THE PROSPECTS OF GREEN AND BLUE HYDROGEN PRODUCTION IN NORWAY FOR ENERGY EXPORT

Claudia Siew Wan Cheng
University of Stavanger
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AUTHOR:
Claudia Siew Wan Cheng

SUPERVISOR:
Oluf Langhelle

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Abstract

As the threat of climate change impacts looms, with global temperatures rising to 1.5°C as early as 2030, the need for rapid low-carbon energy transition is more urgent than ever. As a global leader in climate change negotiations, the EU has committed to become carbon neutral by 2050 and hydrogen is set to play a critical role in decarbonising sectors which are difficult to electrify such as freight transport, energy-intensive industries required high-grade heat and power generation sectors. This offers an opportunity for Norway to mitigate the risk of declining demand and supply of its fossil-fuel based energy exports. This thesis provides an overview of the key drivers and barriers that could affect the prospects of blue and green hydrogen export in Norway. Given that transitions, in general, do not follow a linear-process, the thesis uses exploratory scenarios as a framework to enhance the understanding of how the interplay of these drivers could affect the trajectories of the pathways of blue and green hydrogen developments in Norway. The findings and analysis show that Norway is well-positioned in terms of natural resources availability, existing compatible infrastructure and technological expertise for the development of both types of hydrogen and has a great potential for becoming a market leader in the export of hydrogen. As its natural gas reserves deplete, the role of green hydrogen in a low-carbon energy system is likely grow more significantly. Therefore, it is critical for policymakers to consider the eventual phase-out of blue hydrogen and scaling up of green hydrogen in its strategy as early as possible. Overall, blue hydrogen should be viewed as a short-term solution to enable a rapid hydrogen transition, but green hydrogen would offer better prospects for a more sustainable economy for Norway.

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List of abbreviations and acronyms

AFC	Alkaline Fuel Cell
ALK	Alkaline
ATR	Auto-thermal reforming
CCS	Carbon capture and Storage
CGH_2	Compressed gas hydrogen
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EIB	European Investment Bank
ETS	Emission Trading System
EU	European Union
EU-28	EU consisting of 28 group members: Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, United Kingdom
GDP	Gross Domestic Product
GHG	Greenhouse gas
H_2	Hydrogen
HRS	Hydrogen Refuelling Station
HVDC	High-Voltage Direct Current
IEA	International Energy Agency
IGC Code	International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMDG Code	International Maritime Dangerous Goods Code
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Energy
LH_2	Liquid hydrogen
LOHC	Liquid organic hydrogen carrier
MLP	Multi-level perspective
MSR	Market Stability Reserve
NCS	Norwegian Continental Sea
NH_3	Ammonia
NPD	Norwegian Petroleum Directorate
NTNU	Norwegian University of Science and Technology
NVE	Norges vassdrags- og energidirektorat (Norwegian Water Resources and Energy Directorate)
PEM	Proton exchange membrane
PESTEL	Political, Economic, Social, Technological, Environmental, Legal
POX	Partial oxidation
RE	Renewable Energy
RQ	Research question
SMR	Steam methane reforming
SOEC	Solid oxide electrolyser cell
TCM	Technology Centre Mongstad
VRE	Variable renewable energy

List of units of measurements

bcm o.e.	Billion cubic meters of oil equivalent
EJ	Exajoules
GWh	Gigawatt hours
kg H_2	Kilogram of hydrogen
kg/m^3	Kilogram per cubic metre
kWh	Kilowatt hour
kWh_{H2}	Kilowatt hour generated from hydrogen
m/s	Metre per second
m3	Cubic metre
MMBTU	Million British Thermal Unit
MT	Metric ton
MW	Megawatt
MWh	Megawatt hour
Nm^3	Normal cubic metre
Sm^3	Standard cubic metre
Sm^3 o.e.	Standard cubic metre oil equivalent
t	ton
tpd	Ton per day
TWh	Terawatt hour

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1.0 Introduction

Based on the latest IPCC estimates, global warming is likely to reach 1.5^{o}C as early as 2030 (Allen et al., 2018). In order to limit global warming to 1.5^{o}C, the global net emissions of carbon dioxide (CO_2) will need to be reduced by 45% by 2030 compared to 2010 levels and achieve 'net zero' levels around 2050 (Allen et al., 2018). According to the fifth assessment report of the IPCC, about 78% of the total increase in greenhouse gas (GHG) emission between 1970 and 2010 is attributed to CO_2 emissions from fossil fuel combustion and industrial processes (IPCC, 2014). In 2010, 70% of the global GHG emissions were attributed to the energy supply sector (35%), the industry (21%) and the transport sector (14%) (IPCC, 2014).

Recognizing that a global effort is paramount to combatting climate change, as of 27th Aug 2019, 185 governments around the world have united together through the ratification of the 2015 Paris Agreement (UNFCCC, 2019), to undertake ambitious efforts to "holding the increase in the global average temperature to well below 2^{o}C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 degrees Celsius above pre-industrial levels" (UNFCCC, 2015, p. 2). At the forefront of the international climate negotiations is the European Union (EU), who is also the third largest CO_2 emitter after USA and China since 2002 (Muntean et al., 2018). Owing to the increasing share of RE in the final energy consumption mix and energy efficiency improvements (European Commission, 2014), the GHG emissions in 2017 by the European Union (EU) were lower than 1990 levels by 19.5% (Muntean et al., 2018), indicating that it is well on track to meet its 2020 targets for GHG reduction of 20% by 2020. The positive developments led to a revision of the 2030 climate and energy framework in 2018 in the target share for RE in the final energy consumption mix (from 27% to 32%) and the improvement target for improvement in energy efficiency (from 27% to 32.5%), while maintaining the GHG reduction target of 40% by 2030. As a long-term strategy, the EU envisions to become the first major economy to be carbon neutral by 2050, which is compatible with the findings of the IPCC special report on 1.5^{o}C on the requirements to meet the Paris Agreement targets (Climate Action Tracker, 2018).

Concerned with the costs and risks to energy supply security due to a rapidly growing energy demand which is highly dependent on fast-depleting fossil fuel resources that are mostly imported from politically unstable sources (such as oil from the Middle East and natural gas from Russia), the EU is inherently motivated to reach the targets it has set for itself (Pacesila, Burcea, & Colesca, 2016). Moreover, unlike the Paris Agreement, under the RE and energy efficiency directives, the EU Climate and Energy framework targets are binding for its members. As such, it is likely that RE's share in the final energy demand mix will continue to increase as more sectors become electrified. If so, the fate of the oil and gas sector in Norway would seem uncertain given that 72% of its oil exports and 95% of its natural gas exports are dependent on EU demand (Norwegian Petroleum Directorate, 2019d). This could have a significant consequence on Norway's economy since 50% of its total exports in 2018 was based on this sector, which contributed to 17% of its gross domestic product (GDP) (Norwegian Petroleum Directorate, 2018d).

Given its economic importance, it is no surprise that natural gas exports bear significant importance in the Norwegian political agenda to promote natural gas as a transition energy source as Europe moves away from coal towards a RE-based future, which forms the key justification for further oil and gas exploration in the Arctic (Safari, Das, Langhelle, Roy, & Assadi, 2019). However, faced with increasing competition from RE in a carbon-constrained world, the future of natural gas in Norway is at stake and begets the question of how long this transition is expected to last before being substituted by alternative low carbon energy sources. As Jim Watson, the director of the UK Energy Research Centre, pointed out "…in the UK we have been using gas as a transition fuel since the 1970s. It has stopped being a solution and will become a problem without carbon capture" (Dempsey, 2019). While increasing the domestic use of natural gas in Norway is favoured by some politicians, it is highly disputed since substituting energy generated by 96% hydropower and 2% by wind power with natural gas would increase Norway's carbon emissions and conflicts with its climate change commitments (IEA, 2017; Statistics Norway, 2018a). The resignation of the coalition government in 2000 over gas-fired power plants and climate change concerns demonstrates the importance of the issue at the parliamentary level and would ensure that domestic use of natural gas remain limited unless carbon capture storage (CCS) is employed.

Meanwhile, Norway's hydrocarbon reserves are estimated to peak in mid-2020s based on today's production rate (Norwegian Petroleum Directorate, 2018c).

Half of the undiscovered hydrocarbon resources of Norway is estimated to lie in the little-explored Barents Sea, whose geology is fairly unknown, thus increasing significantly the risk of not finding a commercially viable well. This risk is further amplified when one takes into consideration of more complicated structure of the wells in the Barents Seas, bringing average cost of exploration in the Barents Sea to around 300 million NOK per well, compared to around 200 million NOK per well in the North Sea (Norwegian Petroleum Directorate, 2018c).

While the energy supply sector continues to experience accelerating growth of RE, about one third of the global energy-related GHG are being emitted by sectors that are difficult to decarbonize through electrification such as energy-intensive industries that require high-grade heat and the freight transport sector due to current limitations of batteries (IRENA, 2018b, 2018a). For these sectors, hydrogen could become a cost-effective solution for deep decarbonization, and could potentially meet 18% of the global final energy demand by 2050, that is about 78 exajoules (EJ) (Hydrogen Council, 2017; IRENA, 2018b). According to the Hydrogen Council, the largest industry-led initiative to develop the hydrogen economy, of which partially-state-owned energy company, Equinor (former Statoil) is a steering member, the transport and industry sector is expected to account for almost half of this demand (Hydrogen Council, 2017; IRENA, 2018b).

2.0 Objective

Hydrogen generation market is estimated to be valued at $115.25 billion USD in 2017 and it is expected to increase to $154.74 billion in USD in 2022 (De Valladares, 2017). Globally, the 50 million tons of hydrogen per year is being used for ammonia production while 35% is being used to refine oil which contributes to GHG emission cuts (Hanley, Deane, & Gallachóir, 2018). As applications of hydrogen expand to other sectors such as passenger and freight transport, power and heat, and other industries, the demand for hydrogen is expected to soar. According to the technology outlook for hydrogen by Hydrogen Council (2017) and IRENA (2018b), the main source of demand for hydrogen will come from the transport sector.

As the EU transitions towards a carbon neutral society in 2050, the future of Norway's economy, which is highly dependent on EU's demand for its petroleum resources, faces great uncertainties. To complicate things further, its current hydrocarbon reserves is reported to be fast-depleting and without further exploration in the Barents Sea, where half of the remaining undiscovered hydrocarbon resources lie, Norway's economy is at stake. As such, Norway needs to quickly restructure its economy to adapt to the imminent changes in energy demand in the EU. One of the potential markets that Norway can tap into is the hydrogen fuel export market, where Norway has an advantage over its European neighbours for the production of both blue hydrogen (due to its access to large volumes of natural gas resources and large-scale geological carbon storage sites, as well as to its leadership in CCS technology implementation), and green hydrogen (attributed to its access to vast amount of water resources and relatively lower cost of electricity from hydropower). Against this background, the objective of the thesis is to address the following research questions (RQ):

RQ 1. What are the prospects of green and blue hydrogen in Norway for energy export?

RQ 2. How will hydrogen affect the regime and interact with the broader energy landscape?

To deal with the complexity of energy systems and the large uncertainties about the future pathways of hydrogen in addressing the above-mentioned questions, the development of multiple scenarios is useful for enhancing the understanding of the broader energy landscape by way of capturing the plurality of views expressed by multiple key actors of how the future of hydrogen may unfold in Norway (O’Brien, 2004). O’Brien (2004, p. 709) defines a scenario as “a story of how the future might turn out” and it “denotes the future of external environment”. Scenarios can be used as a way to describe and assess how future uncertainties can impact them (O’Brien, 2004). While scenarios provide depictions of possible futures, it is important to note that they are not meant to be predictions of the future (Martinot, Dienst, Weiliang, & Qimin, 2007; McDowall, 2016).

As described by Coates (2016, p.99), the “great value of a scenario is being able to take complex elements and weave them into a story which is coherent, systematic, comprehensive, and plausible.” By using scenarios as a framework, the prospects of emerging technologies like hydrogen fuel could be better visualized in economic, social and environmental terms, which could lead to better mobilization of key resources that are vital for its implementation (Mcdowall & Eames, 2006).

In the next section, a background on the hydrogen export infrastructure is presented. This is followed by Section 4, which provides a description of the theories used in the analysis. Section 5 lays out the research design and methodology of the thesis. Section 6 is divided into 6 sub-sections that corresponds to the PESTEL framework (political, economic, social, technological, environmental and legal), which focuses on the key factors affecting the prospects of large-scale production of blue and green hydrogen in Norway. Section 7 will draw on some of the factors mentioned in Section 6 to build the scenarios for analysing and discussing the prospective pathways of blue and green hydrogen in Norway, how the energy regime maybe affected by hydrogen and how the changes interact with the broader energy landscape, as well as identify conditions that may affect the broader energy landscape. Section 8 concludes with a brief summary.

3.0 Background on hydrogen

With a higher energy content by weight than natural gas and gasoline (three times more), hydrogen is an attractive fuel not only for transport applications, but also for applications in other sectors, heat, industry and power generation sector (IEA, 2019c; World Energy Council, 2019). While hydrogen is the most abundant element in the universe, it does not exist in free form in nature (IEA, 2019c; World Energy Council, 2019). Like electricity, hydrogen is an energy carrier and can be extracted via a production process which varies according to the type of feedstock used and the energy source (IEA, 2019c; World Energy Council, 2019). With a low-carbon production process, hydrogen could play a significant role in reducing global carbon emissions and our dependency on fossil fuels.

While hydrogen is a non-toxic gas, it is odourless and its flame is invisible to the naked eye when burning, which makes it more difficult for people to detect fire and leaks, and understandably raises some safety concerns considering that it is highly flammable (IEA, 2019c). Fortunately, hydrogen has been produced and used industrially for decades. In Norway, large-scale production of hydrogen began since 1927 for the purpose of manufacturing ammonia fertilizer, methanol and oil refining processes (Aarnes, Haugom, Norheim, Dugstad, & Ellassen, 2019). Norway not only has the know-how of producing large volumes of hydrogen and is experienced in establishing safe handling protocols to ensure a safe production environment.

Since hydrogen is available everywhere, it can technically be produced anywhere. However, the ability to produce large volumes of it at a reasonable cost depends on the resources and the infrastructure that the country has at its disposition. In the case for Norway, the country is well-endowed with hydrocarbons resources, of which the natural gas mix is increasing year-on-year. The domestic use of natural gas is very limited due to the availability of near 100% green electricity which can more than meet the current domestic energy consumption and produce electricity cheaply. As such, the gas pipelines in Norway were built for export purposes, linking Norway to Europe through UK, France, Germany and Belgium (Norwegian Petroleum Directorate, 2019h). Taking these into consideration, the next section will highlight the pathways that are most relevant for Norway.

3.1 Hydrogen export infrastructure

As the distance between Norway and the importing country has major consequences on the cost of transport, and thus cost of hydrogen, it follows that the market with the highest profitability for Norway to export hydrogen would be the EU. With the EU as the key trading partner, this thesis identifies three pathways illustrated in Figure 1, as the most relevant for exploring Norway's prospects for the export of blue and green hydrogen. The first pathway is to produce blue hydrogen in the importing EU country with the natural gas imported from Norway. While the production of hydrogen does not take place in Norway, this thesis considers this as a Norwegian export product when the production process is co-managed by the same Norwegian-based company that exports the natural gas as feedstock[1]. The second pathway is to produce blue hydrogen using natural gas in Norway before exporting it to the importing country via hydrogen pipelines that are either repurposed from natural gas pipelines or built from scratch or by ship. The third pathway is by using RE electricity to produce green hydrogen in Norway and to export it to the importing country either via the newly built hydrogen pipelines or by ship.

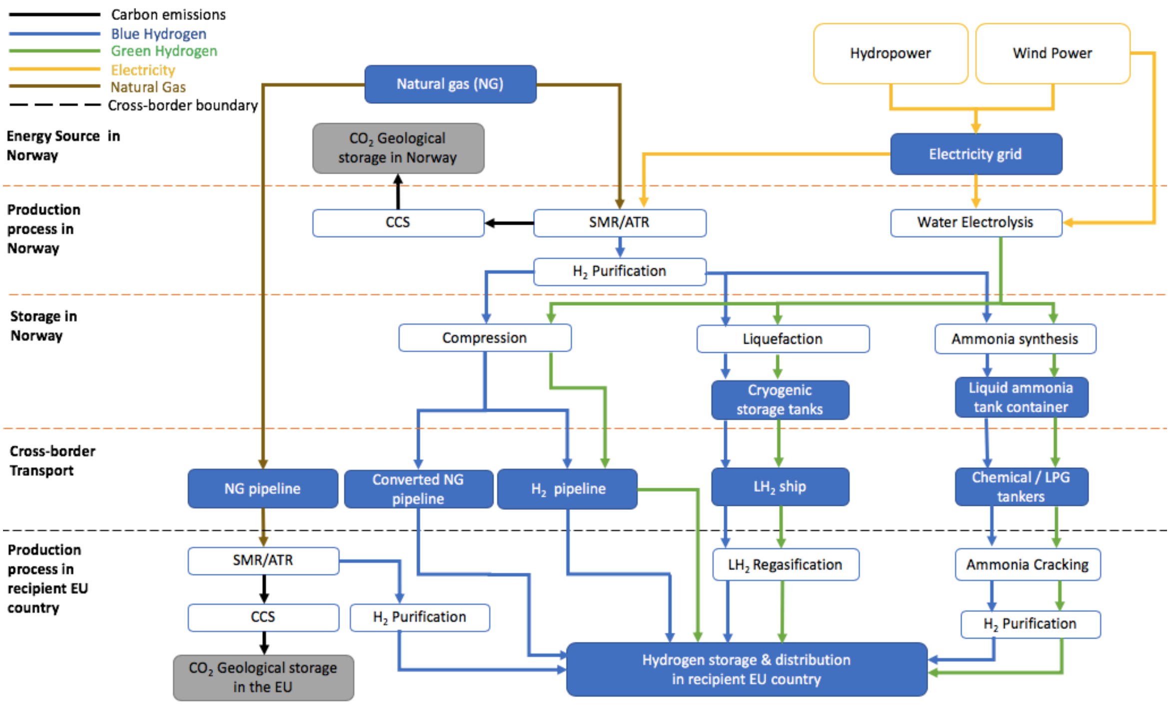

Figure 1: A simplified and non-exhaustive diagram of hydrogen export pathways from Norway to the EU. Adapted from Aarnes et al. (2019); IEA (2019c); Staffell et al. (2019).

[1] The pathway of hydrogen production in importing country using green electricity imported from Norway is ruled out due to the risk of contamination of fossil fuel-based electricity in the electricity grid and the unlikelihood of a direct electricity cable connection from Norway to the production plant.

3.2 Hydrogen production

Currently, more than 95% of hydrogen produced globally is based on fossil fuel, with steam methane reforming (SMR) being the most common production method (around 48%), followed by partial oxidation (POX) of crude oil products (30%) and coal gasification (18%) (IEA, 2015; IRENA, 2018b; Staffell et al., 2019; Voldsund, Jordal, & Anantharaman, 2016). When coal, natural gas or lignite are used as feedstock for producing hydrogen, the corresponding type of hydrogen produced are called "black hydrogen", "grey hydrogen" and "brown hydrogen" respectively (IEA, 2019c). There are three reforming methods of natural gas: SMR (where water is used as the oxidant and a source of hydrogen), POX (which uses oxygen in the air as the oxidant) and auto thermal reforming (ATR) (which is a combination of SMR and POX) (IEA, 2019c).

In order for hydrogen fuel to be considered as part of the solution in the energy transition, it needs to be produced using clean energy sources. In the context of Norway, one way to produce climate-friendly hydrogen at large-scale is by extraction from natural gas by using SMR or ATR coupled with CCS technology. This type of hydrogen is referred to as "blue hydrogen". Hydrogen produced using the standard SMR method is generally of a lower purity level at 95% and is suitable for energy production use (van Cappellen, Croezen, & Rooijers, 2018). If blue hydrogen is to be used as feedstock for industrial use or fuel cell applications in the transport sector, a purification process is required to achieve the standard purity level which is set at 99.95% and 100% respectively (van Cappellen et al., 2018).

The other established method of producing carbon-lean hydrogen, but accounting for only around 4% of current global production, is electrolysis, in which electricity is used to split hydrogen from oxygen in water (IRENA, 2018b). Provided that the electricity is generated using RE, hydrogen generated using this method is called "green hydrogen" (Statkraft, 2018, p. 19). Since water electrolysis generates hydrogen at purity level of up to 99.9 to 100%, a purification process is not needed. In order for green hydrogen to be price-competitive, access to cheap electricity from RE sources and abundant water resources is paramount. Having one of the cheapest and greenest electricity in Europe, as well as an abundant supply of water resources, Norway has a natural advantage over its neighbours to produce green hydrogen more cost effectively.

