → 13.3	Accessibility of affordable and reliable hydrogen energy will automate transportation and information technology, which are essential to improve education and awareness about climate change issues.	+1
7.2, 7.3 ← 13.3	Higher education and awareness about climate change stimulate transition to renewable energies. This requires more efforts and innovations to increase energy efficiency and find solutions for renewable hydrogen energy challenges. Therefore, awareness alone is not enough.	0/+1
7.2, 7.3 ← 13.2, 13.3	To achieve development in hydrogen energy and energy efficiency, it is important to integrate climate change measures such as carbon tax to make fossil fuels less attractive in national or international policies.	+1
7.1, 7.2, 7.3 → 13.1	Accessibility of affordable clean hydrogen energy helps decarbonize the system, reduce GHG emissions, mitigate climate change and strengthen resilience.	+2

SDG 7 + SDG 14

Targets	Key interactions	Score
7.2, 7.3 → 4.1, 14.2, 14.3	One of the most important applications of hydrogen energy is to use it as a fuel for ships; this will reinforce protection of marine and coastal ecosystem.	+2
7.2 ← 14.1, 14.2	Implementing measure and strategies to minimize marine pollution and ocean acidification aids development of hydrogen energy and energy efficiency.	+1

SDG 7 + SDG 15

Targets	Key interactions	Score
7 → 15	The availability of hydrogen energy as a reliable source of energy helps reduce GHG emissions and conserve biodiversity. However, to achieve the target better and more practical measurements and policies for sustainable use of land and agriculture, deforestation ad other related issues seem necessary.	+1

SDG 7 + SDG 16

Targets	Key interactions	Score
7 → 16	The availability of affordable energy helps improve education, awareness, and reduce inequality in different parts of the world. As a result, it helps smooth the path to achieve the target, but it is not enough and other policies need to be considered.	0/+1

SDG 13 + SDG 1

Targets	Key interactions	Score
13.1 → 1.1, 1.5	Strengthening resilience and adaptive capacity to climate change related issues enable tackling the root causes of poverty, since many of the poor are extremely dependent on natural resources. Improvements in water and soil regulations, which enhance agriculture and food security, are considered as a key driver of impacts on poverty. In addition, strengthening resilience helps the poor manage the risks better and not lose all they have due to natural disasters.	+1
13 ← 1.1, 1.5	Eradicating poverty and building resilience help take more actions against climate change. This stimulates more people to use more sustainable approaches and shift to renewable energies such as hydrogen energy.	+1
13 ↔ 1	There is a bilateral relationship between these goals, so achieving one could enable achieving the other. However, it requires proper policies and supports from governments to smoothen the pathway.	+1

SDG 13 + SDG 2

Targets	Key interactions	Score
13.1, 13.2 ⟶ 2.1, 2.2	Unfortunately, climate change adversely affected the livelihoods of a large number of people. The rural poor are at risk and their vulnerability to food insecurity has increased. Therefore, addressing climate change related issues would positively improve food security. However, it is important to implement strategies, which do not threat food production and agriculture. For example, transition to biomass fuel will negatively affect the agriculture.	+1
13 ⟵ 2.4	Sustainable agricultural practices is a key driver to climate adaptation and mitigation (such as improving soils and land quality, genetic diversity, and bioenergy). As a result, the achievement of this target could positively affect the SDG 13.	0/+1
13 ⟵ 2	Agriculture is an important source of greenhouse gas emissions and so contributes to climate change. Sustainable agricultural systems and practices contribute to ecosystem health. However, increased agricultural production and productivity, if not sustainable, can result in deforestation and land degradation, jeopardizing long-term food security.	+1
13.1 ⟵ 2.3	Doubling the agriculture productivity may stimulate unsustainable agricultural practices, which has adverse effects on climate change.	-1
13.1 ⟵ 2.4, 2.5	Sustainable agriculture and keeping genetic diversity of seeds and plants reinforce combat against climate change.	+2

SDG 13 + SDG 3

Targets	Key interactions	Score
13.2 ⟶ 3.9	Integrating climate change measures into national policies results in more consumption of green fuels such as hydrogen energy, reduces GHG emissions, improves air quality and consequently reinforces decrease in the number of death and illnesses as a result of climate issues.	+2
13.3 ⟶ 3.9, 3.4	Increasing awareness about climate change and negative effects of fossil fuels and hazardous chemicals stimulates practicing more sustainable approaches. This will result in less exposure to fossil fuels and positively affects health.	+1

SDG 13 + SDG 4

Targets	Key interactions	Score
13.1 → 4.1	Strengthening resilience aids empowering poor areas and facilitates providing education opportunities.	+1
13.3 ← 4.1, 4.2, 4.3	Higher education reinforces awareness and knowledge about climate change and increases innovations to mitigate and combat climate change.	+1

SDG 13 + SDG 5

Targets	Key interactions	Score
13.1 → 5	Strengthening resilience aids women empowerment especially in rural and deprived areas, but this is not enough. Therefore, more collaboration and cooperation between different sectors is necessary to achieve this target.	0

SDG 13 + SDG 6

Targets	Key interactions	Score
13.2, 13.3 → 6.3, 6.4, 6.6	Integrating climate change measures into national policies and raising awareness regarding this issue result in more protection of water resources and sustainable use of water. It is important to consider that many of renewable energy production approaches negatively affect water supply.	0/+1
13 → 6.1, 6.2	Increasing water supply and providing sanitized water for all may require energy intensive practices. Therefore, it is important to use clean sources of energies to provide energy for water sanitation.	0/+1

SDG 13 + SDG 8

Targets	Key interactions	Score
13.2, 13.3 → 8.2, 8.4	Integrating climate measure into national policies and raising awareness definitely result in innovations, boosting productivity and reducing environmental degradation.	+3
13.1 ← 8.3, 8.10	Promoting development related policies and strengthening financial institutes, helps provide required financial resources and infrastructures to strengthen resilience.	+1
13 ↔ 8	There is a bilateral relationship between these two SDGs. Achieving one reinforces another and vice versa. Climate change measurement, results in practicing more sustainable approaches to achieve economic growth. In addition, boosting productivity and sustainable development result in climate change mitigation and subsequently reduce environmental degradation.	+2

SDG 13 + SDG 9

Targets	Key interactions	Score
13.1 ← 9.1	Developing reliable and sustainable infrastructure is required to strengthen resilience and enhance adaptive capacity to climate related disasters.	+3
13.2 → 9.1, 9.2, 9.4	Integrating climate change measures into national policies promotes sustainable development, resource efficiency and environmental friendly approaches and technologies such as using green sources of energy and innovations in hydrogen energy production.	+2
13.2, 13.3 → 9.5	Raising awareness and applying climate change actions enhance scientific research and motivate R&D sectors to find new solutions for available problems.	+1

SDG 13 + SDG 10

Targets	Key interactions	Score
13.1 ← 10.2, 10.3, 10.4	Ensuring equal opportunities and reducing inequalities in outcome along with empowering minorities and the poor stimulate building resilience to climate change hazards.	0/+1
13.1 ← 10.6	Increasing the role and the voice of developing countries in international decision-making gives them the opportunity to discuss their climate and environmental issues.	+1

SDG 13 + SDG 11

Targets	Key interactions	Score
13.2, 13.3 → 11.2, 11.3	Integrating environmental measures into policies and increasing awareness reinforce installing sustainable transportation systems. Hydrogen energy can play an important role in transition to zero-emission transportation system.	+1
13.1 → 11.1, 11.5	Strengthening the resilience enables us to protect the poor from natural hazards and disasters and decreases the number of deaths caused by these accidents.	+1

SDG 13 + SDG 12

Targets	Key interactions	Score
13.2, 13.3 → 12.2, 12.4, 12.5	Implementing environmental measures and increasing awareness stimulate sustainable development and better use of natural resources, since they promote utilization of green sources of energy and increase energy efficiency and productivity.	+2
13.3 ← 12.8	Having more knowledge and information regarding sustainable development and protecting the nature leads to becoming more conscious about climate change issues.	+3