3.3 Hydrogen storage

In order to optimize the production capacity of hydrogen and ensure supply security, hydrogen storage is needed to overcome the problem of a mismatch between demand and supply. Currently, there exists technologies that enables storage of hydrogen in the form of gas, liquid or solid. However, given that the technology for hydrogen storage in the solid state by way of metal hydrides is at currently an early stage, it is unlikely to play an important role in the hydrogen infrastructure in the foreseeable future (Hart et al., 2015). Before storage, hydrogen gas needs to be compressed (gaseous state) or liquefied (liquid state) to achieve higher energy densities (van Cappellen et al., 2018). Further, when stored as a liquid, additional energy is required for gasification before distribution to the consumer's end (van Cappellen et al., 2018).

Short-term hydrogen storage helps to buffer for intraday differences, while long-term hydrogen storage is meant to buffer for large-scale and intra-seasonal variations. For the purpose of export, the storage vessels need to have a large storage capacity and light weight so as to lower the transportation cost (Zhang, Zhao, Niu, & Maddy, 2016). For short-term bulk storage in the gaseous state, hydrogen pipelines, either repurposed from existing natural gas pipelines or newly built from scratch, can be used to store compressed hydrogen gas (CGH_2), whereas in the liquid state, options include liquid hydrogen (LH_2) tank containers, large-scale LH_2 storage tanks, liquid ammonia tanks or liquid organic hydrogen carrier[2] (LOHC) tanks (IEA, 2019c; van Cappellen et al., 2018).

CGH_2 tanks are generally used for small-scale hydrogen storage for domestic applications, but they are not suited for the eventual transportation by ship due to the limited storage capacity and large storage vessels would be very costly due to the requirement of strong materials to ensure vessel integrity (Hart et al., 2015; Zhang et al., 2016). Therefore, this option is excluded from consideration in the discussion (Staffell et al., 2019; van Cappellen et al., 2018). The storage of LH_2 in cryogenic tank containers is also discounted from the export value chain due to the restrictions on the storage quantities on-board commercial cargo ships and the requirement for LH_2 to be

[2] LOHC is a chemical that can be "'charged' with hydrogen and then 'discharged'", acting as "a carrier liquid for hydrogen" (Hart et al., 2015, p. 133).

stowed only on top deck, under the International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) and the International Maritime Dangerous Goods Code (IMDG Code) (Hylaw, n.d.; NCE Maritime CleanTech, 2019). The same applies for LOHC tanks, as the technology is currently at a nascent stage and unlikely to play a consequential role in the hydrogen infrastructure in the foreseeable future (Hart et al., 2015).

For long-term and large-scale storage of hydrogen, options include salt caverns and depleted natural gas or oil reservoirs (IEA, 2019c). Hydrogen storage in underground salt caverns is well-established practices in the USA and in the UK (IEA, 2019c). However, this option is not available for Norway as there are no known salt caverns in the region that can be exploited. Alternatively, Norway could store hydrogen in depleted natural gas and oil reservoirs which are typically larger than salt caverns, but they may be more susceptible to hydrogen leakages and contamination from organic reactions between hydrocarbons and the hydrogen stored (IEA, 2019c; van Cappellen et al., 2018). As such, the long-term geological storage of hydrogen in Norway has been excluded from consideration in this thesis.

3.4 Hydrogen transport

For blue hydrogen export, the most cost efficient way is to export natural gas through the existing pipelines as feedstock for hydrogen production with CCS at/or nearer to the site of use (Wietschel & Hasenauer, 2007). Equinor is currently partnering with Gasunie (Dutch energy network operator) and Vattenfall (Swedish energy company) to convert Vattendfall's Magnum gas power plant in Eemshaven (Netherlands) to a hydrogen-powered plant, where hydrogen is produced on site using the imported gas from Norway via ATR and CCS process (Equinor ASA, 2017). This business model offers two business opportunities: 1) it allows Norway to continue exporting natural gas and 2) Norway could sell carbon storage space in the Norwegian Continental Shelf (NCS) to EU countries, assuming the legal barriers posed by the London Protocol can be overcome (see section 5.6 for details).

For domestically-produced hydrogen (both blue and green), two transport vessels exist: hydrogen gas pipelines or ship. For distances below 1500 km, the most economical option is to transport CGH_2 via hydrogen gas pipelines (IEA, 2019c). Without any conversion of the existing natural gas pipelines, the maximum blend of hydrogen is at 20% (van Cappellen et al., 2018). Therefore, existing natural gas pipelines needs to be converted or new hydrogen pipelines needs to be built in order to export 100% pure hydrogen via pipelines (van Cappellen et al., 2018).

For longer distances (above 1500 km), it would be more cost-effective to export hydrogen by ship in the form of liquid ammonia than in the form of LH_2 as the former can leverage on existing infrastructure to be transported on chemical and semi-refrigerated liquid petroleum gas tankers (IEA, 2019c).

4.0 Theory

This section aims to introduce the background and concepts of the two theories that will be used in the analysis and discussion of the prospects of blue and green hydrogen in Norway: Scenario framework and the multi-level perspective (MLP). Combining both theories results in a two-dimensional matrix that leads to four main themes corresponding to the typical pathways taken by niche-innovations under the influence of various conditions as prescribed by the MLP. This matrix is elaborated on in Section 3.3.

4.1 Scenario framework

Scenarios have long been used as a tool to indirectly explore the future of society and its institutions, especially in the military where scenarios were used as a strategic planning tool by military strategists in the form of war game simulations (Bradfield, Wright, Burt, Cairns, & Van Der Heijden, 2005). The need for a methodology to capture the consensus of opinion of a large and diverse group of experts reliably and to develop simulation models for exploring various policy options and their implications in future environments in the US Department of Defence after the Second World War gave rise to the development of modern-day scenario planning techniques by Herman Kahn, 'father' of modern-day scenario planning and former ranking authority on Civil Defence and strategic planning at the RAND (short for Research and Development) Corporation (Bradfield et al., 2005). While the scenario methodology was initially used as a policy planning tool, scenario planning became widely used in the business context after it proved to be a useful tool for the Royal Dutch Shell company to successfully overcome the oil crisis in the early 1970s (Bradfield et al., 2005; O'Brien, 2004). The 'Shell approach' to scenarios is also known as the Intuitive-Logics methodology, where the scenario logics are often defined in the form of matrices and organized around themes and all the generated scenarios are assumed to be equally probable (Bradfield et al., 2005).

Among the different types of scenarios, exploratory scenarios, similar to the intuitive-logic model is the preferred tool for the analysing the thesis topic, owing to its systemic approach in examining drivers and ability to capture broad dimensions of changes (Mcdowall & Eames, 2006). While exploratory scenarios take past trends as their starting point (Berkhout & Hertin, 2002), there is a stronger focus on the drivers of change when building storylines which explore how different potential futures may unfold without pre-determining a desirable end state (Mcdowall & Eames, 2006). While computer model-based scenarios (similar to PMT models) can be powerful tools for incorporating information from the field of science, engineering and economics, as well as for making cumulative projections, they generally focus on the techno-economic variables (Geels, McMeekin, & Pfluger, 2018; McDowall, 2016). In addition, model-based scenarios tend to be built on assumptions which fail to fully capture the reality of the complexities in low-carbon transitions, undermining the relevance and usefulness of a scenario exercise in the real world (Geels et al., 2018; McDowall, 2016). In particular, Geels et al. (2018) noted that the lack of actors and agencies in model-based scenarios, and that variables such as social perceptions and political feasibility are hardly factored in. Furthermore, the transition pathways arising from model-based scenarios are presented as smooth diffusion curves, where policymakers seem to play a role from outside the system, when in fact they are nested within the system and can be influenced by other actors (Geels et al., 2018).

4.2 The Multi-level Perspective

To understand how the prospects of blue and green hydrogen export in Norway could unfold in the different scenarios, the thesis adopts the transition pathways from the multi-level perspective (MLP). The MLP is a useful heuristic device for analysing and understanding how major shifts in socio-technical transitions can take place through the interplay of developments at three levels: socio-technical landscape, socio-technical regime and niche-innovation (Geels, 2011; Geels et al., 2016; Geels & Schot, 2007; Grin, Rotmans, & Schot, 2010). In the context of this thesis, the socio-technical landscape consists of slow-changing factors like increasing climate change awareness, the long-term changes such as the deep decarbonisation process of the EU's economy through the uptake of hydrogen technology, as well as sudden external changes like gas price shocks. The socio-technical regime refers to the energy export regime which functions under a system of semi-coherent practices and rules that is mainly shaped by the key incumbent, Equinor, which was once described as a "state within a state" because of its excessive influence on the energy and economic policies in Norway (Moe, 2015, p. 195; Thurber & Istad, 2010, p. 27). The radical niche-innovations refers to the radical innovations which are being developed in "protected spaces" and are the source for systemic change (Geels, 2002, p. 1262, 2011; Grin et al., 2010). While the technologies required for large-scale hydrogen production are widely considered as market mature in Norway, the key infrastructure required for hydrogen export like large-scale storage and transport, is currently non-existent in Norway. Therefore, hydrogen is considered as a niche-innovation in this framework of analysis.

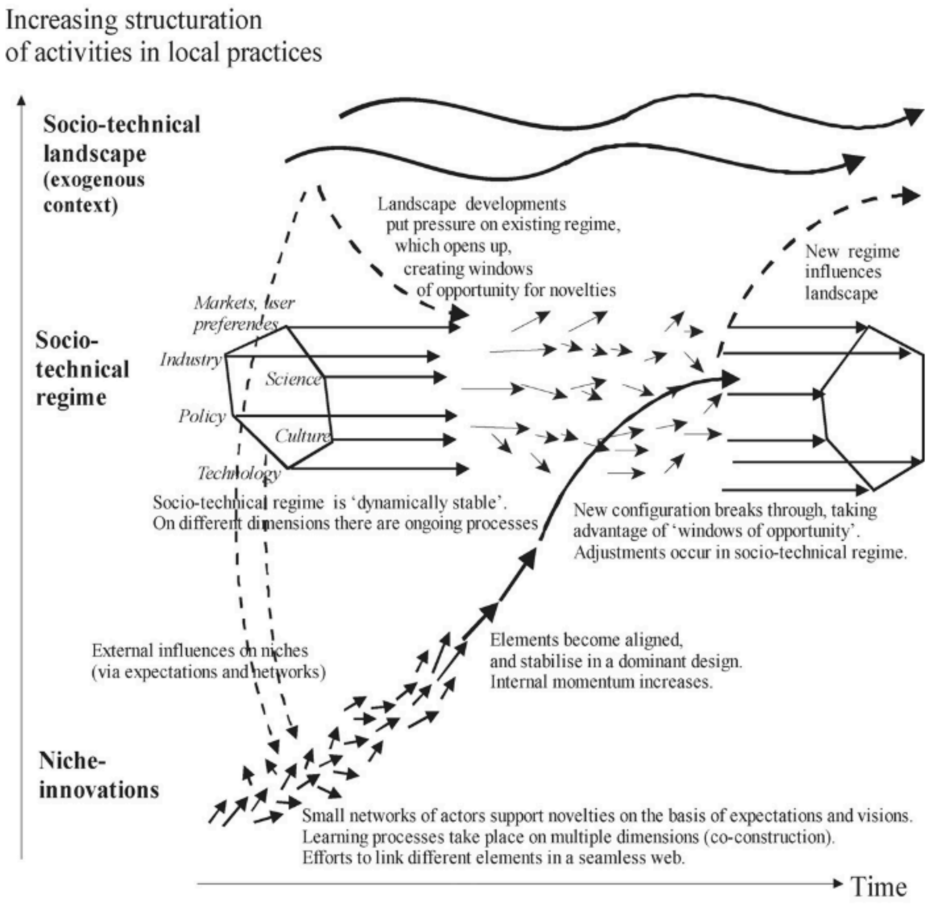

Figure 2: Multi-level perspective on transitions. Source: (Geels & Schot, 2007, p. 401)

Figure 2 is an illustration of the dynamics of the interactions between the three levels of the MLP which suggests that transitions take place when there is alignment in the "interacting processes within and between the incumbent regime, radical niche-innovations and the sociotechnical landscape" (Geels, 2018, p. 225). While regime actors have limited control or no control over the landscape factors in the short run, changes in the landscape factors can create pressures strong enough to cause regimes to destabilise and open up window of opportunity for niche-innovations to break through the regime, depending on the timing and the nature of the interactions between the different levels (Geels, 2011, 2018; Geels et al., 2016; Geels & Schot, 2007). The downward arrows from the landscape and regime level towards the niche-innovation level represent their respective influences on the perceptions of niche actors and size of support networks (Geels & Schot, 2007).

Under the MLP, four main types of transition pathways (substitution, transformation, reconfiguration, or de-alignment and re-alignment) could arise from the different ways the regime interacts with the landscape and niche based on the readiness of the niche-technology at the time of the opening of the window of opportunity and the nature of the relationship that the technology share with the existing regime, whether it is competitive or symbiotic (Geels et al., 2016; Geels & Schot, 2007). In the case of Norway, blue hydrogen is considered as a symbiotic niche-innovation because its production is dependent on the regime's resources, both natural gas and CCS technology. Green hydrogen, on the other hand, would be considered as a competitive niche-innovation because it is developed primarily by actors outside of the regime, such as Green H2 Norway (a newly established joint-venture for large-scale electrolysis-based production of hydrogen) and possibly Yara (largest ammonia producer), if the transport of hydrogen is transported in the form of ammonia. The next four sub-sections will briefly describe each of these pathways and how they are relevant to the thesis.

4.2.1. Substitution pathway

The substitution pathway is likely to take place if niche-innovations have already reached sufficient maturity to compete with regime technologies when the window of opportunity opens, and if the development of the niche technology had taken place outside of the regime, separately by either new entrants who struggle against the established incumbent firms, or outsiders such as activists, social movements actors, citizens or incumbents from other sectors. This pathway has great relevance for green hydrogen since the development of its technology is being undertaken by incumbents from other sectors in Norway, namely NEL and Yara.

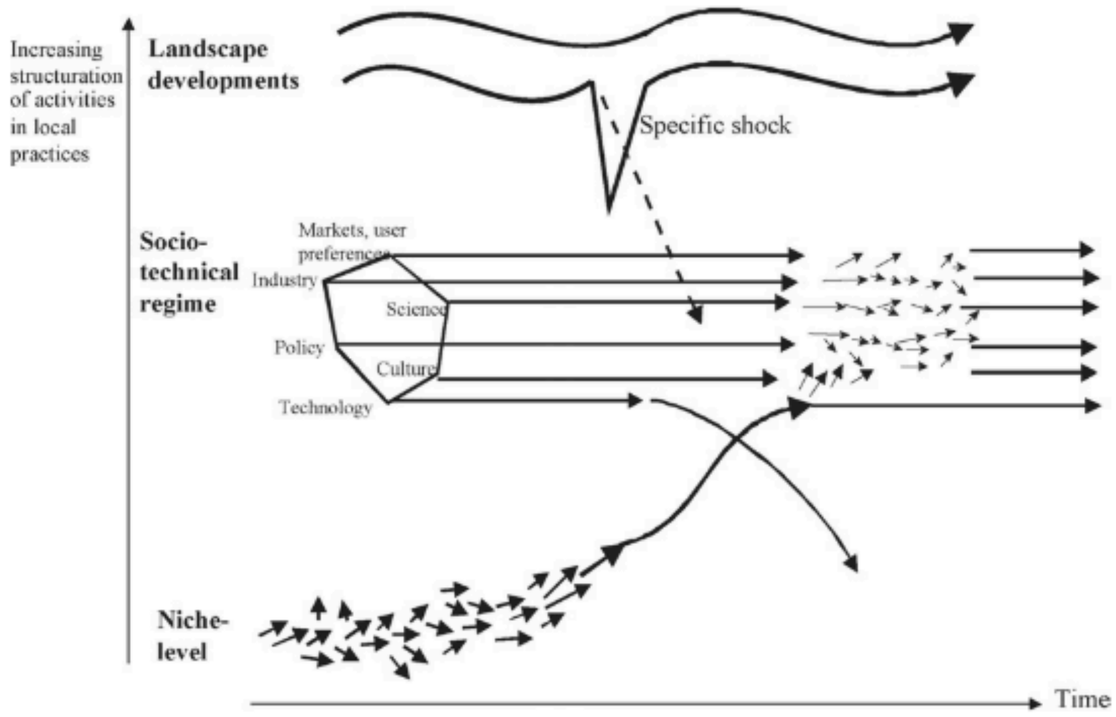

Figure 3: Substitution pathway of the MLP. Source: (Geels & Schot, 2007, p. 410)

As illustrated in Figure 3, the opening of the window of opportunity is triggered by a “specific shock”, “avalanche change” or “disruptive change” in the landscape exerting pressure on the regime and causing major regime tensions (Geels et al., 2016; Geels & Schot, 2007, p. 410). A “specific shock” is defined as a change in the environment that occur rarely and may dissipate after a while, but has the capacity to cause quick and significant changes in a few environmental dimensions, whereas an “avalanche change” differs from a “specific shock” in that the changes extends to multiple environmental dimensions and are likely to remain permanent. A “disruptive change” is an infrequent change that may appear small and moderate initially but gradually intensifies to have a high impact on one environmental dimension. (Geels & Schot, 2007, p. 404). An example is climate change, which was initially viewed as non-threatening, to today being an important consideration in Norway’s politics.

As a result of the opening window of opportunity, green hydrogen has the opportunity to emerge into the mainstream regime to compete with blue hydrogen and achieve further price and performance improvements. This eventually leads to the technological substitution of blue hydrogen with green hydrogen, while blue hydrogen actors (E.g. Equinor) could end up being overthrown by green hydrogen actors (E.g. Green H2 Norway) in this pathway.

4.2.2 Transformation pathway

In the transformation pathway, the niche-innovation is not fully developed at the time when moderate changes in the landscape (or “disruptive changes”) exert pressure on the regime, resulting in only incremental adjustments of the regime rules by incumbent actors (Geels & Schot, 2007). The speed and degree at which the reorientation of the regime takes place depend on how strong the socio-political pressures are and how the market opportunities are perceived (Geels et al., 2016). The dynamics of the transformation pathway is illustrated in Figure 4. This scenario could apply to blue hydrogen, which effectively is an add-on to the existing technology for exporting natural gas that emits less GHG by the fossil fuel regime.

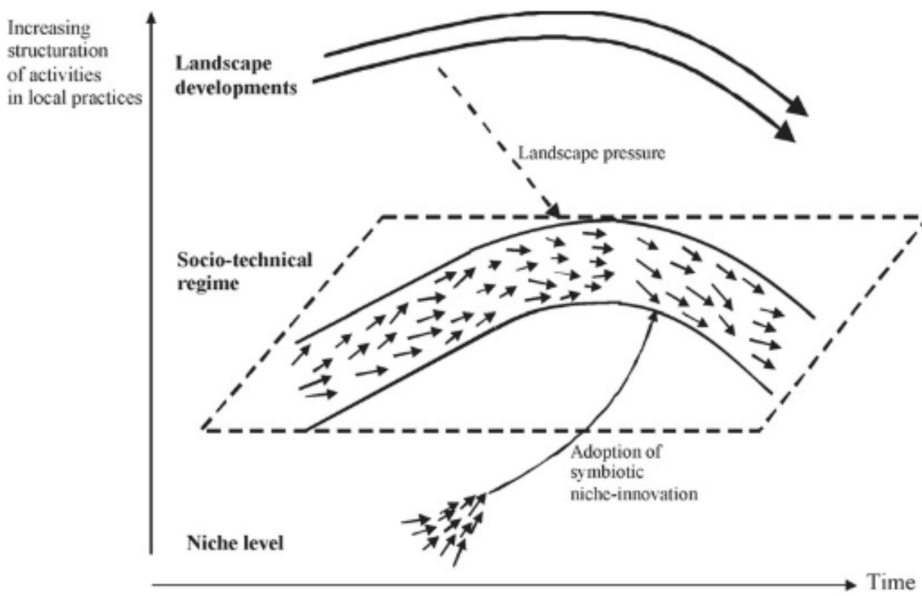

Figure 4: Transformation pathway of the MLP. Source: Geels & Schot (2007, p. 407)

It can be argued that the reorientation of the oil and gas regime in Norway has already began when Equinor changed its company name from Statoil in 2018, in recognition of the global energy transition and the developments in its business portfolio as a broad energy company (Equinor ASA, 2019a). In parallel to its efforts to explore for more oil and gas in the NCS, Equinor has also invested heavily (but to lesser extent compared to petroleum technology) in developing low-carbon technologies like CCS and offshore wind projects, both of which can be linked to hydrogen production. Considering the close connection between blue hydrogen and natural gas, blue hydrogen represents a partial reorientation of the regime where both new and old technologies co-exist, and institutional changes are limited. On the other hand, a full orientation is said to take place when the old technology (blue hydrogen production) is replaced by the new technology (green hydrogen production powered by offshore wind), in which case, one would expect substantial institutional changes (Geels & Schot, 2007).