SDG 13 + SDG 14

Targets	Key interactions	Score
13.2 → 14.1, 14.2, 14.3	Integrating climate change measures into policies promotes the utilization of green sources of energies such as hydrogen energy, which reinforces ocean pollution and acidification reduction and conserves marine ecosystem.	+2
13.1 ↔ 14.1, 14.2, 14.3, 14.4, 14.5	Actions and policies taken to strengthen resilience and adaptive capacity to climate related issues will reinforce the protection of marine ecosystem and sustainable use and managements of oceans and coastal ecosystems.	+2
13.3 → 14.a, 14.3, 14.4	Increasing knowledge and awareness regarding climate related issues draws more attention towards marine ecosystems. Therefore, it stimulates scientific researches addressing problems such as ocean pollution and acidification and sustainable use of marine ecosystems.	+1
13.1, 13.2 → 14.1, 14.2, 14.3	Policies and actions taken to strengthen the resilience or to address climate related issues may negatively affects marine and coastal ecosystem. For example, utilizing wind power and installing windmills in the oceans or many equipment in the coasts to strengthen the resilience may adversely affect the marine ecosystem.	-1

SDG 13 + SDG 15

Targets	Key interactions	Score
13.3, 13.2 → 15.1,15.2, 15.4, 15.5	More awareness and integration of climate change policies enable sustainable management of forests and ensure conservation of terrestrial ecosystem.	+1
13.1 ↔ 15.1, 15.2, 15.3, 15.4, 15.5	Forest landscape restoration approaches and practices provide opportunities for enhancing socio-ecological resilience in landscapes. At the same time, resilience principles can make valuable contributions to forest landscape restoration. This will ensure that socio-ecological resilience is enhanced.	+1

SDG 13 + SDG 16

Targets	Key interactions	Score
13.1, 13.2 ← 16.6	Developing effective and transparent institutions will result in integration of climate change measures into national policies and more efforts to strengthen resilience.	0/ +1

Appendix B

Prioritization of the main criteria of the model

After creating questionnaires based on triangular fuzzy numbers, aggregate of preferences of each expert is calculated by geometric mean of triangular fuzzy numbers.

$F_{AGR} = (\prod(l), \prod(m), \prod(u))$ I, m and u are triangular fuzzy numbers. (B.1)

Table B.1 Aggregation of expert's pair wise comparison matrices for main level criteria

	Technological			Economic			Environmental			Social		
Technological	1	1	1	1.758	1.895	2.334	2.380	3.108	3.537	2.164	2.611	2.936
Economic	0.428	0.528	0.569	1	1	1	1.851	2.117	2.668	2.253	3.602	3.348
Environmental	0.283	0.322	0.420	0.375	0.472	0.540	1	1	1	0.950	1.000	1.178
Social	0.341	0.383	0.462	0.299	0.278	0.444	0.849	1.000	1.053	1	1	1

Then, fuzzy synthetic extend is calculated by Equation B.2 and the result is presented in Table B.2

$\sum_{j=1}^{4} M_{g_1}^{j} = (1,1,1) \oplus (1.75, 1.86, 2.35) \oplus (2.38, 3.1, 3.57) \oplus (2.164, 2.61, 2.94) = (7.30, 8.61, 9.81)$ (B.2)

This should be calculated for all the rows, as it is presented in Table B.2.

$\sum_{i=1}^{4} \sum_{j=1}^{4} M_g^j = (17.93, 21.23, 23.49)$ (B.3)

Then, to normalize each criteria the sum of all of its values should be divided by the sum of all preferences of each column. After that by using Equation B.4, It is possible to normalize the values.

$S_k = \sum_{i=1}^{n} M * (\sum_{i=1}^{n} \sum_{j=1}^{n} M_g^j)^{-1}$ (B.4)

Table B.2 Fuzzy synthetic extend and normalized numbers

Fuzzy			Normalized		
7.30	8.61	9.81	0.311	0.404	0.547
5.53	7.25	7.58	0.236	0.340	0.423
2.61	2.79	3.14	0.111	0.131	0.175
2.49	2.66	2.96	0.106	0.125	0.165
17.93	21.31	23.49			
0.043	0.047	0.056			

Through normalization, it is possible to calculate the non-fuzzy weight vector W, which is defined by:

$$W = \left(\min V\left(\tilde{S}_1 \geq \tilde{S}_k\right), \min V\left(\tilde{S}_2 \geq \tilde{S}_k\right), \ldots, \min V\left(\tilde{S}_n \geq \tilde{S}_k\right)\right)^T \quad \text{(B.5)}$$

The results are shown in tables B.3 and B.4.

Table B.3 Calculation of non-fuzzy weight vector

	L1	M1	U1	L2	M2	U2	Mi>Mk	Ui>Lk	final
V(S1>S2)	0.311	0.404	0.547	0.236	0.340	0.423	1	1.26	1.00
V(S1>S3)	0.311	0.404	0.547	0.111	0.131	0.175	1	2.68	1.00
V(S1>S4)	0.311	0.404	0.547	0.106	0.125	0.165	1	2.73	1.00
V(S2>S1)	0.236	0.340	0.423	0.311	0.404	0.547	0	0.64	0.64
V(S2>S3)	0.236	0.340	0.423	0.111	0.131	0.175	1	3.03	1.00
V(S2>S4)	0.236	0.340	0.423	0.106	0.125	0.165	1	3.11	1.00
V(S3>S1)	0.111	0.131	0.175	0.311	0.404	0.547	0	0.00	0.00
V(S3>S2)	0.111	0.131	0.175	0.236	0.340	0.423	0	0.00	0.00
V(S3>S4)	0.111	0.131	0.175	0.106	0.125	0.165	1	1.10	1.00
V(S4>S1)	0.106	0.125	0.165	0.311	0.404	0.547	0	0.00	0.00
V(S4>S2)	0.106	0.125	0.165	0.236	0.340	0.423	0	0.00	0.00
V(S4>S3)	0.106	0.125	0.165	0.111	0.131	0.175	0	0.90	0.90

Table B.4 Calculation of non-fuzzy weight vector

V(S1>Sk)	1.000	0.611
V(S2>Sk)	0.636	0.389
V(S3>Sk)	0.000	0.000
V(S4>Sk)	0.000	0.000

To defuzzify these numbers, a simple centroid method is used and non-fuzzy weights are considered as the best non-fuzzy performance values (Chang and Chou, 2008). The results are shown in table B.5.

$$x_{\max}^{1} = \frac{l+m+u}{3}$$
$$x_{\max}^{3} = \frac{l+2m+u}{4} \qquad \text{(B.6)}$$
$$x_{\max}^{2} = \frac{l+4m+u}{6}$$

Crisp number = Z^{*} = max { $x_{\max}^{1}, x_{\max}^{2}, x_{\max}^{3}$ }

Table B.5 Defuzzification of calculated normal weights of the main criteria of the model

Crisp	X1max	X2max	X3max	Deffuzy	Normalized
Technological	0.421	0.416	0.412	0.421	0.409
Economic	0.333	0.335	0.336	0.336	0.327
Environmental	0.139	0.137	0.135	0.139	0.135
Social	0.132	0.130	0.128	0.132	0.128

The calculated inconsistency rate is 0.04 (that is less than 0.1). As a result, it is possible to validate the computations. Saaty (1980) mentioned that one way to calculate inconsistency is to use Equation B.7: (Meixner, 2009).

$$CI = \frac{\lambda_{\max} - n}{n-1} \text{ and } CR = \frac{CI}{RC} \leq 0.1 \qquad \text{(B.7)}$$

λ is the maximum eigenvalue of the comparison matrix.