4.2.3 Reconfiguration pathway

The reconfiguration pathway involves new alliances that are formed between symbiotic niche-innovations and the existing regime (Geels et al., 2016). The initial phase is similar to the transformation pathway whereby symbiotic niche-innovations are adopted as add-on or component replacement to existing technologies to solve minor problems such as performance improvements while the basic architecture of the regime remains relatively intact (Geels et al., 2016; Geels & Schot, 2007). However, as the new alliances encounter new problems or identify new opportunities due to knock-on effects and innovation cascades, more substantial changes are introduced to the system components and relations, resulting in major reconfigurations of the regime's basic architecture as can be observed in Figure 5 (Geels et al., 2016; Geels & Schot, 2007).

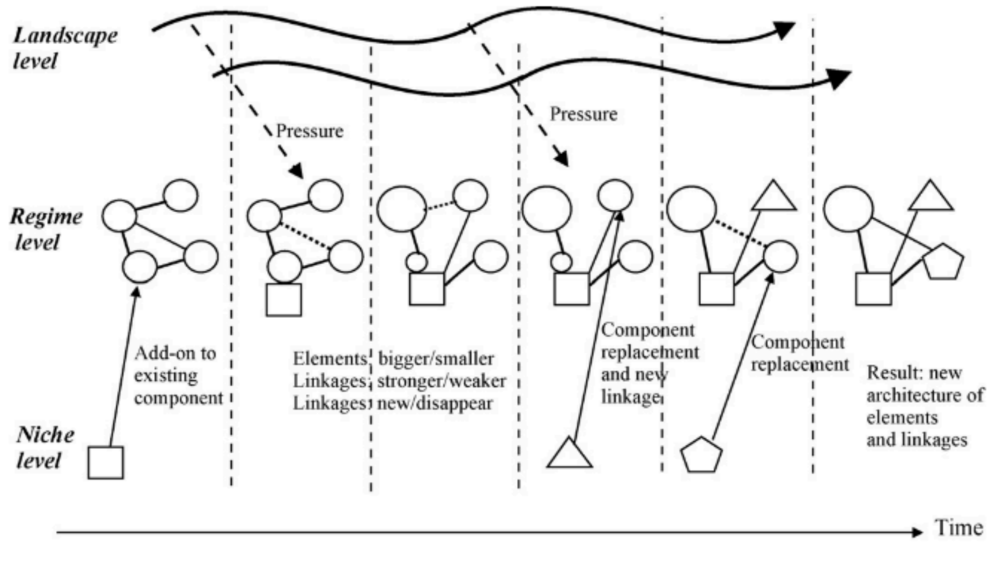

Figure 5: Reconfiguration pathway of the MLP. Source: Geels & Schot (2007)

This pathway may be more relevant if the object of analysis is studying the entire energy system comprising of the production, distribution and consumption value chain up to the end-use applications. As the focus of the supply chain in this thesis ends at the distribution to the wholesale customers and does not include the distribution to the end-users, the reconfiguration pathway is deemed to be not relevant.

4.2.4 De-alignment and Re-alignment pathway

This pathway is likely to take place if the energy export regime collapses due to a combination of major internal problems such as failure to find new gas fields, and large sudden external shocks (or “avalanche change”) such as plummeting natural gas prices and changes in EU energy import strategy. The collapse results in a regime vacuum where there is an extended period of uncertainty and co-existence of multiple niche-innovations, that is the alternative energy export technologies, due to their nascent state of technology.

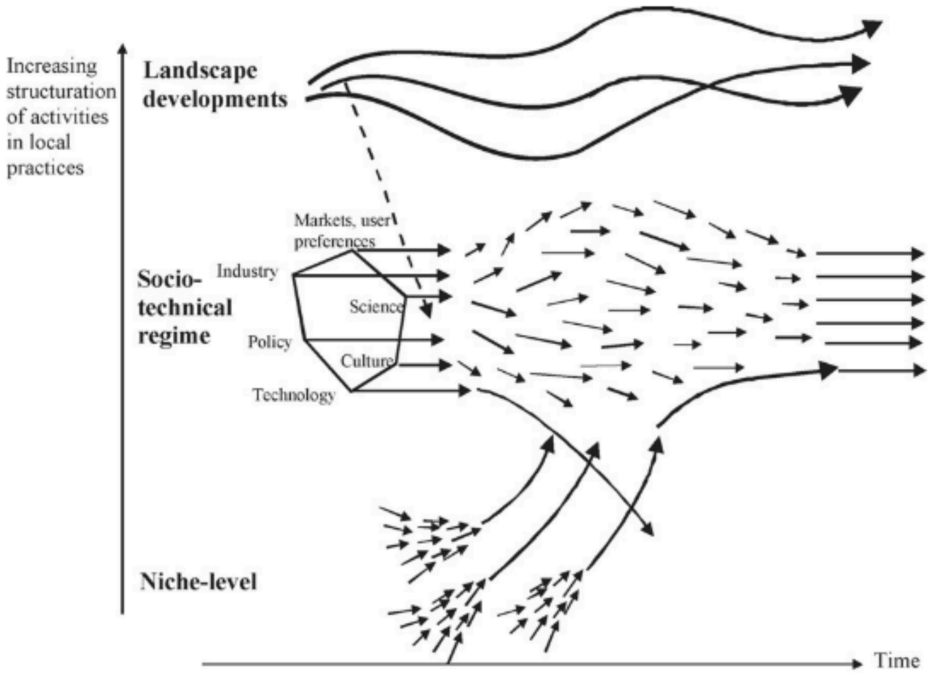

Figure 6: De-alignment and re-alignment pathway of the MLP. Source: Geels & Schot (2007)

The potential alternatives for energy export in Norway consist mainly of large-scale green hydrogen export and surplus electricity export from onshore and offshore wind. Struggles and tensions are expected to intensify between multiple groups and constituencies as they compete with each other for attention and resources, as well as to establish new institutions to replace the old ones (Geels et al., 2016; Geels & Schot, 2007). As shown in Figure 6 illustrates, the regime will re-align itself and become re-established as a new regime when one niche-innovation gains momentum and becomes prevalent (Geels et al., 2016; Geels & Schot, 2007).

5.0 Research design and methodology

This section is comprised of three parts. The first part describes and explains the research strategy used in this thesis, while the second part details the process of the main methodology used in this thesis, an in-depth literature review. Limitations of the thesis are highlighted in the third part.

5.1 Research strategy

The purpose of this thesis is to explore the potential futures of hydrogen in Norway as an energy export by adopting the critical social science approach. Adopting this methodology allows one to gain a better understanding of the role hydrogen can play in the Norwegian energy export market and seeks to unravel the conditions that govern the existing basic structure of the regime by exposing the social and political relations, as well as the unacknowledged constraints (Neuman, 2014). In so doing, one hopes to enlighten and help key actors in the energy market of Norway make more informed policy changes to enable a move towards a low-carbon energy transition.

Given the uncertainties surrounding the developments of hydrogen technology for export purposes, this thesis adopts an abductive research approach as a way to advance learning through the development of alternative possible scenarios (Neuman, 2014). The storyline of each scenario is built upon two frameworks: exploratory scenarios and the PESTEL analysis. The exploratory scenarios set the framework in which the prospects of blue and green hydrogen are explored, while the PESTEL analysis provide an overview of the driving forces that could underpin the developments of the future environment in which the energy export regime in Norway operates. The PESTEL analysis consists of an in-depth literature review to categorize the factors into six dimensions: political (P), economics (E), social parameters (S), technology (T), the natural environment (E) and legal structures (L) (Walsh, 2005; Wright, Cairns, O'Brien, & Goodwin, 2019). With the factors identified, this thesis then takes the MLP as a starting point to deductively fit the information gathered in the PESTEL framework within each scenario to construct the storylines at the three levels: niche, regime and landscape, and discusses the interplay of the various factors which could impact the prospects of a hydrogen economy for Norway.

Exploratory scenario approach has been chosen as analytical tool is used in this thesis to create a two-dimensional matrix as it allows for a systematic analysis of the underlying drivers of change upon which the storylines of the possible futures is built. The matrix is created by combining the two top uncertainties in the energy landscape of Norway, identified as EU's 2050 climate change commitment to become carbon neutral and the availability of Norway's natural gas reserves, which is contingent on the discovery and exploitation of new hydrocarbon fields by 2023 (Hall, 2018). A two-dimensional matrix is thus derived in Figure 7.

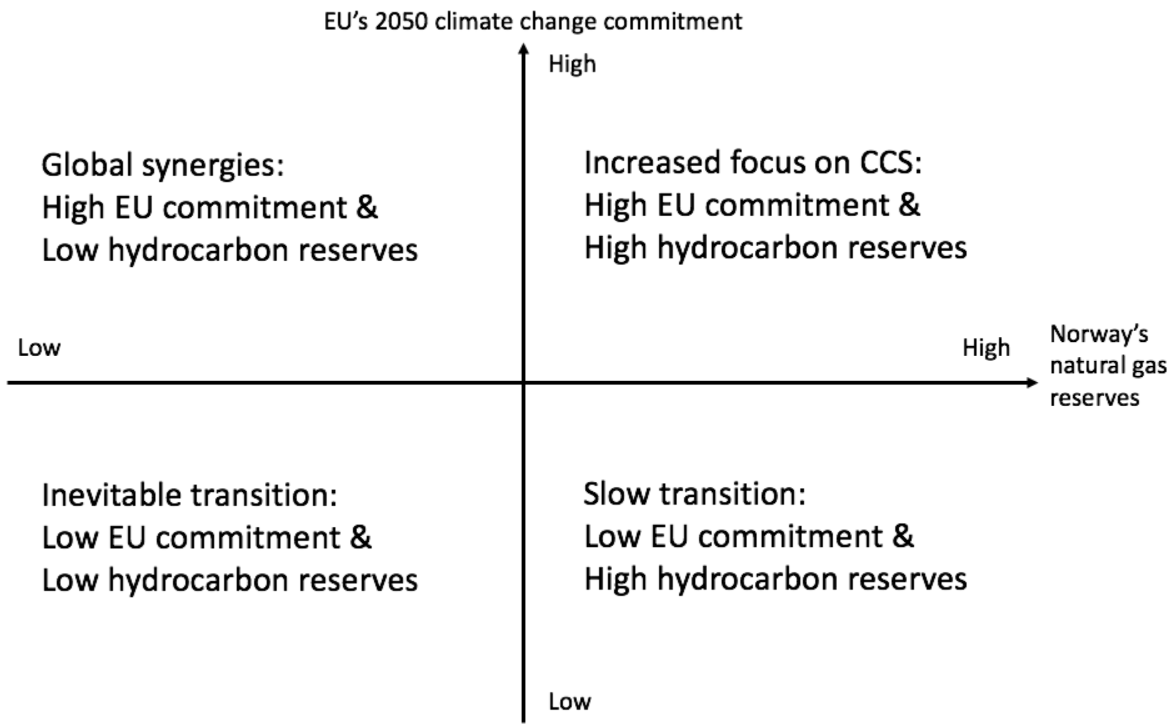

Figure 7: Four Norwegian contextual futures scenarios

The choice of these two key uncertainties stems from the observation of a lack of a balanced consideration of these plausible futures and their impacts on Norway from the government and the oil and gas industry. Although the EU is said to be not on track to reaching their 2020 climate goals, there is still time for the EU to catch up and reach its 2050 climate goals (European Environment Agency, 2019). Given that the non-linear nature of transition, it would be economically too risky for Norway to dismiss EU's carbon targets for 2050 as overly ambitious and remain complacent in their efforts to reduce their carbon footprint. The uncertainty on "EU's climate change commitment" is represented by the vertical y-axis, where a low commitment assumes a gradual transition in the EU energy system where fossil fuel is expected to still play a dominant role in 2050. On the other end of the spectrum, a high commitment assumes a rapid energy transition in the EU due to a strong commitment to become carbon neutral by 2050.

The uncertainty over the future of the availability of Norway's natural gas reserves to support the energy export market arises from the somewhat excessive optimism for the undiscovered resources to start contributing to future production of fossil fuel in the NCS as early as 2025 onwards (Norwegian Petroleum Directorate, 2018c). By 2030, 24.1 million standard cubic meters of natural gas oil equivalent (Sm^3 o.e.) of undiscovered resources is expected to account for 13% of production (Norwegian Petroleum Directorate, 2018a). This projection seems to disregard the fact that the average lead time between 2014 and 2018 for developing new fields is 16 years (Norwegian Petroleum Directorate, 2018c, 2019f). To complicate things further, 66% of the undiscovered natural gas lies in the Barents Sea, where the gas transport infrastructure is limited to the liquefaction plant in Melkøya whose capacity is expected to be fully utilized by the early 2040s (Norwegian Petroleum Directorate, 2018c). Representing this uncertainty is the horizontal x-axis, where the low end of the scale assumes that a decreasing production of natural gas due to the lack of new commercially exploitable fields, whereas the high end assumes that new gas resources are discovered in time to prolong the future of fossil fuel export well into 2050 for Norway.

The four scenarios in the quadrants in Figure 7 will be described more in detail in the discussion section (Section 6), but may be briefly summarized as follows:

- *Global synergies*: EU is strongly committed to reach its climate change goals by 2050 and does so by implementing coordinated policies to facilitate a rapid and smooth phase-out of fossil fuel in its energy system. Additionally, the EU actively strives to foster greater international cooperation both within the EU and with Norway, who is forced to re-orientate its economy due to the risk posed by its fast-depleting natural gas reserves.
- *Increased focus on CCS*: Similar to the "Global synergies" scenario, EU is strongly committed to achieve its 2050 climate change goals which entails phasing out fossil fuel. However, a discovery of a big natural oil and gas field in the NCS leads to an abundant reserve of natural gas. In order for the EU to accept natural gas exports from Norway, the Norwegian government and petroleum industry intensify efforts to make CCS commercially available.

- *Inevitable transition*: The pace of energy transition in the EU remains sluggish relative to the pace needed to the transition to a carbon-neutral society by 2050. While demand for natural gas remains high in the EU at the end of 2030, the anticipation of Norway running out of natural gas reserves forces EU to turn to other suppliers, causing the regime in Norway to destabilize. While Norway takes the lead to push for the decarbonization of EU's energy system in order to secure new market opportunities for its niche-innovations, tensions and struggles arise among niche-innovations in Norway as they compete for resources to try and fill in the void.
- *Slow transition*: With a low climate change commitment, EU is likely to miss its 2030 climate targets and as a result, 2050 climate goals are not likely to be achieved. With the new discovery of oil and gas fields in the NCS, Norway intensifies exploration activities in the Barents Sea in order to extract its remaining uncovered gas resources in the shortest time possible to avoid having assets "stranded" in the ground. Research in alternative niche-innovations is still expected to continue to prepare for the eventuality of fully depleted gas resources post-2050.

5.2 Literature review

The literature review used in the work of this thesis can be categorized into three main types: content review, historical review and integrative review. A content review is conducted in order to link hydrogen to the broader framework of energy transitions in Norway, while a historical review is used to trace back the developments of hydrogen and other niche-innovation technologies in Norway to unravel the political and social relations in the energy sector (Neuman, 2014). An integrative review is done in order to present and summarize the current state of knowledge on hydrogen technology (Neuman, 2014).

For the content review, the literature reviewed consisted of articles concerning 1) Norwegian fossil fuel 2) hydrogen technology 3) EU climate change commitments. Literature related to the Norwegian fossil fuel and its importance to Norway were based on data and reports found on government websites, particularly the Norwegian Petroleum Directorate (NPD), Government.no, Energy Facts Norway and Statistics Norway. To gain a basic understanding of state of play and potential role that hydrogen and fuel cell technology can play in a low-carbon energy future, the IEA (2015) technology roadmap report for hydrogen and fuel cells served as a good starting point. The data was later revised accordingly upon the publication of IEA (2019c) report with the latest updates on the current state of technology. Literature pertaining to EU's climate change commitments were mainly based on information sourced from the European Commission and EU websites.

The peer-review scientific journal articles used to conduct a historical review of hydrogen developments in Norway, was sourced using an advanced search combining the keywords "hydrogen" and "Norway" of the library database of the University of Stavanger. This search yielded 26,652 results, which included hydrogen used in different context. To yield more relevant results, a filter was added to include only articles published in the International Journal of Hydrogen Energy which yielded a more manageable result of 647 articles. It is worth mentioning that the paper by Godoe & Nygaard (2006) on the historical developments of hydrogen technology in Norway was key in identifying the key players in this sector and their connections with each other, which eventually led me to other valuable sources of scientific literature.

A historical review of the development of other niche-innovations in Norway was also done using mainly literature that had been part of the curriculum of my current 2-year Master program. In particular, the book chapter by Moe (2015) and scientific papers by Gullberg (2013) and Langhelle, Kern, & Meadowcroft (2017) were found to provide a clear understanding of Norway's politics in the energy sector.

To summarize the state of play for the various new technologies (e.g. electrolysers, CCS, wind turbines, etc), an integrative review was done on literature from a variety of sources, including peer-review scientific papers, hydrogen-related reports from organizations such as Hydrogen Council, Hydrogen Europe, Norwegian Hydrogen Forum, reports from research institutes such as FCH JU and SINTEF, as well as reports from energy consultancy agencies like DNV GL.

5.3 Limitations of scope

The chosen timeframe for the analysis is limited to the year 2050, when the demand for hydrogen is expected to be developed in the EU as it transitions to a carbon-neutral economy.

Due to the lack of proficiency in the Norwegian language, most of the literature reviewed are in English. A handful of reports which contained critical information for the analysis, were only available in Norwegian, such as the DNV GL report on the production and uses of hydrogen in Norway (Aarnes et al., 2019), the NVE reports on long-term power production market analysis in the Nordics (Bartnes, Amundsen, & Holm, 2018; Gogia et al., 2019; Veie et al., 2019). For these reports, Google Translation tool was used to translate the content.

While the scenario framework used was inspired by the 'Shell approach' to scenarios, which is a group-process-based approach to capture the consensus of opinions from a large group of experts through multiple sessions, the time and resource constraints does not allow for this methodology to be adopted for this thesis. As such, the thesis adapted the scenario framework by fitting in the MLP pathways, as described in in Section 4.2.

This thesis is limited to the study of prospects of the blue and green hydrogen production for export purposes for Norway, based on a value chain that ends at the point of export. Due to the extensive research required, considerations of the geographical distribution of the energy sources in Norway, the destination points for end-use application in the importing country has been excluded.

6.0 A PESTEL analysis of hydrogen as an energy export in Norway

To provide an overview of the key factors affecting the energy regime, the broader energy landscape and the development of hydrogen in Norway, a PESTEL analysis is employed. It is a popular technique used in scenario development to list the driving forces related to the political, economic, social, technological, environmental and legal factors influencing the environment in which the regime operates (Walsh, 2005). Some of these factors will be then used to construct scenarios for each of four themes mentioned in Section 3.3, that is reconfiguration, de-alignment and re-alignment, substitution and transformation.

6.1 Political factors (P)

***Enabler (blue hydrogen)* – Strong governmental support for CCS in Norway:** Among energy-related technologies in Norway, CCS has been afforded generous amount of government support (close to 1 billion EUR invested between 2007 and 2012) despite not adhering to the usual policy criteria of cost-effectiveness (Moe, 2012, 2015; Normann, 2017). This is due to CCS being viewed as a solution to a political conflict that arose in 2000 over the building of two natural gas-fired power plants (Kårstø and Mongstad) when Norway became a net electricity importer for a number of years between mid-1990s and mid-2000s due to falling investments in new generation of electricity and relatively high energy demand growth (Aune, Bye, & Johnsen, 2000; Energy Facts Norway, 2017, 2019b). The conflict was eventually resolved with a compromise where CCS must be applied for the building of the gas-fired power plants to be approved whereas the government would subsidise majority of the research cost for CCS (Normann, 2017). As such, CCS functioned as a political glue that unites various governmental parties and makes governmental coalitions possible (Langhelle et al., 2017). However, despite the fact CCS did not materialize in both plants due to high costs, the gas-fired power plants had to close down due to low electricity prices and high natural gas prices (Langhelle et al., 2017; Normann, 2017; Reuters, 2017). Nevertheless, CCS continue to enjoy strong government support as the focus turned to industrial applications as a way to demonstrate the viability of CCS as a mitigation measure for climate change to a global audience (Langhelle et al., 2017; Roettereng, 2016). The continued interests in CCS could also be linked back to the concerns about the future value of natural gas exports in anticipation of more ambitious international climate policies (Normann, 2017).