Prioritization of technological sub-factors

Table B.6 Aggregation of expert's pair wise comparison matrices for technological criteria

	C11			C12			C13		
C11	1	1	1	1.201	1.778	2.595	1.053	2.262	1.644
C12	0.385	0.563	0.833	1	1	1	0.470	1.236	1.102
C13	0.608	0.442	0.950	0.908	0.809	2.128	1	1	1

Table B.7 Fuzzy synthetic extend and normalized numbers

Fuzzified			Normalized		
3.254	5.039	5.239	0.266	0.499	0.687
1.855	2.799	2.934	0.151	0.277	0.385
2.516	2.251	4.078	0.205	0.223	0.535
7.625	10.089	12.250			
0.082	0.099	0.131			

Table B.8 Calculation of non-fuzzy weight vector

	L1	M1	U1	L2	M2	U2	M>Mk	U>Lk	final
V(S1>S2)	0.266	0.499	0.687	0.151	0.277	0.385	1	1.71	1.00
V(S1>S)	0.266	0.499	0.687	0.205	0.223	0.535	1	2.35	1.00
V(S2>S1)	0.151	0.277	0.385	0.266	0.499	0.687	0.000	0.349	0.349
V(S2>S3)	0.151	0.277	0.385	0.205	0.223	0.535	1.000	1.434	1.000
V(S3>S1)	0.205	0.223	0.535	0.266	0.499	0.687	0.000	0.493	0.493
V(S3>S2)	0.205	0.223	0.535	0.151	0.277	0.385	0.000	0.876	0.876

Table B.9 Calculation of non-fuzzy weight vector

V(S1>S)	1.000	0.543
V(S2>Sk)	0.349	0.190
V(S>Sk)	0.493	0.268
	1.843	1

The calculated inconsistency rate is 0.03 (that is less than 0.1). As a result, it is possible to validate the computations.

Prioritization of economic sub-factors

Table B.10 Aggregation of expert's pair wise comparison matrices for sub-criteria of economic criteria

	C21			C22			C23		
C21	1	1	1	1.199	1.289	1.516	0.982	1.590	1.514
C22	0.660	0.776	0.834	1	1	1	0.780	0.768	1.133
C23	0.661	0.629	1.018	0.882	1.301	1.281	1	1	1

Table B.11 Fuzzy synthetic extend and normalized numbers

Fuzzified			Normalized		
3.181	3.879	4.029	0.309	0.415	0.494
2.440	2.544	2.968	0.237	0.272	0.363
2.543	2.930	3.300	0.247	0.313	0.404
8.164	9.353	10.296			
0.097	0.107	0.122			

Table B.12 Calculation of non-fuzzy weight vector

	L1	M1	U1	L2	M2	U2	Mi<Mk	Ui<Lk	final
V(S1>S2)	0.309	0.415	0.494	0.237	0.272	0.36	1	2.25	1.00
V(S1>S3)	0.309	0.415	0.494	0.247	0.313	0.40	1	1.70	1.00
V(S2>S1)	0.237	0.272	0.363	0.309	0.415	0.49	0.00	0.27	0.27
V(S2>S3)	0.237	0.272	0.363	0.247	0.313	0.40	0.000	0.738	0.738
V(S3>S)	0.247	0.313	0.404	0.309	0.415	0.49	0.00	0.48	0.48
V(S3>S2)	0.247	0.313	0.404	0.237	0.272	0.36	1.00	1.32	1.00

Table B.13 Calculation of non-fuzzy weight vector

V(S1>Sk)	1.000	0.568
V(S2>Sk)	0.277	0.157
V(S3>Sk)	0.484	0.275
	1.761	1

Table B.14 Defuzzification of calculated normal weights of the sub factors of economic criteria of the model

Crisp	X1max	X2max	X3max	Deffuzy	Normal
C21	0.406	0.408	0.410	0.410	0.401
C22	0.291	0.286	0.281	0.291	0.284
C23	0.321	0.319	0.317	0.321	0.314
				1.023	1.000

The calculated inconsistency rate is 0.004 (that is less than 0.1). As a result, it is possible to validate the computations.

Prioritization of social sub-factors

Table B.15 Aggregation of expert's pair wise comparison matrices for sub-factors of social criteria

	C41			C42		
C41	1	1	1	0.917	1.331	1.389
C42	0.720	0.752	1.090	1	1	1

Table B.16 Fuzzy synthetic extend and normalized numbers

fuzzified			Normalized		
1.917	2.331	2.389	0.428	0.571	0.657
1.720	1.752	2.090	0.384	0.429	0.575
3.637	4.082	4.479			
0.223	0.245	0.275			

Table B.17 Calculation of non-fuzzy weight vector

	L1	M1	U1	L2	M2	U2	Mi>Mk	U>Lk	final
V(S1>S2)	0.428	0.571	0.657	0.384	0.429	0.575	1	2.08	1.00
V(S2>S1)	0.384	0.429	0.575	0.428	0.571	0.657	0.000	0.508	0.508

Table B.18 Calculation of non-fuzzy weight vector

V(S1>Sk)	1.000	0.663
V(S2>Sk)	0.508	0.337
	1.508	1.000

Table B.19 Defuzzification of calculated normal weights of the sub factors of social criteria of the model

Crisp	X1max	X2max	X3max	Deffuzy	Normal
C41	0.552	0.557	0.561	0.561	0.548
C42	0.463	0.454	0.446	0.463	0.452
				1.024	1.000

Prioritization of environmental sub-factors

Table B.20 Aggregation of expert's pair wise comparison matrices for environmental sub-factors

	C31			C32			C33		
C31	1	1	1	0.627	0.764	0.921	0.56	0.66	0.97
C32	1.085	1.310	1.595	1	1	1	0.55	0.59	0.70
C33	1.028	1.495	1.780	1.423	1.671	1.799	1	1	1

Table B.21 Fuzzy synthetic extend and normalized numbers

Fuzzy			Normalized		
2.189	2.402	2.708	0.200	0.247	0.314
2.594	2.882	3.207	0.237	0.297	0.372
3.830	4.423	5.019	0.350	0.456	0.583
8.613	9.707	10.934			
0.091	0.103	0.116			

Table B.22 Calculation of non-fuzzy weight vector

	L1	M1	U1	L2	M2	U2	M>Mk	Ui>Lk	final
V(S1>S2)	0.203	0.256	0.349	0.245	0.306	0.398	0	0.68	0.68
V(S1>S3)	0.203	0.256	0.349	0.320	0.438	0.553	0	0.14	0.14
V(S2>S1)	0.245	0.306	0.398	0.203	0.256	0.349	1.000	1.345	1.000
V(S2>S3)	0.245	0.306	0.398	0.320	0.438	0.553	0.000	0.370	0.370
V(S3>S1)	0.320	0.438	0.553	0.203	0.256	0.349	1.000	2.089	1.000
V(S3>S2)	0.320	0.438	0.553	0.245	0.306	0.398	1.000	1.754	1.000

Table B.23 Calculation of non-fuzzy weight vector

V(S1>Sk)	0.137	0.091
V(S2>Sk)	0.370	0.246
V(S3>Sk)	1.000	0.663
	1.508	1

Table B.24 Defuzzification of calculated normal weights of sub factors of environmental criteria of the model

Crisp	X1max	X2max	X3max	Deffuzy	Normalized
C31	0.270	0.266	0.263	0.270	0.263
C32	0.316	0.314	0.311	0.316	0.309
C33	0.437	0.437	0.438	0.438	0.428
				1.024	1.000

Appendix C

One of the questionnaires that was used in this research is presented in Table C.1.

Please rank relative importance of important factors in the success of hydrogen energy in hydrogen market.

1= Equal, 3= Moderate, 5= Strong, 7= Very strong and 9= Extreme

Table C.1 A-questionnaire sample

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria
Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Economic
Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental
Technology	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Social
Economic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental
Economic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Social
Environmental	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Social