***Enabler (blue hydrogen) / Barrier (green hydrogen)* – A petro-industrial complex in Norway:** Norway politics is said to be dominated by the petro-industrial complex, in which policymakers create policies that prioritizes the economic interests of the petroleum industry over climate change concerns (Moe, 2015). The lack of cost control by the government on Equinor (former Statoil), who was responsible for running the original full-scale CCS demonstration project in the Technology Centre Mongstad (TCM) demonstrates the tight relationship between the policymakers and Equinor (Moe, 2015). Despite the previous setbacks with CCS projects, including the termination of the original full-scale CCS project in 2013, the Norwegian long-term energy strategy is likely to include CCS as it fits the interests of the oil and gas sector to continue the exploitation of fossil fuel reserves in a carbon-constrained world and to prevent structural changes that could have benefited the RE sector (Meadowcroft & Langhelle, 2009; Moe, 2015). While this may boost the development of blue hydrogen production, it may divert resources away from the needed investment for RE projects, that is critical to the development of green hydrogen production in Norway.

Enabler (blue and green hydrogen)* – Rising carbon prices and tax in the EU*: As of 1st Jan 2018, Norway's full carbon tax rate was increased to 500 NOK/tCO_2e (around 51 EUR[3]/tCO_2e) (Energifakta Norge, 2017). Carbon taxes in Norway are perceived to be more costly than investing in CCS technology, and such acted a key driver for the implementation of CCS in Equinor's Sleipner facility in the North Sea in 1996 and the original Technology Centre Mongstad (TCM) project dedicated to CCS research (Global CCS Institute, 2018; Moe, 2015). In contrast, carbon prices in the EU ETS had been significantly low at below 10 USD/tCO_2e (9 EUR[4]/tCO_2e) between 2012 and 2018 due to surplus allowances cumulated since the 2009 global financial crisis and recession (Carbon Tracker Initiative, 2018; World Bank Group, 2019). To calibrate the system, the EU introduced the Market Stability Reserve (MSR) mechanism in January 2019 and other reforms, which drove carbon prices up by more than triple to around 32 USD/tCO_2e (29 EUR[5]/tCO_2e) based on nominal prices as of 1st Nov 2019 (World Bank Group, 2019). According to the impact modelling conducted by carbon

[3] Based on average exchange rates for the period 1st Jan 2019 to 28th Dec 2019: 1 EUR = 9.8511 NOK (European Central Bank, 2019)
[4] Based on average exchange rates for the period 1st Jan 2019 to 28th Dec 2019: 1 USD = 0.8934 EUR (European Central Bank, 2019)
[5] Based on average exchange rates for the period 1st Jan 2019 to 28th Dec 2019: 1 USD = 0.8934 EUR (European Central Bank, 2019)

market analyst firm ICIS, the implementation of phase 4 of the EU ETS in the period 2021 to 2030 will likely see carbon prices peak at 35 EUR/tCO_2e in 2023-2024 before declining to around 20 EUR/tCO_2e by 2030 (De Clara & Mayr, 2018). However, should the EU decide to align its current policies with the Paris Agreement through the adoption of the newly unveiled European Green Deal, the EU's roadmap to becoming climate neutral by 2050 (European Commission, 2019), carbon prices could be expected to reach as high as 55 EUR/tCO_2e by 2030 (Carbon Tracker Initiative, 2018). For CCS to be economical feasible, van Cappellen et al. (2018) estimates that carbon prices needs to be at least 50 EUR/tCO_2e, accompanied by a supportive policy environment.

Enabler (blue and green hydrogen) **– Deep decarbonisation of the EU by 2050:** As part of its climate goal to be become a carbon-neutral economy by 2050, the EU would need to decarbonize its transport, building and industry sector, driving a strong demand for hydrogen (FCH JU, 2019). If the full program of the European Green Deal is adopted by the EU, there is a higher chance for the 2050 climate goal to be achieved (European Commission, 2019). In its ambitious scenario for the deployment of hydrogen in the EU to achieve the two-degree target under the Paris Agreement, about 2,250 terawatt hours (TWh) of hydrogen will be needed to fulfil 24% of the total forecasted energy demand in 2050 (FCH JU, 2019). In spite of plans of domestic production of hydrogen in the EU, high volume production will be challenging due to competing use for the electricity generated from its RE resources (Wietschel & Hasenauer, 2007). This presents an opportunity for Norway to meet part of that demand through export.

Barrier (blue hydrogen) **– Diminishing political support for further offshore exploration in Norway:** In July 2019, the largest political party as well as the biggest worker union in Norway, the Labour party, voted against the impact assessment of petroleum activity in the Lofoten islands, which is a pre-requisite for opening new areas for oil exploration (Holter, 2019a; Schober, 2019). Despite assurances from the leader of the Labour party of his continuous support for the oil and gas industry, the move nevertheless creates uncertainties about the future developments of policies governing oil exploration in the Arctic, which raises the stakes for further investments in the region (Schober, 2019). This could potentially affect the amount of natural gas resources available for blue hydrogen production.

6.2 Economic factors (E)

***Enabler (blue and green hydrogen)* – A growing global demand for hydrogen in EU:** Demand for hydrogen in the EU is projected to grow as EU strategizes towards a carbon-neutral economy through deep decarbonisation of its various sectors with hydrogen as a low-carbon energy carrier. Although there have been two major waves of fervour for hydrogen previously, there is reason to believe that the current interests in hydrogen is gaining some traction at a much bigger scale due to the falling costs of other low-carbon technologies such as batteries and RE, as well as the expansion of its applications beyond the transport sector to hard-to-decarbonized sectors such as the industry, building and power generation sectors (IEA, 2019c). According to the 2019 Europe Hydrogen Roadmap, the hydrogen demand under the business-as-usual scenario in 2050 amounts to 780 TWh (or 20 MT H_2) and 2 251 TWh (or 57 MT H_2) (FCH JU, 2019).

Table 1: Hydrogen demand in the EU in 2050 (MT)

	Hydrogen Demand in the EU in 2050 (MT)		
Sector	**2015**	**Business as usual 2050**	**Ambitious 2050**
Industy Feedstock	8	10	16
Industry Energy		1	6
Buildings		5	15
Transportation		2	17
Power generation		1	3
Total hydrogen demand	8	20	57

Note: Conversion based on 1 TWh = 7/278 MT (Hydrogen Council, 2017). Source: FCH JU (2019).

***Enabler (blue and green hydrogen)* – Limited electricity surplus in the EU due to low curtailment rates of VRE:** Given the relatively high electricity prices in the EU compared to Norway, it would be more cost-effective to produce green hydrogen using surplus RE in the EU which is otherwise curtailed. However, looking at the low curtailment rates of Variable RE (VRE) projected in IRENA (2018c) for 2030 at the EU level of 0.8% (6.0 TWh based on VRE power generation of 753 TWh) under the REmap Case (decarbonization scenario) and 0.6% (6.7 TWh based on VRE power generation of 1 122 TWh) under the Reference Case (business as usual) scenarios, it is unlikely that the volume of hydrogen production based on only surplus electricity from RE sources would be sufficient to meet the demand (IFPEN & SINTEF, 2019). Therefore, this presents an opportunity for Norway to tap into the hydrogen export market to meet the demand of the EU, provided that the total cost, including the cost of converting hydrogen into a transportable form (compressed gas, ammonia, LOHC or LH_2) and the cost of transport, is relatively cheaper than domestic hydrogen production in the EU.

***Enabler (blue hydrogen)* – Access to substantial natural gas resource:** About 77% of EU's gas demand in 2018 is met through natural gas imports, of which 25% is supplied by Norway (Norwegian Petroleum Directorate, 2019d). As the world's third largest natural gas exporter (Norwegian Petroleum Directorate, 2019d), Norway has access to cheap natural gas to produce blue hydrogen more cost-effectively than its neighbours in the EU, provided that the final price of hydrogen including the transportation is lower than exporting natural gas as feedstock for hydrogen production at or near the site of use (currently deemed to be the more efficient pathway) (Wietschel & Hasenauer, 2007). Based on the 2017 natural gas prices assumed in the IEA G20 Hydrogen report for the EU of 0.277 USD[6]/Sm^3, the average blue hydrogen production cost in Europe using SMR and CCS technology is estimated to be around 2.30 USD/kgH_2 (IEA, 2019c). Compared to Norway, this is almost double that of the cost estimated at around 1.21 to 1.82 USD/kgH_2[7] (10 to 15 NOK/kgH_2) based on natural gas price prices of 0.21-0.27 USD[8]/Sm^3 (Aarnes et al., 2019).

***Enabler (blue hydrogen)* – Lower risk of stranded assets:** From the Norwegian perspective, blue hydrogen could minimize the risk of stranded assets in the form of hydrocarbons reserves being left underground, which is expected to last for another 50 years of production (Norwegian Petroleum Directorate, 2019e). In addition, the current existing gas infrastructure can be adapted to transport both blue and green hydrogen to Europe. Furthermore, blue hydrogen could be used as a justification for further exploration for natural gas in the Barents Sea. However, from an economic perspective, the investment is CCS and steam-reforming facilities in Norway could potentially create a technological lock-in of the investments in blue hydrogen production which may delay the development of green hydrogen production,

[6] IEA (2019a) assumptions annex: USD 7.30/MMBtu converted at 1 Sm^3 = 0.037913 MMBtu at 2017 exchange rates (Norwegianpetroleum.no, n.d.)
[7] Based on average 2017 exchange rates to compare with IEA report data for EU natural gas prices: 1 USD = 8.263 NOK (Norges Bank, 2019)
[8] Based on average 2017 exchange rates to compare with IEA report data for EU natural gas prices: 1 USD = 8.263 NOK (Norges Bank, 2019)

unless strong governmental policies are put in place to ensure parallel development of both technologies.

***Enabler (green hydrogen)* – Low electricity prices:** Compared to the rest of Europe, Norway has one of the cheapest and cleanest electricity, attributed to the massive expansion of hydropower plants in the 1990s. On average, Norway electricity prices for non-household consumers have been lower than EU28 by 15% to 38% in the period 2013-2017 (Eurostat, 2019). This trend is expected to continue up to 2040 despite the fact that NVE expects an increase in the average electricity prices from 40.6 EUR/MWh in 2022 to 43.6 EUR/MWh in 2040 (see Table 4) (Gogia et al., 2019). The increase in prices between 2022 and 2025, and between 2030 and 2040 is due to higher domestic electricity consumption as a result of increased electrification in Norway, as well as electricity price increases in countries whose electricity grids are interconnected with Norway's (Gogia et al., 2019). The key reasons for the increase in electricity prices in Europe include electricity consumption growth, higher carbon prices, the phase out of coal power plants with gas power plants, increasing natural gas prices, and the decommissioning of old Swedish and Finnish nuclear power plants towards 2040 (Gogia et al., 2019). The fall in electricity prices between 2025 and 2030 are mainly due to the expected electricity surplus from large-scale wind power development in Sweden and the decommissioning of the carbon floor in UK, which is assumed to take place when coal power is fully phased out in 2025 (Gogia et al., 2019). Lower electricity prices implies that green hydrogen can be produced more cost-competitively in Norway than if it was produced domestically in the EU (Aarnes et al., 2019). Based on an electricity price of 46 USD[9]/MWh (380 NOK/MWh) excluding taxes, Aarnes et al. (2019) estimated the cost of green hydrogen production via ALK in Norway in 2030 to be around 2.66 USD[10]/kg H_2 (22 NOK/kg H_2), which is about 1.5 to 2 times more than the price of blue hydrogen.

[9] Based on average 2017 exchange rates: 1 USD = 8.263 NOK (Norges Bank, 2019)
[10] Based on average 2017 exchange rates: 1 USD = 8.263 NOK (Norges Bank, 2019)

Table 2: Average electricity prices estimated by NVE for Baseline scenario 2022-2040

Average electricity prices (USD/MWh)						
Year	Norway	Germany	UK	Netherlands	Denmark	France
2022	48.4	52.0	61.7	50.8	50.8	50.8
2025	52.0	54.5	64.1	53.2	54.5	55.7
2030	44.8	54.5	56.9	53.2	49.6	55.7
2040	52.0	60.5	59.3	56.9	55.7	58.1
Difference vs. Norway (%)						
2022		+7%	+28%	+5%	+5%	+5%
2025		+5%	+23%	+2%	+5%	+7%
2030		+22%	+27%	+19%	+11%	+24%
2040		+16%	+14%	+9%	+7%	+12%

Source: Gogia et al. (2019). All figures converted at 2017 average exchange rates of 1 USD = 8.263 NOK (Norges Bank, 2019). Figures in green signify lower prices than the previous period and figures in red signify and increase in price compared to previous period.

***Barrier (blue hydrogen) / Enabler (green hydrogen)* – Cutback on fossil fuel funding by EIB:** In an attempt to align its strategy with the Paris Agreement targets, the European Investment Bank (EIB), the EU's lending arm and the biggest public bank in the world, recently announced its decision to curtail funding for energy projects that emits more than 0.25 kg of CO_2e per kWh produced, which would exclude traditional gas power plant projects, coal and oil projects ("European Investment Bank drops fossil fuel funding," 2019; Watts, 2019). The new policy is expected to into effect at the end of 2021, sending a strong signal to markets and other lenders to start phasing out high carbon projects. In addition, this move would benefit renewable energy developments as more funding will become available (Watts, 2019).

6.3 Social factors (S)

***Enabler (blue hydrogen) / Barrier (green hydrogen)* – Heavy reliance on oil and gas export for social welfare:** The energy export market in Norway is dominated by the oil and gas sector, which contributes to 17% of Norway's gross domestic product (GDP) and about 6% to the labour market with 170 200 out of 2.8 million jobs in 2017 (Norwegian Petroleum Directorate, 2018b; Statistics Norway, 2018b). Majority of profits from the activity are invested into Norway's sovereign wealth fund, worth 1 trillion USD in 2019, the largest in the world. Understandably, there is strong resistance in Norway among its citizens to transition away from being an oil-and-gas exporting economy.

***Enabler (Green hydrogen) / Barrier (Blue hydrogen)* – Uncertainty over the future of oil and gas:** The collapse of the oil prices in mid-2014 in the wake of shale oil revolution, which forced the oil companies in Norway to lay off an estimated 12,000 employees in the industry between 2014 and 2016 and caused unemployment rate, to peak at 4.9% in mid-2016 made people realize how vulnerable the economy is to volatility in oil and gas prices (Norwegian Petroleum Directorate, 2018b; Statistics Norway, 2017). The decision by the central Norges Bank, which manages Norway's sovereign wealth fund, to divest away from oil and gas companies in 2019 reinforces the perception that the low oil and gas prices are likely to remain permanent (Davies, 2019). Moreover, the over-supply of natural gas imports from US, Qatar and Russia which caused market prices of natural gas to plunge recently, as well as the construction of Nord Stream 2, a new gas pipeline that connects Russia directly to Germany, alludes to the increasingly tough competition that Norway will face in the natural gas export market to the EU (Ambrose, 2019; BBC, 2019).

Enabler (green hydrogen) / Barrier (blue hydrogen) **– Rising climate change awareness among youths:** In Norway, the gloomy outlook for the oil and gas sector coupled with increasing environmental and climate awareness are causing concerns among youths, as can be noted in the sharp decline in the number of applications for Norway's leading programs in petroleum geosciences and engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim, from 420 in 2013 to only 33 in 2018 (Adomaitis, 2019a). Furthermore, seven out of nine youth party organizations representing the different political parties are in support for the restriction or complete phase-out of petroleum activities (Adomaitis, 2019a). This would undoubtedly reduce the pool of qualified employees available to replace the rapidly aging workforce of the petroleum industry, half of whom are expected to retire in the next decade (Adomaitis, 2019a). In addition, the participation of millions in the global climate strike movement started by Swedish youth climate activist, Greta Thunberg, have led to the declaration of climate emergency by leaders around the world including the European Parliament (Alter, Haynes, & Worland, 2019; The European Parliament, 2019). While the declaration is non-binding, it represents the first step for the acceleration of efforts to reduce GHG emissions, which could imply more pressure to keep fossil fuels in the ground and better prospects of green hydrogen.

Enabler (green hydrogen) **– Concerns about electricity being an energy export:** As Norway prepares for a transition towards a future with lower oil and gas revenues, a window of opportunity opens up for the growth of RE for export in the form of electricity or hydrogen. In order to export electricity, Norway would need to connect its electricity grids with its neighbouring countries via high-voltage direct current (HVDC) cables, but known to enjoy one of the cheapest electricity prices in Western Europe, trade unions in Norway have voiced out concerns about an increase in electricity prices in Norway as the cost of building the new infrastructure are passed on to customers and as Norway succumbs to pressure to align its prices to match EU electricity prices (Mollestad, 2018; Tomasgard & Korpås, 2018). If the surplus electricity can be exported in the form of green hydrogen, Norwegian citizens may have less concerns about their electricity prices being affected by the EU market.

***Enabler (blue and green hydrogen)* – General public receptiveness towards hydrogen:** Based on a survey conducted two years after the first hydrogen refuelling station (HRS) was opened in 2006 in Stavanger, residents living near the HRS and further away in the region were generally receptive towards hydrogen vehicles and refuelling stations (Thesen & Langhelle, 2008). The HRS was part of the HyNor project, a government-supported joint-industry initiative that started in 2003 to explore the application of hydrogen in the transport sector for the first time in Norway, in response to the fears of peak oil between 2003 and 2008 when the speed of production of oil was lagging behind a strong additional demand for crude oil from Asia, particularly China (Baumeister & Kilian, 2016) and concern for climate change (IEA, 2019c; Sataøen, 2008). The objective of the project was to build a hydrogen highway that consists of a 580 km-long hydrogen corridor between Oslo and Stavanger, as a way to demonstrate how a hydrogen energy infrastructure could be implemented in real life (Sataøen, 2008; Simonsen & Hansen, 2010; Thesen & Langhelle, 2008). The receptiveness towards hydrogen could be mean less barrier to the building of large-scale hydrogen facilities in Norway.

***Barrier (green and blue hydrogen)* – Concerns for the safety and reliability of hydrogen:** Research showed that safety issues concerning hydrogen are comparable to that of natural gas and that while hydrogen is more flammable than natural gas, it dissipates quickly (IEA, 2019c; Staffell et al., 2017; van Cappellen et al., 2018). Nevertheless, four hydrogen accidents had been reported worldwide in 2019 alone, of which two in South Korea, one in the USA and one in Norway (Hernández & Cassidy, 2019; Jin & Chung, 2019; NEL ASA, 2019b). While these accidents raise questions about the safety and reliability of hydrogen, it is interesting to note the difference in the focus of the concerns between South Korea and that of Europe[11] and the USA. Perhaps due to the casualties involved in both accidents and the relatively new experience in handling hydrogen, the public in South Korea was concerned about the safety in handling of hydrogen, whereas in Europe and the USA, this is less of an issue due to a longer history of experience in hydrogen production, hence the public were more concerned about the disruption of hydrogen supply particularly for hydrogen vehicle owners who have not been able to refuel their vehicles after the explosions. The lack of confidence in the reliability in supply may dampen the domestic demand for hydrogen in Norway, which could negatively impact the attractiveness of the investment in hydrogen infrastructure necessary for large-scale production and export.

6.4 Technological factors (T)

In this section, we will analyse the status and future developments of the key technological factors related to the hydrogen infrastructure which can impact the prospects of the export of blue and green hydrogen in Norway. These factors are broken down based on the four main parts of the infrastructure: energy sources, production, storage and transport.

6.4.1 Energy input sources

One of the key factors that will impact the prospects of blue hydrogen production is the capacity to find and extract more natural gas from the undiscovered reserves of hydrocarbon, particularly in the Barents Sea. The cost of exploration is also an important factor to consider as it impacts the profitability of natural gas and the cost of blue hydrogen production.

The prospects of green hydrogen production for export depends highly on Norway's capacity to generate electricity from RE sources to meet green hydrogen demand, after accounting for the domestic consumption of electricity. As at the end of 2018, the total electricity generated in Norway amounted to 147 TWh, of which 140 TWh was produced from hydropower plants and 4 TWh from onshore wind power. (Statistics Norway, 2019). Gross consumption of electricity in Norway stood at 137

[11] Following the explosion in Norway, a total of 11 HRS supplied by NEL have been temporarily closed across Europe in Norway (3), Denmark and Germany (4) pending investigations (Hampel, 2019; Lorentzen, 2019).

TWh, which led to a surplus electricity of 10 TWh (Aarnes et al., 2019; Statistics Norway, 2019).

Table 4 shows NVE's latest estimates of the electricity generation in Norway in 2030 and 2040 according to the *Baseline* scenario. It assumes that hydropower is expected to generate more electricity due to increased precipitation from rainfall and glacier melting, and that wind power from onshore turbines is expected to peak by 2030 after the building of all the currently approved projects and technical improvements from reinvestments in wind turbines that have reached their technical life, but no new projects are expected to be built after due to public protests (Bartnes et al., 2018; Veie et al., 2019). Offshore wind power is expected to pick up from 2040 onwards with around 4 TWh (Bartnes et al., 2018; Veie et al., 2019). 2050 electricity balance in Norway is built based on the assumption that the total electricity generated by hydropower, thermal power and solar power will remain the same as 2040, while offshore wind is forecasted by Skar et al. (2018) to increase to 65 TWh in 2050. The domestic electricity demand is expected to increase steadily from 137 TWh to 159 TWh in 2040 according to Veie et al. (2019) and the same percentage increase between 2040 and 2030 is assumed for 2050, driven mainly by industrial growth and electrification of the transport sector (Aarnes et al., 2019; Bartnes et al., 2018). Therefore, by 2050, a surplus electricity of 80 TWh is available for green hydrogen production.

Table 3: Electricity balance in Norway 2018 – 2050

	2018	2030	2040	2050
Total Electricity production (TWh)	**147**	**174**	**184**	**245**
Hydropower	*140*	*147*	*151*	*151*
Onshore wind power	*4*	*22*	*22*	*22*
Offshore wind power	-	*3*	*4*	*65*
Thermal power	*3*	*1*	*1*	*1*
Solar power		2	7	7
Gross Consumption of Electricity (TWh)	**137**	**153**	**159**	**165**
Surplus electricity (TWh)	**10**	**21**	**25**	**80**

Figures for 2018: Statistics Norway (2019b); Figures for 2030 & 2040: Veie et al. (2019) and Gogia et al. (2019); Figures for 2050: Adapted from Skar, Jaehnert, Tomasgard, Midthun, & Fodstad (2018). Note: Thermal power includes energy sources such as waste, surplus heat and fossil fuel (Energy Facts Norway, 2019b).

6.4.1.1 Natural gas

Enabler (blue hydrogen) – Decreasing average cost per development well: Following the downturn in the petroleum sector in Norway in 2013, the industry had a strong focus on cost controlling and efficiency improvements, which led to a more than 40% drop in the average operating cost per well in 2017 compared to 2013 (Norwegian Petroleum Directorate, 2019f). However, since the Barents Sea remain mostly unexplored, the lower cost pertains to the more accessible fields in the North Sea and the Norwegian Sea. Nonetheless, the lower cost of operation could translate to lower cost of production of blue hydrogen, boosting its prospects in the medium term

Barrier (blue hydrogen) – Lack of infrastructure in the Barents Sea: The Barents Sea is estimated to hold about 66% of the total unproven gas resources in the NCS as at end of 2017, where there is a lack of infrastructure and gas transport capacity (Norwegian Petroleum Directorate, 2018c). The current gas transport capacity is dependent on the liquefaction plant in Melkøya, which is expected to reach full capacity by early 2040s (Norwegian Petroleum Directorate, 2018c). It would be challenging to explore for more gas without the necessary infrastructure and additional gas transport capacity, yet at the same time, it is questionable if there would be enough volume of gas resources to justify a new infrastructure (Norwegian Petroleum Directorate, 2018c).

Barrier (blue hydrogen) – High geological risk in the Barents Sea: Despite the potential of finding larger finds in the less-explored Barents Sea, the success rate for finding a commercially viable field is much lower. Further, the harsher weather conditions and more complicated geological formations in the Barents Sea meant that cost of drilling per well is also much higher than that in the North Sea and the Norwegian Sea (Norwegian Petroleum Directorate, 2018c). The cost overruns and early production problems encountered by the only two operating fields of the Barents Sea, Snøhvit (natural gas production) and Goliat (oil production), as well as the subsequent failure to find significant discoveries in the wells drilled in new exploration area in the Barents Sea southeast, highlight the high geological risk in the area, so much so that Equinor has decided to divert its exploration efforts away from the frontier areas (Hall, 2018; Holter, 2019b). This adds uncertainty to the availability of cheap natural gas for blue hydrogen production.

6.4.1.1 Hydropower

***Enabler (green hydrogen)* – Higher efficiency by upgrading and extension projects:** Norway finished the year 2018 with 1 626 hydropower plants of a total production capacity of 32 257 MW and an average annual generation of about 135 TWh (NVE, 2019). Since the construction of a major controversial hydropower project in Alta which triggered massive protests from the indigenous community in the 1980s, no large-scale hydropower project was constructed for fear of public retaliation (Karlstrøm & Ryghaug, 2014; Moe, 2015). Coupled with the fact that there remains few rivers and waterfalls for exploitation, it is unlikely that new dams will be built in the foreseeable future (Energy Facts Norway, 2019b; Moe, 2015). However, a recent study done by NTNU suggests that upgrading with extension of existing hydropower plants could potentially increase the total capacity by 10 to 15 per cent, that is an additional 22 to 30 TWh per year (Lia, Aas, & Killingtveit, 2017). This potential has not been taken into account in NVE's long-term outlook for energy production until 2040, which could imply an additional surplus for more green hydrogen production (Veie et al., 2019).

6.4.1.2 Wind power

Enabler (green hydrogen) – Rapidly falling LCOE for onshore wind: Despite having one of the best wind resources in Europe, with an average wind speed of 7-9 m/s at 50m above the ground in exposed areas in Norway, onshore wind power plant developments have been slow due to lack of sufficient subsidies, representing only 3% of 2018 electricity generation (IEA, 2017). After the establishment of the Norwegian-Swedish Green Certificate system in 2012, onshore wind power projects began to pick up growth, especially after 2017 when technological developments drove the levelized cost of energy (LCOE)[12] down rapidly by -30% versus 2012 (Bartnes et al., 2018; Moe, 2015). While the electricity certificate scheme has been extended from 2020 to 2036, wind power projects in Norway that are not operational by 31 Dec 2021 will not be entitled to receive the electricity certificates (Energy Facts Norway, 2019a). In spite of this, with the expected decline in LCOE of onshore wind, wind power in Norway can be profitable even without subsidies (Statnett, 2018).

***Enabler* (green hydrogen) – World's leading developer of offshore floating wind turbines:** Unlike the offshore wind projects in Europe which consists of only bottom-fixed installations, the conditions of the seafloor topography in Norway, the

[12] LCOE refers to the cost of energy generation per kWh over its lifetime, taking into account of the cost of ownership and use of the generation asset.

longer development area-to-land distances and deeper waters make it complicated and more expensive to install similar bottom-fixed offshore wind installations (Veie et al., 2019). For this reason, Norway's offshore wind projects are focused on floating wind turbines, of which Equinor is the world's leading developer (Equinor ASA, 2019c). Following the commissioning of the world's first full-scale commercial 30MW floating wind farm, Hywind Scotland, in 2017, Equinor is currently working on building the world's largest floating offshore wind park, Hywind Tampen, capable of producing 384 GWh of electricity per year to power the oil and gas platforms in the Tampen area in the North Sea by 2022 (ASA, 2019; Ministry of Climate and Environment, 2019). As the technological maturity of floating offshore wind is still far behind fixed offshore wind, the development costs today are significantly higher and not economically profitable (Veie et al., 2019). Hence, NVE's "medium" scenario foresees offshore wind in Norway picking up growth from 2040 onwards, when reductions in the LCOE reach a profitable level driven by technological advances and economies of scale.

Barrier (green hydrogen) **– Major protests against onshore wind projects:** Since 2017, the number of onshore wind power plants installed in Norway has seen a rapid increase which triggered major protests across the country (Karagiannopoulos & Adomaitis, 2019). The public opposition has led to majority of the municipalities to reject the proposal for a national onshore wind power framework which identified 13 areas with the highest potential for onshore wind projects with regards to the wind conditions and environmental impact (Solberg, Skel, & Befring, 2019). With the national framework being shelved, the approval of new onshore wind projects is at a standstill. This corresponds to NVE's "medium" scenario on the market analysis, where all the onshore wind projects that have already obtained the green certificates by 2019 will be built, while new onshore wind projects will not be approved (Veie et al., 2019). In the eventuality that public resistance gains more traction, there is a risk that approved onshore wind projects which are not built by 2023 may have their certificates withdrawn, limiting the peak to 19 TWh in 2025 with no further developments until 2040 ("low scenario") (Veie et al., 2019).

6.4.2 Hydrogen production technologies

Norway has a long track record for producing hydrogen at large scale, which dates as far back as the 1920s where hydropower electricity was used to power water electrolysis for ammonia fertilizer production during the pre-petroleum era, but this method was later replaced by the more cost-efficient production method, the SMR in 1963 after the discovery of hydrocarbons in the NCS. Therefore, this section will limit the review to the current two most dominant technologies for blue and green hydrogen production, that is SMR and CCS, and water electrolysis respectively.

6.4.2.1 SMR

***Enabler (blue hydrogen)* – Mature technology for hydrogen production via SMR:** The SMR is a mature technology which uses natural gas as both fuel and feedstock, where natural gas is burnt as fuel in order to generate heat and energy for 1) converting the natural gas feedstock into methane, 2) producing steam which allows methane to react with a catalyst and be converted into syngas made up of hydrogen, carbon monoxide and carbon dioxide, 3) producing heat in the water-gas-shift reactor in which water and the carbon monoxide produced are converted into carbon dioxide and more hydrogen is produced, and lastly for 4) separating hydrogen from the syngas via pressure-swing adsorption (IEA, 2019c; NCE Maritime CleanTech, 2019; van Cappellen et al., 2018). When CCS is applied to SMR plants, the current carbon capture rate is limited to 90% (IEA, 2019c; NCE Maritime CleanTech, 2019; van Cappellen et al., 2018). Nonetheless, owing to the favourable economics afforded by its technological maturity, SMR is likely to be the leading technology for large-scale production of hydrogen in the near term, provided CCS makes further technological advancements (IEA, 2019c).

6.4.2.2 CCS technology

***Enabler (blue hydrogen)* – World leader in the CCS technology:** CCS has been implemented for more than twenty years since 1996, making Norway a world leader in the technology. Currently, Norway boasts of two large-scale CCS facilities in Sleipner field (since 1996) and a LNG production plant at Snøhvit field (since 2008), both being operated by Equinor (former Statoil), both of which have successfully been storing close to 1.7 million tons of CO_2 annually (Global CCS Institute, 2018; Norwegian Petroleum Directorate, 2019b; Storset et al., 2019). Further, since 2012 Norway has the world's largest test centre for the development and validation of industrial-scale CCS technologies, Technology Centre Mongstad (TCM). (Storset et al., 2019).

***Enabler (blue hydrogen)* – Full-scale CCS demonstration project underway:** Norway may be on its way to becoming the first to launch an industrial CCS project in Europe that involves carbon capture of flue gas using post-combustion method (where CO_2 is captured after combustion) from two industrial sites, Norcem, a cement factory in Brevik and Fortum Oslo Varme, a waste-to-energy recovery plant in Oslo (Gassnova, 2018; Ministry of Petroleum and Energy, 2016). The sequestered carbon will then be transported to an onshore facility on the west coast of Norwegian by ship for temporary storage before being transported through a pipeline to a subsea formation in the North Sea for permanent storage (Gassnova, 2018; Ministry of Petroleum and Energy, 2016). The learnings from the project could help industries around the world overcome barriers to the uptake of CCS, such as cost and scale. The project is expected to commence operations in 2023/2024 after the approval of the funding by the Norwegian Parliament which is expected to be finalised in 2020/2021 (Bellona Europa, 2018; Fortum, 2018; Gassnova, 2018; Norcem, n.d.-b). Norcem aims to be become emission-free by 2030 (Norcem, n.d.-a). In addition, the success realization of the project will open up future opportunities for CO_2 storage from other projects, such as those from the Magnum project in Netherland which is expected to be completed in 2023 (Equinor ASA, 2017; Gigler & Weeda, 2018).

***Barrier (blue hydrogen)* – CCS is energy intensive:** Despite having 2 large-scale CCS facilities in operation, where CO_2 is being captured from natural gas, CCS technology for application in power stations and industrial plants requires carbon capture from flue gas, which is technically more complicated (Ministry of Petroleum and Energy, 2014). One of the biggest technical barriers is the large amount of energy needed, which translates to significant cost (Ministry of Petroleum and Energy, 2014). Based on current state of technology, the cost of CO_2 capture could cost between 80 USD/tCO_2 and 115 USD/tCO_2 (IEA, 2019c)..Recent research in the technology claimed to have found solutions that can potentially reduce the energy requirement significantly, some of which would be implemented in the full-scale CCS demonstration project, and if successful, the cost of the technology would be significantly reduced (Storset et al., 2019).

6.4.2.3 Water electrolysis

Electrolysers and fuel cells technology are similar, except that the processes are reverse. While water electrolysis requires the use of an electrolyser to split water in hydrogen and oxygen so that hydrogen can be extracted, fuel cells are used to produce direct current by recombining hydrogen and oxygen to form water (Adolf et al., 2017). Therefore, to simplify, the points in this section applies to both technologies, but only electrolyser technology will be mentioned. There are currently three main types of electrolysers: alkaline (ALK) electrolysers, proton exchange membrane (PEM) electrolysers and solid oxide electrolyser cell (SOEC). Of the three electrolysers, ALK is the most well-suited electrolyser for large-scale centralised hydrogen production where electricity supply is stable, that is either generated either directly from hydropower or from the electricity grid. PEM is more well-suited for hydrogen production where electricity supply is generated from VRE due to its higher flexibility (with a cold start-up time of 5 to 10 min. vs. ALK: 1 to 2 hours) and capacity to supply hydrogen within a short period of time period or where space is a constraint (IEA, 2019c; IRENA, 2018b). Although introduced since the 1960s, market maturity is at early stage and is mostly used for small-scale applications as due to high costs related to the significant use of precious metals like platinum and iridium and short lifetime (about half of ALK) (IEA, 2019c; IRENA, 2018b).

SOEC could potentially be a game-changer with very high electrical efficiency and material cost is relatively low as it uses mainly ceramics and few rare materials (IEA, 2019c; IRENA, 2018b). Moreover, it may be used in reverse to convert hydrogen back to electricity or used for power grid balancing services, and can be used to produce synthetic fuel (IEA, 2019c; IRENA, 2018b). However, the high operating temperature means that lifetime is short due to rapid degradation of materials (IEA, 2019c; IRENA, 2018b). Also, SOEC technology is relatively new (developed since the 1970s) which has only been tested in labs at small scale and has not been commercialised yet, creating a high level of uncertainty about investment costs (Buttler & Spliethoff, 2018; IEA, 2015, 2019c; IRENA, 2018b). A 20MW power plant using SOEC technology is expected to start operations for the production of low-carbon synthetic crude oil only in 2020 (Doyle, 2019; Sunfire.de, 2017).

Table 4: Techno-economic characteristics of different electrolyser technologies

	ALK Electrolyser			PEM Electrolyser			SOEC Electrolyser		
	2017	2030	Long Term	2017	2030	Long Term	2017	2030	Long Term
State of the art (d)	Mature technology			Early market maturity: commercially available but mostly used for small-scale applications			Not yet widely commercialised. Developed and demonstrated at lab scale.		
Gas purity (c)	> 99.5%			99.99%			99.99%		
Electrical efficiency (%, Lower Heating Value) (b)	63 - 70	65 - 71	70 - 80	56 - 60	63 - 68	67 - 74	74 - 81	77 - 84	77 - 90
Operating pressure (bar) (b)	1 - 30			30 - 80			1		
Operating temperature (°C) (b)	60 - 80			50 - 80			650 - 1 000		
Stack lifetime ('000 operating hours) (b)	60 - 90	90 - 100	100 - 150	30 - 90	60 - 90	100 - 150	10 - 30	40 - 60	75 - 100
Load range (%, relative to nominal load) (b)	10-110	-	-	0-160	-	-	20-100	-	-
Scaling potential (d)	Large-scale operation			Up-scaling in progress			20MW plant to start operating in 2020		
Max. nominal power per stack (MW) (a)	6	-	-	2	-	-	< 0.01	-	-
Capacity range per unit (Nm^3/h) (a)	1 400	-	-	400	-	-	< 10	-	-
Material cost (d)	Low due to avoidance of previous metals			High due to use of expensive platinum catalyst and fluorinated membrane materials			Low due to avoidance of previous metals		
CAPEX (USD/kW) (b)	500 - 1 400	400 - 850	200 - 700	1 100 - 1 800	650 - 1 500	200 - 900	2 800 - 5 600	800 - 2 800	500 - 1 000
Cold start-up time (a)	1-2h			2 -10 min			hours		
Warm start-up time (a)	1-5 min	-	-	< 10 sec	-	-	15 min	-	-
Plant footprint (m^2/kW) (b)	0.095	-	-	0.048	-	-	-	-	-
Preferred application (d)	• Centralised large-scale production • Preferably constantly in operation • Low capacity for grid balancing			• Decentralised small to medium-scale production • High security • High capacity for grid balancing			• Centralised large-scale production • Preferably near sites producing waste heat • Low capacity for grid balancing		

Sources: (a) Buttler & Spliethoff (2018); (b) IEA (2019c); (c) Schmidt et al. (2017); (d) Schnuelle et al. (2019)

Based the above-mentioned reasons, ALK electrolyser is likely to be the choice of technology for large-scale production of green hydrogen for export in Norway in the short to long term, except in off-grid production, particularly in the case of offshore wind, PEM electrolyser would be the preferred choice.

***Enabler (green hydrogen)* – Pioneer in electrolyser technology:** Since 1927, NEL (previously the hydrogen electrolyser division of Hydro, NHEL) has played a central role in the development of water-electrolysis-based hydrogen production in Norway (Nel ASA, 2019; Norwegian Hydrogen Forum, 2016). In fact, NEL was responsible for developing the world's first and largest electrolyser plant with a capacity of supplying 30 000 Nm^3 of hydrogen per hour for the production of ammonia fertilizer in Rjukan (1929) and Glomfjord (1953) in Norway (Nel ASA, 2019). Following the switch from electrolysis to SMR for Hydro's ammonia production in the 1980s and the incorporation of NHEL as a subsidiary of Hydro in 1993, NEL was forced to compensate for the loss of internal sales by reorganising itself to orient towards external industrial customers, which was one of the key drivers for its hydrogen initiatives and demonstrations both internationally (Iceland[13] and Germany[14]) and domestically (Koefoed, 2011). One of the most important national initiatives, led by the then-managing director of NHEL, Christopher Kloed, was the establishment of the Norwegian Hydrogen Forum in 1996, which brought together a community of actors from the industry, environmental organisations, energy companies and research institutions in Norway to promote hydrogen as an energy carrier (Koefoed, 2011). Another notable legacy of Kloed was the launch of the HyNor project in 2003, which consists of building a hydrogen highway between Oslo and Stavanger (Koefoed, 2011; Sataøen, 2008). Today, NEL is the largest electrolyser producer in the world, specializing in both ALK and PEM (proton exchange membrane) technology, as well as a market leader in the manufacture of hydrogen fuelling stations (Nel ASA, 2019).

***Enabler (green hydrogen)* – Plans for large-scale centralised green hydrogen production plants:** In anticipation of the demand for Hyundai hydrogen trucks that are expected to be ready in 2020 in Norway, NEL established Green H2 Norway, a green hydrogen joint venture (JV) was established on 20th Dec 2019 with Greenstat (a green hydrogen industrial supplier in Norway), H2 Energy and Akerhus Energi, with the objective to be the exclusive supplier of green hydrogen for these trucks (Greenstat, 2019; H2 Energy, 2019; NEL ASA, 2019a). As part of the plan, a large-scale hydrogen production plant based on electrolysis is being planned just outside Oslo (Greenstat, 2019; H2 Energy, 2019; NEL ASA, 2019a).

***Barrier (green hydrogen)* – Heavy reliance on rare precious metals for PEM electrolyser:** If hydrogen production plant is powered directly by VRE, particularly offshore wind, PEM electrolyser would likely be the choice of technology owing to its load flexibility and short start-up time (Buttler & Spliethoff, 2018; IEA, 2019c). This is also the preferred technology for fuel-cell-powered transport. However, PEM technology relies heavily on rare precious metals such as platinum and iridium, which are concentrated in few geological locations (Fernandez, 2017; Sealy, 2008), namely South Africa (73%) and Russia (11%) who were the two biggest producers of platinum in 2018 (Cowley, 2019). In addition, given that 95% of the current known

[13] NEL delivered Iceland's first HRS in 1999 as part of an EU-sponsored project, Ecological City Transport System (ECTOS) (Equinor ASA, 2019b).

[14] NEL partnered with German companies to deliver a HRS in Hamburg as part of EU-sponsored project, Clean Urban Transport for Europe (CUTE) in 2003 and in Berlin as part of Clean Energy Partnership (CEP) in 2004 (Koefoed, 2011).

reserves are estimated to be located in South Africa, the level of geopolitical risk to the security of supply are estimated to be medium-to-high (Habib, Hamelin, & Wenzel, 2016). Fortunately, some of the risk could be mitigated by recovering both precious metals from used catalysts in PEM electrolysers at a recycling rate of more than 90% and reuse them without significant loss in cell performance according to recent studies (Carmo et al., 2019).

6.4.3 Hydrogen storage

As hydrogen has a low volumetric energy density, hydrogen needs to be compressed or liquefied before being stored in order to achieve higher energy density comparable to other fuel and minimize the amount of storage space needed. Both hydrogen compression and liquefaction technology are mature technologies which have been deployed commercially in many countries (Hart et al., 2015), but the biggest challenge today is to make it cost-effective to store hydrogen at large scale (Niaz, Manzoor, & Pandith, 2015). This section will review the three forms in which hydrogen can be stored as: CGH_2, LH_2 gas and ammonia (a hydrogen-based fuel), as well as their respective storage vessel.

6.4.3.1 Compressed hydrogen gas (CGH_2)

Enabler **(blue and green hydrogen) – Compression process is less energy intensive than liquefaction:** While both compression and liquefaction technology are mature, compression requires less energy than liquefaction. The energy consumption to compress hydrogen from 20 bar to 875 bar is 2.67 kWh/kgH_2 whereas liquefaction currently consumes around 10 kWh/kgH_2 on average, about 3.7 times more energy (Cardella, Decker, & Klein, 2017; van Cappellen et al., 2018). In addition, since most end-applications for hydrogen are gas-based, CGH_2 can be used as it is, unlike LH_2 which needs to be re-gasified (van Cappellen et al., 2018).

Barrier **(blue and green hydrogen) – Line packing in converted natural gas pipelines may be more expensive than other storage solutions:** For large volumes of storage, compressed hydrogen could be line-packed in converted natural gas pipelines or newly built hydrogen pipelines. Line-packing is being used to store natural gas today and it consists of altering the pressure within the gas network (van Cappellen et al., 2018). However, research showed that pressure variations in natural gas pipelines with 100% hydrogen can lead to a growth of cracks in the pipeline material ten times faster than with 100% natural gas (van Cappellen et al., 2018). Therefore, existing gas infrastructure needs to be converted first through additional reinforcements, maintenance and replacements, at potentially 5% to 30% of the cost of building a new gas network (van Cappellen et al., 2018). Given that a new gas pipeline entails very high capital costs, the conversion could end up costing more than other storage solutions.

6.4.3.2 Liquid hydrogen (LH$_2$)

***Enabler* (blue and green hydrogen) – Higher volumetric energy density than CGH$_2$:** With a higher volumetric density of 70 kg/m^3 compared to 30 kg/m^3 for CGH$_2$ at 700 bar pressure, more volume of LH$_2$ can be stored in a given volume than compressed gas tanks (Hart et al., 2015; Niaz et al., 2015). Cryogenic storage tanks measuring 300m^3 are already commercially available with a capacity to store 21 tons of LH$_2$ and these could be used to provide seasonal storage of hydrogen on a local scale (NCE Maritime CleanTech, 2019; van Cappellen et al., 2018). Currently, NASA owns the largest cryogenic storage tank in the world, which measures 3 800 m^3 with a storage capacity of 270 tons of LH$_2$ and future developments could see such tank becoming 13 times bigger with a capacity to store up to 3500 tons of LH$_2$ (NCE Maritime CleanTech, 2019).

***Enabler* (blue and green hydrogen) – High potential for significant reduction of liquefaction cost:** In order to convert hydrogen from gaseous state to liquid state, the temperature has to be lowered to minus -253°C (IEA, 2019c; Staffell et al., 2019; van Cappellen et al., 2018). Hydrogen liquefaction is typically done using state-of-the-art 5 tpd (tons per day) LH$_2$ hydrogen liquefier, which results in a relatively high energy consumption of around 10 kWh/kg LH$_2$ (Cardella et al., 2017). However, studies have shown that the specific energy consumption for liquefaction can be reduced to between 5.9 and 6.6 kWh/kg LH$_2$ based on 100 tpd LH$_2$ plant within the next 5 years, with the potential to reduce liquefaction costs by 67% compared to a conventional 5 tpd LH$_2$ plant (Cardella et al., 2017).

***Barrier* (blue and green hydrogen) – No hydrogen liquefaction facility in Norway:** At present, there are no hydrogen liquefaction facility in Norway although two medium-scale liquefaction plants (between 5 to 20 tpd LH$_2$) are being planned, of which one is at Equinor's Tjeldbergodden plant and another in Kvinnherad by Gasnor (gas supplier), Sunnhordland Kraftlag (hydropower) and the Kvinnherad municipal (NCE Maritime CleanTech, 2019). The only large-scale hydrogen liquefaction plants exist in North America, which were built for NASA during the space race (NCE Maritime CleanTech, 2019). In Europe, liquid hydrogen is being produced at medium scale (between 5 to 10 tpd LH_2) in France, Germany and Netherlands (NCE Maritime CleanTech, 2019). The market for commercial liquefaction plants are currently dominated by the Linde group (Germany), Air Liquid (France) and Air Products (USA) (NCE Maritime CleanTech, 2019). In terms of the know-how, Norway may be at a disadvantage compared to its European neighbours.

***Barrier* (blue and green hydrogen) – Unsuitable for long-term storage due to boil-off:** An estimated 0.2% to 0.5% of LH_2 per day is lost due to the boil-off phenomenon as the unavoidable heat enters the storage vessel during the loading and unloading process, regardless of how well the insulation is (Bouwkamp et al., 2017; NCE Maritime CleanTech, 2019; Zhang et al., 2016). This makes it challenging to store and transport LH_2 for an extended period of time.

6.4.3.3 Liquid ammonia (NH_3)

***Enabler* (blue and green hydrogen) – World's largest ammonia producer:** Since the 1920s, Norsk Hydro (now Yara), the largest ammonia producer in the world, has been producing ammonia fertilizers using hydrogen via water electrolysis in Norway (IEA, 2019c; Nel ASA, 2019; Norwegian Hydrogen Forum, 2016). Since late 1980s, Norsk Hydro switched to using the SMR method to produce the hydrogen feedstock for manufacturing ammonia fertilizers following the discovery of petroleum (Koefoed, 2011). However, as part of its sustainability efforts, Yara signed an agreement with NEL in August 2019 to produce green ammonia in Norway by leveraging on the latter's next generation alkaline electrolyser (Nel ASA, 2019; Yara International ASA, 2019). If liquid ammonia is to become a hydrogen carrier for long-distance transport, Yara could potentially become a key player in boosting the prospects of green hydrogen, particularly if it is serious in becoming carbon neutral by 2050 (Yara International ASA, 2019).

***Enabler* (blue and green hydrogen) – Less energy demanding than liquefaction:** 1 kg of ammonia requires 10 to 12 kWh to produce, including the energy used for hydrogen production via water electrolysis (Andersson & Grönkvist, 2019;

Brekke, Møller-Holst, Sundseth, Ødegård, & Brekke, 2018). Excluding the energy input for electricity used in water electrolysis of around 7 kWh (theoretically speaking), converting hydrogen to ammonia requires around 2 to 4 kWh/kg NH_3 (Andersson & Grönkvist, 2019; Bruce et al., 2018; Giddey, Badwal, Munnings, & Dolan, 2017). Compared to the energy input for liquefaction (currently at around 10 kWh/ kg LH_2) (Cardella et al., 2017, the prospects for hydrogen storage in ammonia look promising.

Enabler **(blue and green hydrogen) – Higher hydrogen storage density than LH_2:** With a density of 682.61 kg/m^3 (Aarnes et al., 2019) and a high gravimetric hydrogen storage density of 17.7% (Andersson & Grönkvist, 2019), liquid ammonia has a volumetric hydrogen density of 121 kg/m^3 (stored at a temperature of -33˚C and 1 bar), which is around 1.7 times more than in LH_2 with 70 kg/m^3 at 1 bar (Andersson & Grönkvist, 2019; Bruce et al., 2018; IEA, 2019c). Its high energy density of 4 300 kWh/m^3 means that large volumes of energy can be stored in a small space (Sadler & Anderson, 2018).

Enabler **(blue and green hydrogen) – Potential long-term energy storage medium:** Liquid ammonia is typically stored a single- or doubled-walled and refrigerated storage tank, and the biggest tank to date is built in Qatar, measuring 50 meters in diameter and 40.5 meters in height, with a storage capacity of 50 000 tonnes (Sadler & Anderson, 2018). 5 such tanks can store as much energy as 10 salt-cavern hydrogen storage sites, which makes liquid ammonia an attractive alternative to liquid hydrogen as an inter-seasonal hydrogen storage (Giddey et al., 2017; IEA, 2019c). Furthermore, since ammonia liquefies at -33°C at bar 1 pressure and stay liquefied at room temperature at around bar 10, it is subjected to much less energy loss through boil-off and the operational cost of storage is lower than liquid H_2 due to less energy needed to maintain the storage vessel at cool temperature (Andersson & Grönkvist, 2019; Giddey et al., 2017). A study in 2008 estimates the cost of hydrogen storage in liquid ammonia form to be USD 0.54/kg H_2 as compared to liquid H_2 at USD 14.95/kg H_2 for six months (Philibert, 2017; Valera-Medina, Xiao, Owen-Jones, David, & Bowen, 2018).

Barrier **(blue and green hydrogen) – High energy consumption for ammonia cracking to extract hydrogen:** In most cases, ammonia needs to go through a dehydrogenation process called ammonia cracking before it can be used in hydrogen end-use applications in the receiving importing country (Andersson &

Grönkvist, 2019; Giddey et al., 2017; NCE Maritime CleanTech, 2019). The most common method to “crack” or decompose ammonia is through thermolysis, which requires the use of ruthenium-based catalysts at high temperatures of typically above 650˚C, in order to achieve complete conversion of ammonia to hydrogen (Andersson & Grönkvist, 2019; Giddey et al., 2017). Assuming an electricity consumption of 2.8 kWh/kg m^3 NH_3 for ammonia cracking and 85% hydrogen recovery rate from ammonia, the energy penalty for ammonia cracking is estimated to be 14.1 kWh/kg H_2, which is higher than liquefaction (Giddey et al., 2017). The dehydrogenation of ammonia may eventually be bypassed if solid oxide fuel cells (SOFC) technology matures as the cracking can leverage on the high operating temperature and occur within the latter, or if ammonia is used as feedstock in alkaline membrane fuel cells (AFC) (currently at early development phase) (Giddey et al., 2017; NCE Maritime CleanTech, 2019).

Barrier **(blue and green hydrogen) – Challenges in scaling up ammonia cracking process:** For large-scale conversion, ruthenium-based catalysts are not feasible due to the high operating costs incurred to achieve high temperature and the need for more expensive reactor materials to support the heat (Andersson & Grönkvist, 2019; Giddey et al., 2017). To scale up the conversion process, recent research on the use of alkali-based catalysts such as sodium and lithium looks promising in lowering the cracking temperature to below 500°C (Andersson & Grönkvist, 2019; Valera-Medina et al., 2018).

Barrier **(blue and green hydrogen) – Purification of hydrogen after ammonia cracking:** With the industry feedstock and transportation sector accounting for majority of the demand for hydrogen, hydrogen needs to go through a purification process after the dehydrogenation process from ammonia in order to increase its purity level to more than 99.99% (Giddey et al., 2017). This translates into additional cost and lower overall efficiency.

6.4.4 Hydrogen transport

6.4.4.1 Pipelines

Enabler (blue hydrogen) / Barrier (green hydrogen) **– Possibility to leverage on existing gas pipelines:** There is currently close to 8 000 km of high-pressure subsea pipelines connecting Norway to Europe (Skar et al., 2018) These pipelines could be converted into hydrogen pipelines for exporting hydrogen to EU when they are no longer in use for natural gas exports. However, since majority of the gas pipelines is jointly owned by Gassled in partnership with all the major oil and gas companies, including Equinor and wholly stated-owned Petoro, it is likely that the transmission via gas pipelines will prioritize blue hydrogen over green hydrogen (Gassco, 2019; Norwegian Petroleum Directorate, 2019g, 2019h).

***Barrier (blue hydrogen) – Risk of hydrogen embrittlement of pipelines*:** The existing gas pipelines connecting Norway to Europe are typically made of high-strength steel such as API 5L X65 and X70 and has a high pressure capacity of about 150 bar which allows natural gas to be transported over long distances without compressor stations along the way (Aarnes et al., 2019). Unlike the existing polythene natural gas pipelines in the UK and other parts of Europe which operates at a limit of 7 bar pressure, the higher operating pressure in subsea pipelines make them more prone to hydrogen embrittlement and may not be easily repurposed for the transport of 100% pure hydrogen (Aarnes et al., 2019; IEA, 2019c; Staffell et al., 2017). While the rate of hydrogen embrittlement could be slowed down by lowering the maximum operating pressure to about 55% of the current limits for natural gas transport without hydrogen, this would significantly reduce the transport capacity of hydrogen to only 30% of current transport capacity based on natural gas (Aarnes et al., 2019).

***Barrier (blue and green hydrogen)* – Dedicated hydrogen pipelines are costly to build:** Although the most economical way for transporting large volumes of hydrogen over distances less than 1 500 km is through pipelines, the upfront capital cost for building a new network of subsea hydrogen pipelines is expected to be more expensive than building a new natural gas pipeline due to considerations related to hydrogen embrittlement (Andersson & Grönkvist, 2019; Bouwkamp et al., 2017). Therefore, it is unlikely that such pipelines will be built unless it can be justified by a significant volume of long-term hydrogen demand. In the USA, the capital cost for building a hydrogen transmission pipeline is estimated to be around USD 1 million per mile (USD 625K per km) and are generally installed in areas with where the daily hydrogen demand is at least hundreds of thousands of kg and remains stable for at least 15 to 30 years (Bouwkamp et al., 2017).

***Barrier* (blue and green hydrogen) – Prototype stage for hydrogen-compatible pipeline compressors:** Since hydrogen has a density of low molecular weight compared to natural gas, the volume flow in the pipeline needs to be three times more than natural gas in order to deliver the same energy capacity (Witkowski, Rusin, Majkut, & Stolecka, 2017). However, as hydrogen travels through the gas pipelines, a drop in pressure may occur due to various factors like changes in temperature or flow velocity, which can result in choking conditions (Witkowski et al., 2017). To mitigate this problem, centrifugal compressors are typically installed at regular spacing along the pipeline to re-pressurize the gas (Staffell et al., 2017, 2019; Witkowski et al., 2017). However, conventional centrifugal compressors not designed to handle hydrogen at high volume flow rate (Staffell et al., 2017, 2019; Witkowski et al., 2017) A multi-stage centrifugal compressor is being developed to overcome this, but the technology is still at prototype stage (Bouwkamp et al., 2017; Di Bella, 2015; Witkowski et al., 2017).

6.4.4.2 Ships

Enabler (blue and green hydrogen) **– Low transport cost for ammonia-based hydrogen carrier:** While ammonia production and ammonia cracking are highly energy intensive which lead to high production cost, the relatively low transportation costs make ammonia an attractive hydrogen carrier (IEA, 2019c). In addition to having a higher hydrogen storage density than LH_2, ammonia can be shipped by existing chemical and semi-refrigerated liquefied petroleum gas tankers which has an established intercontinental transmission and distribution network, making it much cheaper to transport at USD 1.20/kg H_2 compared to LH_2 at USD 2/kg H_2, including cost of conversion prior to shipping (IEA, 2019c). As such, a number of projects like H21 North of England (Sadler & Anderson, 2018) and Australia's National Hydrogen Roadmap (Bruce et al., 2018) have considered ammonia as a possible hydrogen carrier in their scenarios. It was also recommended as an energy carrier in the study of energy transition towards RE in Svalbard (Aarnes et al., 2019; Brekke et al., 2018).

Enabler (blue and green hydrogen) **– First liquid hydrogen transport vessel launched in 2019:** As mentioned in Section 1.2.2, the large-scale transport of liquid hydrogen by sea is not feasible under current restrictions of the IGC and IMDG, which limit the volume permissible and the location of containers on board of cargo ships (Hylaw, n.d.; NCE Maritime CleanTech, 2019). Following the signing of a memorandum between Australia and Japan in 2017 to allow the transportation of LH_2 in bulk in specialized ships (Australian Maritime Safety Authority, 2017; Kyodo, 2017), Kawaski Heavy Industries (KHI), the first Asian company to build LNG transport vessels, developed and launched the world's first liquid hydrogen carrier in Dec 2019 (Bruce et al., 2018; Harding, 2019; Kawasaki Heavy Industries Ltd., 2019a, 2019b). The vessel, Suiso Frontier, runs on diesel and will be installed with a 1 250 m^3 vacuum-insulated double-shell hydrogen storage tank, as part of a pilot project to transport LH_2 from Victoria in Australia to Japan in 16 days by end of 2020 (Bruce et al., 2018; Harding, 2019; Kawasaki Heavy Industries Ltd., 2019a, 2019b). The trials will serve as a building block for the design and construction of a commercial-scale hydrogen-powered vessel with a storage capacity of 160 000 m^3, equivalent to four tanks of modern LNG carriers, by around 2030 (Harding, 2019).

***Barrier (blue and green hydrogen)* – High transport cost for LH_2:** Assuming the successful implementation of a commercial scale LH_2 tanker ship of 160 000 m^3 storage capacity by 2030, the transport cost is expected to be USD 2/kg H_2, almost double that of liquid ammonia (USD 1.20/kg H_2) (IEA, 2019c, 2019a). Part of the high cost may be attributed to the fact that the transport vessel is assumed to return to the port of origin with an empty tank, unless another high-value liquid can be transported on its way back (IEA, 2019c).

6.5 Environmental factors (E)

***Enabler (blue and green hydrogen)* – Regional GHG emissions reduction:** According to van Cappellen et al. (2018), the carbon footprint of blue hydrogen production in Norway ranges between 0.82 and 1.14 kg CO_2e/kg H_2 today, whereas based on the emission factor of Norwegian electricity mix of 17 g of CO_2/kWh, green hydrogen production in Norway results in a carbon footprint of 1.13 kg CO_2e/kg H_2 and 0.92 kg CO_2e/kg H_2 in 2015 and 2030 respectively. Compared to its neighbours in Europe, such as Netherlands, the GHG emissions from hydrogen production are significantly higher than that of Norway in both 2015 and 2030 (van Cappellen et al., 2018).

***Enabler (green hydrogen)* – Water availability:** In theory, 1 kg of hydrogen requires around 8 to 9 L of water (IEA, 2019c; Schnuelle et al., 2019). However, after taking into account of the water loss in the purification process, around 15 L of water is needed to produce 1kg of hydrogen or 0.45 L per kWh_{H2}, that is, to produce 1 TWh of hydrogen, a volume of 450 million L of water is needed (Schnuelle et al., 2019). Although the water consumption via electrolysis is roughly double that of blue hydrogen production, the fact that Norway has an abundant supply of surface water makes this parameter less critical for the production of green hydrogen (IEA, 2019b). As a matter of fact, Norway is endowed with a storage capacity of water resources equivalent to half of Europe's reservoir storage capacity (Energy Facts Norway, 2019b).

***Barrier (blue hydrogen) / Enabler (green hydrogen)* – Depleting natural gas resource:** The prospects of blue hydrogen production depends highly on the availability of natural gas resources. Table 6 shows the total estimated natural gas resources on the NCS as at end of 2017. According to the NPD (2018e), the natural gas resources that have been discovered as at end of 2017 stood at 2.3 bcm o.e.[15] (36% of the total estimated resource of 6.5 bcm o.e.). Assuming a constant average annual export volume of 120 bcm o.e. (based on average production forecast between 2018 and 2023) and that all the discovered resources can be 100% extracted, the resources is expected to last about 19 years until 2036 (Norwegian Petroleum Directorate, 2019f, 2019a). Assuming that all the undiscovered resources can be fully extracted and exported at the same average volume, the natural gas resources would last another 15 years until 2052. However, the reality shows that the production output is expected to start declining after mid-2020s due to lower recovery rates in maturing fields and in undiscovered fields which are expected to be smaller in size, as can be observed in Figure 8. Hence, the production timeline may extend for a longer period but with decreasing export volume every year.

Table 5: Total natural gas resources on the NCS as at 31 Dec 2017.

Gas (million scm oe)	2017	North Sea	Norwegian Sea	Barents Sea
Sold and delivered	2,341			
Reserves	1,729	1,152	400	177
Contingent resources	605	350	208	48
Undiscovered	1,870	245	395	1,230
	6,545	**1,747**	**1,003**	**1,455**

Source: Norwegian Petroleum Directorate (2018d)

[15] bcm o.e. stands for billion cubic meters of oil equivalent, where 1 Sm^3 o.e. is equivalent to 1 000 Sm^3 of natural gas (Norwegian Petroleum Directorate, 2019c).

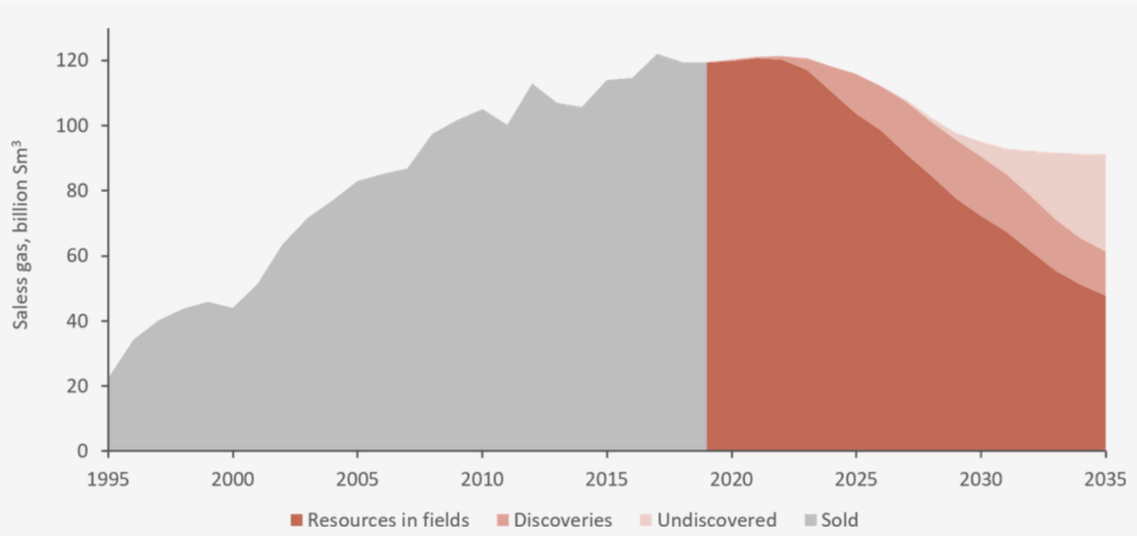

Figure 8: Sales volume forecast of gas from Norwegian fields until 2035. Source: Norwegian Petroleum Directorate (2019d)

Furthermore, the high uncertainties due to the lack of information on the geology in the Barents Sea and the perceived low profitability of its undiscovered fields by major oil companies such as Chevron, ExxonMobil, BP, Total and Shell (Adomaitis, 2018, 2019b; Bousso & Nasralla, 2019) may result in the failure to extract from the undiscovered fields in the Barents Sea to offset the decline. Excluding the undiscovered fields in the Barents Sea, the total natural gas resources in the NCS would probably last until 2042, assuming an average gas export volume of 120 bcm o.e. per year. This would likely have serious implications for the return on investment on the technologies related to blue hydrogen production, particularly CCS.

***Barrier (blue hydrogen)* – Fugitive emissions from CCS:** While using CCS can significantly reduce the carbon footprint of blue hydrogen, the current carbon capture rate for SMR with CCS is at 90% with an emission intensity of 0.99 kg CO_2e/kg H_2 and 95% for ATR with CCS with emission intensity of 0.64 kg CO_2e/kg H_2 (IRENA, 2019; van Cappellen et al., 2018). This means that 5 to 10% of all the CO_2 generated from blue hydrogen production will be leaked, increasing the carbon footprint of the country where the site of production is located. In addition, there is potentially a risk of fugitive methane emissions along the value chain of gas due to flaring, venting or leakage, which needs to be addressed for it to be truly a sustainable solution in the energy transition.

***Barrier* (blue and green hydrogen) – Ammonia is highly toxic:** If hydrogen is stored in the form of ammonia, one should note that it is highly toxic and can be lifethreatening or fatal when exposed for too long at high concentration of ammonia in the air, requiring careful handling by professionally trained operators (IEA, 2019c; Valera-Medina et al., 2018). Fortunately, ammonia has a distinctive odour that allows for easy detection of leaks at very low concentrations (Philibert, 2017). Despite the existence of well-established and tested health and safety protocols, as well as regulations for handling ammonia in all aspects of industrial applications which can help to minimize the risk of exposure, negative public perception of the toxicity of ammonia and of its strong odour even at low concentrations may impede deployment of ammonia as a hydrogen-based fuel (Valera-Medina et al., 2018).

6.6 Legal factors (L)

***Enabler (blue and green hydrogen)* – Existing regulations and standards for hydrogen production:** While there are no hydrogen-specific regulations in hydrogen, the production of hydrogen in Norway generally follows the regulations set by the *Act on protection against fire, explosion and accidents with dangerous substances*, which calls for risk assessments and demarcation of safety zones around the production facility (NCE Maritime CleanTech, 2019). For production and onsite storage of hydrogen of volumes more than 5 tons, consent must be requested from the Directorate for Civil Protection and the Major Accident Regulation must be followed with additional duties and responsibilities (NCE Maritime CleanTech, 2019).

***Barrier (green hydrogen)* – Lack of a standard for green hydrogen:** To distinguish green hydrogen from other types of hydrogen that are produced from fossil fuels, global certification scheme is necessary to allow one to trace back to the origins of the hydrogen, but this requires first and foremost, an established standard for green hydrogen (Staffell et al., 2019). Depending on the energy resources and priorities of the country, green hydrogen standards are defined differently, varying from hydrogen produced from only RE sources, to those produced from low-carbon sources which include nuclear and CCS (Staffell et al., 2019). Without a common green hydrogen standard agreed with the EU, the prospects for green hydrogen exports could be negatively impacted.

***Barrier (blue hydrogen)* – Limitations on hydrogen blend in the gas grid:** One of the ways being explored for transportation of hydrogen is in the form of blended natural gas using the existing natural gas pipelines. However, the current allowable limits for hydrogen blend in natural gas in the EU are set at arbitrarily low levels and varies from country to country (Aarnes et al., 2019; Quarton & Samsatli, 2018). For example, the legal limits set in UK is at 0.1%, whereas in Germany and Netherlands, the limits are 10% and 12% respectively (Quarton & Samsatli, 2018; Staffell et al., 2019). However, even if the legal limits are relaxed, studies show that the maximum allowable mix of hydrogen in the gas grid without the need for major upgrades to the current infrastructure and the need for major adjustments to end appliances is at 20% in volume. In addition, industries which rely on carbon content for its processes or use gas engines and turbines that are not designed to tolerate hydrogen blend of more than 2% will not be able to use the newly blended gas without pre-treatment (IEA, 2019c). Hence, this would mean that this pathway would not be feasible for a deep decarbonisation of the EU.

***Barrier (blue hydrogen)* – London protocol:** According to Article 6 of the London Protocol, it is prohibited to export waste for the purpose of dumping at sea (IMO, 2019). This implies that if Norway exports blue hydrogen to Europe by way of transporting natural gas to the recipient country and reforming it on-site with CCS, the CO_2 captured needs to be stored in that country or on land in another European country (Aarnes et al., 2019). In early Oct 2019, a provisional application of the 2009 amendment of Article 6 of the London Protocol was approved to allow cross-border transport and export of CO_2 for storage purposes in sub-seabed geological formations (Global CCS Institute, 2019). This means that Norway will be able to transport the CO_2 out of Europe and store it in the Norwegian continental shelf. However, only CO_2 transported by pipelines and stored in geological formations can benefit from the carbon price under the EU ETS system, while projects that count on transporting CO_2 via ships and trucks are currently excluded (Global CCS Institute, 2019).

Table 7 attempts to list the PESTEL factors in two columns, blue hydrogen and green hydrogen, and highlighting the enablers and barriers in large-scale export of blue and green hydrogen in Norway.

Table 6: PESTEL analysis

	Blue Hydrogen	Green Hydrogen
Political	*Enabler:* • CCS as a political glue • A petro-industrial complex • Rising carbon prices and tax • Deep decarbonization of the EU by 2050 *Barrier:* • Diminishing political support for further offshore exploration	*Enabler:* • Rising carbon prices and tax • Deep decarbonization of the EU by 2050 *Barrier:* • A petro-industrial complex
Economics	*Enabler:* • A growing global demand for hydrogen • Limited electricity surplus in the EU due to low curtailment rates of VRE • Access to substantial natural gas resource • Lower risk of stranded assets *Barrier:* • Cutback on fossil fuel funding from EIB	*Enabler:* • A growing global demand for hydrogen • Limited electricity surplus in the EU due to low curtailment rates of VRE • Low electricity prices • Cutback on fossil fuel funding from EIB
Social	*Enabler:* • Heavy reliance on oil and gas export for social welfare • Concerns about electricity being an energy export • General public receptiveness towards hydrogen *Barrier:* • Rising climate change awareness among youths • Uncertainty over the future of oil and gas • Concerns for the safety and reliability of hydrogen	*Enabler:* • Rising climate change awareness among youths • Uncertainty over the future of oil and gas • Concerns about electricity being an energy export • General public receptiveness towards hydrogen *Barrier:* • Heavy reliance on oil and gas export for social welfare • Concerns for the safety and reliability of hydrogen
Technological: Energy input sources	*Enabler:* • Decreasing average cost per development well *Barrier:* • Lack of infrastructure and limited gas transport capacity in the Barents Sea • High geological risks in the Barents Sea	*Enabler:* • Higher efficiency by upgrading and extension of hydropower projects • Rapidly falling LCOE for onshore wind • World's leading developer for offshore wind power *Barrier:* • Major protests against onshore wind projects
Technological: Hydrogen production	*Enabler:* • Mature technology for hydrogen production via SMR • World leader in CCS technology • Full-scale CCS demonstration project underway *Barrier:* • CCS is energy intensive	*Enabler:* • Pioneer in electrolyser technology • Plans for large-scale centralised green hydrogen production plants *Barrier:* • Heavy reliance on rare precious metals for PEM electrolyser
Technological: Hydrogen Storage	*Enabler:* • Compression process is less energy intensive than liquefaction	*Enabler:* • Compression process is less energy intensive than liquefaction

<table>
<tr><td></td><td>LH_2 has higher volumetric energy density than CGH2
High potential for significant reduction in liquefaction cost
World's largest ammonia producer
Ammonia production is less energy demanding than liquefaction
Ammonia has higher hydrogen storage density than LH_2
Ammonia as a potential long-term energy storage medium
Barrier:
Line packing in converted natural gas pipelines may be more expensive than other storage solutions
No hydrogen liquefaction facility in Norway
LH_2 unsuitable for long-term storage due to boil-off
High energy consumption for ammonia cracking to extract hydrogen
Challenges in scaling up ammonia cracking process
Purification of hydrogen after ammonia cracking</td><td>LH_2 has higher volumetric energy density than CGH2
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Purification of hydrogen after ammonia cracking</td></tr>
<tr><td>Technological: Hydrogen Transport</td><td>Enabler:
Possibility to leverage on existing gas pipelines
Low transport cost for ammonia-based hydrogen carrier
First liquid hydrogen transport vessel launched in 2019
Barrier:
Risk of hydrogen embrittlement of pipelines
Dedicated hydrogen pipelines are costly to build
Prototype stage for hydrogen-compatible pipeline compressors
High transport cost for LH_2</td><td>Enabler:
Low transport cost for ammonia-based hydrogen carrier
First liquid hydrogen transport vessel launched in 2019
Barrier:
Leveraging on existing gas pipelines
Dedicated hydrogen pipelines are costly to build
Prototype stage for hydrogen-compatible pipeline compressors
High transport cost for LH_2</td></tr>
<tr><td>Environmental</td><td>Enabler:
Regional GHG emissions reduction
Barrier:
Depleting natural gas reserves
Fugitive methane emissions</td><td>Enabler:
Regional GHG emissions reduction
Water availability
Depleting natural gas reserves</td></tr>
<tr><td>Legal</td><td>Enabler:
Existing regulations and standards for hydrogen production
Barrier:
Limitation in hydrogen blend in gas grid
London protocol</td><td>Enabler:
Existing regulations and standards for hydrogen production</td></tr>
</table>

7.0 Discussion

Using the MLP framework, this section presents a summary of the key findings from the PESTEL analysis to set a common starting point for the construction of the narratives in the next sub-section for the four contextual futures scenarios briefly described in section 5.1. This is then followed by a discussion of these scenarios with respect to the research questions (Section 7.2), on how the prospects of blue and green hydrogen production in Norway for energy export vary in each scenario and how different conditions affect the nature of the interactions between hydrogen and the regime, as well as the broader landscape.

Sociotechnical Landscape

The sociotechnical landscape is predominantly influenced by developments in the energy transition in the EU, which in turn is driven by two key factors: climate security and energy security. With respect to climate security, the accelerating climate change impacts and growing pressure from youth climate activists in Europe may have contributed to recent efforts to combat climate change such as the EU ETS reforms in 2019 (which led to the tripling of carbon prices), the phase-out of fossil fuel lending by EIB by end of 2021, the climate emergency declaration by the EU parliament and the proposal of European Green Deal aimed at ramping up climate mitigation efforts. As part of its strategy to reach its 2050 target to become carbon neutral, the EU have shown great interests in hydrogen and CCS applications in the transport, power and industrial sectors, which will likely drive the demand for both technologies and create new market opportunities for Norway.

At the same time, energy security concerns due to the overdependence on energy imports for economic growth are one of the key motivations for increasing RE capacity and driving energy efficiency improvements in the EU. These factors will undoubtedly dampen the demand for oil and gas in Europe in the future. However, given the fact that the EU is currently not on track to meet most of its 2020 targets according to the European Environment Agency, the commitment level of the EU to achieve its 2050 climate goals is questionable. Moreover, the construction of the new gas pipeline connecting Russia to Germany raises the risk of a lock-in for continued heavy reliance on natural gas as an energy source.

Sociotechnical Regime

Half of the total value of Norway's exports in 2018 was attributed to the crude oil and natural gas. Since oil production peaked in 2000, the contribution mix of natural gas to total oil and gas production has increased from 23% to around half since 2009 (Norwegian Petroleum Directorate, 2019d). As domestic consumption of natural gas is limited, majority of the natural gas extracted is exported. While Norway is the world's third largest natural gas exporter (in 2018), 95% of its exports is transported to the EU (UK 29%, Germany 39%, France 15%, Belgium 13%) through its 8 800 km subsea gas pipeline network (Norwegian Petroleum Directorate, 2019d). As such, Norway is particularly sensitive to changes in EU's energy system, especially concerning its gas exports which is more restricted geographically compared to oil exports due to transport challenges. In an attempt to secure the future of its gas exports, Norway have repeatedly employed discursive strategies to shape the public discourse into focusing on the lower carbon footprint of natural gas compared to coal (rather than RE sources) and the cost-effectiveness of natural gas in the decarbonisation of EU's economy (Lien, Helgesen, & Aspaker, 2016).

In the face of mounting scientific evidence of the threats of anthropogenic climate change, natural gas is increasingly being perceived negatively by Norwegian citizens (Karlstrøm & Ryghaug, 2014) and was the cause of a political divide in the Norwegian parliament in the mid 2000s. University applications for petroleum-related subjects, as a result, have reached all-time low, raising concerns for the lack of talents to replace an aging workforce in the oil and gas sector. To preserve the petro-industrial complex in the regime, the Norwegian government and the Equinor (the key regime actor), have stepped up the developments of low-carbon technologies like CCS and blue hydrogen. These technologies are considered symbiotic to the regime because it legitimises further offshore exploration in the Barents Sea and the continued reliance of natural gas in a carbon-constrained world.

As natural gas is a finite resource, a move towards a low-carbon energy transition in Norway is inevitable once its reserves are depleted. According to the NPD's 2018 estimates, natural gas production is expected to peak in the mid-2020s and natural gas from the undiscovered fields (half of which lies in the Barents Sea) is expected to start production as early as 2025 (Norwegian Petroleum Directorate, 2019e). However, considering the challenging geological and weather conditions, as well as the lack of infrastructure in the Barents Sea, the economic viability of offshore activities in this area is put in question. Nevertheless, as mentioned in Section 5.5, in a hypothetical situation where all the natural gas reserves in the discovered fields are successfully extracted and exported at the same rate as today, the natural gas reserves will last until 2036 and if the resources in the undiscovered fields are included, the reserves could last until 2052. This is an important consideration for the prospects of blue hydrogen since its production depends on natural gas input.

Niche-innovation:

Similar to fossil fuel exports, the prospects of large-scale hydrogen production in Norway will likely depend on the demand for hydrogen in the EU, which can vary between 20 MT to 57 MT in 2050 depending on the pace of energy transition. Since blue hydrogen is supported by Equinor, it is likely to benefit from lower internal natural gas prices which could lead to more competitive prices for blue hydrogen compared to that produced in the EU. Similarly, production cost of green hydrogen in Norway is likely to be cheaper than in the EU as a result of lower electricity prices, but it is unclear if it will still be the case after including the cost of storage, transport, and reconversion back to hydrogen (assuming ammonia is used as hydrogen carrier).

Based on the production cost alone, blue hydrogen is 1.5 to 2 times cheaper than green hydrogen in Norway. Furthermore, from an export value chain perspective, blue hydrogen has a major advantage over green hydrogen because the site of production of blue hydrogen could be shifted from Norway to the importing country in the EU by transporting equipment for CCS. Due to the presence of fossil-based electricity sources in the electricity grid in the EU, and the highly prohibitive capital cost installing direct electrical connection with Norway (assumed to be not economically feasible within the period of analysis), it would be challenging for the hydrogen produced in the importing country to be certified as green.

However, the prospects of blue hydrogen production hinges on the reserve level of natural gas resources in the NCS. As mentioned earlier under the regime dynamics, the prospects of finding new resources of natural gas for blue hydrogen are unclear and may entail higher costs compared to current natural gas extraction cost due to the lack of infrastructure. This adds to more incertitude in the viability of blue hydrogen production, especially if one considers the potentiality of increasing carbon prices and possibility of a phase-out of blue hydrogen under an ambitious deployment of hydrogen in the EU. On the other hand, there is an abundant level of the natural resources (water and electricity) for green hydrogen production in Norway.

As a symbiotic niche, blue hydrogen receives strong support from the current regime. In the case for green hydrogen, Equinor could potentially be one of the key actors, but it is dependent on the advancement of floating offshore wind developments in Norway, which unlike bottom-fixed offshore wind turbines, is not expected to reach maturity before 2040. Until then, the green hydrogen network in Norway is likely to be dominated by niche-actors such Yara before 2030, and eventually joined in by Green H2 Norway when the world's first LH_2 ocean tanker with a capacity of 160 000 m^3 becomes available from 2030 onwards (Harding, 2019).

7.1 Narratives of the four futures scenarios

Before the construction of the narratives, an overview of the key characteristics of the four scenarios is summarised in the Table 8 below. Due to the uncertainties in each scenario, the unfolding of the pathways is assumed to be equally likely.

Table 7: Key characteristics of the four scenarios

Scenarios	**Global synergies**	**Increased focus on CCS**	**Inevitable transition**	**Slow transition**
EU commitment	High	High	Low	Low
Gas reserves	Low	High	Low	High
EU 2050 hydrogen roadmap scenario	Ambitious: 57 MT	Ambitious: 57 MT	Business-as-usual: 20 MT	Business-as-usual: 20 MT
Blue hydrogen mix in EU sectors	Before 2030: 50% After 2030: 0%	Transport: 50% Other sectors: 85%	Transport: 50% Other sectors: 85%	Transport: 50% Other sectors: 85%
Green hydrogen mix in EU sectors	Before 2030: 50% After 2030: 100%	Transport: 50% Other sectors: 10%	Transport: 50% Other sectors: 10%	Transport: 50% Other sectors: 10%
Nature of landscape pressure	Disruptive changes: Moderate pressure	Disruptive changes: Moderate pressure	Avalanche changes: Sudden strong pressure	Disruptive changes: Low pressure
MLP pathways at niche-level in Norway	Before 2030: Transformation After 2030: Substitution	Transformation	De-alignment and Re-alignment	Transformation

In addition, the following assumptions are applied across all the scenarios:

1) A surplus of RE electricity of 80 TWh in Norway is available by 2050 driven by increased precipitation in hydropower plants, onshore wind installations which will peak in 2025, and offshore wind technology maturing in 2040 (refer to section 5.4.1).
2) Based on the current EU policies, the carbon prices in the EU ETS are expected to peak in 2023 at 35 EUR/tCO_2e and end up at around 20 EUR/tCO_2e in 2030 (De Clara & Mayr, 2018). If the European Green Deal is adopted, carbon prices may rise up to 55 EUR/tCO_2e by 2030 (Carbon Tracker Initiative, 2018).
3) Meeting the increase in demand for hydrogen in the EU is likely to require hydrogen imports due to competing demands for electricity generated from RE sources in the EU (in the case of green hydrogen) and existing dependence of natural gas imports (in the case of blue hydrogen). Hydrogen may initially be imported in the form of ammonia as demand is expected to be still modest and specialised LH_2 ocean tanker will not be ready before 2030 (FCH JU, 2019).

4) The full-scale CCS demonstration project will be completed in 2024 and the Magnum project will be completed in 2023 as planned. Thus, theoretically speaking, market maturity could be achieved in the period between 2024 to 2030.
5) The conversion of existing sub-sea natural gas pipelines is not considered in any of the scenarios due to the high costs for replacement and maintenance, as well as the complexity of coordinating between parties of both ends of the pipelines on the timing of conversion.
6) Hydrogen transport via hydrogen pipelines in all scenarios is not feasible before 2050 due to the high upfront capital costs which can only be justified with high stable hydrogen demand for at least 15-30 years.
7) The export pathway for blue hydrogen is assumed to follow the model of the Magnum project, where natural gas is exported through existing gas pipelines to the country of the customer, and hydrogen is produced onsite vis ATR with CCS. The incumbent, Equinor is expected to play a key role in this pathway.
8) The export pathway for green hydrogen assumes a centralised electrolysis-based production by Yara, and ammonia-based storage and transport, since it is the most cost-effective hydrogen carrier compared to CGH_2 and LH_2 before 2030. After 2030, Green H2 Norway may emerge as a competitor to store and transport green hydrogen in the form of LH_2.

Global synergies scenario: High EU commitment & Low gas availability

Under this scenario, the broader energy landscape is characterised by a strong commitment by the EU to align its current policies with the 2050 climate change goals to be carbon-neutral. This implies the adoption of the full program of the European Green Deal and the deployment of the water-electrolysis-dominant scenario under the EU Hydrogen Roadmap up to 2050, where political acceptance of CCS is assumed to be low, majority of the hydrogen is expected to be produced via water electrolysis from 2030 onwards, and the cost of production is expected to be cheaper than blue hydrogen in the long-term (FCH JU, 2019). In addition, the annual demand for hydrogen in the EU is assumed to grow to 57 MT by 2050 (FCH JU, 2019). Meanwhile, the depletion of Norway's natural gas resources obliges Norway to explore other market opportunities presented by the transition in the EU, leading to synergies of both economies. Against this background, the key drivers affecting the prospects of blue and green hydrogen in Norway for energy export at the landscape, regime and niche levels may be presented as follows:

Table 8: Global synergies scenario in 2050 from a MLP perspective

MLP levels	Key factors
Landscape	• Deep decarbonisation of the EU • Rising carbon prices in the EU • Cutback on fossil fuel funding by EIB • Demand for hydrogen increases gradually from 2025 onwards • Rising climate change awareness among youths in Norway
Regime	• Depletion of natural gas resources from 2023 onwards • Strong uncertainty over the future of oil and gas in Norway by 2023 • Diversification of portfolio by incumbents
Niche	• Green hydrogen production technologies reach maturity by 2030 • Infrastructure for hydrogen storage and export will be ready in 2030 • Green hydrogen is expected to be more price-competitive than blue hydrogen by 2030

Following the cutback on funding from EIB, offshore exploration projects in the Barents Sea are expected to face increased difficulties in attracting investment to build the necessary infrastructure. The oil and gas sector in Norway is also expected to face increasing pressure to keep the undiscovered resources in the ground as a result of growing climate change awareness among youths in Norway. Under these circumstances, hydrogen developments are likely to follow the MLP's transformation pathway before 2030 due to the nascent state of the hydrogen market in EU. As more infrastructure are in place in the EU, the pathway may switch to the substitution pathway after 2030.

Under the transformation pathway, the incumbent, Equinor realises that it needs to have a backup plan in anticipation of not finding new gas reserves in Norway by 2023, the critical timeline for current projections for gas productions up to 2035 to be feasible (Hall, 2018). This prompts Equinor to partially re-orientate itself to diversify its domestic portfolio by ramping up research developments in CCS in to produce blue hydrogen at large-scale for the growing demand in the EU before 2030, followed by a full orientation towards green hydrogen production based on energy generated from offshore wind technology. At the niche level, Yara partners up with NEL, the world's biggest electrolyser producer, to develop the value chain for large-scale production of green hydrogen for the eventual export in the form of ammonia.

A window of opportunity is expected to open up around 2030 when the energy regime in Norway is destabilized as a result of low availability of natural gas and the EU imposes restrictions on the import of blue hydrogen to allow only imports of green hydrogen. This pathway is similar to MLP's substitution pathway where price and performance improvements for green hydrogen export, as well as landscape pressure from the EU facilitate the dominance of green hydrogen export from Norway over blue hydrogen. As demand for hydrogen increases and large-scale LH_2 ocean tankers become available around 2030, the green hydrogen market expects new entrants like Green H2 Norway to emerge and compete with Yara. Equinor is expected to join the competition in the green hydrogen export market from 2040 onwards when floating offshore wind turbines are commercially mature.

<u>Increased focus on CCS scenario: High EU commitment & High gas availability</u>

The narrative for the *Increased focus on CCS* scenario assumes similar landscape pressures from the EU as that of the *Global synergies* scenario, due to strong climate change commitment. As such, hydrogen deployment in EU is likely to follow the ambitious scenario of the Europe hydrogen roadmap, with annual demand reaching 57 MT by 2050 (FCH JU, 2019). Unlike in the previous scenario, Norway is expected to make new discoveries of commercial gas fields which delays the inevitable depletion of its reserves to beyond 2050. Faced with stricter restrictions on the import of fossil fuel in EU, the incumbent in Norway leverages on its lobbying power to persuade the EU to compromise for a *SMR-/ATR-dominant* scenario under its hydrogen roadmap for hydrogen production until 2050 (FCH JU, 2019). The scenario assumes a 85% mix of blue hydrogen and 10% mix of green hydrogen in 2050 for application in the power, heating and industrial sectors, whereas for the transport sector, the mix is equally split between blue and green hydrogen (FCH JU, 2019). Furthermore, CCS is assumed to be both feasible and politically acceptable, and blue hydrogen is expected to be cheaper than green hydrogen. Against this background, the key landscape, regime and niche factors in Norway energy export market are listed below:

Table 9: Increased focus on CCS scenario in 2050 from a MLP perspective

MLP levels	Key factors
Landscape	• Deep decarbonisation of the EU • Rising carbon prices in the EU • Cutback on fossil fuel funding by EIB • Demand for hydrogen increases gradually from 2025 onwards
Regime	• Natural gas resources will last beyond 2050 • Increased focus on CCS developments by incumbents • Strong support for blue hydrogen market by incumbents
Niche	• Green hydrogen production technologies reach maturity by 2030 • Infrastructure for hydrogen storage and export will be ready in 2030 • CCS reaches maturity earlier, before 2030 • Blue hydrogen is expected to be more price-competitive than green hydrogen until 2050

The dynamics of the transition of the energy export market from fossil fuel-based to hydrogen-based in Norway is assumed to follow the MLP's transformation pathway until 2050. In this pathway, very few institutional changes will be expected and Equinor is expected to dominate the regime the whole period until 2050. Under moderate landscape pressures from the EU, a partial reorientation is expected to take place in the form of higher investments to speed up the maturity of CCS technology. In tandem, in anticipation of the falling demand of natural gas in the EU, more resources are allocated for the further expansion of Norway's LNG export capacity in order to focus on the international LNG markets, particularly Asia where market prices are higher, and demand is expected to grow.

While both blue and green hydrogen production technology reach commercial maturity at around the same time in 2030, export volumes of green hydrogen are expected to be modest throughout the period up to 2050 due to it being less price-competitive than blue hydrogen. Green hydrogen will remain a niche until Equinor takes the lead to reorient the regime towards it when the full depletion of natural gas resources in NCS become apparent.

Inevitable transition scenario: Low EU commitment & Low gas availability

Underlying this scenario is the assumption that EU will miss the current 2030 climate goals, making it very unlikely to achieve the climate goals of 2050. Taking a gradual approach in its energy system transition, the deployment of hydrogen in EU is likely to pursue the business-as-usual scenario where hydrogen demand in the EU reaches less than half of the two previous scenarios, with only 20 MT by 2050, and production process is dominated by SMR/ATR with CCS (FCH JU, 2019). On the other hand, as the EU policymakers plan a phase-out of coal plants which have become increasingly unprofitable due to falling LCOE of RE and rising carbon prices, natural gas demand is expected to increase. Since Norway fails to discover new gas resources to maintain the production levels at current rate, the natural gas resource levels are expected to decline from 2023 onwards. In anticipation of this, the EU reduces its imports from Norway and increasingly imports natural gas from other suppliers. The combination of these factors causes the regime to lose faith in the oil and gas sector by 2023, paving the way for MLP's de-alignment and re-alignment pathway. The key drivers at each MLP levels are presented in Table 10.

Table 10: Inevitable transition scenario in 2050 from a MLP perspective

MLP levels	Key factors
Landscape	• EU misses its 2030 climate goals • Rising carbon prices in the EU forces coal plants to be phased out by 2030 • Cutback on fossil fuel funding by EIB • Demand for hydrogen increases gradually from 2030 onwards • Rising climate change awareness among youths in Norway
Regime	• Depletion of natural gas resources from 2023 onwards • Regime lose faith in the Norwegian oil and gas sector by 2023 • Struggles and tensions are expected between multiple groups and constituencies until new institutions are established to replace the old ones
Niche	• Competition intensifies between niche-innovations offering alternative energy export solutions • Green hydrogen production technologies reach maturity by 2030 • Infrastructure for hydrogen storage and export will be ready in 2030 • CCS reaches maturity in 2030 • Blue hydrogen is expected to be more price-competitive than green hydrogen until 2050

Following the de-alignment and re-alignment pathway, the destabilization of the oil and gas sector leads to a collapse of the regime, causing tensions and struggles to arise between various groups advocating for the rapid development of alternative niche-innovations to fill in the vacuum. These niche-innovations in RE export mainly consist of green hydrogen, onshore wind electricity and offshore wind electricity. Meanwhile, at the institutional level, the Norwegian government takes on an active role in lobbying for a faster energy transition in the EU so as to create market opportunities for its niche-innovations.

Among all the niche-innovations, onshore wind is the most mature, but as mentioned in Section 6.4.1, major public protests against onshore wind are likely to prevent it from further development after 2025. Green hydrogen and infrastructure-related technologies are expected to mature by 2030, whereas offshore wind electricity is likely to mature only in 2040. Based on this, green hydrogen has the highest potential to gain dominance before offshore wind, but export volumes will be limited due to the slow pace of energy transition in the EU.

Slow transition scenario: Low EU commitment & High gas availability

The slow transition scenario explores an energy future where the EU misses its climate targets for 2030 and the 2050 climate goals become unreachable. The deployment of hydrogen in EU is assumed to follow the business-as-usual scenario envisioned in its Hydrogen roadmap, with a modest annual demand of 20 MT by 2050, produced mainly via SMR/ATR with CCS (FCH JU, 2019). Meanwhile, Norway is expected to make new discoveries of commercial gas fields in the next five years, which adds certainty that the natural gas resources will last beyond 2050. However, as a finite resource, the depletion of natural gas resources is only a matter of time and there is still a need for Norway to restructure its economy for a post-fossil fuel future. Against this background, the transition in Norway will likely follow the MLP's transformation pathway but at a slower pace than the other scenarios, where fossil fuel export dominates the energy export market and institutional changes are minimal up to 2050. Table 11 highlights the key drivers affecting the development of hydrogen export in Norway at each of the MLP level.

Table 11: Slow transition scenario in 2050 from a MLP perspective

MLP levels	Key factors
Landscape	• EU misses its 2030 climate goals • Rising carbon prices in the EU forces coal plants to be phased out by 2030 • Cutback on fossil fuel funding by EIB • Demand for hydrogen increases gradually from 2030 onwards
Regime	• Natural gas resources will last beyond 2050 • Prioritised allocation of resources for further offshore activities in the Barents Sea • Incumbents continues in investing in new niche-innovations for post-2050 transition
Niche	• Green hydrogen production technologies reach maturity by 2030 • Deployment of hydrogen storage and export infrastructure are expected only after 2040 • CCS reaches maturity in 2030 • Blue hydrogen is expected to be more price-competitive than green hydrogen until 2050

Following a transformation pathway, Equinor is expected to continue investing in niche-innovations like CCS, blue hydrogen and offshore wind as part of its strategy to reorient its portfolio towards a post-2050 future with low oil reserves. However, the pace of reorientation may be slower than the other three scenarios as the development of fossil fuel infrastructure in the Barents Sea may be prioritised in terms of resource allocation over other technologies.

In view of the limited demand of hydrogen imports in the EU, the market for hydrogen in Norway is likely to be dependent on domestic demand and the presence of a petro-industrial complex is likely to favour the prospects of blue hydrogen over green hydrogen. The deployment of green hydrogen infrastructure for storage and export may be delayed until floating offshore wind turbines reach technological maturity in 2040. In the meantime, green hydrogen will be produced to meet domestic refuelling needs of a small fleet of hydrogen trucks.

7.2 Prospects of blue and green hydrogen in Norway in 2050 for energy export

Compared to the last wave of enthusiasm of hydrogen in mid-2000s in Norway, there has been a broadening of options for hydrogen applications across multiple sectors, as well as a variety of alternative options for its storage and transport. In particular, the possibility of using ammonia as a hydrogen carrier for storage and transport means that it is technically feasible to start exporting green hydrogen now, and that a large-scale export of hydrogen is foreseeable in the next 5 years. Several positive hydrogen-related news in the last 2 years show signs of acceleration in this area, such as the plans for large-scale electrolysis-based hydrogen plant in Norway, and the launch of the first ocean tanker for LH_2. From a technological perspective, Norway is well-positioned to be a forerunner in this market.

From an economic perspective, blue hydrogen is likely to grow more rapidly than green hydrogen in the short term. However, based on the estimated remaining reserves of natural gas in both discovered and undiscovered fields, Norway is likely to run out of its reserves faster than its competitors like Russia and Qatar. Hence, there is a need for Norway to strategize for an eventual phase-out of blue hydrogen in order to pave the way for green hydrogen and remain relevant as an actor in the global energy market.

The different outcomes that arise from the four scenarios in the last section underline the significance of variations in the timing and nature of the interactions between the three MLP levels. Table 12 provides a summary of these different prospects.

Table 12: Summary of prospects of hydrogen export in Norway

Scenarios	Summary of prospects of hydrogen export in Norway
Global synergies	• Diversification of regime portfolio with blue hydrogen export until 2030. • Substitution of both natural gas and blue hydrogen export by green hydrogen from 2030 onwards.
Increased focus on CCS	• Diversification of regime portfolio with blue hydrogen export until 2050 • Green hydrogen production remains limited to domestic applications towards 2050.
Inevitable transition	• Collapse of the natural gas export regime by 2023 due to major internal problems. • Increased tensions and struggles between various groups until 2030. • Green hydrogen arises as the dominant energy export from 2030 onwards.
Slow transition	• Hydrogen export market is expected to be immature by 2050. • Limited production of both blue and green hydrogen until 2050 for domestic applications, with blue hydrogen dominating the market share.

From the various pathways, it is observed that the green hydrogen is expected to play an increasingly dominant role in a low-carbon energy system and that the pace of growth is dependent on the availability of natural gas reserves in the NCS. However, from a climate perspective, the *Global synergies* and *Inevitable transition* scenarios represent the highest possibility for achieving the GHG emission reduction targets, whereas the *Slow transition* scenario implies a delay in climate action and further acceleration of climate change impacts which could be irreversible.

Furthermore, the *Global synergies* and *Inevitable transition* scenarios highlight the need for rapid development of floating offshore wind turbines by Equinor to mitigate the risk of lack of significant new discoveries in the NCS and the risk of drastic changes in the EU climate policies. Failure to do so could lead to the substitution of the regime actor by new entrants like Yara or Green H2 Norway.

Before more investments is poured into further offshore activities, it is important to note that it takes 25 years for an industrial sector and all its value chain to be fully transformed (European Commission, 2019). Assuming that EU is highly committed to becoming carbon-neutral by 2050, drastic changes in its climate and energy policies should be expected in the next 5 years. Also, taking into consideration of the average lead time for developing new fields (16 years), there is a risk that the value of natural gas will be lower by the time the new fields are developed.

In addition, it should be noted that a number of the technologies that are assumed to be technically available in the scenarios have not been commercially demonstrated at large-scale. In particular, the technical and economic viability of CCS applications in industrial sites have yet to be proven, and the closure of two natural gas power plants that attempted to implement CCS in Norway puts in question the cost advantage of blue hydrogen over green hydrogen production.

7.3 Recommendation for future research

Given the complexities in the export value chain of hydrogen, the structure framework of PESTEL analysis was particularly useful for capturing the various uncertainties. At the same time, the categorical structure proves a little too rigid to link the key agencies in a chronological manner. This results in the weakening in the link between the findings from PESTEL analysis and the exploratory scenarios. The inclusion of interviews with key actors and experts in Norwegian energy policies and hydrogen developments for the construction of the narratives, could be one possible way to overcome this weakness. In addition, for a deeper understanding of the prospects of blue and green hydrogen, it would be useful to include an assessment of the geographical distribution of the natural resources as well as the end-use applications.

8.0 Conclusion

Due to the ubiquity of hydrogen and its versatile applications across sectors, blue and green hydrogen is expected to play a critical role in a low-carbon energy system in the next 30 years, especially if the EU is expected to be carbon neutral by 2050. Since majority of Norway's oil and gas exports are dependent on the EU, this will have serious implications for the future of its petroleum sector, notably for gas due to transport challenges. At the same time, the expectation of Norway's natural gas production to peak in mid-2020s and the lack of significant discovery of new oil and gas fields add further uncertainties concerning future of its energy export market.

On the other hand, the higher demand for hydrogen due to a deep decarbonisation of EU's economy presents a great market opportunity for which Norway can tap into. For both blue or green hydrogen, Norway is well-positioned in terms of natural resources availability, existing compatible infrastructure and technological expertise, to become a market leader in the export of hydrogen.

Based on the scenario analysis, the role of green hydrogen in a low-carbon energy system is likely grow more significantly as natural gas reserves in the NCS depletes. However, to maintain Norway's role in EU's energy system, it is critical to plan a strategy to phase out blue hydrogen and pave the way for increasing demand of green hydrogen in the EU since Norway is likely to run out of its natural gas reserves before its biggest competitors, Russia and Qatar.

Overall, while blue hydrogen allows Norway to preserve its petro-industrial complex, it seems that green hydrogen offers better prospects for a more sustainable energy export regime. As Sir John Browne, the chief executive officer of British Petroleum in 1997 has famously said, "The time to consider the policy dimensions of climate change is not when the link between greenhouse gases and climate change is conclusively proven but when the possibility cannot be discounted and is taken seriously by the society of which we are part"(Romm, 2004, p. 134). Judging from the recent trends on EU energy politics and Norway's petroleum reserves status, that time may be now.

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